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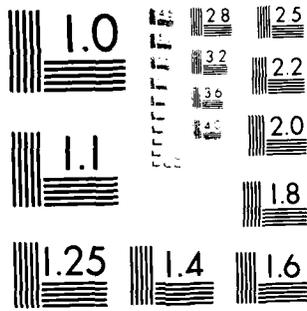
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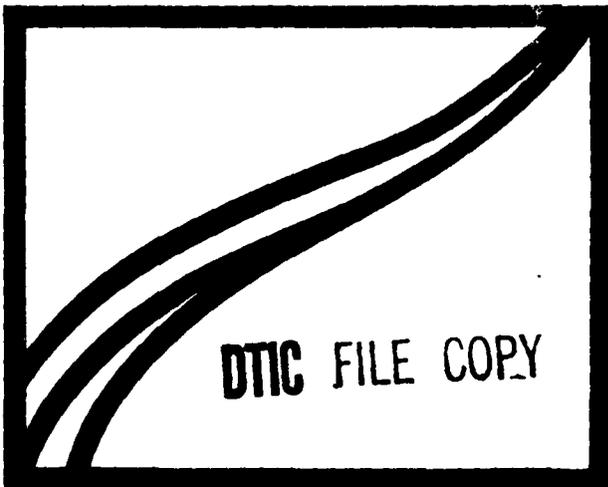
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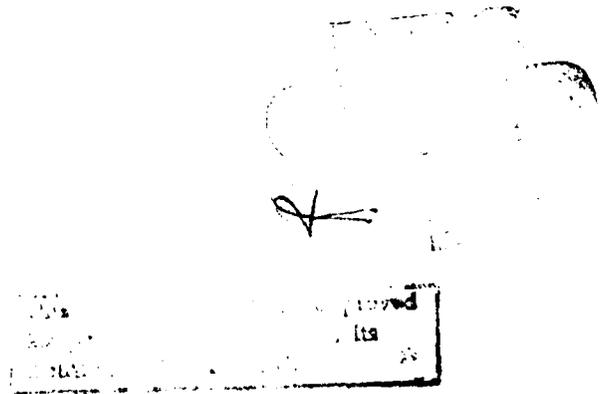
# Symposium on Wood Moisture Content - Temperature and Humidity Relationships

Virginia Polytechnic Institute and State University, Blacksburg, Virginia, October 29, 1979

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## PREFACE

The interaction of wood and moisture is fundamental to wood processing, wood properties, and the performance of wood products. If wood did not contain moisture, it would be a totally different material in terms of how it is processed and used. For the most part, the presence of moisture in wood creates problems and undesirable characteristics. Large amounts of time, energy, and degraded wood are consumed in removing water from wood before it can be used for most products. Subsequent shrinkage and swelling of wood create performance problems in wood products.

The purpose of the Symposium is to, first, examine our basic understanding of how moisture is held in wood and the factors that determine the quantity held. The second objective is to examine the practical effects of moisture in wood and how they influence processing, properties and performance. In all of the papers presented, the authors have been asked to identify gaps in knowledge and fruitful research areas wherever possible.

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THE HYGROSCOPIC NATURE OF WOOD<sup>1/</sup>

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Fort Collins, Colorado

When I first heard the title of this Symposium, two long-time friends immediately came to mind. These old friends are a couple of figures that have been around a long time and are probably familiar to most of you too—but I daresay for not so long a time. I refer first to the plotting of a series of isothermal curves for equilibrium moisture content of wood versus relative humidity (or relative vapor pressure of water) as shown in figure 1. We all know this figure, from Al Stamm's book on Wood and Cellulose Science, I'm sure. It tells us that EMC, at a given level of relative humidity, is inversely related to temperature. Need I explain that moisture content in wood is expressed on the basis of mass of removable water per unit mass of oven-dry wood?

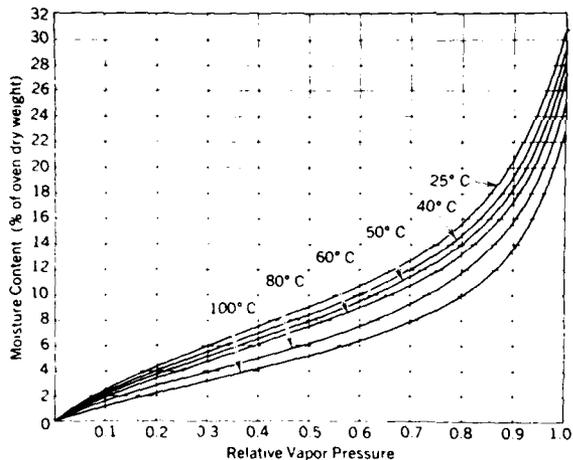


Figure 1.-- EMC of wood versus relative vapor pressure at different isothermal levels.

Stamm: Wood and Cellulose Science

The second figure that came to mind is more complicated and not so well known or understood. It introduces into the first relationship another term -- absolute vapor pressure. We see how these parameters interact in figure 2.

<sup>1/</sup> Presented at Symposium on Wood Moisture Content -- Temperature and Humidity Relationships, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, October 29, 1979.

I was particularly careful in selecting the caption for this figure for this Symposium. Many years ago I included the same graph in Section 29 on Wood for Mantell's Engineering Materials Handbook (McGraw-Hill, 1958) and went off to the Philippines on sabbatical leave. To my chagrin, much later, when I received my copy of the handbook I discovered that this figure, which I regarded as so important, bore the caption "Recommended moisture-content averages for interior-finishing woodwork for use in various parts of the United States." Where that came from, or how this figure could possibly be interpreted as recommending anything, I'll never know. But I am certain that its usefulness to readers of that handbook was seriously damaged.

Let's look now at figure 2 more carefully than a McGraw-Hill editor did back in 1958. In this figure, individual levels of EMC are plotted on a rectangular grid of relative humidity (ordinate) and temperature (abscissa). From the slight positive slope of the EMC lines we see that, to maintain any given level of EMC, it is necessary to increase relative humidity as temperature increases. We can visualize the same thing from figure 1 by projecting a horizontal line (representing a given level of EMC) to the right so that it crosses successive isotherms of higher temperature. At each successive isotherm relative vapor pressure is higher.

The new insight to be derived from figure 2 comes from recognizing the effect on EMC of increasing temperature while holding absolute vapor pressure constant. For example, at 30° F and 60% relative humidity, EMC is about 11%. Absolute vapor pressure is about 0.100 in. of mercury. Now, if temperature alone is increased, let's say to 75° F, EMC drops to less than 3%. How does this come about? The slope of those constant EMC lines is really not all that great. Were 60% relative humidity to be maintained, EMC would drop only about 1/2 percent. The key, of course, is that as temperature increases to 75° at constant absolute vapor pressure, relative humidity drops from 60% to about 12%. The latter kind of change with temperature is by far more common than the former. I find figure 2 a lot more useful than figure 1 for this reason. It is relevant to what happens in our homes, offices, and factories, in

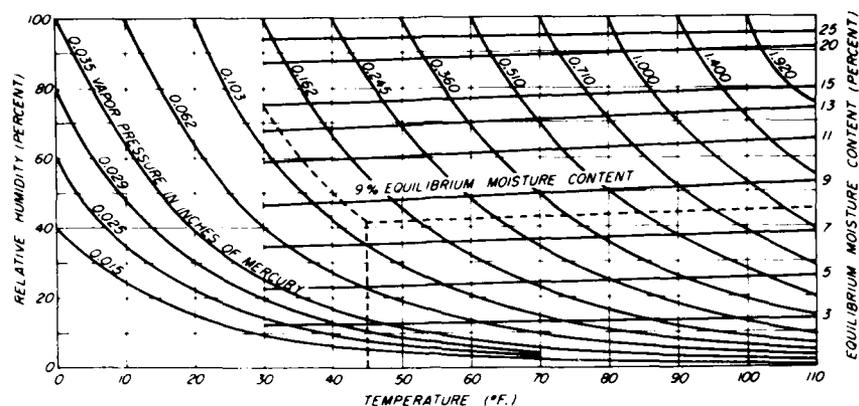


Figure 2. -- EMC of wood in relationship to relative humidity, absolute vapor pressure of water, and temperature.

USDA Forest Products Laboratory

northern winters at least, when heating is not accompanied by humidification. If next winter we heat our buildings to a maximum of 65° F, as mandated under President Carter's energy conservation guidelines, moisture content would not drop quite so low -- a bonus that I doubt the administration has given much thought to. But no more of this -- you will be hearing more from other interpreters of these relationships more competent than I am.

We have been looking at some evidence of the hygroscopic nature of wood -- its affinity for moisture -- and now may be the time to look more closely at the actual interactions that take place between wood substance and water. The cell walls of wood are organized as a structural system involving filamentous microfibrils, mostly cellulose and crystalline in composition, and oriented essentially in the direction of the longitudinal axis embedded in an amorphous matrix of noncrystalline cellulose, hemicelluloses, and lignin. The molecules in the amorphous regions, primarily because of the prominence of -OH groups in their structure, are all capable of forming hydrogen bonds. Unlike the close-packed cellulose chains in the crystal lattice within the microfibrils, they are accessible to water molecules through diffusion from the surrounding atmosphere. Water molecules are themselves highly susceptible to hydrogen bonding. The intermolecular hydrogen bond that develops between them when a water molecule approaches within 0.3 nm (we used to say 3Å) of the attractive site on the polymer is the basis for the hygroscopicity of wood. The adsorbed water is "bound" to molecular surfaces within the polymer matrix which expands in proportion

to the quantity of water adsorbed. The microfibrillar network is distended, mostly laterally, and we observe that the wood swells.

The forming of a hydrogen bond releases energy in the form of heat and conversely its disruption requires an input of energy -- mechanical, thermal, chemical, etc. The energy of the bond is expressed by differential heat of adsorption -- the total energy released when one mol of liquid water is added to an infinite amount of wood substance. Initially, when the wood substance is bone dry, the released energy amounts to approximately 5 kcal per mol. As moisture content increases, the amount of energy released per mol of added water decreases, indicative of the operation of lesser attractive forces such as van der Waals forces. At 12% moisture content, differential heat of adsorption has decreased to about 1 kcal per mol. On reaching fiber saturation at about 30% moisture content, no energy is released upon further addition of liquid water.

The EMC balance between vapor and bound water -- when holding relative humidity constant but increasing temperature -- shifts toward a reduction in bound water (EMC) due to the increased thermal agitation of the interacting molecules. To maintain EMC constant, it is necessary that absolute vapor pressure be increased substantially as temperature rises. As you look back at figures 1 and 2, now, you will see the consequences of these molecular interactions.

The range of hygroscopic activity is limited to the range of equilibria between bound water and water vapor below the fiber-saturation point. Above fiber saturation, the fully swollen cell wall can take up no more water. Consequently, all moisture content change occurs through the addition or subtraction of free water held in the cell cavities.

Green wood contains considerable free water, hardwoods, for example, typically averaging about 80% in total moisture content, but this is far below the fully-saturated condition when all cell cavities are completely filled with water. All wood cells are "born" under conditions of full saturation -- with moisture content ranging in the hundreds of percent -- hence nature has emptied many of those cells through capillary-imposed forces of liquid tension as they are neatly removed from the active conducting system in the tree. Our processes of drying wood merely complement the job already done by nature. However, I must admit she left us the hardest part to remove!

What are the problems of moisture in wood? You are going to hear much about them in this Symposium. They cover the spectrum from drying wood through all phases of processing and distribution to the installation and protection of the finished product. It is hardly necessary to stress their importance.

A long time ago I presented a paper titled "How Wood Absorbs and Swells" at a seminar on Dimensional Stabilization of Wood held at the Forest Products Laboratory in Madison. It was a straight-forward technical discussion of the phenomena of swelling and shrinking. After the symposium, the editor of a Canadian trade journal asked for a copy of my paper so that he could consider it for publication. He did publish it (Canadian Woodworker, May 1959) and it appeared under the somewhat ambiguous title "What You Should Know About Wood" -- a title rather lacking in keywords as bibliographers might point out. Spread prominently across the top of the title page was the threatening admonition: "This could affect your job!" I do not doubt the truth of that one bit. Jobs and markets too, have undoubtedly been affected -- I mean literally lost -- by neglect on the part of manufacturers, distributors, suppliers, designers, architects and builders to consider the consequences of improper control of moisture content, of inadequate measures to accommodate unavoidable moisture variation in their processing, storing, handling, and use of wood and wood-based materials. Nor

should we overlook misuse by the ultimate user of wood, largely due to his lack of awareness of the problems of wood and moisture.

The specialists who will speak to you this morning and this afternoon will be addressing some of these problems. But to cover all of them would take more than one day.

AD-P003 435

PSYCHROMETRIC RELATIONSHIPS AND EQUILIBRIUM  
MOISTURE CONTENT OF WOOD AT TEMPERATURES  
UP TO 100°C<sup>1</sup>

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ABSTRACT

The response of wood to its temperature and humidity environment is extremely important in efficient utilization of wood, as many properties and characteristics (such as shrinkage, machinability, and strength) vary with relative humidity. Historic data is reviewed and factors affecting wood's response in the temperature range of 32° to 212°F (0° to 100°C) are discussed.

HISTORIC RELATIONSHIPS

The relationship between the moisture content of wood and the humidity in the environment is an extremely important relationship with practical significance. Many characteristics and properties of wood in-use are affected by changes in moisture content, and thereby changes in humidity; some such properties include strength, weight, size, dimensional stability, and machinability.

In the United States, the most widely used expression of the relationship between moisture content and relative humidity is published by the U. S. Forest Service's Forest Products Laboratory (US FPL 1974). This data, called US FPL data hereinafter, was obtained in the early 1900's and is based on a few data points primarily from spruce shavings in initial (first time dried), oscillating (the relative humidity during the test varied ±1, or more, about the mean during the test) desorption. This spruce data was supplemented by data from other species.

<sup>1</sup>Paper presented at the "Symposium on Wood Moisture Content, Temperature, and Humidity Relationships," Blacksburg, VA, October 29, 1979.

These data were graphed, curves drawn, and the familiar tabular data obtained. Simpson (1971b) has fitted these tabular data to several desorption models to provide the data in a computer adaptable form.

Although today we might question the adequacy of these data for all uses, the original intent was to collect desorption data for kiln drying research. The past half century has shown the adequacy of these data.

In addition to the US FPL data, other government laboratories have conducted similar experiments and have produced similar data. The compilation (Table 1) permits comparison of these data.

PSYCHROMETRIC OBSERVATIONS

In the U. S. psychrometric data are obtained with a wet and dry bulb thermometer exposed to air velocities in excess of 600 feet per minute (3 m/s). The wet and dry bulb temperatures are converted to relative humidity by the established empirical data from the U. S. Weather Bureau's Bulletin No. 28<sup>2</sup> (Marvin 1941). Errors in this procedure are usually less than the errors of observation.

Table 1.--Wood moisture content as a function of relative humidity at several temperatures.

Source	Relative Humidity		
	30%	50%	80%
(70°F (21°C))			
US FPL	6.1	9.2	16.0
CANADIAN	6.2	9.6	17.3
GERMAN	5.9	8.9	16.4
BRITISH	7.4	10.8	17.7
(120°F (49°C))			
US FPL	5.2	8.0	14.1
CANADIAN	4.7	7.9	14.9
GERMAN	5.2	8.1	14.3
BRITISH	5.8	8.8	15.1
(180°F (82°C))			
US FPL	3.8	6.0	11.3
CANADIAN	3.4	5.7	12.2
GERMAN	3.8	6.0	11.2
BRITISH	--	6.5	12.1

Source: US FPL (FPL 1974), Canadian (Coch and Pfaff 1977), German (Hildebrand 1970), British (Pratt 1974).

A thermodynamic analysis of the wet and dry bulb thermometer is provided by Bird *et. al.* (1960, p. 649) wherein

$$\frac{t_w - t_d}{1 - \phi_2} = (DB - WB) \left( \frac{C_p}{\Delta H} \right) \left( \frac{S_c}{Pr} \right)^{2/3}$$

where

- $\phi_2$  = saturated vapor pressure of water at DB/atmospheric pressure (or mole fraction of water in saturated air)
- $\phi_1$  = mole fraction of water in air (the desired number)
- DB = dry bulb temperature, °F
- WB = wet bulb temperature, °F
- Cp = Specific heat of air, Btu/lb-mole °F
- ΔH = heat of vaporization, 18,900 btu/lb-mole at 70°F
- Sc = Schmidt number
- Pr = Prandtl number

It has also been extensively described by Lamer (1972).

#### FACTORS AFFECTING THE SORPTION EQUILIBRIUM

The relationship between wood moisture content (MC) and relative humidity (RH) is affected by three variables--temperature, species, and specimen history. These variables probably account for the differences noted in Table 1. The effect of these three variables is discussed in the next three sections.

#### Temperature

Increases in ambient temperature reduce hygroscopicity of wood. The decrease, at 65% RH, is on the order of 0.05 MC/°F (approx. 0.05% MC/°C). The decreased hygroscopicity also results in a lowering of the fiber saturation point (frequently, the MC at 99.5% RH). U. S. Forest Service data (Schumussen 1961) indicate at 100% RH a MC of 34% at 70°F (21°C), 27% at 141°F (61°C), and 21% at 212°F (100°C). These same data indicate a uniform reduction in hygroscopicity with increasing temperature throughout the relative humidity range. This relationship will be discussed in more detail in a following paper on sorption theories by Simpson.

#### Species

There is quite a wide variation in the MC values for various species and even within species. For example, Shear (1972, p. 21) reports that at 40°C and at 76% RH, the MC of tropical hardwoods from Venezuela varied--sapwood samples had a desorbing mean MC of 16.246% (±0.7676%); heartwood samples were 15.960% (±1.082%).

Kengert (1976) reported a range of equilibrium MC values for 8 North American hardwoods at 80°F and 80% RH of 16.5% to 19.3%.

Spalt (1958) examined the sorption characteristics of various tropical species, with the MC at 100% RH ranging from 33.6% to 21.8%.

Although the proportion of hemicellulose, holocellulose, and lignin may slightly influence the sorption behaviour between species, much of the variation is caused by extractives. Extractives reduce the hygroscopicity. A further discussion of extractives will be discussed in a subsequent paper by Spalt at this symposium.

### Specimen History

There are six major influences or treatments that can be grouped under the heading of specimen history: a) hysteresis, b) stress, c) temperature, d) mechanical, e) chemical, and f) radiation. The first of these will be discussed in detail by Skaar in a subsequent paper in this symposium; the remainder are discussed herein.

#### b. Stress

The fact that internal or external stresses affect the moisture content of wood at equilibrium is not as well known as the fact that other external factors affect wood moisture content. The equation presented by Barkas (1949) relates vapor pressure, moisture content, and the applied directional stress, and was derived using thermodynamic considerations. The theory states that wood in compression will decrease in moisture whereas wood subjected to a tensile stress will increase in moisture content.

Studies have been done using swelling restraints as a means of inducing compressive stress on wood blocks. Using steel rings as swelling restraints, Bello (1968) found an average moisture content reduction of 0.51 and 1.44 percent for restrained samples of five North American hardwoods when exposed to relative humidities of 58 and 87 percent, respectively. He also observed a greater reduction in moisture content for the denser species. The greater reduction in moisture observed with increasing humidity and density was attributed to the higher compressive stresses associated with these conditions. Bello noted that the results were in good agreement with Barkas' theory.

Simpson and Skaar (1968a) used unidirectional swelling restraint on red oak. Unrestrained samples attained a higher moisture content than samples restrained from swelling, the largest reductions occurring when the oak blocks were exposed to high relative humidities (80%), the moisture content reduction being about 0.25 to 0.50 percent. Other work by these authors (1968b) confirmed an increased reduction in moisture content due to compressive stress as initial moisture content increased, and also gave the appearance that there may be a greater reduction in moisture content at higher stress levels (Figure 1). It can also be seen from this figure that a tangentially directed stress is more effective in reducing the moisture content than a radial stress.

Simpson (1971) induced either compression or tension stresses in red oak samples. The results indicated conclusively that moisture

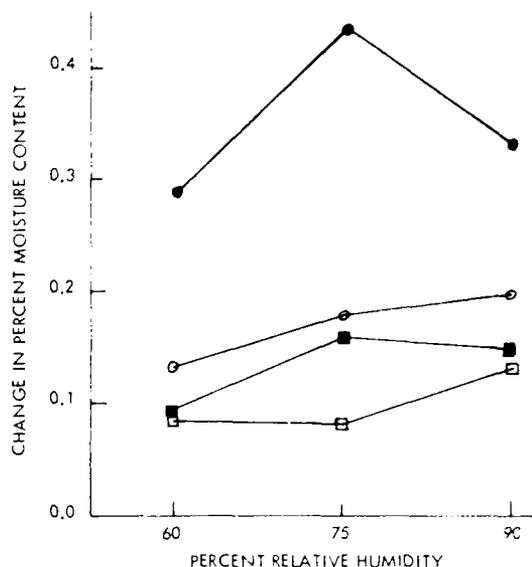


Figure 1.--Change in moisture content as a function of relative humidity. Solid circle, tangential stress at 90% fiber stress at proportional limit (FSPL); open circle, tangential stress at 60% FSPL; solid square, radial stress at 90% FSPL; and open square, radial stress at 60% FSPL (Simpson and Skaar 1968).

content decreases when wood is compressed and increased when wood is subjected to tension. The rate of moisture change per unit stress was greater for specimens loaded in tension than those loaded in compression, and the effect of stress induced moisture change was more pronounced in the tangential direction than the radial direction, as had been indicated in the previously mentioned work. The moisture change per unit stress showed no significant differences at different levels of stress. Although predicted changes in moisture contents from the Barkas theory were higher than the experimental values, application of the theory appeared to be valid.

Studies (Libby and Haygreen 1961 and Lyon 1963) on moisture changes induced by transverse tensile stresses showed that the magnitude of moisture content increase for Douglas-fir decreased with increasing initial moisture content, and that this was a greater factor in stress induced moisture changes than the stress level. The moisture content increase due to the tangentially directed tensile stress ranged from

0.02 to 0.20 percent, depending on test conditions. From these results, it was concluded that few new sorption sites are exposed at higher moisture contents when tension is applied, and that most new sorption sites are exposed at the low stress levels. Results of tension applied parallel to the grain gave an initial loss and then an increase in moisture content with time. The initial loss, the authors suggest, may be due to an increase in crystallinity.

The discussion of stress effects has, up to this point, been confined to external stresses. Stresses can result from internal factors such as moisture gradients, which if severe enough during drying will result in case-hardened lumber. Microscopic tissue anisotropy, due to rays and differences between earlywood and latewood, and microscopic anisotropy exhibited by 1) fibril orientation differences in the S1 and S3 compared to the S2, and by 2) interfibril bonds which limit swelling between fibrils, also result in causing internal stresses (Skaar 1972). Four different conditions of stress have been applied by Barkas (1949) in calculating the isotherms for spruce shown in Figure 2.

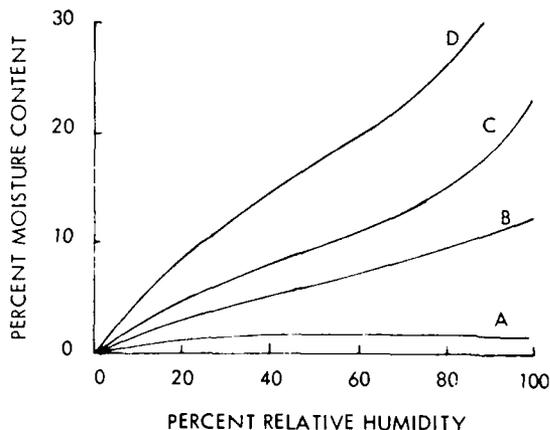


Figure 2.--Sorption isotherms calculated by Barkas (1949) for spruce. A, constant volume of cell wall; B, constant volume of gross wood; C, natural sorption; and D, stress-free sorption.

Isotherm A represents a restraining condition which keeps the cell wall at constant volume. Gross wood volume remains constant in isotherm B, so that swelling occurs in the cell cavities. The natural sorption isotherm C, depicts wood unrestrained externally, but still subject to the microscopic restraints previously mentioned.

Isotherm D includes only those stresses exerted by the microfibrils (microscopic stresses).

In summary, stress does affect the sorption isotherm. As depicted in Figure 3, a compressive force decreases the EMC while a tensile force increases it. The initial moisture content

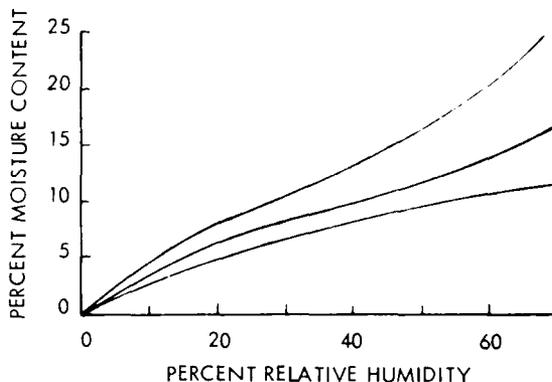


Figure 3.--Sorption isotherms for sitka spruce showing shift due to tension (upper curve) and compression (lower curve) (Skaar 1972).

at which the stress is applied is a significant factor. High moisture contents result in a greater reduction in moisture when stressed in compression, and a smaller increase in moisture when tension stresses are applied, compared to lower moisture contents. The effect that level of stress has is probably small. Compressive stresses applied in the tangential direction reduce the moisture content more than those applied radially. The rate of moisture change per unit stress is greater for specimens exposed to tension stresses than for those loaded in compression.

The effect of stress on moisture content would be present in plywood as it shrinks and swells, and large wood members as well as drying wood due to the stresses caused by moisture gradients.

#### e. Temperature

Many researchers have reported the suppressing effect exposure to high temperatures for lengthy periods of time has on the subsequent wood moisture content when equilibrium is reached. Several studies on the physical and mechanical properties of high temperature dried wood have been done and all indicate the reduction in the equilibrium moisture content (EMC) in high temperature drying is of the same magnitude.

The reduction is usually from 0.5 to 3.0 percent compared with conventional temperature kiln drying and from 1.0 to 5.0 percent when compared to air drying. The magnitude of the reduction is affected primarily by species and high temperature drying schedule, with some effect of other factors such as the conventional drying schedule used for comparison, equilibrium moisture condition, initial moisture content at start of equalizing, and extractives content. (Huffman 1977, Koch and Wellford 1977, Lozlick 1976, Richards 1958, Salamon 1963, Salamon et al. 1975, and Troxell and Luna 1972.)

Salamon et al. (1963) compared sorption for eleven different western softwoods using high temperature, conventional, and air drying methods. The reduction in hygroscopicity due to high temperature drying for amabilis fir and yellow cedar, showed a difference of 1 percent moisture content after 2 years storage. Greater moisture differences of up to 3% between conventional and high temperature drying schedules was exhibited with mountain Douglas-fir, lodgepole pine, and Western red cedar. From the isotherms generated by closely controlled sorption conditions in this same study the greatest differences occurred at higher relative humidities of 70 to 90 percent. This agrees with results obtained by Richards (1958), who noted that the magnitude of the reduction in the hygroscopicity of seven high temperature dried hardwoods was more pronounced at the higher EMC conditions.

Using small samples and heating several species at oven dry conditions, Millett and Gerhards (1972) recorded reductions in hygroscopicity for different temperatures and times. As can be seen in Figure 4, the effect of increasing time and increasing temperature resulted in decreasing EMC. Although not shown here, their results also indicated that the reduction rate for the EMC was greater for hardwoods than for softwoods. Although heating wood in oven-dry conditions produced a noticeable reduction in EMC, the changes in hygroscopicity when wood is steamed or heated in water are less understood (McLean 1945 and Stamm 1964).

The reduction in hygroscopicity due to heating the wood results in some degree of dimensional stabilization. Stamm et al. (1955) expressed the reduction in hygroscopicity as the antishrink efficiency, as determined by weight changes in relative cycles from 30 to 90 percent. Figure 5 shows the antishrink efficiency plotted against heating temperature. This graph indicates the linear increase in antishrink efficiency (reduction in hygroscopicity) with increasing temperature for a given time, as well as the effect of increasing time on reducing hygroscopicity.

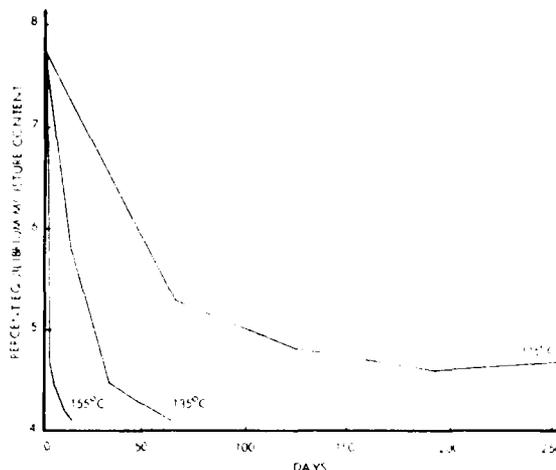


Figure 4.--Average equilibrium moisture content of six species as a function of exposure time and temperature (Millett and Gerhards 1972).

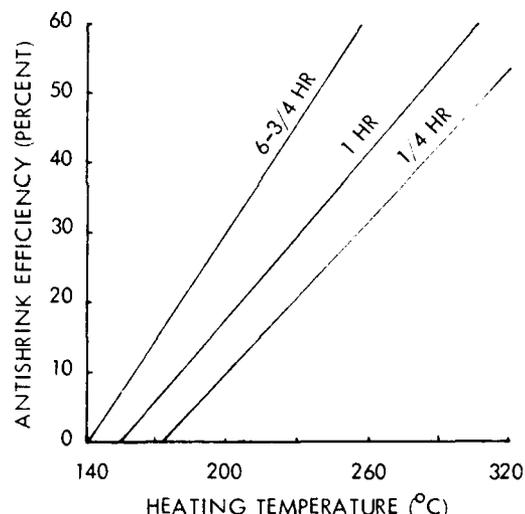


Figure 5.--Antishrink efficiencies obtained by heating western white pine cross-sections 1/2 inch thick under molten metal at different temperatures for different periods of time (Stamm et al. 1946).

Currently, the widely supposed reason for the thermal induced reduction in hygroscopicity is the hydrolysis reaction in the degradation of the hemicellulose which results in the destruction of sorption sites. Other explanations have been offered such as a moisture content reduction due to large drying stresses created during high temperature drying, or a hysteresis effect created in the high temperature kiln.

When wood is heated (as opposed to dried), it can be seen that the reduction in hygroscopicity when wood is boiled in water or steamed has been less explored and is thus less well known. There is an effect due to species, perhaps due to extractives content, and it appears that the rate of reduction in hygroscopicity is larger for hardwoods than for softwoods. Work conducted by Stamm et al. (1955) indicates that the reduction in hygroscopicity due to thermal treatment will last indefinitely.

The shift in the sorption isotherm would be expected to occur for other heated products such as heated veneer logs, plywood, particleboard, and charcoal.

#### d. Mechanical

Mechanical treatments refer to the mechanical breakdown of solid wood. As the wood is broken down, it becomes slightly more absorptive. Stamm (1964) speculates that mechanical breakdown may cause a breakdown of the crystallinity at the surface of the fibers. However, at 75% RH, the increase in absorptivity is only 1/2% MC for loblolly pine that is thoroughly beaten.

#### e. Chemical

Chemical treatments can affect wood and its sorption properties in many ways by modifying the extractives and/or cellulose constituents.

As extractives are removed, increased hygroscopicity will be noted, unless the extractives are more hygroscopic than the wood.

One of the most influential treatments increasing hygroscopicity (Stamm 1964) is the treatment of pulp with a strong alkali. Increase of 1.3 to 1.5 times greater hygroscopicity at high humidities were noted.

#### f. Radiation

The effect of gamma radiation on Sitka spruce wood shows a distinct decrease in hygroscopicity (on the order of 1 to 2% MC with a radiation of  $10^8$  rads) (Paton and Hearmon 1957).

### IMPLICATION OF SORPTION ISOTHERM VARIATION

Initially, we stated that the relationship between moisture content and relative humidity is extremely important. Yet, as shown by many researchers, the relationship is affected by many variables. In many in-use situations, the standard US FPL data may be sufficient. However, it is clear that this data is sufficiently generalized that it does not apply to several

current situations--high temperature dried softwood dimension lumber, many panel products, and some imported, tropical species.

High temperature dried dimension lumber, as mentioned earlier, has been shown to have decreased hygroscopicity when compared to normal kiln-dried or air-dried lumber. This in turn raises a question of determining strength related properties. Should strength be determined at a standard moisture content or should strength be determined after reaching moisture equilibrium at a specified relative humidity (without respect to the moisture content level)? Another question is the application of the 19% and 15% moisture content limits of the voluntary lumber standard used in marketing softwoods, as to reach these limits means that high temperature dried lumber is in equilibrium with higher relative humidities.

A second area of practical significance is with panel products. In addition to the strength question raised above, it is also important to realize that when panels are fabricated into items such as furniture, having all pieces--veneer, solid wood, and the panel--at the same moisture content may not assure stability as the three components may be initially at equilibrium with three different humidities.

The third area of practical significance is with those species that have high extractives and depressed isotherms. In purchase of this lumber with a moisture content specification it is necessary to specify lower moistures than with domestic hardwoods. Further, hardwood kiln schedules (which are based on "normal" isotherms) will result in unsuspected acceleration of the temperature schedule and possible degrade.

### FUTURE ISOTHERM DATA

There are probably many ways to handle the sorption isotherm variation, ranging from developing an isotherm for every piece of wood to ignoring the problem. We hope that this symposium will discuss rational approaches.

We would suggest that a series of perhaps five standard isotherms (perhaps the isotherm should be the average of ad- and desorbing) be developed to represent the range from the most hygroscopic to the least hygroscopic cases. Then wood and wood products could be indicated as behaving according to one of these standard isotherms. As processing evolves further and as specificity for wood and wood products increases, the question of how to handle the variable isotherm must be addressed.

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PSYCHROMETRIC RELATIONSHIPS AND EQUILIBRIUM MOISTURE CONTENT<sup>1</sup>  
OF WOOD AT TEMPERATURES ABOVE 212 °F

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ABSTRACT

Equations are derived to evaluate psychrometric relationships over a range of dry bulb temperatures from 200 to 500 °F and wet bulb temperatures from 100 to 210 °F. Wet bulb temperature, adiabatic saturation temperature, dew point, relative humidity, steam content, and enthalpy of humid air streams are discussed. Graphs and a chart are presented that relate relative humidities and dry and wet bulb temperatures to equilibrium moisture content of wood. The practical problems relevant to evaluation and usage of psychrometric-equilibrium moisture content interactions are discussed and several areas of future research are suggested.

NOTATION		
A	area of wetted surface, ft <sup>2</sup>	$\dot{Q}$ heat transfer rate, Btu/hr
c	heat capacity, Btu/lb °F	RH relative humidity, percent
$D_v$	diffusion coefficient, ft <sup>2</sup> /hr	SC steam content, percent
h	heat transfer coefficient, Btu/hr ft <sup>2</sup> °F	T temperature, °F
H	enthalpy, Btu/lb dry air	W mass rate of evaporation, lb/hr
$\Delta H_v$	latent heat of vaporization, Btu/lb	Y humidity based on $T_{AS}$ , lb water vapor/lb dry air
k	thermal conductivity, Btu/ft °F hr	Y' humidity based on $T_{wb}$ , lb water vapor/lb dry air
M	molecular weight, lb/lb mole	$\kappa$ mass transfer coefficient, lb/hr ft <sup>2</sup> atmos
$N_{Le}$	Lewis number, $k/cpD_v$	$\bar{\kappa}$ mass transfer coefficient, lb/hr ft <sup>2</sup> unit humidity difference
p	partial pressure of water vapor, psi	$\rho$ density
$p^*$	saturated pressure of water vapor, or above 212 °F, vapor pressure of water, psi	Subscripts
$\bar{p}$	average partial pressure of air, psi	a air
$p_t$	total pressure of drying atmosphere, psi	av average
Q	heat transfer, Btu/lb dry air	db dry bulb
		dp dewpoint

<sup>1</sup>Paper presented at the Symposium on Wood Moisture Content--Temperature and Humidity Relationships, Virginia Polytechnic Institute and State University, Blacksburg, VA, Oct. 29 1979.

f air film  
 m air-water vapor mixture  
 s at adiabatic saturation temperature  
 t total  
 T at dry bulb temperature  
 w water  
 wb at wet bulb temperature  
 wv water vapor

Psychrometry is a simple and inexpensive method to measure the relative amounts of air and water vapor in a humid air stream. The method requires measuring the actual air temperature (dry bulb temperature,  $T_{db}$ ) as well as the temperature of a wetted "sock" from which water is vaporized into a gas (wet bulb temperature,  $T_{wb}$ ). Worrall (1965) states that the psychrometer is well suited for measuring humidities up to temperatures of 500 °F.

Until recently the forest products industry had little interest in psychrometric relationships and the influence of humidity on equilibrium moisture content of wood at temperatures above the boiling point of water. This interest has been encouraged recently for two reasons: first, the increased use of high temperature kilns to dry lumber and, second, the need for energy conservation in wood processing. Moisture content control, especially important when drying lumber for furniture stock, depends on maintaining a prescribed humidity in the kiln. Also, humidity determinations are required for evaluating energy use and for energy recovery potentials from lumber kilns and veneer dryers (Corder 1976, Rosen 1979a).

Considerable experimental data have been presented to justify the theory for developing psychrometric charts below 210 °F (Wengert 1979). But psychrometric charts for temperatures above 210 °F have been based on an extension of the low temperature theory with very little experimental justification (Anon. 1976, Evans and Vaughan 1977, Zimmerman and Lavine 1964).

In this paper I derive the mathematical equations for calculating psychrometric charts, show the limitations of the equations, present high temperature psychrometric charts best suited for the conditions encountered in processing wood products (200-500 °F  $T_{db}$  and 100-210 °F  $T_{wb}$ ), and present high temperature

equilibrium moisture content (EMC) data from the literature. I also discuss the major gaps in psychrometric-EMC technology above 212 °F and where the emphasis on research should be placed to fill these gaps.

## DEVELOPMENT OF PSYCHROMETRIC CHARTS

### Adiabatic Saturation Temperature

When unsaturated air is brought in contact with water, the air is humidified and cooled. If the system is operated so that no heat is gained or lost to the surroundings, the process is adiabatic. Thus, if the water remains at a constant temperature, the latent heat of evaporation must equal the sensible heat released by the air in cooling. If the temperature reached by the air when it becomes saturated is the same as the water, this temperature is called the adiabatic saturation temperature,  $T_s$ .

When air at temperature,  $T_{db}$ , and humidity,  $Y$ , is cooled to  $T_s$  (symbols are defined in the Notation section), the air will give up a quantity of heat,  $Q_1$ :

$$Q_1 = (H_a)_T + Y (H_{wv})_T - (H_a)_s - Y (H_{wv})_s \quad (1)$$

As the air cools, its humidity increases from  $Y$  to  $Y_s$  at saturation, and the heat absorbed by the vaporization,  $Q_2$ , is:

$$Q_2 = (Y_s - Y) [(H_{wv})_s - (H_w)_s] \quad (2)$$

Because the process is adiabatic,  $Q_1 = Q_2$ , and after rearrangement:

$$Y_s [(H_{wv})_s - (H_w)_s] + (H_a)_s - (H_a)_T = Y [(H_{wv})_T - (H_w)_s] \quad (3)$$

Enthalpies are based on zero for liquid water at 32 °F [ $(:H_v)_{32} = 1075.1$  Btu/lb]; thus

$$(H_{wv})_s = (:H_v)_{32} + \int_{32}^{T_s} c_{wv} dT, \quad (4)$$

$$(H_{wv})_T = (:H_v)_{32} + \int_{32}^{T_{db}} c_{wv} dT, \quad (5)$$

$$(H_a)_s - (H_a)_T = \int_{T_{db}}^{T_s} c_a dT, \quad \text{and} \quad (6)$$

$$(H_w)_s = \int_{32}^{T_s} c_w dT. \quad (7)$$

Saturation humidity is related to the partial pressure of the water vapor at the adiabatic saturation temperature,  $p_s^*$ , for one atmosphere

total pressure (Zimmerman and Lavine 1964) by:

$$Y_s = \frac{0.6244 p_s^*}{(14.70 - p_s^*)} \quad (8)$$

For the range of conditions from 100 to 212 °F, partial pressure (fig. 1) can be accurately related to  $T_s$  by:

$$p_s^* = 1.236 \times 10^7 \exp\left(-\frac{9160}{T_s + 459.6}\right) \quad (9)$$

Values for  $c_{wv}$ ,  $c_a$ , and  $c_w$  as a series function of temperature are obtained from the literature (Appendix).

The integrated forms of Equations (4) to (7), as well as Equation (8), were substituted into Equation (3) to obtain  $Y$  as a function of  $T_{db}$  and  $T_s$ .

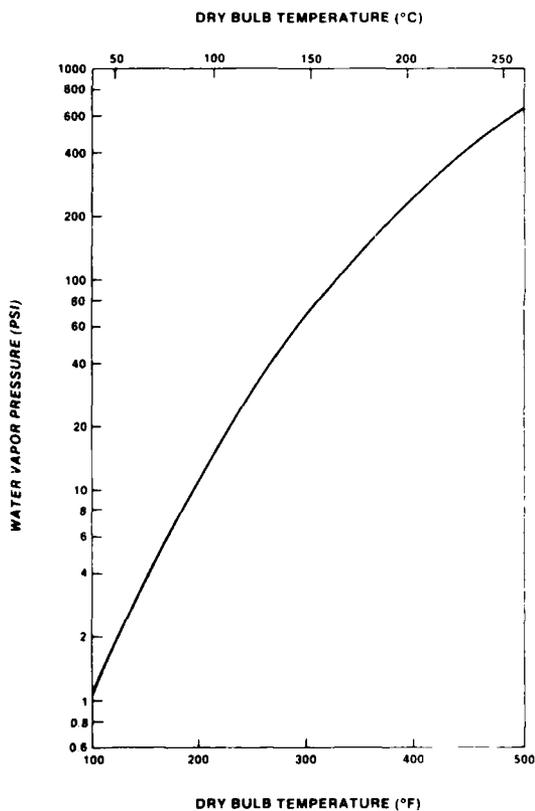


Figure 1.--Vapor pressure of water as a function of temperature (to convert psi to kPa, multiply by 6.895).

#### Wet Bulb Temperature

Unsaturated air is passed over a wetted thermometer bulb such that water evaporates from the wetted surface causing the thermometer bulb to cool (fig. 2). An equilibrium temperature,

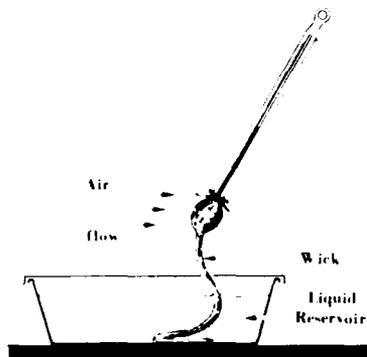


Figure 2.--Diagram of a wet bulb thermometer.

called the wet bulb temperature,  $T_{wb}$ , is reached when the rate of heat transfer from the wetted surface by convection and conduction is equal to the rate at which the wetted surface loses heat in the form of latent heat of evaporation. The heat transferred as sensible heat from the air to the wetted thermometer bulb,  $\dot{Q}_1$ , is

$$\dot{Q}_1 = h_f A (T_{db} - T_{wb}) \quad (10)$$

Heat lost by evaporation, which must diffuse through the air film that covers the wetted surface, is expressed as  $\dot{Q}_2$ :

$$\dot{Q}_2 = (\dot{H}_v)_{wb} W \quad (11)$$

where

$$W = M_{wv} A \kappa (p_{wb}^* - p) \quad (12)$$

When the partial pressure of water vapor is small compared to that of air, the following expression can be used (Treybal 1955):

$$(p_{wb}^* - p) = \frac{M_a p}{M_{wv}} (Y_{wb} - Y') \quad (13)$$

Redefining  $\kappa$  in terms of a humidity difference,  $\bar{\kappa} = M_a p \kappa$ , and combining Equations (11) to (13) yields:

$$\dot{Q}_2 = (\dot{H}_v)_{wb} A \bar{\kappa} (Y_{wb} - Y') \quad (14)$$

at  $T_{wb}$ ,  $\dot{Q}_1 = \dot{Q}_2$ . Thus,

$$Y' = Y_{wb} - \frac{h_f}{\bar{\kappa} (\dot{H}_v)_{wb}} (T_{db} - T_{wb}) \quad (15)$$

The following relationship was found to be true for dilute concentrations (Bennett and Myers 1962):

$$\frac{h_f}{k c_m} = (N_{Le})^{2/3} = \left( \frac{k}{c \rho D_v} \right)^{2/3} \quad (16)$$

Combining Equations (15) and (16):

$$Y' = Y_{wb} - \frac{(N_{Le})^{2/3} c_m}{(\Delta H_V)_{wb}} (T_{db} - T_{wb}) \quad (17)$$

Values of  $N_{Le}$  and  $c_m$  are functions of temperature and humidity (see Appendix) and  $(\Delta H_V)_{wb}$  can be represented by (Zimmerman and Lavine 1964):

$$(\Delta H_V)_{wb} = 1094 - 0.576 T_{wb} \quad (18)$$

We cannot obtain an explicit relationship between  $Y'$ ,  $T_{db}$ , and  $T_{wb}$ . Thus, Equation (17) must be solved by trial and error.

Figures 3 and 4 show plots of Equations (3) and (17) for the range of conditions from 100 to 212 °F  $T_{wb}$  and 200 to 500 °F  $T_{db}$ .

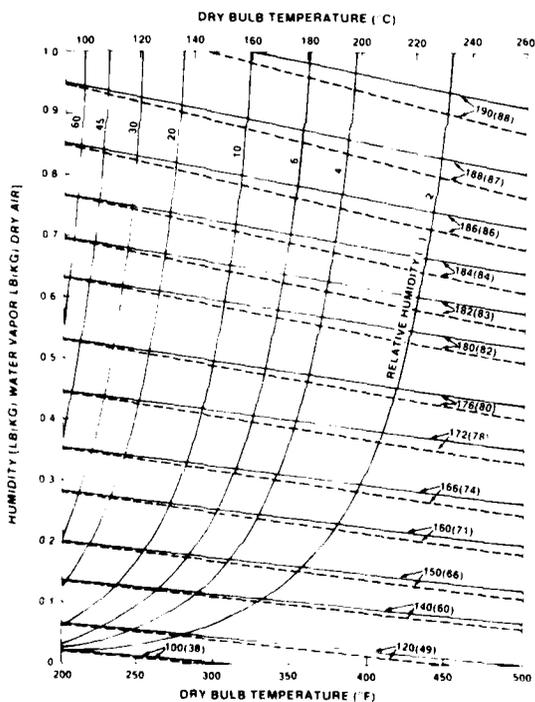


Figure 3.--Psychrometric chart for low humidity--solid horizontal lines are constant wet bulb temperature (°F/°C), dotted lines are constant adiabatic saturation temperature.

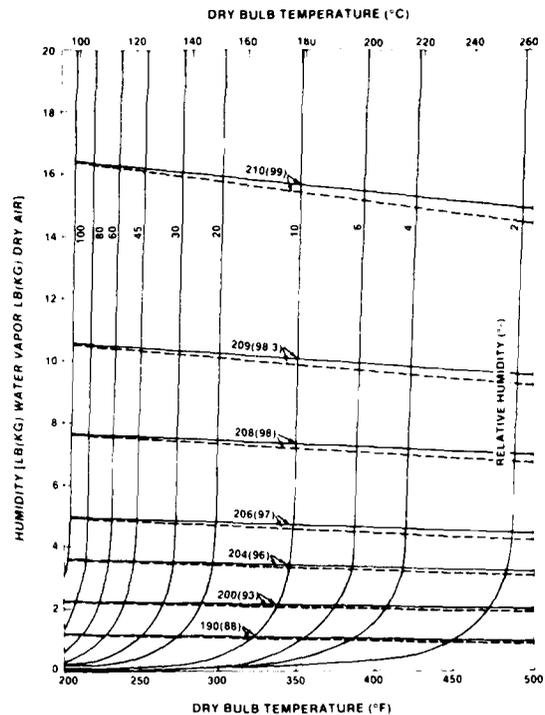


Figure 4.--Psychrometric chart for high humidity--solid horizontal lines are constant wet bulb temperature (°F/°C), dotted lines are constant adiabatic saturation temperature.

#### Comparing $Y$ and $Y'$

Equations (3) and (17) can be compared after some terms are redefined and certain assumptions are made.

Because,

$$(\Delta H_V)_S = (H_{wv})_S - (H_w)_S \quad (19)$$

or

$$(H_w)_S = (H_{wv})_S - (\Delta H_V)_S \quad (20)$$

equation (3) can be rearranged to yield

$$Y = \frac{Y_S (\Delta H_V)_S + (H_a)_S - (H_a)_T}{(\Delta H_V)_S + (H_{wv})_T - (H_{wv})_S} \quad (21)$$

Average values of heat capacities in Btu/lb °F (0.24 for air and 0.46 for water) are substituted into Equations (4) to (6), which after integration yield:

$$(H_{wv})_S = (\Delta H_v)_{32} + 0.46 (T_S - 32), \quad (4a)$$

$$(H_{wv})_T = (\Delta H_v)_{32} + 0.46 (T_{db} - 32), \text{ and } (5a)$$

$$(H_a)_S - (H_a)_T = 0.24 (T_S - T_{db}). \quad (6a)$$

Equations (4a) to (6a) can be substituted into Equation (21) to yield:

$$Y = Y_S - \frac{(0.24 + 0.46 Y)}{(\Delta H_v)_S} (T_{db} - T_S). \quad (22)$$

Equation (22) is in the same form as Equation (17) and the two are identical for  $N_{Le} = 1.0$  and  $c_m = 0.24 + 0.46 Y$ .

Because  $T_{wb}$  is usually measured in practical application, further concepts will be based on  $Y'$  rather than  $Y$ .

#### Dew Point Temperature, $T_{dp}$

The dew point is the temperature at which a given sample of moist air becomes saturated as it is cooled at constant pressure. Dew point temperatures can be evaluated by constructing a horizontal line on a psychrometric chart from a point corresponding to the original temperature and humidity to a point with the same humidity on the 100 percent saturation curve (fig. 4). The dew point also can be calculated directly by knowing the humidity:

$$T_{dp} = \frac{9160}{16.33 - \ln p_{wb}^*} - 459.6 \quad (23)$$

where

$$p_{wb}^* = \frac{14.70 Y'}{0.6244 + Y'}$$

A large difference exists between  $T_{dp}$  and  $T_{wb}$ , especially at  $T_{wb}$  below 160 °F (fig. 5).

#### Relative Humidity, RH/Steam Content, SC

Relative humidity expressed on a percentage basis is defined by:

$$RH = \frac{p}{p^*} \times 100. \quad (24)$$

Above 212 °F at atmospheric conditions, RH must be less than 100 percent because at the most  $p$  can be 1 atmosphere and  $p^*$  must be greater than 1 atmosphere. At 500 °F, the maximum relative humidity is only 2.2 percent.

A useful concept called the steam content, SC, is helpful when describing high temperature environments (Sturney 1952):

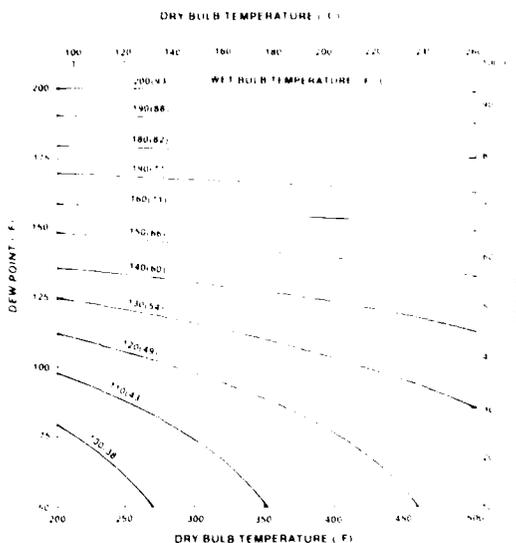


Figure 5.--Dew point temperature as related to wet and dry bulb temperature.

$$SC = \frac{p}{p_t} \times 100. \quad (25)$$

Constant SC lines are thus lines of constant partial water vapor pressure and are coincident with dew point lines.

Combining Equations (24) and (25), at atmospheric pressure,

$$RH = \frac{14.7}{p^*} SC. \quad (26)$$

Thus, the 100 percent SC line gives the greatest RH that can exist at each temperature.

#### Enthalpy, H

Enthalpy, or heat content of a substance, is generally the difference between the enthalpy at some temperature and an arbitrary temperature (32 °F in this paper). The enthalpy of a humid air stream,  $H$ , is thus

$$H = (H_a)_T + Y' (H_{wv})_T \quad (27)$$

$$H = \int_{32}^{T_{db}} c_a dT + Y' [(\Delta H_v)_{32} + \int_{32}^{T_{db}} c_{wv} dT]. \quad (28)$$

Substituting the values of  $c_a$  and  $c_{wv}$  from the Appendix, and  $Y'$  from Equation (17),  $H$  can be evaluated for the range of  $T_{db}$  and  $T_{wb}$ . For a constant wet bulb temperature, the change in enthalpy from 200 to 500 °F dry bulb temperature is small. As dry bulb temperature rises, the increase in sensible heat of the humid air is approximately equal to the decrease in latent heat due to a decrease in humidity.

The average values of  $H$  for each wet bulb temperature are within 1 percent of  $H$  values for the range of dry bulb temperatures (fig. 6).

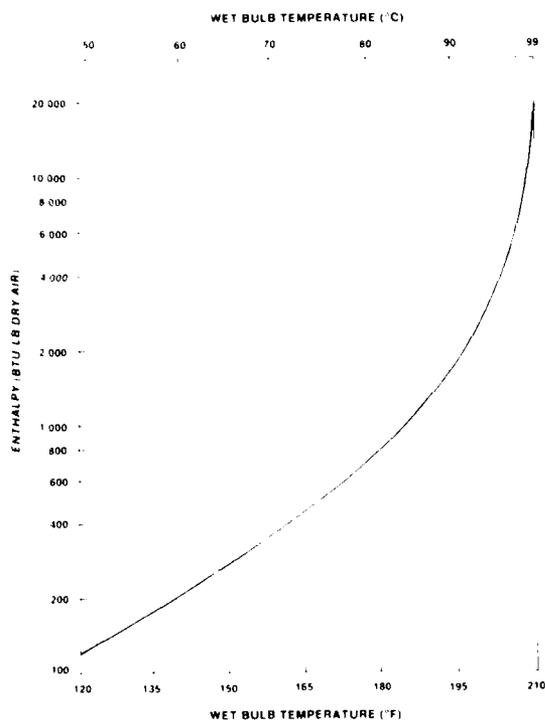


Figure 6.--Enthalpy of humid air streams as a function of wet bulb temperature (to convert Btu/lb to kJ/kg, multiply by 2.325).

#### THE RELATIONSHIP OF EMC TO WET AND DRY BULB TEMPERATURE

Much of the basic data and mathematical techniques evaluating EMC at temperatures above 212 °F were developed in the late 1940's and early 1950's in Germany and Australia (Kauman 1956, Kollmann 1961). Until recently, the only EMC data available above 212 °F was for pure superheated steam at atmospheric conditions (Hann 1965) (fig. 7). The pure superheated steam curve ( $T_{wb} = 212$  °F) represents the

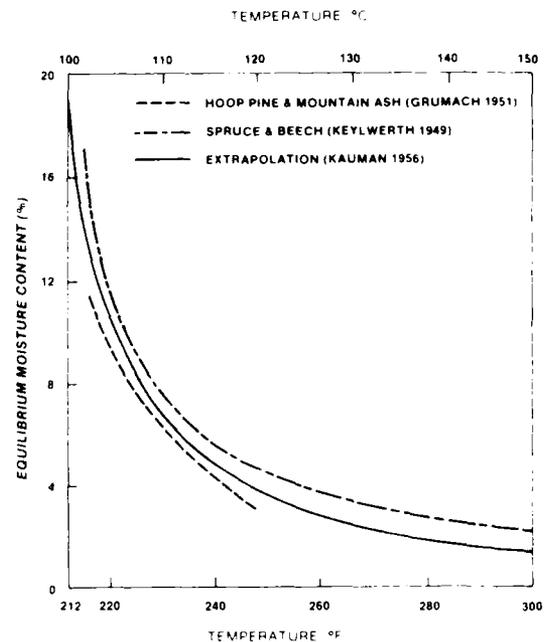


Figure 7.--Equilibrium moisture content values for wood in pure superheated steam at atmospheric pressure.

maximum EMC attainable at each dry bulb temperature. Above 212 °F, EMC drops rapidly with increasing temperature to less than 3 percent at 275 °F. Rosen (1978, 1979b) has presented EMC values for wood in air-steam mixtures (fig. 8).

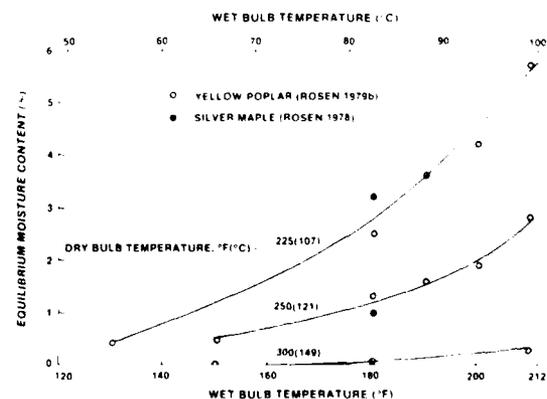


Figure 8.--Equilibrium moisture content of wood in air-water vapor mixtures (points are based on the average of 7 to 12 values).

The charts and tables in the literature (Kauman 1956, Ladell 1957) relating EMC to conditions in humid air streams above 212° F at atmospheric pressure are based on an extrapolation technique (table 1). Stamm and Loughborough (1935) observed from desorption isotherm data (fig. 9) that a plot of the logarithm of water vapor pressure against the reciprocal of absolute temperature (isosteres) for a number of different moisture contents yielded a straight line (fig. 10). Extension of the isosteres to temperatures above 212 °F agree within 1 percent moisture content of experimental data in pure superheated steam (fig. 7).

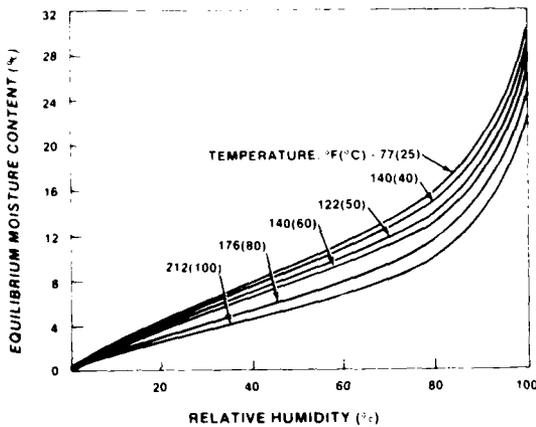


Figure 9.--Desorption isotherms at several temperatures for Sitka spruce (Stamm 1964).

To illustrate the method, find the EMC at  $T_{db}$  of 225 °F and  $T_{wb}$  of 200 °F.

$RH = 60$  percent (fig. 4)

$p^* = 18.9$  psi (fig. 1)

$$p = 18.9 \times \frac{60}{100} = 11.2, \text{ Equation (24)}$$

Thus,  $EMC = 5.8$  (fig. 10).

Several investigations also showed the extrapolation technique could be used to evaluate EMC for pressures other than atmospheric above 212 °F (Czepek 1952, Kauman 1956, Keylwerth and Noack 1964, Kröll 1951) (fig. 11). Equilibrium moisture content data for a range of pressures and temperatures above 212 °F are given in several adsorption isotherm studies (Engelhardt 1979, Noack 1959, Strickler 1968). Interpretation of EMC data at the higher temperatures is complicated by partial thermal degradation and loss of wood mass, but investigators have shown methods to correct for this loss. Separate investigators found

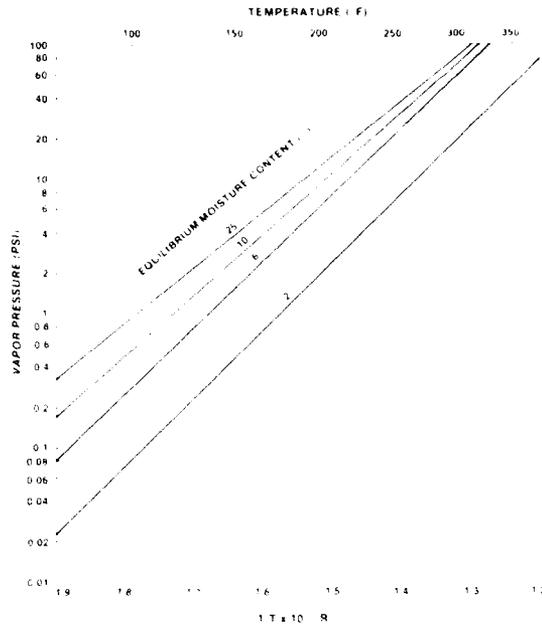


Figure 10.--Extrapolation of vapor pressure versus temperature for several EMC's.

big differences in EMC values, especially above 80 percent relative humidity, as typified by the 338 °F isotherms (fig. 12). Differences in experimental technique and wood species might account for the disparity.

#### PROBLEMS IN PRACTICAL USAGE OF PSYCHROMETRIC-EMC INFORMATION

Accurate measurement of wet bulb temperatures is more difficult at dry bulb temperatures above 212 °F than below 212 °F. The design of the wet bulb thermometer and wick must be such that the surface of the bulb remains wet and adequate humid air is circulated across the wick to ensure that all the heat of evaporation of water from the wick is transferred as sensible heat to the humid air. Wet bulb sensing devices that are adequate for low temperature operations are not necessarily adequate for high temperature operations.

Many of the psychrometric charts and tables in the literature assume that the adiabatic saturation and wet bulb temperatures are equal and neglect the change in properties of the physical parameters with temperature and humidity. Thus, humidities are calculated from relationships similar to Equation (22). Figures 3 and 4 clearly show a difference between humidities evaluated at the same  $T_s$  and

Table 1.--High-temperature relative humidity and equilibrium moisture content table  
(Kauman 1956, Ladell 1957).

Dry bulb temperature, °F/°C	Wet bulb temperature, °F/°C									
	150/66	160/71	170/77	180/82	190/88	195/91	200/93	205/96	210/99	215/100
200/93	3.3 <sup>1</sup> (32) <sup>2</sup>	4.2 (41)	5.3 (51)	6.9 (62)	10.8 (79)	14.7 (90)	20.3 (100)			
205/96	2.9 (29)	3.7 (37)	4.6 (46)	5.9 (57)	8.1 (70)	10.8 (90)	15.0 (91)	21.5 (100)		
210/99	2.6 (26)	3.3 (33)	4.0 (41)	5.0 (51)	6.6 (63)	8.4 (72)	10.8 (81)	14.5 (91)	19.7 (100)	
215/102	2.4 (24)	2.9 (30)	3.5 (38)	4.5 (47)	5.7 (58)	7.0 (66)	8.7 (74)	10.7 (82)	14.0 (90)	18.6 (94)
220/104	2.1 (22)	2.6 (27)	3.2 (34)	3.9 (42)	5.0 (52)	5.9 (61)	6.9 (67)	8.3 (74)	10.4 (82)	11.3 (85)
225/107	1.9 (20)	2.3 (25)	2.8 (31)	3.4 (38)	4.3 (48)	5.1 (56)	5.8 (62)	6.6 (67)	8.0 (64)	8.7 (77)
230/110	1.7 (18)	2.1 (23)	2.5 (28)	3.1 (35)	3.8 (44)	4.5 (51)	4.9 (55)	5.5 (61)	6.3 (67)	6.9 (73)
235/113	1.5 (16)	1.9 (21)	2.3 (26)	2.7 (31)	3.4 (40)	3.9 (46)	4.3 (51)	4.7 (55)	5.4 (61)	5.9 (65)
240/116	1.3 (14)	1.7 (19)	2.1 (24)	2.5 (29)	3.1 (37)	3.5 (42)	3.8 (46)	4.2 (51)	4.7 (56)	5.2 (59)
250/121	1.0 (12)	1.3 (16)	1.6 (20)	2.0 (24)	2.4 (30)	2.8 (35)	3.1 (39)	3.4 (43)	3.6 (47)	3.8 (49)
260/127	0.8 (10)	1.0 (13)	1.3 (17)	1.6 (20)	2.0 (26)	2.2 (30)	2.4 (33)	2.7 (36)	2.9 (40)	3.1 (42)
275/135	0.5 (8)	0.7 (10)	0.9 (13)	1.1 (16)	1.4 (20)	1.7 (23)	1.9 (26)	2.1 (29)	2.3 (31)	2.4 (32)
300/149	0.1 (5)	0.2 (7)	0.3 (9)	0.4 (11)	0.5 (13)	0.7 (15)	0.9 (17)	1.1 (19)	1.3 (21)	1.4 (22)

<sup>1</sup>Relative humidity--air-water vapor mixtures at atmospheric pressure.  
<sup>2</sup>Equilibrium moisture content for Sitka spruce.

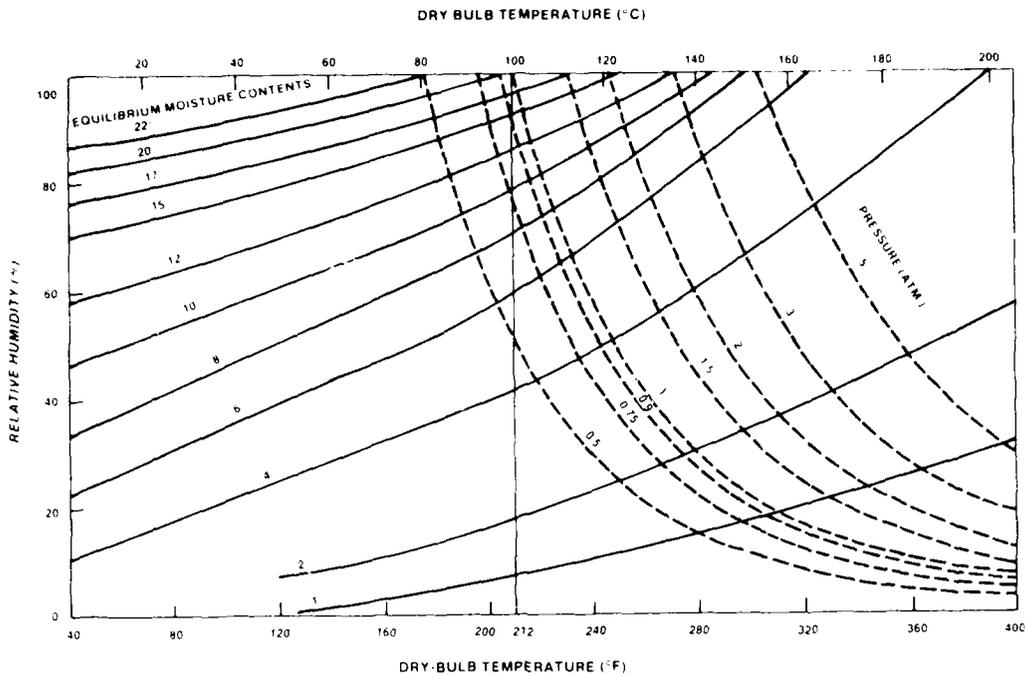


Figure 11.--Equilibrium moisture content of wood and 100 percent steam content lines at various total pressures (Kauman 1956).

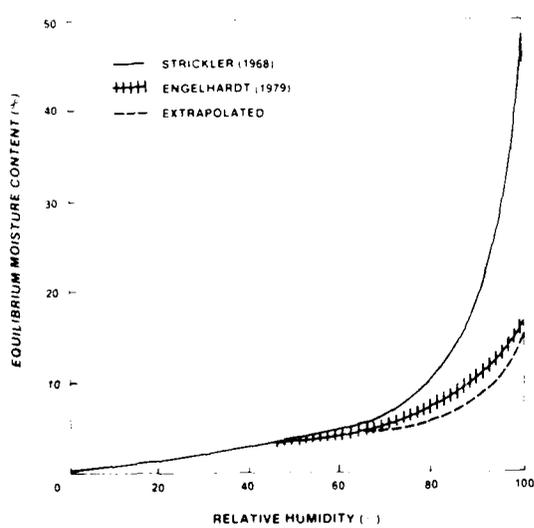


Figure 12.--Comparison of experimental and extrapolated isotherms at 338 °F.

$T_{wb}$  at  $T_{db}$  above 200 °F. Even though the analysis of this paper takes into account the changes in physical parameters with changing conditions, several relationships [such as Equations (13) and (16)] need to be examined more carefully for high humidities. Because there is minimal experimental verification of psychrometric relationship above 212 °F, the best mathematical approach for describing the interaction of  $Y'$ ,  $T_{db}$ , and  $T_{wb}$  will remain arbitrary.

The lack of EMC data and differences in existing EMC data above 212 °F is a major problem. Although the isostere extrapolations fit well for pure superheated steam at atmospheric pressure, they predict high for air-steam mixtures (compare values from table 1 with those of figure 8).

#### RECOMMENDATIONS FOR FUTURE RESEARCH

1. A simple, economical, and accurate method to measure humidity in air-water vapor mixtures at temperatures above 212 °F should be developed.
2. Experimental verification of psychrometric charts above 212 °F dry bulb temperature should be undertaken.

3. Experimental values of EMC as a function of temperature above 212 °F, humidity, and total pressure (especially at one atmosphere) need to be obtained.

#### APPENDIX

- I. Heat capacities of components as a function of temperature.

$$c_a = 0.2317 + 9.01 \times 10^{-7} T + 1.22 \times 10^{-9} T^2 - 2.78 \times 10^{-12} T^3$$

$$c_{wv} = 0.427 + 1.416 \times 10^{-5} T + 4.318 \times 10^{-9} T^2 - 8.171 \times 10^{-12} T^3$$

where  $c_a$  and  $c_{wv}$  are in Btu/lb °F and T is in °F (Hougan et al. 1959)

$$c_w = 0.991 + 8.04 \times 10^{-5} T$$

where  $c_w$  is a linear fit of the data from 100 to 212 °F and T is in °F (Perry 1963).

- II. Evaluation of the Lewis Number ( $N_{Le}$ ) and humid heat ( $c_m$ )

The Lewis ( $\frac{k}{c_o D_v}$ ) numbers for the air-water vapor mixtures were evaluated at the average condition of wet and dry bulb temperature,

$$T_{av} = \frac{T_{wb} + T_{db}}{2}$$

Density  $\rho_m$  (lb/ft<sup>3</sup>)

From the ideal gas law,

$$\rho_m = \frac{1 + W}{(T_{av} + 459.6)(0.0252 + 0.0407 W)}$$

heat capacity or humid heat,  $c_m$  (Btu/lb °F)

based on average values of heat capacities of air and water vapor over  $T_{av}$  from 150 to 355 °F

$$c_m = 0.243 + 0.455 W'$$

Diffusion coefficient,  $D_v$  (ft<sup>2</sup>/hr)

From a linear fit of the data presented by Evans and Vaughan (1977)

$$D_v = 0.663 + 4.03 \times 10^{-7} T_{av}$$

Thermal conductivity,  $k_m$  (Btu/hr ft °F)

The thermal conductivity of the components

$$k_{wv} = 0.0083 + 2.5 \times 10^{-6} T_{av} \quad (\text{Weast 1966})$$

$$k_a = 0.0132 + 2.39 \times 10^{-5} T_{av} \quad (\text{Bennett and Myers 1962})$$

were used to estimate the thermal conductivity of the moisture as described by Bird et al. (1960).

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## MOISTURE SORPTION HYSTERESIS IN WOOD

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### ABSTRACT

The occurrence of moisture sorption hysteresis in wood, and several proposed theories for explaining it, are discussed. Hysteresis is shown to be beneficial when wood is in use because it reduces changes in moisture content (lower effective slope of the sorption isotherm) and therefore in dimensions (lower humidity expansion coefficient) associated with environmental humidity changes.

### INTRODUCTION

The term hysteresis is derived from the Greek word hysterein, which means "to lag behind." The term was first used late in the 19<sup>th</sup> century by Irving, a British physicist, to describe the observed lag in magnetization of ferromagnetic material subjected to changing magnetic fields.

Hygroscopic gel materials such as wood also exhibit an analogous phenomenon to magnetic hysteresis, known as sorption hysteresis, or moisture sorption hysteresis. This refers to the lag or reduction in the sorption isotherm of equilibrium moisture content (EMC) of wood against relative humidity (H) compared with its EMC when it desorbs or loses moisture (Figure 1).

Sorption hysteresis appears to be a characteristic of hygroscopic gel materials such as cotton, wool, and silk, as well as wood. We will consider three aspects of sorption hysteresis in wood. These are:

1. Phenomenological or descriptive discussion.
2. Theories or mechanism of hysteresis.
3. Implications for the behavior of wood in use.

### OCCURRENCE OF HYSTERESIS

The EMC of wood at a given relative humidity H is generally highest during the initial desorption of the green wood. Figure 1, taken from Spalt (1958), shows the initial desorption isotherm as well as subsequent adsorption and desorption

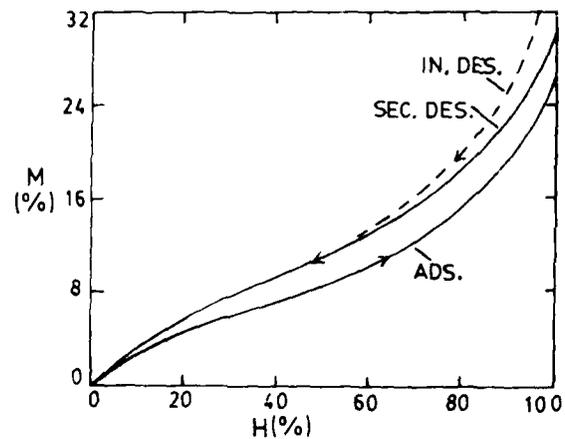


Figure 1. Initial desorption (IN DES), adsorption (ADS), and secondary desorption (SEC DES) isotherms for Douglas fir (adapted from Spalt, 1958).

isotherms for Douglas fir. The initial desorption isotherm was obtained by exposing two mm. thick sections of green wood to successively lower humidities and measuring the equilibrium weight at each humidity. All measurements were made in a vacuum system at 90° F (32° C).

The lowest curve in Figure 1 shows the adsorption isotherm obtained after the sample was vacuum dried and subsequently exposed to successively increasing humidities up to essentially 100 percent H. A second desorption resulted in the intermediate curve shown.

It lags below the initial desorption curve down to about 50 percent humidity, below which it essentially coincides with it. This indicates that there is an initial irreversible loss in hygroscopicity at humidities above about 50 percent after the initial drying of green or water-soaked wood. In this paper, we will be referring primarily to the cyclic or reversible hysteresis loop unless stated otherwise.

Figure 2 shows the mean adsorption and desorption isotherms for ten U.S. hardwood samples, measured by Okoh (1976) at 25°C.

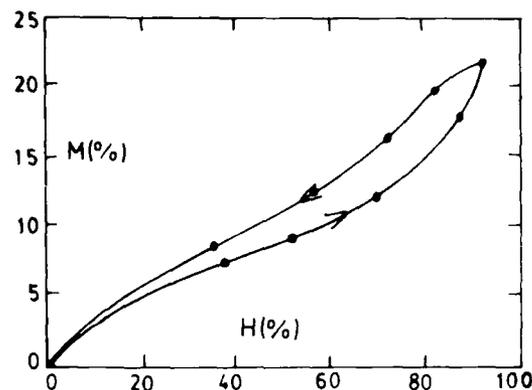


Figure 2. Mean adsorption and desorption isotherms for 10 U.S. hardwoods at 25°C, measured by Okoh, (1976).

The samples were 3 mm. thick along the grain. Each point on the adsorption isotherm was measured after vacuum drying the samples overnight. The desorption experiments, however, were carried out in successive steps following the last adsorption exposure to 94 percent H.

Experimental evidence indicates that a closed hysteresis loop is obtained when successive adsorption and desorption cycles are carried out. The magnitude of the hysteresis effect is sometimes expressed as the ratio of adsorption to desorption EMC's (the A/D ratio) at a given H. The A/D ratio usually varies with H, as is shown in Figure 3, taken from Okoh (1976). Table I shows some A/D ratios given by Stamm (1964).

Spalt (1958) calculated mean A/D ratios for eight hardwoods and eight softwoods over the entire hygroscopic range. This was done by taking the ratio of the total area under the hygroscopic isotherm for adsorption to that for desorption. The mean A/D ratios for

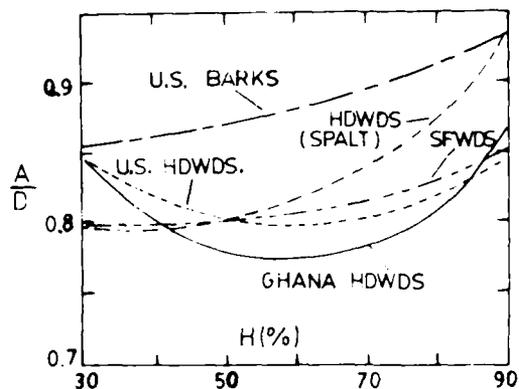


Figure 3. Variation of A/D ratios with humidity for various wood samples as reported by Okoh (1976).

Table I. Mean A/D ratios for various cellulose and similar materials as tabulated by Stamm (1964), from various sources.

MATERIAL	A/D RATIO
White spruce	0.83
Klinki pine	0.78
Eucalyptus, holzschluse	0.86
Lignin	0.78-0.79
Loblolly pine pulp	0.83-0.88
Western hemlock	0.82-0.84
Western hemlock pulp	0.87
Kapok	0.81
Cotton	0.77-0.87
Viscose rayon	0.78
Silk	0.81-0.84
Wool	0.81-0.85

the hardwoods ranged from 0.790 to 0.849 (mean = 0.8279 ± 0.0178) while those for the softwoods varied between 0.785 to 0.844 (mean = 0.8120 ± 0.0311). The overall mean was 0.8200.

Higgins (1957) reported mean A/D values for 12 woods, including five U.S. woods and seven tropical woods, as ranging from 0.80 to 0.88 with a mean of 0.84. He used saturated salt solutions with relative humidities of 21, 43, 81, and 93 percent at 90°F (32°C).

Skaar (1972) reports a mean A/D ratio, at 40°C and 76 percent H, of 0.803 ± 0.032 for 15 sapwood samples and of 0.805 ± 0.028 for 24 heartwood samples, with a pooled mean

of  $0.804 \pm 0.028$ , all tropical hardwoods from the Guayana region of Venezuela. They were 8 mm. along the grain and 25 x 25 mm. in transverse dimensions. The mean A/D ratio of approximately 0.80 was probably low because the initial rather than cyclic or secondary desorption value was measured (Figure 1). Another factor is the possible evaporation of volatile constituents from the green samples when they were oven-dried at  $103^\circ\text{C}$  prior to adsorption.

Okoh (1960) also measured the adsorption and desorption cyclic isotherms for the inner bark of ten North American hardwoods. He found that the A/D ratio was considerably higher for the bark (Figure 3) than for the wood from the same trees. The mean A/D values  $0.884 \pm 0.018$  for the inner bark samples compared with  $0.808 \pm 0.010$  for the corresponding woods. Most of the difference was due to the appreciably greater desorption isotherms for wood compared with bark, since the adsorption isotherms were essentially identical. Okoh also measured the sorption isotherms for ten woods from Ghana in the same study. The mean A/D ratio for these woods was  $0.786 \pm 0.017$ .

Several factors may enter into the variation in sorption hysteresis as measured by the A/D ratio. Some of these factors are incomplete attainment of time equilibrium, immediate past history such as the number of adsorption steps and possibly even the time at each step, temperature, physical-chemical differences in the cell wall, the presence of various extractives, etc.

Incomplete attainment of equilibrium, either in adsorption or desorption would tend to increase the A/D ratio. Figure 4, adapted from Morton and Bearle (1962) shows the effect

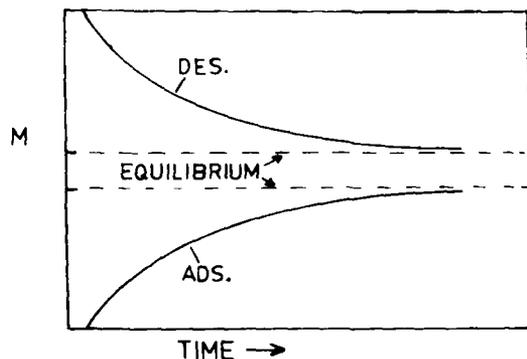


Figure 4. Hypothetical curves showing the approach to adsorption and desorption equilibrium with increasing time (adapted from Morton and Bearle, 1962).

of time on the attainment of equilibrium from both desorption and adsorption assuming that the process of attaining equilibrium is an exponential function of time. It may require weeks or even months to attain true equilibrium. This may be due to the fact that slow molecular rearrangements may be occurring in the wood as the structure accommodates itself to swelling forces (Skaar, Prichananda and Davidson, 1970).

The effect of immediate past history, as reflected in the number of adsorption steps to which a sample is exposed, on the magnitude of the adsorption isotherm (and therefore on the A/D ratio) was first reported for wood by Christensen and Delsey (1959). Table 2, taken from data of Prichananda (1966) shows the

Table 2. Desorption and Adsorption EMC's and A/D ratios at several relative humidities on yellow birch (*Betula alleghaniensis*). Adsorption EMC's were obtained in single steps or in several steps (multistep). From Prichananda (1966).

H(%)	Desorption (D)		Adsorption (A)		
	M(°)	M(°)	A/D	M(°)	A/D
40	5.47	5.16	0.734	5.47	0.778
50	7.47	7.05	0.817	7.47	0.866
60	9.11	8.60	0.819	9.11	0.868
70	10.54	10.19	0.821	10.54	0.849
80	14.19	13.69	0.846	14.19	0.877
Mean A/D ratio		0.807 ± 0.043 - multistep			
		0.848 ± 0.017 - single-step			

direct effect of this factor on the A/D ratio. Here are shown the desorption EMC's, calculated at several values of H, together with the single-step and multistep adsorption EMC's at the same humidities. The data for the single-step adsorption was obtained by equilibrating a sample to each humidity after first drying it in an oven at  $103 \pm 2^\circ\text{C}$ . The data for the multistep adsorption were obtained by exposing each sample to increasingly higher humidities after equilibrating at the previous humidity condition.

As Table 2 indicates, the EMC was always higher for the single-step than for the multistep adsorption. Therefore, the A/D ratio where D is the desorption value obtained only by multistep desorption, was always higher for the one-step (mean = 0.848) than for the multistep adsorption (mean = 0.807).

Sorption hysteresis in wood decreases with increasing temperature according to Weichert

(1963), and disappears at temperatures between 75 and 100° C for European spruce. Data of Kelsey (1957) show agreement with this tendency in that hysteresis in *Aranearia klinkii* of Australia decreased in magnitude in going from 25 to 55° C.

The complete adsorption and desorption isotherms, that is those obtained from complete dryness and near saturation, respectively, give the greatest A/D ratio. Urquhart (1960) gives a thorough treatment of sorption hysteresis in textile materials, and points out that cyclic isotherms carried over smaller humidity ranges tend to fall between the complete isotherms. In other words, quoting from Urquhart (1960), "the two (adsorption and desorption) curves do not form an equilibrium locus but define an equilibrium area." Stamm (1964) generally concurs with this same viewpoint. Figure 5

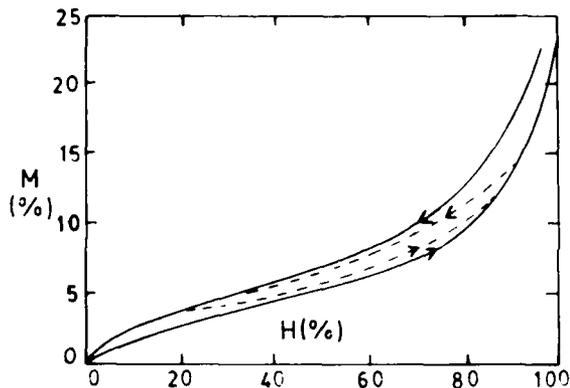


Figure 5. Illustration of intermediate hysteresis loop (adapted from Urquhart, 1960).

illustrates an intermediate hysteresis loop of the type given by Urquhart (1960).

Differences in the physical-chemical constitution of the wood, including extr-actives, probably account for the variation in the A/D ratio among different woods. For example, the data as reported above for Spalt (1958), Okoh (1976), etc., probably reflect these differences. According to Stamm (1964), the mean A/D ratio is higher for wood pulp and holocellulose (0.86) than for gross wood (0.82). The ratio for lignin is lower, averaging about 0.78 (Table 1). Regenerated cellulose also gives lower values, 0.78 and 0.77 for viscose and cuprammonium rayon, respectively.

Hysteresis has also been demonstrated in the heat of wetting wood. Argue and Maass (1935) reported that the heat of wetting was

higher for cotton which attained a given EMC by desorption than by adsorption. More recently, Kajita (1976) found a similar relationship for the wood of Hinoki cypress (*Chamaecyparis obtusa*). Figure 6 shows the curves, calculated by Kajita, of the heats of wetting in adsorption and in desorption for both cotton and Hinoki cypress. The curves are based on equations of

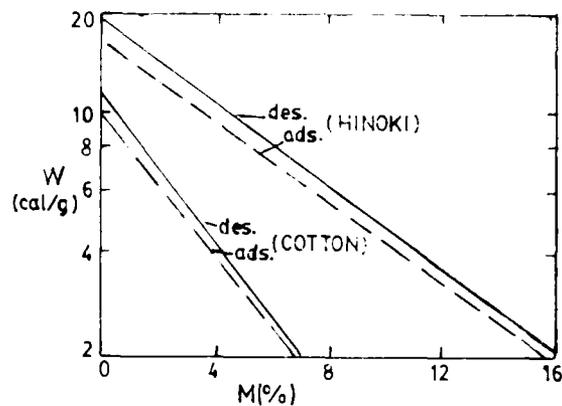


Figure 6. Heat of wetting  $W$  curves (log scale) for Hinoki cypress and for cotton against initial moisture content  $M$  for both adsorption and desorption equilibration (from Kajita, 1976).

the form,  $\log W = A - Bm$ , where  $W$  is the heat of wetting (calories/g dry wood),  $A$  and  $B$  are constants, and  $m$  is the initial wood moisture content (g/g).

The heat of wetting hysteresis results described above can be accounted for by the greater number of available sorption sites (or surface area as viewed by Argue and Maass) in the wood during desorption. This is because the heat of wetting is generated primarily by the strong interaction of water with the available primary sorption sites. There are more of these unoccupied at a given moisture content during desorption, based on either the Bailwood-Horrobin (1946) or the Dent (1977) model. This is because the total number of available sorption sites, indicated by the magnitude of  $m_0$ , is appreciably higher for desorption. However, the number of sites actually occupied, proportional to  $m_1$ , is not greatly different for adsorption and desorption, particularly at lower moisture contents. Therefore, the difference ( $m_0 - m_1$ ) at any given total moisture content  $m$  is greater for desorption than for adsorption. Consequently, the heat generated during wetting is greater for desorption since this should be primarily a function of ( $m_0 - m_1$ ).

## THEORIES OF SORPTION HYSTERESIS

### Capillary theories

Several theories have been proposed for explaining sorption hysteresis. The earlier theories were based on the assumption that moisture sorption was primarily by capillary forces within the tiny interstices in the wood cell wall. One of these theories, attributed by Kollman and Cote (1968) to Zsigmondy (1911), postulated that hysteresis was caused primarily by the lower contact angle of water within these cell wall capillaries during adsorption than during desorption.

Chen and Wangaard (1968) gave evidence which appears to support the theory of Zsigmondy. Using the inclined plate method they measured the water wettability hysteresis of 28 tropical woods. This was defined as the ratio of the cosines of the advancing and receding contact angles during the wetting of wood samples with water. For 13 of the woods for which they had complete adsorption and desorption data, they calculated the curves of dissolved (which they called polymolecular) water as a function of relative humidity  $H$ , using the Hailwood-Horrobin equations. They then took the value of dissolved water at equilibrium with  $H = 90\%$  for adsorption and calculated the desorption equilibrium humidity  $H_d$  for the same amount of dissolved water (Figure 7). The ratio  $\ln(100/90)/\ln(100/H_d)$  was designated as the relative humidity hysteresis.

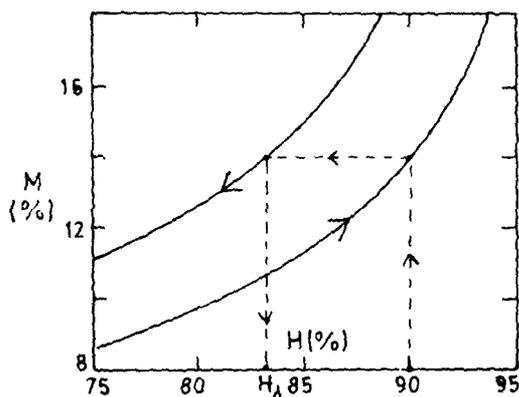


Figure 7. Diagram illustrating the method for calculating the relative humidity hysteresis (adapted from Chen and Wangaard, 1968).

A plot of the relative humidity hysteresis against wettability hysteresis (Figure 8) showed a positive correlation. Chen and Wangaard interpreted this to support the contact angle theory of Zsigmondy for explaining sorption hysteresis, based on the Kelvin equation, at least at high humidities. Their reasoning was based on the relationship given by the Kelvin equation between relative vapor pressure, capillary radius and contact angle. They also cited other analyses of their data which tended to support the capillary contact angle theory of sorption hysteresis.

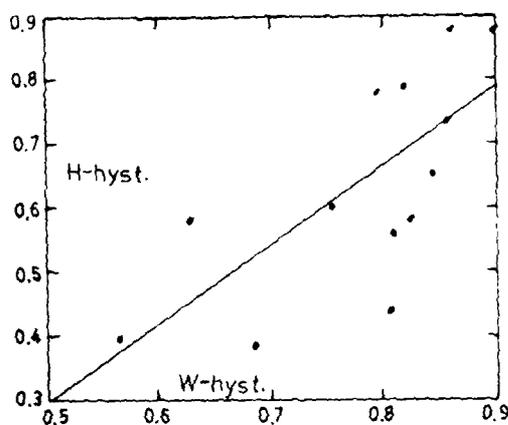


Figure 8. Plot of relative humidity hysteresis (H-hysteresis) and wettability hysteresis (W-hysteresis) (adapted from Chen and Wangaard, 1968).

The capillary contact angle theory may be useful in explaining sorption hysteresis at high humidities but not at low humidities, as Barkas (1949) points out. Capillaries of the type considered by the Kelvin equation cannot occur at low humidities, since calculated capillary radii approach the order of magnitude of molecular dimensions. In this case, classical surface film properties such as surface tension no longer apply.

McBain, according to Barkas (1945), proposed the "ink bottle" theory, also based on the concept of capillary condensation within the cell walls. According to this theory, capillaries are not of even taper, but contain constrictions. During adsorption the capillaries will gradually fill from the smaller to the larger spaces. However, during desorption some of the water in the larger spaces between the narrower "bottlenecks" will tend to be trapped at lower vapor pressures, in equilibrium with these lower vapor pressures. This would tend to be a state of unstable equilibrium because of the high tension in the water. Both the Zsigmondy and McBain theories may explain some of the hysteresis at high humidities but certainly not at lower values.

#### Sorption site availability theory

The mechanism of sorption hysteresis most generally held (Cruikshank, 1969; Stamm, 1964) we will designate as the sorption site availability theory. It is based on the reduction in the availability of hydroxyl sorption sites on wood which is absorbing moisture after having been dried. These hydroxyl groups are believed to be the primary, though not necessarily the only, sorption sites for the attachment of water molecules in the accessible regions of the cell wall.

In green or water swollen wood, according to this concept (Stamm, 1964), the hydroxyl groups are attached to water molecules. When the wood dries some of the hydroxyl groups are freed from the attached water molecules and mutually bond with each other as they draw closer due to shrinkage. When water is regained or adsorbed, some of the hydroxyl groups are no longer easily available to bond with water molecules. This results in less adsorption of water at a given humidity compared with the initial desorption.

As humidity increases still further, and additional water is taken up, the swelling pressures tend to break some of the hydroxyl-hydroxyl bonds, freeing some but not all of the originally water-bonded hydroxyl groups or sorption sites. These are then available to be rehydrated or to adsorb water molecules. During subsequent or secondary desorption the EMC is therefore higher than for adsorption. However, it is generally lower than during initial desorption from the green condition, particularly at higher humidities, presumably because some of the bonds which formed between hydroxyl groups during initial desorption are not broken. The process repeats itself during subsequent cycling of the relative humidity, forming a more or less repetitive hysteresis loop (Figure 1).

There is evidence to support the accessible sorption site theory for hysteresis, in that the value for the maximum amount of water  $m_0$  held in hydrated form (Hailwood and Horrobin (1946) solution model) or in the monolayer (Dent (1977) modified BET model), is considerably less for adsorption than for desorption. For example, data given in Table 1 of Spalt (1958) on 16 different woods to which he applied the Hailwood-Horrobin model shows that the mean ratio of the maximum water of hydration  $m_0$  (g/g) in adsorption compared to desorption is  $0.726 \pm 0.071$ . In other words, on the average, only 72.6 percent as many sorption sites are hydrated during adsorption as during desorption. The maximum water of hydration  $m_0$  (g/g) was

calculated by dividing the molecular weight of water (18 g/mole) by the molecular weight of wood per mole of hydration (sorption) sites. The more recent sorption theory of Dent (1977) which is a modification of the BET theory yields the same value for  $m_0$  as does the Hailwood-Horrobin model. However, in the Dent model,  $m_0$  is interpreted to be the moisture content corresponding to complete monolayer coverage of all the sorption sites, rather than complete hydration.

Chen and Wangaard (1968) also calculated the ratio of the average water of hydration in adsorption to that in desorption over the humidity range from 60 to 90%, using the Hailwood-Horrobin model, for 13 wood species for which they had data. They then plotted this ratio against the wettability hysteresis ratio, and calculated the linear regression curve. There was a significant relationship, but it was negative, indicating the unexpected result that wettability appears to be inversely related to the extent of hydration of the wood. The authors gave no explanation for this apparent anomaly except to point out that the hysteresis in water of hydration or monomolecular water was only a small portion of the total hysteresis. Nevertheless, one would expect that even small increases in accessible internal surface area would open up microcapillaries for sorption of additional water in succeeding layers in approximate proportion to the increased accessibility.

#### Thermodynamic hysteresis theory

The explanations for hysteresis given above are mechanistic, that is, they postulate one or more specific mechanisms. Barkas (1949, 1945) has proposed a more general theory based on thermodynamic considerations only. It does not propose a specific mechanism for hysteresis and therefore may be compatible with those mentioned previously.

Barkas points out that wood and other hygroscopic gels exhibit plastic or inelastic behavior when subjected to mechanical stresses. This behavior results in the familiar hysteresis loop in the stress-strain diagram of wood and other incompletely elastic materials.

Barkas' explanation of sorption hysteresis is based on an extension of his theory for explaining the effect of stress on the sorption isotherms of hygroscopic gels such as wood, which he used as a model material. Figure 2 shows a hypothetical pressure-volume diagram for wood for the reversible elastic case, as proposed by Barkas.

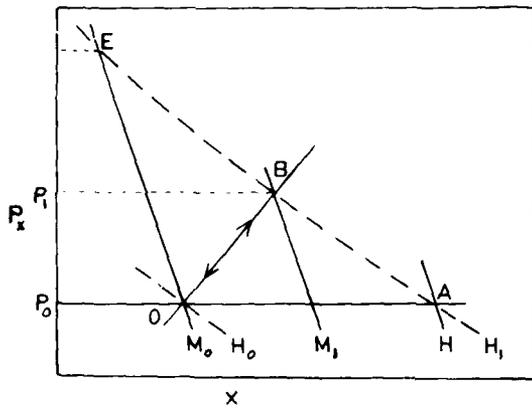


Figure 9. Diagram showing unidirectional stress  $P_x$  against displacement  $x$  for wood during moisture change for the elastic, perfectly reversible case (adapted from Barkas, 1949).

In order to illustrate the principles involved, Barkas used the example of a wood specimen partially restrained from swelling in one dimension by a linear elastic spring shown in Figure 10. In this case, the pressure is a unidirectional stress  $P_x$  in the  $x$  direction and the change in volume is represented primarily by the change in the  $x$ -dimension. For simplicity of concept the stresses and dimensional changes in other directions are not considered.

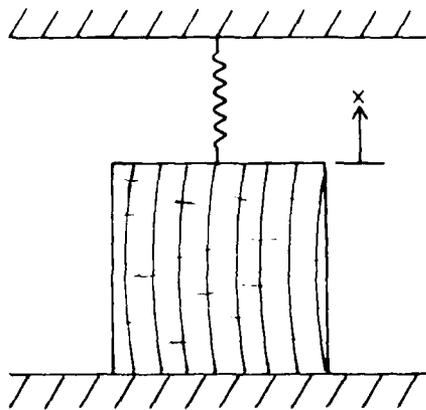


Figure 10. Schematic diagram showing wood sample swelling and shrinking against a linear spring.

Following Barkas, we will consider two cases. In the first case the wood is assumed to be perfectly elastic with no plastic flow when a stress is applied, illustrated by Figure 9. In the second case the wood will exhibit rheological properties, as it in fact does, resulting in some irreversible plastic flow (Figure 11).

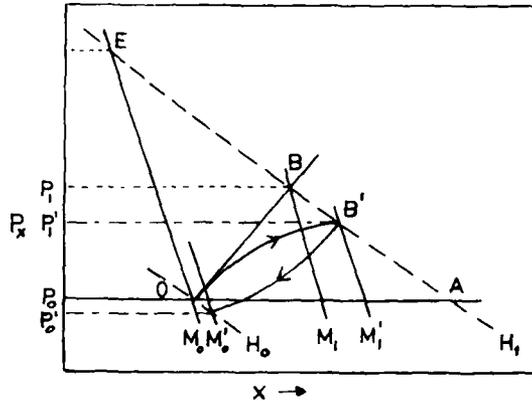


Figure 11. Diagram showing unidirectional stress  $P_x$  against displacement  $x$  for wood during moisture sorption for the inelastic case (adapted from Barkas, 1949).

In the first, reversible case, shown in Figure 9, the wood is perfectly elastic. It is initially at a moisture content  $M_0$ , at equilibrium with a relative humidity  $H_0$  under the initial stress  $P_0$  exerted by the elastic spring. If the humidity increases from  $H_0$  to  $H_1$ , the wood will adsorb moisture and swell against the spring until some new equilibrium point is reached at stress  $P_1$  and moisture content  $M_1$ . Thus, it will move from point  $O$  to point  $B$  on the diagram. The actual magnitude of  $M_1$  is inversely related to the increase in stress  $P_1 - P_0$ . If the humidity  $H$  is now decreased back to the initial value  $H_0$ ,  $M_1$  will decrease to  $M_0$  and  $P_1$  to  $P_0$ , thus returning exactly to the starting point  $O$ .

It should be noted that the actual location of point  $B$ , and therefore the values of  $P_1$  and  $M_1$ , depend on the stiffness of the restraining spring shown in Figure 10. If this spring becomes more stiff, the equilibrium point  $B$  moves toward the point  $E$  with a greater compressive stress  $P_1$  and reduced moisture content  $M_1$ . The converse is true if the spring is weaker or less stiff. However, for the reversible, perfectly elastic case the equilibrium point returns to  $O$  when  $H$  is reduced to  $H_0$ , regardless of the location of  $B$  along the line  $H_1$ .

In the reversible perfectly elastic case cited above sorption hysteresis would not occur. According to Barkas, this in fact is the situation one would expect to find in aqueous solutions where shear stresses do not occur at equilibrium.

In the second case such as for wood where irreversible plastic flow occurs, the location of point B after increasing the humidity from  $H_0$  to  $H_1$  is closer to the point A than for the perfectly elastic case. This is because the wood relaxes as it approaches the stress  $P_1$  and never quite reaches that level. Rather it moves toward the point B' as shown in Figure 11. When equilibrium is finally attained at point B' the stress  $P_1'$  is lower than the elastic value  $P_1$ , and the equilibrium moisture content  $M_1'$  is higher than  $M_1$ .

Lowering the humidity to the original value of  $H_0$  results in a reduction in moisture content and stress. The final equilibrium value  $P_0'$  will be lower than  $P_0$  and that of  $M_0'$  will be higher than the original value  $M_0$ . The area within the loop represents the difference in the work done by the wood on the spring during adsorption and the work recovered by the wood during desorption. There is therefore a net energy loss in the cycle. As Barkas points out the humidity must be lowered below  $H_0$  for the wood to attain its original moisture content  $M_0$ , since it is now in tension.

Barkas, (1949) has used the example of the wood subjected to swelling against an external spring (Figure 10) to illustrate a principle. Actually there are restraining forces within the cell wall itself which act similarly to the external spring in resisting swelling. It is difficult or impossible to reproduce the pressure-volume diagram of Figure 11 for the cell wall. However, Barkas suggests using the corresponding pressure-volume diagram for the water vapor itself to calculate the loss in energy or work during a sorption cycle. This is possible in an isothermal system if it is assumed that the same amount of energy is required to evaporate water at a given moisture content during desorption as is recovered during condensation at the same moisture content.

The vapor pressure-volume diagram corresponding to the wood pressure-volume diagram of Figure 11 is shown in Figure 12. It can be calculated from the adsorption and desorption isotherms at any given temperature. The area between the adsorption and desorption curves in Figure 12 gives the work-loss during sorption hysteresis. It can be calculated easily and should correspond to the area between the curves in Figure 11.

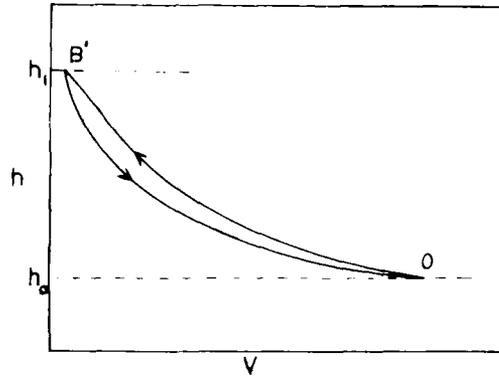


Figure 12. Diagram showing hysteresis in the relative vapor pressure  $h$  versus vapor volume phase (adapted from Barkas, 1949).

Barkas (1949) has calculated that this area represents approximately 17 percent of the total work of desorption for spruce wood. If we assume that this area is proportional to the mean difference between the adsorption and desorption isotherms, the A/B ratio can be approximated as  $1 + 0.17 = 1.83$ . This approximates the A/B ratios given in Table 1 and elsewhere.

#### IMPLICATIONS OF SORPTION HYSTERESIS

Moisture sorption hysteresis has an important effect in reducing the moisture and dimensional changes in wood when it is exposed in use to cyclic humidity changes. For example, wood used indoors in temperate climates may be exposed to wide annual fluctuations in average humidity. The EMC fluctuations however, and the consequent dimensional changes, are significantly less than would be anticipated based on the mean sorption isotherm. Before amplifying this statement, we define certain important dimensional stability parameters or coefficients, following the notation and treatment of Chencharn (1975).

The first important coefficient is the "moisture expansion coefficient"  $X$ , defined as,  $X = (1/x_0)(dx/x)$  or  $X = ds/s$  where  $s$  is the fractional change ( $dx/x_0$ ) in dimension  $x$  (radial, tangential, etc.) based on the initial dimension  $x_0$ , and  $\pi$  is the fractional moisture content ( $g$  water  $\div$  dry wood). The equation applies for either swelling or shrinkage because changes in  $s$  and  $\pi$  are in the same direction. By analogy with the coefficient of thermal expansion defined similarly we will use the term moisture expansion coefficient, although it is

often used for wood to describe shrinkage based on green dimensions.

The moisture expansion coefficient  $X$ , based on initial green dimensions, is linear over most of the hygroscopic range of moisture content: (Kevlwerth, 1964) for transverse dimensional changes.

The Wood Handbook (1974) lists "dimensional change coefficients" over the moisture range from 6 to 14 percent for a number of U.S. as well as imported woods. They are based on the dimension  $x$  at the mean moisture content of 10 percent and, since moisture changes are expressed in percent of dry weight, the  $\Delta x$  are approximately equal to  $X/100$ . The mean value of  $\Delta x$  between 6 and 14 percent M.C. was calculated from data based on initial shrinkage from the green condition.

Another important coefficient, defined by Chomcharn (1975) is designated as the "humidity expansion coefficient,"  $Y$ . It is defined as  $Y = (1/x_0)(\Delta x/h)$  or,  $Y = \Delta s/h$  where  $h$  is the relative vapor pressure ( $h = H/100$ ). The coefficients  $X$  and  $Y$  are therefore related as follows:

$Y = X(\Delta m/h) = X(\Delta M/H) = XZ$  where  
 $Z = \Delta m/h = \Delta M/H$ , the effective rate of change of moisture content  $M$  (or  $m$ ) with respect to relative humidity  $H$  (or  $h$ ).

If the sorption isotherm was perfectly reversible, that is, if sorption hysteresis did not occur, the value of  $Z$  would be the slope of the sorption isotherm. This varies with both moisture content and humidity as Figure 5 indicates. The mean value  $\bar{Z}$  over any range of moisture content or humidity is then given by

$$\bar{Z} = \frac{1}{m_2 - m_1} \int_{m_1}^{m_2} Z(m) dm = \frac{1}{h_2 - h_1} \int_{h_1}^{h_2} Z(h) dh$$

between any two limits of moisture content  $m_1$  and  $m_2$ , or between the corresponding limits of relative vapor pressure  $h_1$  and  $h_2$ .

Quoting from Chomcharn (1975), "In practice the humidity expansion coefficient  $Y$  is a more important property of wood than the moisture expansion coefficient  $X$  since one is usually more interested in the dimensional changes associated with humidity changes in the atmosphere rather than with

moisture changes in the wood. However more information is available in the literature on the moisture expansion coefficient  $X$ , or some variation of it, than of  $Y$ . This has been partly because of tradition and custom. The relationship between them is not as straightforward as it appears, since the term  $Z$  is a function not only of species, temperature, and moisture content, but also of sample history, particularly as related to hysteresis."

Wengert (1975, 1977) has pointed out that sorption hysteresis can have an appreciable effect in studies of moisture migration in wood, particularly in relating moisture gradients to flow rates of moisture. He shows (Figure 13) three hypothetical steady-state moisture gradients which might exist in a wood sample with two fixed humidities, say  $H_1$  and  $H_2$ , on opposite sides of the sample, all at the same temperature. Case A would apply if the entire sample came to equilibrium by adsorbing moisture from a lower equilibrium humidity. Case B applies if the sample was previously wetter than the existing condition. Case C

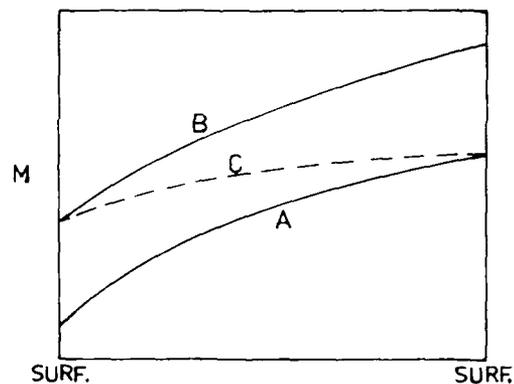


Figure 13. Hypothetical moisture ( $M$ ) distribution curves for a wood sample exposed to two constant but different humidities at each face, with different sorption histories (after Wengert, 1975).

is for the condition when the left side has desorbed and the right side has adsorbed moisture to attain equilibrium. It is evident that the relationships between vapor pressure and moisture gradients are different for the three cases. Therefore, the relationships between transport coefficients based on moisture content and vapor pressure gradients will also be different for the three cases, especially for case C compared with cases A and B.

Bramhall (1939) showed the hysteresis effect to adjust the equilibrium vapor pressure profile calculated in wood under non-isothermal and non-uniform moisture steady-state conditions. Such conditions were attained in wood samples by Choong (1963), for example, following a procedure first used by Laine et al. (1949). They were attained by subjecting opposite faces of sealed and insulated wood samples to different but fixed temperatures for sufficiently long times to reach moisture and temperature equilibrium. Bramhall concluded that the hysteresis-adjusted vapor pressures throughout such a wood sample at equilibrium were "very nearly uniform" than those calculated from the moisture and temperature distributions without considering sorption hysteresis (figure 14).

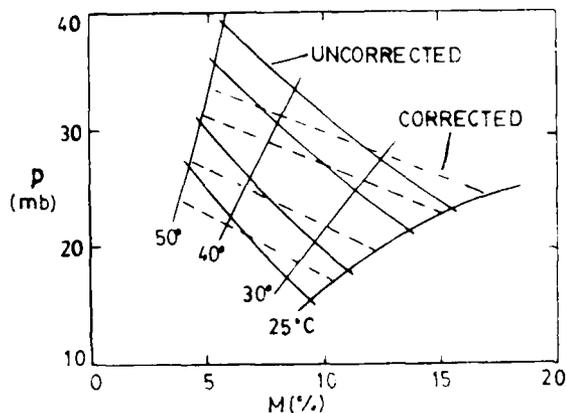


Figure 14. Vapor pressure  $p$  versus moisture content  $M$  in wood for the non-isothermal case as reported by Choong (1963) and after correction for hysteresis after Bramhall, 1939.

Hysteresis was involved in this case since the samples were originally conditioned to various uniform moisture contents prior to being exposed to the temperature gradient. The conditions of the experiments described here involved incomplete adsorption-desorption isotherms and also a range of temperatures. Since both of these factors affect the magnitude of hysteresis, the hysteresis correction of Bramhall, while it moves in the right direction, can probably be refined if these factors are better known.

The discussion heretofore has been confined to hysteresis under conditions of true equilibrium. When wood is subjected to the varying humidity conditions as it is in service a true equilibrium rarely occurs. This is due primarily to the fact that moisture migrates into and out of the wood slowly, that is, there is a lag in the average wood moisture content behind the changes in external humidity conditions. This phenomenon is most apparent during the lumber drying period when conditions are sometimes reversed.

Choong (1963) carried out a series of experiments during which he subjected small sections along the grain of wood to various humidity cycles to imitate actual humidity conditions. The cycles were carried out in a desiccator chamber and the wood samples were conditioned at various temperatures and humidities. The results of the experiments were reported in terms of the moisture content and the vapor pressure of the wood. The hysteresis effect was clearly demonstrated in the moisture content curves as well as in the vapor pressure curves. The hysteresis effect was also observed in the vapor pressure curves.

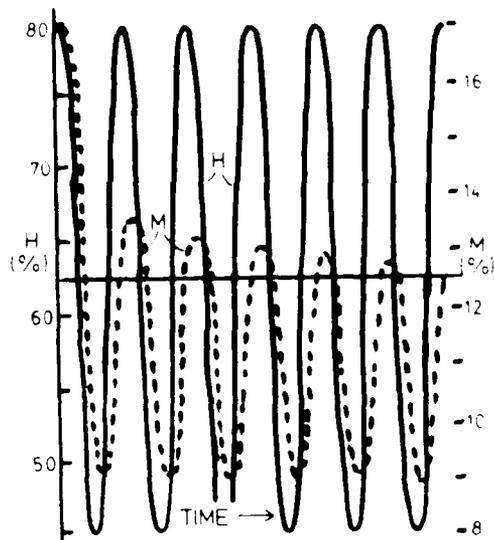


Figure 15. Curves of humidity  $H$  and moisture content  $M$  as a function of time for a wood block at the 26.67° C. period after Choong (1963).

Figure 15 shows the mean moisture content  $M$  of birch as the humidity cycle sinusoidally, with a cycling period of 26.67 hours. Both the humidity and moisture content curves are curves of best fit to the data as recorded during the experiments. The observations can be made from the moisture response curve shown.

First, both the amplitude and the mean value of the moisture curve decrease with increasing number of cycles, gradually approaching constant repetitive values. The decrease in mean value of the moisture content probably occurred because the wood was initially green prior to being dried to equilibrium with normal 8% relative humidity. It therefore started out on the initial desorption isotherm. Upon exposure to successive humidity cycles it approached the region between the isotherms

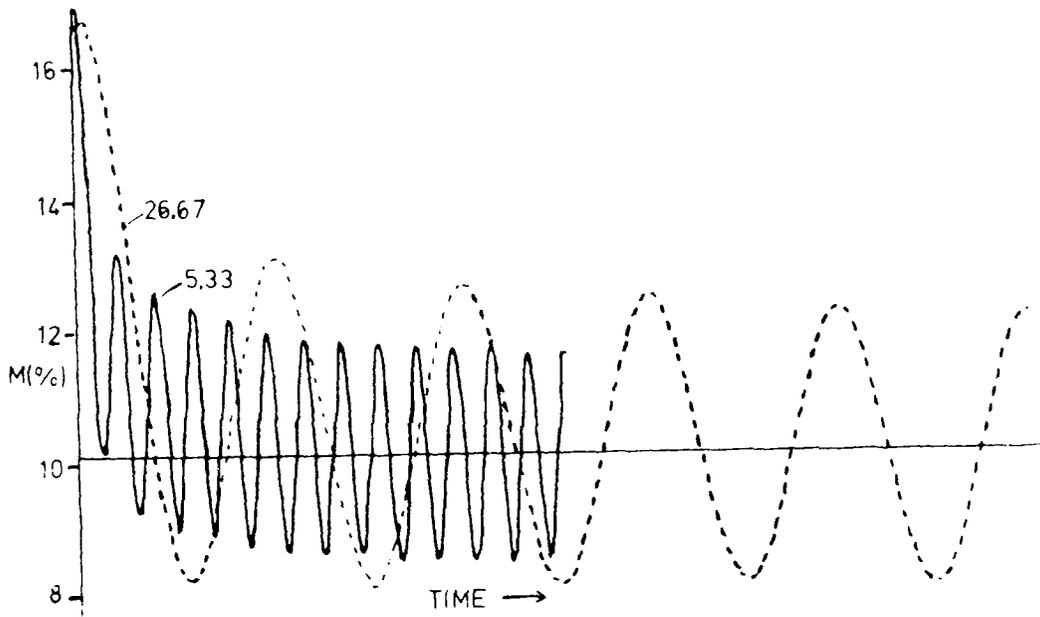


Figure 16. Curves of mean moisture content  $M$  against time for lined wood at constant RH. Two periods (adapted from Chouharn, 1973).

adsorption-desorption isotherms. The decrease in amplitude was probably associated with the dampening of the mean moisture content of the wood, lowered from a value near the initial desorption isotherm towards a lower value between the cyclic isotherms. It should also be noted however that computer simulation of the process gave somewhat similar results, except that cyclic equilibrium was attained in fewer cycles. In the simulation model sorption hysteresis was neglected.

The second observation (Figure 15) is that the moisture fluctuations lag behind those of the humidity curve. This results, not from the sorption hysteresis itself, but from the finite time required for the water to migrate into and out of the wood. The effect becomes less pronounced as the length of the cycling period increases. Finally it disappears when the time interval is so long that the wood is always essentially at equilibrium throughout its thickness at a given time and all parts cycle uniformly with external EMC condition.

Figure 16, also adapted from Chouharn (1973) shows the moisture content curves, on the same time axis, for the longest repetitive period (26.67 hours) and also for the shortest (period of 5.33 hours). It is evident that the amplitudes and mean values of both curves tend to decrease with increasing time, as in the previous figures. Larger moisture excursion amplitudes are evident in the curve with the

longer period. This is as expected since a longer cycling period permits the material to more nearly follow the sorption isotherms compared with the shorter cycling periods. At the cyclic period of 5.33 hours, the mean moisture content will remain essentially constant because of the relative lag due to moisture migration into and out of the wood.

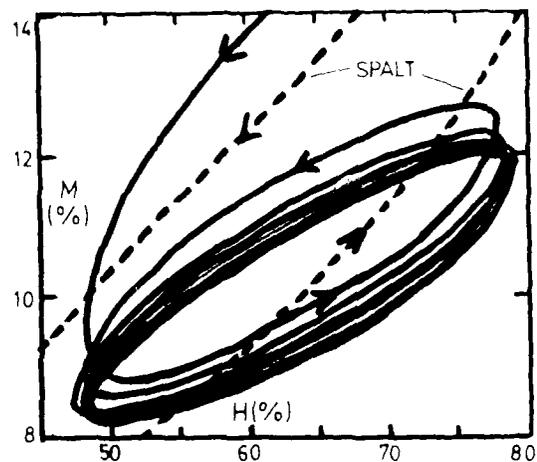


Figure 17. Plots of mean moisture content  $M$  against relative humidity  $H$  during cyclic moisture cycling of basswood at a period of 26.67 hours. Also shown are portions of SPALT wood's adsorption and desorption isotherms for basswood (after Chouharn, 1973).

Figure 17 shows a plot of mean sample moisture content  $M$  against relative humidity  $R$ , for a number of cycles for larchwood at the 5.33 hour cycling period, according to Chenohara (1975). Also shown are portions of the static adsorption and desorption isotherms for larchwood taken from Spalt (1977). The arrows on the curves show the direction of sorption. The cyclic dynamic sorption curve begins with desorption at the upper right portion of the diagram ( $M$  near 16% and  $R$  near 80%). During the first few cycles the sorption loop moves towards a lower mean moisture content, gradually approaching a reproducible loop. This final equilibrium loop has a long axis which has a lower slope  $Z^*$  ( $= \Delta M / \Delta R$ ) than either the adsorption or desorption isotherms.

The reason for the small slope  $Z^*$  is twofold in this case. One is the fact that the wood sample is moving back and forth between the adsorption and desorption curves (Figure 16). The second is that the diffusion lag of moisture into and out of the specimen prevents the complete specimen from following the changes in EM<sub>0</sub> at the surface. Longer cycling times reduce the diffusion lag, until at sufficiently long cycling times, compared with sample dimensions,  $Z^*$  approaches a maximum value determined by the magnitude of the effective hysteresis loop.

In conclusion it may be stated that the mean effective slope  $Z^*$  of the sorption isotherm is reduced by hysteresis. Thus, the mean humidity expansion coefficient  $\bar{\gamma}$  is also reduced substantially below the value based on either the adsorption or desorption isotherms.

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SORPTION THEORIES FOR WOOD<sup>1/2</sup>

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## ABSTRACT

Presents a general discussion of sorption theories. Several well-known theories are discussed in detail and tested with experimental data.

## INTRODUCTION

Dozens of theories have been derived for sorption of gases on solids, many of which can be applied to the sorption of water vapor by wood. Why has such effort been expended, and what success has been achieved? What can sorption theories tell us, and is what they tell realistic? Can they tell us anything useful about the wood-water system? This paper attempts to answer some of these questions.

The paper reviews the nature of sorption and how water is held in wood, sorption isotherms, and thermodynamics of sorption, and how it all relates to sorption theory. A description of some of the theories is presented, and finally some tests of the theories developed. This should lead us to the point where we can answer some questions on the usefulness of sorption theories.

Our present theoretical understanding does not allow us to estimate the variations of equilibrium moisture content with relative humidity and temperature from first principles. At this point mathematical models, or sorption theories, have been developed. From the most optimistic standpoint they describe the mechanism of how water is held in wood. From the most pessimistic standpoint they merely provide an equation that, through curve fitting of data, furnishes a means of correlating and interpolating data. Probably the truth lies somewhere between, and the theories really do give us a glimpse of the mechanism of sorption.

<sup>1/2</sup>Presented at Symposium on Wood Moisture Content-Temperature and Humidity Relationships held at Virginia Polytechnic Institute, Blacksburg, Oct. 29, 1979.

## GENERAL NATURE OF SORPTION

Hearle and Peters (1960) and Skaar (1972) have reviewed sorption from the molecular standpoint so it will not be presented here. Water is believed to be hydrogen-bonded to the hydroxyl groups of the cellulosic and hemicellulosic portions of wood. Not all hydroxyl groups are accessible to water molecules because cellulose molecules form crystalline regions where the hydroxyl groups of adjacent molecules hold the molecules in a parallel arrangement.

## Sorption Isotherms

Five general types of sorption isotherms have been identified for various gas-solid systems (fig. 1). The Type 1 isotherm is characteristic of sorption where a layer of vapor only one molecule thick is formed on the solid. Type 2 sorption is characteristic of sorption where more than one layer of vapor is formed on the solid and where the forces of attraction between the vapor and solid are large. (Wood exhibits this type of sorption.) Type 3 sorption is similar to Type 2 (except that the forces between the vapor and solid are relatively small. Types 4 and 5 characterize the case where the ultimate amount of

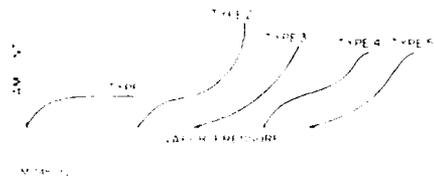
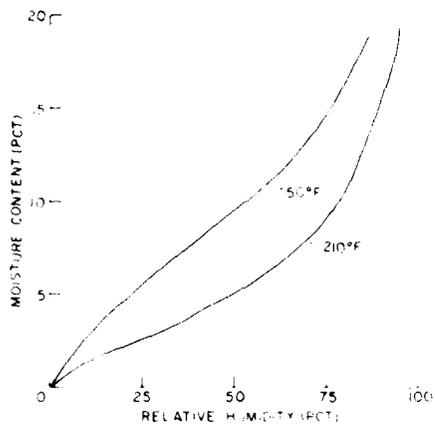


Figure 1.--Types of sorption isotherms.



M 148 153

Figure 2.--Effect of temperature on the sorption isotherm of wood.

adsorption is limited by capillary condensation in rigid capillaries.

Sorption isotherms are generally temperature dependent. As temperature increases, the amount of vapor adsorbed at any given vapor pressure decreases (fig. 2). Differences of up to 5 percent moisture content exist at equal relative humidities between different temperatures.

#### Thermodynamics of Sorption

The adsorption of water by wood is an exothermic process. Most sorption theories are derived in such a way that energies of adsorption are an integral part of the theory. The principal thermodynamic quantity of interest for this purpose is the differential heat of adsorption, which is discussed in detail in Hearle and Peters (1960), Stamm (1964), and Skaar (1972).

The energies of adsorption (cal/g water) of water on wood involve (fig. 3): The energy released when water is adsorbed by the cell wall of wood (or the energy required to evaporate water from the cell wall of wood) is termed  $Q_v$ ; the energy released when water vapor condenses to water (or the energy required to evaporate water from the liquid state) is termed  $Q_o$ , which is the heat of vaporization of water. The difference between these two quantities

$$Q_L = Q_v - Q_o$$

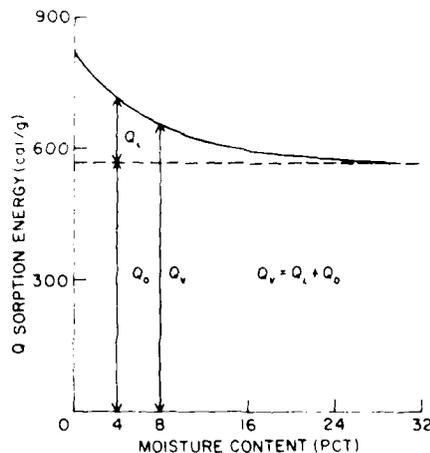
is the differential heat of adsorption. The  $Q_o$  is the additional energy released, above the heat of vaporization of water, when water is adsorbed by wood. It is also the additional energy, above the heat of vaporization, required to evaporate water from wood.

There are two methods of determining  $Q_L$  (Skaar, 1972). One method involves the use of the Clausius-Clapeyron equation and the temperature dependence of the sorption isotherm of wood. The other method involves the measurement of the heat given off during the adsorption of water by wood. This readily measured quantity is termed the integral heat of wetting  $\bar{W}$  (cal/g wood) and is related to  $Q_L$  by:

$$Q_L = - \frac{d\bar{W}}{d\bar{m}}$$

where  $\bar{m}$  is moisture content (g water/g wood).

Another relationship relevant to the thermodynamics of adsorption and how it relates to sorption theories is the Gibbs-Helmholtz equation. This equation relates the temperature dependence of the equilibrium constant of a chemical reaction to the enthalpy for



M 148 154

Figure 3.--Energies of adsorption of water by wood.

$Q_v$  = Energy of evaporate water from cell wall.

$Q_o$  = Heat of vaporization of water.

$Q_L$  = Differential heat of adsorption.

the reaction. A number of the sorption theories contain parameters that are either considered equilibrium constants in the model or are analogous to one. The equation can be written:

$$\frac{d \ln K}{d (1/T)} = \frac{-H}{R} \quad (1)$$

where  $K$  is the equilibrium constant,  $T$  is temperature in  $^{\circ}K$ ,  $H$  is the heat of reaction, and  $R$  is the gas constant. The equilibrium constant can be plotted against the reciprocal of temperature and the heat of reaction calculated from the slope of the curve. In an exothermic reaction, such as the adsorption of water by wood,  $K$  should decrease with an increase in temperature.

#### SORPTION MODELS

Many theoretical sorption models have been offered as explanations for the adsorption phenomena observed in many polymers. The approach here will be to describe only a few, and to do so in more detail than would be possible if many models were covered. The two main criteria for choosing models for description were the extent to which the model can be tested, and how well it is known and how widely it is used. Venkateswaran (1970) has listed the equations of a number of these sorption models. Hearle and Peters (1960), Skaar (1972), and Simpson (1973) have also discussed several models.

There are several general categories of sorption theories. In one category, a few theories or modifications to theories attribute some portion of sorption to condensation of bulk liquid in capillaries as a result of the lowering of equilibrium vapor pressure over these small capillaries. Another group of theories considers sorption to occur as a result of the buildup of water molecules in layers on the adsorbent. A monolayer is laid down first, and then in some systems multiple layers are built on it. A third category of sorption theories considers the polymer-water system to be a solution.

#### Brunauer, Emmett, and Teller (BET) Theory

The BET theory (1938) is one of the best known and most widely used sorption theories. Its greatest use is probably in estimating surface area from the adsorption of gases on solids where the gas does not swell the solid. Since the wood-water system does swell, this

application of the theory is of limited value. In the BET theory, gas molecules are built up on the solid surface in layers on sorption sites. The derivation can consider any number of layers, and for the general case the final equation is:

$$m = \frac{W_m C h}{1 - h} \left\{ \frac{1 - (n + 1)h^n + nh^{n+1}}{1 + (C - 1)h - Ch^{n+1}} \right\} \quad (2)$$

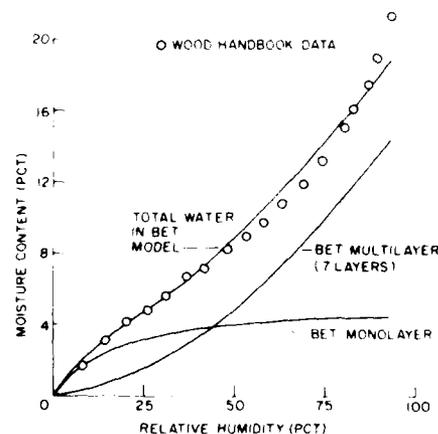
and for the case of a monolayer of water vapor ( $n = 1$ ):

$$m = \frac{W_m C h}{1 + C h} \quad (3)$$

where

- $m$  = fractional moisture content
- $h$  = relative vapor pressure
- $W_m$  = moisture content when monolayer is full
- $n$  = number of layers of molecules on a sorption site
- $C$  = constant related to the energy of adsorption

Equations (2) and (3) allow us to calculate and examine the complete isotherm once the parameters  $W_m$ ,  $C$ , and  $n$  are known, and to visualize how the model predicts the way that water is held in wood. Figure 4 shows how



M 148 155

Figure 4.--Brunauer, Emmett, and Teller sorption theory fitted with sorption data at  $40^{\circ}C$  from Wood Handbook (1974).

water is partitioned in wood according to the BET model. Equation (3) predicts the moisture content from the first layer of molecules adsorbed on the sorption sites. This sorption rises rapidly with relative vapor pressure at first, but soon levels off at 4 to 5 ( $W_m$ ) percent moisture content. Before monomolecular sorption is complete, the second, third, etc., layers begin to form, and at high relative vapor pressures most of the total sorption is in the multilayer form. The number of layers of molecules on the sorption sites of wood turns out to be in the range of 5 to 10, according to the model.

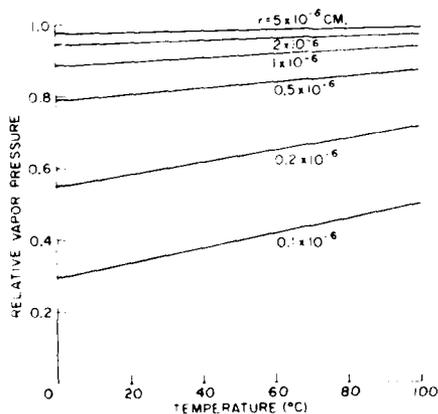
#### BET Model with Capillary Condensation

A number of modifications have been made to the BET theory. One possibility is to add a term to account for capillary condensation. Water vapor will condense in small capillaries according to the Kelvin equation:

$$r = \frac{2 S M}{RT \ln(1/h)} \quad (4)$$

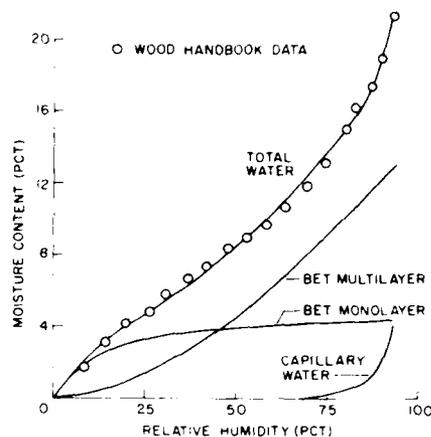
where

$r$  = radius of capillary  
 $S$  = surface tension of liquid  
 $M$  = molecular weight of the liquid  
 $\rho$  = density of the liquid  
 $R$  = gas constant ( $8.31 \times 10^7$  erg. mole<sup>-1</sup> - °K<sup>-1</sup>)  
 $T$  = temperature (°K)  
 $h$  = relative vapor pressure



M 148 156

Figure 5.--Dependence of temperature and capillary radius on the relative vapor pressure at which capillary condensation occurs.



M 148 157

Figure 6.--Sorption model consisting of BET model and capillary condensation. Fitted with sorption data at 40° C from Wood Handbook (1974).

Equation (4) predicts that the relative vapor pressure at which capillary condensation occurs decreases with decreasing capillary radius--small capillaries fill more readily than large capillaries (fig. 5). Using equation (4) as a basis, a model for capillary condensed water can be derived (Simpson, 1973). If all capillaries that contain water are assumed cylindrical with volume  $v$  and length  $d$ , then

$$r = \sqrt{v/\pi d} = \frac{2 S M}{RT \ln(1/h)} \quad (5)$$

The water in these capillaries is thus the portion of total moisture content,  $M_c$ , attributable to capillary condensation. Thus,

$$M_c = \frac{V}{W} = \frac{\pi d}{W} \left[ \frac{2 S M}{RT \ln(1/h)} \right]^2 \quad (6)$$

where  $W$  is the dry weight of wood.

If the assumption is made that capillary condensation is a separate sorption mechanism that operates in addition to mono- and multilayer sorption, then total sorption can be modeled as an additive combination of the BET model (eq. (2)) and the capillary condensation model (eq. (6)). The components of this model are shown in figure 6. The monolayer component is much the same as the BET model alone

(fig. 4), but the multilayer component is reduced at high relative vapor pressures because the model now allows for capillary water, which becomes significant at relative vapor pressure above about 0.7.

The inclusion of capillary condensation adds another parameter,  $d/W$ , to the model that has some physical significance. It is the total length of capillaries (equivalent to cylindrical capillaries) per unit weight of wood. The value of  $d/W$  for wood is in the order of  $10^{10}$  centimeters per gram (cm/g), indicating a considerable network of fine capillaries where water can condense.

A further indication of the intimacy with which water permeates the fine structure of wood comes from the term  $W_m$  in the BET equation. The  $W_m$  is the moisture content that corresponds to complete filling of the monolayer, and has been used to estimate surface area. Stamm (1964) has described this analysis for swelling systems. The effective contact area  $A$  can be calculated from:

$$A = aN W_m / M \quad (7)$$

where

- $a$  = area of a water molecule
- $N$  = Avogadro's number ( $6.02 \times 10^{23}$ )
- $M$  = molecular weight of water

The value of  $A$  for wood is in the order of 200 square meters per gram, again indicating that there must be an enormous contact area between water and wood.

#### Hailwood and Horrobin (HH) Theory

Hailwood and Horrobin (1946) developed a sorption theory that considers a polymer-water system to be a solution. Water adsorbed by a polymer is assumed to exist in two states: Water in solution with the polymer (dissolved water) and water combined with units of the polymer to form hydrates. The theory is based on the equilibria between polymer, hydrated polymer, and the dissolved water. There are two types of equilibria: One between the dissolved water and the water vapor of the surroundings, and any number of equilibria between the hydrated water and dissolved water. The general form of the model can be written:

$$m = \frac{18}{M_p} \left[ \frac{K_1 h}{1 - K_1 h} + \frac{\sum_{i=1}^n \frac{K_1^i (K_2)^i K_3 K_4 \dots K_i}{1 + \sum_{i=1}^n \frac{K_1^i (K_2)^i K_3 K_4 \dots K_i}{1 - K_1 h}}}{1 + \sum_{i=1}^n \frac{K_1^i (K_2)^i K_3 K_4 \dots K_i}{1 - K_1 h}} \right] \quad (8)$$

where

- $m$  = fractional moisture content
- $h$  = relative vapor pressure
- $M_p$  = molecular weight of polymer unit that forms a hydrate
- $K$  = equilibrium constant between dissolved water and surrounding water vapor
- $K_1, K_2, \dots, K_i$  = equilibria constant between dissolved water and hydrates.

For the case of one hydrate, the model is:

$$m = \frac{18}{M_p} \left( \frac{K_1 h}{1 - K_1 h} + \frac{K_1 K_2 h}{1 + K_1 K_2 h} \right) \quad (9)$$

For two hydrates:

$$m = \frac{18}{M_p} \left( \frac{K_1 h}{1 - K_1 h} + \frac{K_1 K_2 h + 2K_1 K_2 K_3 h^2}{1 + K_1 K_2 h + K_1 K_2 K_3 h^2} \right) \quad (10)$$

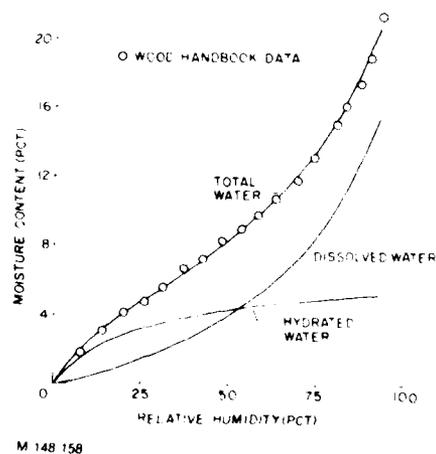


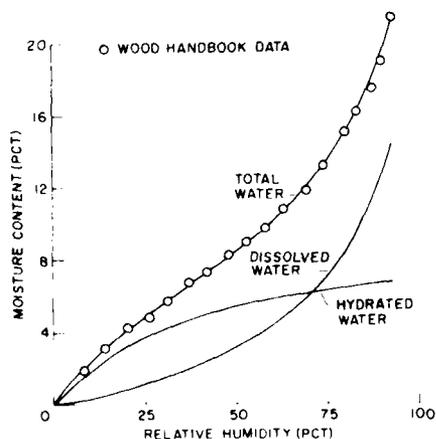
Figure 7.--Hailwood and Horrobin sorption model (one hydrate) fitted with sorption data at 40° C from Wood Handbook (1974).

The sorption isotherms from the one- and two-hydrate models are shown in figures 7 and 8. The model is very similar to the BET model in the partitioning of water. The hydrated water of the HH model is comparable to the monolayer of the BET theory ( $W_m$  of BET comparable to hydrated water component at  $h = 1$ ), and the dissolved water of the HH model is comparable to the multilayer water of the BET model (compare figs. 4 and 7). The values of  $W_m$  of the BET models and the amount of hydrated water at  $h = 1$  in the HH models are shown in figure 9 as a function of temperature for wood sorption data of the Wood Handbook (USDA, 1974). All of the models predict similar amounts of this water that is intimately associated with wood in hydrate or monolayer form.

#### King Theory

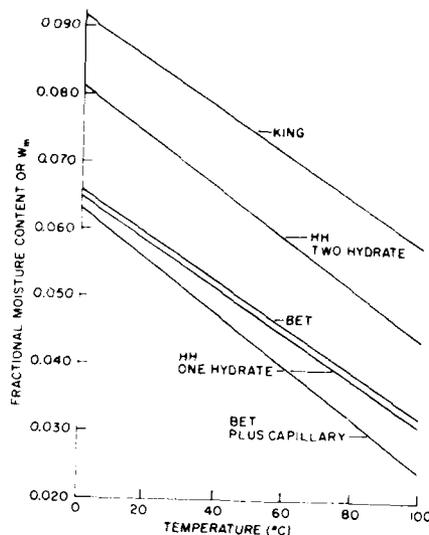
King (1960) derived a sorption model whose final equation is of a form similar to the HH one-hydrate model, but is derived from considering sorption similar to the BET model, that is, monolayer adsorption and multilayer adsorption. The final equation of the model can be written as (Simpson, 1973):

$$m = \frac{18}{M_p} \left( \frac{B K_1 p_o(h)}{1 + K_1 p_o(h)} + \frac{D K_2 p_o(h)}{1 - K_2 p_o(h)} \right) \quad (11)$$



M 148 159

Figure 8.--Hallwood and Horrobin sorption model (two hydrates) fitted with sorption data at 40° C from Wood Handbook (1974).



M 148 160

Figure 9.--Monolayer or hydrated water in wood at relative vapor pressure of 1.

where

- $m$  = fractional moisture content
- $p_o$  = vapor pressure
- $h$  = relative vapor pressure
- $M_p$  = molecular weight of polymer unit
- $B$  = constant proportional to the number of sorption sites in a monolayer
- $D$  = constant proportional to the number of sorption sites in a multilayer
- $K_1$  = equilibrium constant between monolayer water and external vapor pressure
- $K_2$  = equilibrium constant multilayer water and external vapor pressure

The model partitions water into two major portions similar to the BET and HH theories: Water that is directly associated with wood and water that is somewhat removed from direct association (fig. 10). The amount of monolayer water at saturation is slightly higher than the BET and HH models (fig. 9).

### Peirce Theory

Peirce (1929) developed a sorption theory based on two types of water--"a" phase and "b" phase--held in a polymer. The "a" phase is water bound intimately to the polymer, and the "b" phase is water less tightly held by forces similar to those in a liquid state. Peirce's model can be written as (Skaar, 1972):

$$1 - h = (1 - Kw_m_a) \exp(-Bw_m_b) \quad (12)$$

where

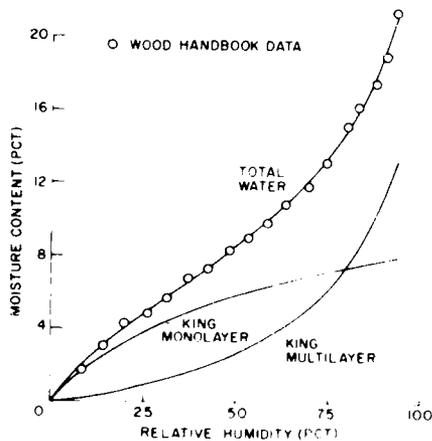
- h = relative vapor pressure
- $m_a$  = fractional moisture content of "a" water
- $m_b$  = fractional moisture content of "b" water
- W and B = constants
- K = constant that can be considered an equilibrium constant between "a" water and polymer

The moisture contents  $m_a$  and  $m_b$  can be written:

$$m_a = \frac{1 - \exp(-Wm)}{W} \quad (13)$$

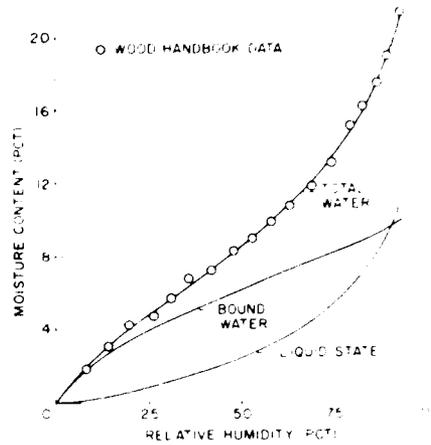
$$m_b = \frac{Wm + \exp(-Wm) - 1}{W} \quad (14)$$

where  $m$  is total fractional moisture content. When equations (13) and (14) are substituted into equation (12), the total isotherm can be calculated.



M 148 161

Figure 10.--Sorption model of King fitted with sorption data at 40° C from Wood Handbook (1974).



M 148 162

Figure 11.--Sorption model of Peirce fitted with sorption data at 40° C from Wood Handbook (1974).

Peirce's model is shown for wood in figure 11. Again, the model depicts the same general sorption as the BLT, HB, and King models, i.e., water intimately bound to wood and a less tightly held component.

### TESTS OF SORPTION THEORIES

One of the first demands of a sorption theory is that it gives an experimentally correct sorption isotherm. From a strictly mathematical standpoint, it is relatively easy to develop a sorption isotherm that, with the use of several adjustable coefficients, can be made to fit experimental data quite well. As a matter of fact, a polynomial with enough terms (six adjustable parameters, Simpson, 1973) can be made to fit data very well. However, the test of goodness-of-fit of experimental isotherms is not a sufficient test of a theory, and a more sensitive test requires a consideration of the energy of adsorption.

### Fit of Experimental Data

Although fitting sorption models with experimental data is an insufficient test, it is worth examining as a first requirement, as well as a possibly useful way to correlate and interpolate experimental data. Figures 4, 6, 7, 8, 10, and 11 and table 1 indicate the degree of fit of the experimental models to sorption data for wood (Wood Handbook, 1974). These

data involve a series of isotherms from 0° to 100° C, and have been fitted by nonlinear regression to a number of sorption models (Simpson, 1973). With the exception of the BET, all models reviewed in this paper give an excellent representation of the isotherm. Deviations between actual data and the fitted isotherms are 1 percent moisture content or less. The BET model (fig. 4, eq. (2)) fits poorly at high relative vapor pressures, where deviations are as high as 3.2 percent moisture content.

#### Heat of Adsorption Tests

A far more critical test of the sorption models is their ability to predict observed values of the heat of adsorption of water by wood. The parameter  $\bar{C}$  of the BET model is defined as:

$$C = K \exp \left( - \frac{(Q_v - Q_o)}{RT} \right) \quad (15)$$

where

$K$  = constant (assumed to have a value of 1)

$Q_v$  and  $Q_o$  = as defined previously

$R$  = gas constant

$T$  = temperature

Thus, the differential heat of adsorption,  $Q_L = Q_v - Q_o$ , can be calculated from values of

Table 1.--Moisture content deviation between fitted isotherms and actual sorption data for wood (Wood Handbook, 1974)

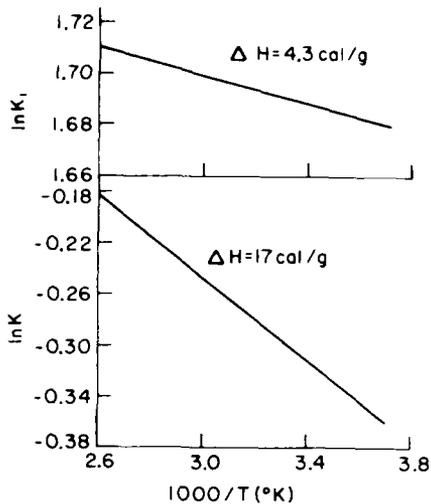
Sorption model	Equation number	Worst deviation (Pct moisture content)	Average deviation (Pct moisture content)
BET	1	3.2	0.5
BET + capillary	1 and 5	0.9	0.2
HH-- one hydrate	8	0.8	0.1
HH-- two hydrates	9	0.5	0.1
King	10	0.8	0.1
Peirce	11	1.0	0.3

$\bar{C}$  determined by fitting data to the BET model. In the BET model only adsorption of the first layer results in a heat of adsorption. The values of  $Q_L$  calculated from equation (15) at, for example, 50° C are 67 and 82 calories per gram (cal/g), respectively, for the data from the Wood Handbook fitted to the BET model of equation (2) and the BET plus capillary model of equations (2) and (6). Heats of adsorption determined either calorimetrically or by the Clausius-Clapeyron equation are in the range of 260 to 280 cal/g (Volbehr, 1896; Kelsey and Clarke, 1956; Skaar, 1972).

The remainder of the models reviewed in this paper can be tested for agreement of heats of adsorption by considering the temperature dependence of the equilibrium constants of the models, as reviewed previously (eq. (1)). When reviewing the temperature dependence of these equilibrium constants, keep in mind that adsorption of water vapor by wood is an exothermic reaction, and as such, an equilibrium constant should decrease with an increase in temperature (or the constant should increase with the reciprocal of temperature). In a plot of the logarithm of the equilibrium constant versus the reciprocal of absolute temperature, the heat of adsorption is proportional to the slope, i.e.:

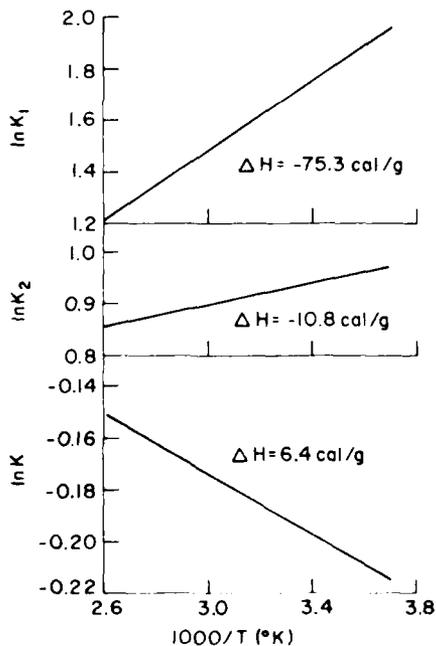
$$\Delta H = - (\text{slope}) R$$

The equilibrium constants of the sorption models reviewed here have all been determined as a function of temperature (Simpson, 1973). The  $K$  values of the one- and two-hydrate HH models are plotted (as fitted by linear regression) as  $\ln K$  versus  $1/T$  in figures 12 and 13. In the one-hydrate model (fig. 12), the values of the heats of adsorption associated with the hydrated and dissolved water are 4.3 and 17 cal/g, respectively. The positive sign indicates an endothermic reaction, which is contrary to observed behavior. The two-hydrate model (fig. 13) does predict an exothermic reaction with the two constants associated with hydrated water,  $K_1$  and  $K_2$ , where the values of  $\Delta H$  are -75.3 and -10.8 cal/g, respectively. The sum of these two heats is  $Q_v$ , and the  $\Delta H$  associated with the dissolved water-water vapor equilibrium ( $K$ ) is  $Q_o$ , the latent heat of vaporization of water (550 to 600 cal/g in this temperature range). The value of  $Q_o$  is, however, +6.4 cal/g. Thus, the two-hydrate model predicts a heat of adsorption of



M 148 163

Figure 12.--Temperature dependence of the equilibrium constants of the one-hydrate Hailwood and Horrobin sorption model.



M 148 164

Figure 13.--Temperature dependence of the equilibrium constants of the two-hydrate Hailwood and Horrobin sorption model.

$$Q_L = Q_V - Q_G = (-75.3 - 10.8) - 6.4 = -79.7 \text{ cal/g}$$

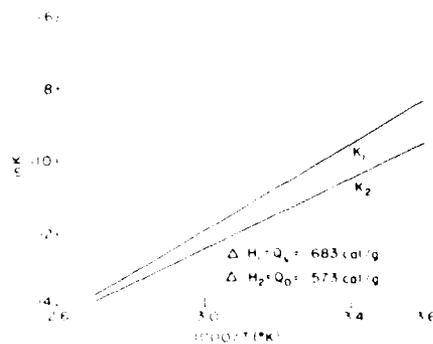
which should compare in absolute value to 260 to 280 cal/g.

In the King model, equilibrium constant  $K_1$  is associated with the reaction between water vapor and polymer, and the constant  $K_2$  is associated with the reaction between multilayer water and water vapor. Thus, the heat associated with  $K_1$  is  $Q_V$  and the heat associated with  $K_2$  is  $Q_G$ . The temperature dependence of  $K_1$  and  $K_2$  is shown in Figure 14, and the heat of adsorption is:

$$Q_L = Q_V - Q_G = -683 - (-573) = -110 \text{ cal/g}$$

This value should compare with experimental values of 260 to 280 cal/g.

The Peirce theory has one constant  $F$  that can be interpreted as an equilibrium constant between water and polymer (Giarle and Peters, 1960). The temperature dependence of this constant for wood is shown in Figure 15. The value for the heat of adsorption calculated from the slope of the curve is -144 cal/g, which should be compared with values of 260 to 280 cal/g as before. The heats of adsorption of all models are summarized in table 2.



M 148 165

Figure 14.--Temperature dependence of the equilibrium constants of the King sorption model.

Table 1.--Heats of adsorption predicted by sorption models

Sorption model	Heat of adsorption cal/g	Sorption model	Heat of adsorption cal/g
BET	67	III-- two hydrates	79.7
III + capillary	82	King	110
III-- one hydrate	12.7	Peirce	144

#### Mechanical Property Tests

One of the extensions of Peirce's model is the prediction that the relative modulus of rigidity should be linearly related to the amount of "a" water. (Peirce, 1929; Meredith, 1957). Meredith (1957) has shown this to be true for a number of natural polymers. This relationship can be tested for modulus of elasticity in bending from the known variation of this property with total moisture content (Wood Handbook, 1974), and is shown in Figure 16 where the relative modulus (ratio of modulus at moisture content  $m$  to modulus at zero moisture content) is plotted against "a" water content (calculated from eq. (13)). The results are not linear as predicted by the theory.

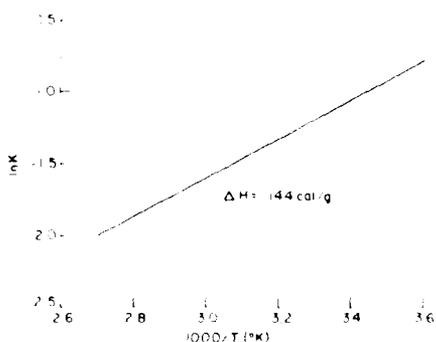


Figure 15.--Temperature dependence of equilibrium constant of Peirce sorption model.

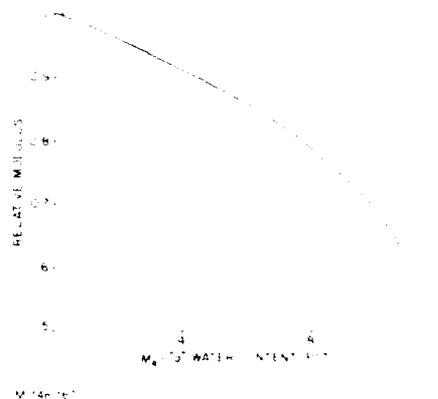


Figure 16.--Effect of "a" water content of Peirce model on relative modulus of elasticity in bending on Douglas-fir at 70° F.

#### Are Sorption Theories Useful?

Only a few of the many theories that could be applied to the sorption of water by wood have been discussed, and thus no claim is made for a comprehensive review. The models discussed represent some of the most widely known theories--ones that have been applied to wood in the past, and ones that can be evaluated with actual sorption data.

The critical test of the theories is how well they can predict the heat of adsorption. The models presented here do not do at all well in this test, which means the theories are weak or the experimental data are faulty. Values predicted by the models are in error by 50 percent or more, and in some cases the models predict endothermic reactions that are known to be exothermic. All models incorporate simplifying assumptions that are necessary in order to derive a mathematical model. Perhaps it is too much to expect these simplified models to accurately predict the energy associated with adsorption. For example, one of the simplifying assumptions in the BET model, that all of the energy of adsorption is in monolayer adsorption, probably precludes it from accurately predicting the heat of adsorption.

If one will accept the premise that the simplified models fail crucial tests because they are simplified, then it may be possible to accept the premise that they are not totally invalid, and that at least they create a general concept of how water is held in wood. All of the theories discussed here paint the same general picture of adsorption: part of the water is intimately associated with cellulose

molecules (monolayer, hydrated, bound water) and part is distinctly less intimately associated (multilayer, dissolved, liquid). This general view has become the accepted concept of how water is held in wood (and many other polymers).

It has long been well known that most mechanical properties of wood (and most hygroscopic polymers) decrease with moisture content. Peirce has made the attempt to link sorption theory to changes in mechanical properties. Mechanical properties are vitally important to the use and performance of wood products, so perhaps this would be a fruitful area of research.

The models reviewed here can be fitted with nonlinear-regression techniques to experimental data, and most of them with excellent results. If there is one practical use of these models at present, it is their excellent ability to correlate, interpolate, and compactly store a large amount of sorption data for wood. The analysis of Simpson (1973) shows that moisture content can be calculated with deviations of no more than 1/2 percent moisture content over the entire moisture content and temperature range. This accurate and compact storage of sorption data can be very useful in many kinds of mathematical or computer modeling.

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## RELATIVE HUMIDITY AND MOISTURE CONTENT INSTRUMENTATION

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This paper discusses the characteristics, use, and problems associated with commonly-employed RH and MC instruments. RH instruments include hygrometers, psychrometers, and dew-point sensors. Further information on these may be found in Anon. (1979), Considine (1957), Considine and Ross (1964), Norton (1969), and Wexler (1965). MC instrumentation coverage is limited to portable electrical moisture meters. Additional background information on moisture meters may be obtained from ASTM (1968), James (1963), James (1975), and Skar (1972).

## Relative humidity instrumentation

Relative humidity instruments generally fall into three categories: hygrometers, psychrometers, and dew-point sensors. The hygrometer responds to the direct interaction of water vapor and the sensing material, producing a chemical or physical reaction. Psychrometers measure relative humidity indirectly through evaporative cooling of a temperature sensor and by reference to psychrometric tables for dry bulb and wet bulb temperatures. Dew-point sensors also sense relative humidity indirectly by measuring the temperature at which condensation (or frost) occurs in cooling of the particular gas.

## Hygrometers

Hygrometers may be classified as follows:

1. Mechanical - change in dimensions of a material from sorption of moisture.

2. Electrical reactance - change in resistance or reactance of a material or surface from physical or chemical sorption.

Mechanical hygrometers generally contain a material such as hair or animal skin which expands and con-

tracts during adsorption and desorption. The material is held in tension and mechanically linked to an indicating dial. Such instruments are useful only as trend indicators since they have long time constants (30 to 200 s), display excessive hysteresis (about 5% RH or more over 10 to 90% RH), are non-linear in response, have a poorly-predictable response with temperature changes, and exhibit aging effects. They are not suitable for use in instrumentation for control of relative humidity.

Reactance hygrometers generally consist of hygroscopic salts or activated films which decrease in resistivity with an increase in sorption of water vapor. The most widely used element is made from a low concentration of lithium chloride in a plastic binder which was developed by Dunmore at NBS. The "Dunmore element" is usually fabricated from bifilar windings on a cylindrical tube which are coated with a polyvinyl binder. When connected as part of a bridge, the change in reactance of the sensor may be used to indicate and/or control relative humidity levels. If temperature corrections are applied, most of these sensors are fully usable over a wide RH range (10 to 90%) from about 5 to 50 C (provided condensation does not occur on the element) with a repeatability of about +1 to +3% RH. If uncorrected for temperature, a typical mid-range sensor (30 to 60% RH) will vary in indication by about 0.3% RH/C. Low RH sensors (whose ranges extend below 10% RH) are not designed to be exposed to dew-point temperatures over 38 C. Above 70 C, Dunmore elements may be irreversibly damaged. When used in dirty atmospheres, the element can be enclosed within a cellulose acetate film, although it will increase the response time. Acid or sulfide atmospheres will permanently shift the element calibration. Other chemical contaminants such as

alcohols, ammonia, and glycols can cause temporary displacements. Before Dunmore elements are used over saturated-salt, glycerin-water, or acid-water solutions, contamination should be anticipated, particularly for temperatures above ambient. The normal time constant for these elements is about 3 to 30 s (typically 15 s) depending on the particular design and degree of ventilation. Elements are available in single wide-range (about 5 to 95% RH) or multiple-range (about 10 to 20% RH steps) configurations.

A number of film-type sensors have been developed including surface-activated polystyrene, carbon, and aluminum oxide. These are wide-range sensors having some of the same problems associated with the Dunmore sensor such as contamination from particulates or chemicals. All are susceptible to errors from hysteresis, temperature, and response time.

#### Psychrometers

Psychrometers can be placed in two physical categories: sling and fixed. The following are important factors which affect the accuracy of wet-bulb/dry-bulb sensors:

1. Adequate ventilation of the wet-bulb sensor wick (about 5 m/s minimum).
2. Distilled water (contaminated water causes a shift in the rate of ventilation).
3. Matched dry-bulb/wet-bulb sensors over the temperature range of interest.
4. Shielding of the temperature sensors from extraneous radiant energy.
5. Correction of readings for atmospheric pressure.

When used with care, well-designed sling psychrometers are among the most accurate portable sensors for determining the relative humidity of conditioning rooms. The principle of the sling psychrometer has been incorporated in "aspiration" or Assman psychrometers, which cool the wet bulb by drawing air over the wick.

(Air is not pushed over the wick because of the possibility of the blower motor heating the entering air.)

The type of temperature sensor used includes glass thermometers, thermocouples, thermistors, RTDs and other resistance elements, and fluid-filled tubes. The resistance sensors have the best inherent accuracy, but others are more convenient in installation and in the use of standard laboratory equipment. The fluid-filled bulbs are advantageous because of the simplicity in design of pneumatic controllers/indicators such as are used in lumber dry kilns. However, these sensors may have long time constants (minutes) and calibration of the entire system over a wide range is difficult. The current trend in controller/indicator instruments is toward resistive-type sensors with I-P converters for use with pneumatic controls, or complete conversion to electronic controllers.

#### Dew-point sensors

Dew-point sensors, like psychrometers, measure relative humidity indirectly. Saturation vapor-pressure tables are used to convert dew-point temperature to relative humidity. The dew-point instrument can be remotely located from the measuring environment, using heated and/or insulated lines to insulate the air sample. In this way, a single instrument can monitor multiple chambers through manual or automatic switching. The simplest form of dew-point sensor consists of a polished surface which is cooled until dew or frost first appears. At that point, which can be directly observed by microscope or indirectly using light sensors, the temperature of the surface is measured. By cycling the temperature, the dew-point can be measured as a function of time. These meters can be made to accuracies of  $\pm 0.5$  C or less and can be manually operated or highly automated. The major problems relating to their construction and use are:

1. Temperature sensor. The best quality instruments use resistance-type sensors which are in intimate contact with the cooling surface. Temperature accuracy and response

time over the range of interest is critical for repeatable measurements.

3. Surface contamination. The mirrored surface must be kept clean either manually, or by baking and purging the surface of contaminants.

4. Sample line configuration. For most applications, the sampling line material and temperature are important (Baconarite and Cortina 1979). Most plastics and rubber tubing should be avoided because of their hygroscopicity and vapor transmission. The most suitable wide range materials are glass and stainless steel. Both the sampling line and instrument should be heated if the dew-point is above ambient temperature.

Another form of dew-point measurement uses the vapor equilibrium temperature of a heated saturated salt such as lithium chloride (Considine and Ross 1964). A wick containing the salt solution is heated to the evaporation point, which increases the resistance and therefore reduces the heating, leading to thermal equilibrium. This technique is inherently less accurate than that using a polished surface because of hysteresis and chemical contamination. However, it lends itself to simpler design (no refrigeration) and may be advantageous for readings near ambient temperature.

#### Calibration of RH sensors

Calibration of relative humidity instruments is difficult and often beyond the capability of well-equipped laboratories. The most accurate calibration equipment uses a two-pressure generator in which saturated air is isothermally expanded into a lower pressure calibration chamber. Alternatively, constant relative humidities may be produced by accurately mixing dry and saturated air at constant pressure and temperature. When used with high quality dew-point instruments, the mixed air dew-point may be controlled within  $\pm 0.1$  C between -30 and 40 C. However, these types of equipment are normally available only in laboratories having primary standard measurement capability.

In the typical laboratory, constant relative humidity is often obtained through the use of saturated-salt

solutions. Although they are widely used, large errors may be caused by a number of factors including:

1. Solution preparation (pure chemicals, distilled water, proper mixing, complete saturation, temperature equilibrium).

2. Solution-chamber design (large solution surface to air ratio, minimum volume of hygroscopic materials, continuous stirring of solution and air).

3. Solution-chamber use (closed system, constant temperature).

Under the best of conditions and care in preparation, saturated-salt solutions can be within  $\pm 1\%$  RH of published values. For greater accuracy, a reference-quality RH sensor must be used. Table 1 gives a list of typical saturated salts and their RH values as a function of temperature.

#### Moisture content instrumentation

##### Surface moisture content

The measurement of surface MC has normally been either directly through thin slices from the surface of a sample or indirectly from inference of the EMC conditions. Contact electrodes can be used to obtain direct readings of "surface" resistivity which can be converted to MC, although the depth of reading into the sample is uncontrollable. An intermediate method involves monitoring the mass of end-grain slices of a sample exposed to the same drying conditions. None of these approaches provide an instantaneous measure of the true surface MC or permit dynamic measurement over a wide MC range. An alternative to these methods is the direct reading of surface moisture content using infrared (IR) techniques. Commercial IR moisture meters permit non-contacting measurements over the complete range of MC with a minimum of necessary corrections. The effective depth of measurement is about 0.1  $\mu\text{m}$  for wood at typical wavelengths of 1.4 or 1.8  $\mu\text{m}$ . The most serious limitation is the difficulty in calibrating to obtain sufficient accuracy, however, the precision is probably better than

any other direct or indirect technique. The IR moisture meter has the added advantage of being able to view the wood surface through a window, permitting monitoring of samples in hostile environments. It is also possible to measure surface temperature using other IR wavelengths (independent of MC) and infer surface MC or provide supplemental information on surface conditions.

#### EMC probes

A DC moisture meter can be used to measure MC of small sections of wood, indirectly obtaining the environmental EMC. Wood probes are usually made from Douglas-fir (meter calibration species) with conductive coatings and lead wires attached (Duff 1966). This type of probe can also be inserted into predrilled holes in wooden members to indirectly obtain EMC of wood in service. The response time is long (hours) and conductivity will increase with the time of DC voltage application if a metallic coating is used. In order to avoid the ionic migration from metallic coatings, carbon air also been used.

#### Conductance moisture meters

Commercial DC moisture meters are normally calibrated for a direct reading of moisture content from the published resistance-MC curve of Douglas-fir. The meter operates simply as a wide-range ohmmeter from about  $10^{11}$  to  $10^3$  ohms, as measured between pins usually spaced 25 mm apart. Older models of DC moisture meters used high-input impedance circuits having electrometer tubes; newer solid-state designs incorporate FET DC amplifiers. Meters must be calibrated for the temperature their circuits are exposed to. The practical lower limit of measurement at room temperature using portable DC meters is 6 to 7% MC ( $10^{11}$  to  $10^{10}$  ohms). The upper limit on portable meters varies, but many indicate readings to 70% MC. Any readings made above ESP are qualitative, except when the temperature correction brings the reading below ESP. Permanently installed pins can provide semi-quantitative values for decreasing MC from above ESP, but point-to-point comparisons above ESP are usually unreliable.

Most meters are equipped with either 2- or 4-pin (2 parallel pairs) probes for MC measurement of lumber. Special veneer probes are available with 8 pins (4 parallel pairs). The 2-pin probe may have bare or insulated (except the tip) pins. Characteristics of bare 2-pin probes have been reported by Skaar (1964). A ratio of pin separation to diameter of 12.5 (for a 10 mm immersion length) is required to provide equivalent resistance and resistivity. For the typical 25 mm spacing, the pin diameter should be about 2 mm to maintain this equivalency. Because a nonuniform electric field is developed around and between the pins, resistivity is higher adjacent to the pins (about 0.5 of the total resistance is developed in the region of 0.25 the distance from each pin toward the other; also, doubling the pin spacing increases the resistance only about 25%). The influence of pin depth on readings is largely ignored, but bare pins driven into wood having a uniform MC will give readings which increase with depth because of the greater pin contact area. However, the same effect occurs if the wood has a normal drying gradient (lower MC on the surface). For this reason, the use of insulated pins provides more accurate and consistent readings. Electrodes having different numbers of pins with the same spacing do not give equivalent readings. Since the Douglas-fir resistance-MC curve was based on a 4-pin electrode, the 2-pin electrode reads about twice the resistance of that of the 4-pin at any MC. Meter readings (MC) for 2-pin electrodes tend to be too low (about 0.5% at 10% MC, 1% at 20% MC). A relative increase of 5% at any MC appears sufficient to correct meters which have been calibrated for 4-pin resistivity. Eight-pin (veneer) electrodes read lower in resistance (between 33 and 50%) than that of the 4-pin, depending on relative pin depth and veneer thickness.

When pins are implanted to provide long-term and/or remote readings, several problems may arise. Wood at constant MC gives readings (made intermittently) which decrease with time, apparently because of "fiber relaxation," the rheological deformation of wood tissue under the mechanical force of the pins, which

reduces surface contact pressure. This contact can be restored by lightly tapping the pins. If MC is changing substantially, as in kiln drying, shrinkage of the wood loosens the mechanical fit of the pins, increasing contact resistance. Also, if the MC is high (above about 20%) pin corrosion may increase this interfacial resistance. The integrity of mechanical contact can be improved by using predrilled holes with special pin shapes, such as modified screws.

Since DC resistance meters provide MC readings at specific points, it is not possible to directly obtain average MC in wood with moisture gradients. The most widely-used technique is to drive bare or insulated pins to about 0.2 the total depth of a board which has a normal ("parabolic") drying gradient.

The major two corrections necessary for accurate MC readings are temperature and species, applied in that order. Temperature corrections published by James (1963) are generally reduced to a simpler tabular form by manufacturers. However, there are problems in the interpretation and use of this data -- no information is provided to explain variability, species, significance of the curve-fitting, etc. Skaar (1972) has proposed an approximation for James' data, based on a reference temperature of 21 C and from  $U = 6$  to 28% MC:

$$\frac{dO}{dT} = 0.027 + 0.0085 U$$

However, data provided by Skaar (1974) based on heartwood and sapwood of five species at 12, 18, and 24% MC, appear to fit a relationship closer to:

$$\frac{dO}{dT} = 0.06 + 0.02 U^{0.5}$$

This relationship suggests a reasonably constant slope above about 18% MC, which is supported by the fact that the 18 and 24% slopes were not significantly different. From the variability in Skaar's data (about  $\pm 10\%$  range at 12% MC, and  $\pm 20\%$  range at 18 and 24% MC), it appears that the nominal correction curves proposed by James (1963) are not generally applicable. Apparently, the mode of DC conductivity is not uniform for many

species, particularly at higher moisture content and probably at higher temperatures.

Some newer meters have built-in dials to compensate temperature directly by shifting the meter calibration.

Species corrections are perhaps the greatest uncertainty in MC readings. Such corrections are usually supplied by meter manufacturers, but little effort has been made to provide unbiased, statistical data. For most species below about 15% MC, the correction is small (less than 1% MC), but above this level, the needed corrections may be substantially greater than recommended (Cech and Pfaff 1973). An added problem at this MC level is the apparent decrease in MC with time of voltage application. This occurs from polarization effects, probably near the pins, which increase rapidly with moisture content, particularly above about 20% MC, and are affected by wood extractives. MC readings in this range can be stabilized by using low frequency AC or switched DC voltages.

Data has been published in the Wood Handbook (1955) for the DC resistance of 29 species from 7 to 25% MC. James (1963) has extended this data to cover an additional seven species. Unfortunately, the resistance was not transformed to resistivity (the electrode configuration has also not been fully reported) and no statistical data is presented in either source. In addition, species information such as density, growth rate, EW/LW percentage, and heartwood or sapwood has not been included.

According to Stamm (1964), resistivity perpendicular to the grain is approximately two to three times that measured parallel to the grain. Since moisture meters are calibrated for parallel-to-grain resistance, readings made transverse to the grain may be about 1 to 2% MC lower than the true values. Radial resistivity is usually lower than tangential because of the influence of the rays. It would be anticipated that as density increases, the DC resistance of wood should decrease since the amount of cell wall material per unit volume is greater. An apparent increase in MC

would be caused by this decrease in resistance. For individual wood species, the density variation is too small to cause detectable errors in MC readings. However, the range of relative density of commercial species (nominally 0.3 to 0.8) could cause an error of 0.5 to 1% MC in readings, if density were the sole factor influencing DC resistance. To some extent, this appears to be the case for the species corrections recommended by meter manufacturers. The higher density hardwoods, in general, must have their MC readings reduced, but ion concentration and mobility among species is apparently the controlling variable and obscures the density influence. Venkateswaran (1972) found that the DC conductivity of 14 species of wood at about 12% EMC and in the oven-dry state was highly correlated with lignin percentage (Klason method). Conductivity increased about 10-fold over the range of 18 to 31% lignin content. This may be interpreted in several ways: lignin could have ions associated with it in a reasonably uniform concentration regardless of species and/or the continuity and structure of lignin controls ion mobility. Effects of ash content, extractives, reaction wood, fibril angle, etc. have not been studied sufficiently to be of practical use in DC conductivity measurements.

#### Dielectric moisture meters

Two "types" of dielectric moisture meters are commercially available. "Power loss" meters react primarily to resistive reactance and "capacitance" (or "admittance") meters are more sensitive to dielectric constant. Frequency is the major determining factor for the mode and MC range of operation. For example, a meter operating at 100 kHz (25 C) has a high loss tangent (resistance mode of operation) and is apparently sensitive to MC changes above FSP. At 1 MHz, the meter is about equally sensitive to resistance and dielectric constant below FSP. For 10 MHz, the resistance effect is relatively small ( $\tan \delta < 0.3$ ) and correlates poorly with MC, therefore, the meter responds largely to the dielectric constant.

In the commercially available dielectric meters, the power loss

meter is sensitive to MC between FSP and oven-dry, whereas the capacitance meter is potentially sensitive over the entire MC range (green to oven-dry). Both types of meters have arbitrary readout scales. The meter value is converted to moisture content by a calibration table for the specific species being measured. Power loss meters are influenced primarily by the nature and concentration of extractives in the species. Capacitance meters are influenced more by moisture concentration than MC, particularly above FSP. Dielectric meters use surface contact electrodes, generally of a concentric coplanar configuration which produces an "edge-effect" electric field. The typical electrodes always have a component of the electric field along all three major axes of wood, therefore, the influence of grain angle on electrical properties must be considered. These effects are quite different for the loss tangent and dielectric constant. For all practical purposes, radial and tangential aspects may be combined into "transverse" for dielectric constant. However, above about 20% MC, loss tangent is considerably greater for the radial than the tangential plane, possibly because of the influence of the rays on conductivity. The linear dependence of dielectric constant on MC above FSP has been established by Skaar (1948). Since the electric field intensity will decrease with distance from the electrode, it is expected that dielectric meters may be more sensitive to moisture closer to the electrode. This is particularly true of power loss meters which may be nearly insensitive to MC levels at 2.5 mm below the wood surface (Mackay 1976). In contrast, capacitance meters provide a reasonable integrating effect for widely-varying moisture content distributions (Dennis and Beall 1977). Since contact pressure of the electrode is critical in power loss readings, spring-loaded electrodes are used. Abnormal surface conditions (high moisture content from condensation, chemical contamination) may cause a substantial error in power loss readings, but have negligible effect on capacitance readings. Loss tangent and dielectric constant of wood are temperature dependent (James

1975), but limited data is available for corrections of specific power loss and capacitance meters (ASTM 1978).

Table 1. Equilibrium Relative Humidity Over Saturated Salt Solutions<sup>a</sup>

Nominal RH (%)	Salt	Temperature (C)			Solubility (20 C) (g/100 ml)
		15	20	25	
10	LiCl	11.94	11.14	11.15, 11.05	78.5
20	CaBr <sub>2</sub>		17.9		143.0 (6 H <sub>2</sub> O)
30	CaCl <sub>2</sub>	35.65	32.75	28.98	74.5 (6 H <sub>2</sub> O)
40	NaI	40.54	39.17	37.75, 38.4	178.7 (2 H <sub>2</sub> O)
50	Ca(NO <sub>3</sub> ) <sub>2</sub>			49.97	56.39
60	NaBr			57.7	47.5
70	KI	70.96	69.84	68.76	144.0
80	KBr	82.76	81.74	80.77, 80.71	65.2
90	BaCl <sub>2</sub>	91.03	90.66	90.26, 90.19	35.7

<sup>a</sup> Compiled from Wexler (1965). For additional salts and temperature dependence see Wink and Sears (1950).

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WATER-VAPOR SORPTION BY  
WOODS OF HIGH EXTRACTIVE CONTENT

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ABSTRACT

The state-of-the-art of water-vapor sorption by high extractive woods is reviewed. Woods of high extractive content exhibit lower EMC and shrinkage at lower temperatures but high shrinkage and collapse at high temperatures in kiln drying. Description of extractives is offered as the cause of this behavior but more research in extractive mobility is needed.

INTRODUCTION

Extractive-free wood is composed of two classes of component: one is non-volatile wood substance or high molecular weight (adsorbent) and the other is volatile water (adsorbate). Wood substance is a complex mixture of carbohydrate polymers and phenyl-propane macromolecules formed in aqueous solution and deposited in a highly swollen state. Eventually the cell membrane and contents undergo desiccation and death leaving the fibrous wood cell as a hollow tube with small holes at both ends. When processed for use, the wood is dried which causes the cell wall to increase in density, strength, and stability as the dissolving water is removed.

Extractives in wood, however, are inter-related between wood substance and water in both adsorbent and adsorbate widely in water solubility and volatility. In terms of their nature, by, or influence on sorption, extractives are difficult to classify as to being either adsorbent or adsorbate.

Extractives complicate the drying, shrinking, and stability of woods of high extractive woods are growing in popularity. Traditional American, European, and Mediterranean furniture styles favor dark-colored woods. Wood staining, roofing, and decking favor extractive-rich woods which are reputed to be more durable and stable. These uses require properly seasoned wood which could means kiln-dried

material. But woods of low extractive content are often more difficult to dry with or degrade.

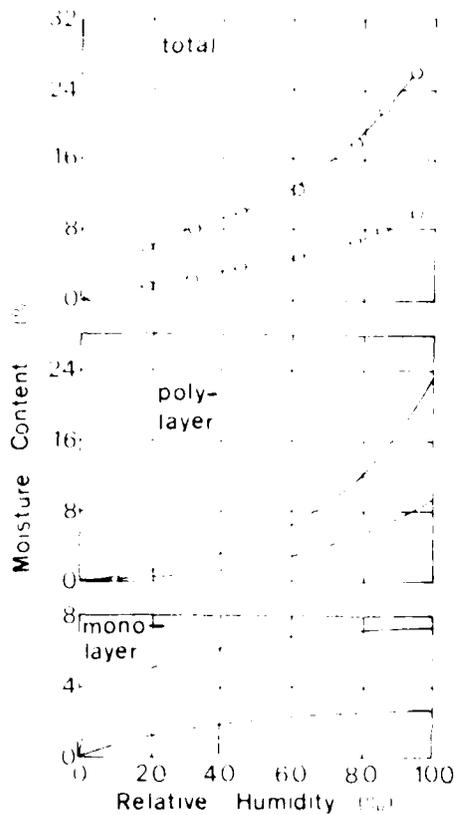
In the past twenty years, numerous wood scientists studied the properties of domestic and tropical woods which have a high extractive content. More recent work has uncovered extractive-related problems in the kiln drying of these woods, especially at higher kiln operating temperatures now coming into wider use.

The purpose of this paper is to present the state-of-the-art of the sorption properties of high-extractive woods with focus on the characteristics of these woods that affect their processing and utilization.

FORMATION AND CLASSIFICATION  
OF EXTRACTIVES IN WOOD

The formation of extractives is closely associated with the transition of sapwood to heartwood (Gillis, 1968). Starch and sugars stored in xylem ray and parenchyma cells are believed to be the raw materials for extractive production (Gosshard, 1962; Gillis, 1968; Benneway and Gillis, 1970). Benneway and Gillis (1970) argue that the factors which control the amount and composition of extractives are programmed into the ray and parenchyma cells in the early stages of their development. At the proposed heartwood boundary, starch and sugars disappear (Gosshard, 1962) and respective compounds increase (Gillis, 1968). As the





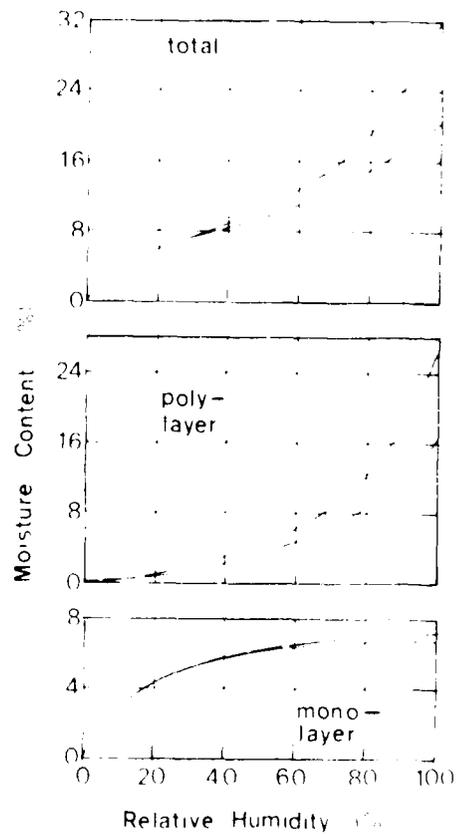
untreated  
extracted

Figure 1.—Description isotherms for untreated spruce and extracted of the spruce at 9 °F divided into monolayer and polylayer forms of sorbed water by the use of the Ballwieser-Hartwig (1961) model.

Figure 1.—Spruce Spalt (1953).

material that amounted to 11 percent of the moisture content. Water sorption in polylayer wood increased considerably after extraction. The moisture was treated at all values for untreated wood. A comparison of Figure 1 and 2 indicates that the extractive material is not present in the cell wall material, and water sorption in the cell wall is not affected by the extraction.

As part of the study that revealed the extractive material in spruce wood, Ballwieser and Hartwig (1961) reported the entire extractive material that the extractive material was available to the monolayer and polylayer forms of sorbed water.



unextracted  
extracted

Figure 2.—Description isotherms for extracted and unextracted mono-amarilla wood at 9 °F divided into monolayer and polylayer forms of sorbed water by the use of the Ballwieser-Hartwig (1961) model.

Figure 2.—Wood Kaysard and Gramades (1964).

removed. The moisture reported in unextracted wood is from both monolayer and polylayer forms of sorbed water. The moisture content of unextracted wood is the sum of the moisture content of the monolayer and polylayer forms of sorbed water.

As part of the study that revealed the extractive material in spruce wood, Ballwieser and Hartwig (1961) reported the amount of water sorption in untreated wood. There was a noticeable decrease in the moisture content in the initial description of the spruce wood to the second description, which was followed by over drying and correction of the water to the third description. The unextracted wood still had the same moisture content as the untreated wood.

results were caused by differences in the handling of the specimens rather than differences in extractive content only. Furthermore, the hot water steeping used to remove approximately 7.0 percent extractives from the heartwood and 1.05 percent extractives from the barkwood. These small amounts would likely have only small effects on desorption compared to the effects of the added overdrying and soaking of the last desorption cycle. Cooper, however, concluded that these results indicated the extractives are more hygroscopic than the cell wall polymers.

#### EFFECT OF EXTRACTIVES ON SHRINKAGE

Stamm (1963) reviewed the dimensional behavior of domestic woods. Within a species, specimens of different specific gravity showed a close relationship between volumetric shrinkage and specific gravity with the regression line passing through the origin. Between species, however, the relationship showed wide variation with silver fir, white spruce, and noble fir with high shrinkage relative to specific gravity and redwood, eastern redcedar, juniper, and Pacific yew having low shrinkage relative to specific gravity. This group with lower than normal shrinkage contained high extractive content. Stamm (1963) stated that after water evaporated from the cell walls, the extractives were left deposited in the fibers which caused the fibers to be swollen by the same amount as if an equal volume of water was left within them.

Nearn (1955) extracted woods in running cold water and in running hot (140°F) water for periods of three or more weeks and compared the shrinkage of the extracted specimens to their unextracted counterpart. In almost every instance, extraction caused an increase in volumetric shrinkage (fig. 3). Little change occurred with Sitka spruce, a species with negligible extractives, but redwood and mahogany exhibited sizable increases in volumetric shrinkage following extraction, especially hot-water extraction.

Nearn (1955) also calculated the slope of the shrinkage-moisture content curves and found that these differed significantly between species but did not differ significantly between extraction treatments within a species. Removing extractives from the cell wall did not change the slope of the shrinkage-moisture content line but shifted the line to the right in proportion to the quantity of extractives removed. Wood containing extractives had to be dried to a lower FSP before water was desorbed from the cell wall and shrinkage began. However, once cell wall desorption started, the magnitude of the shrinkage change with each percent decrease in moisture content was the same.

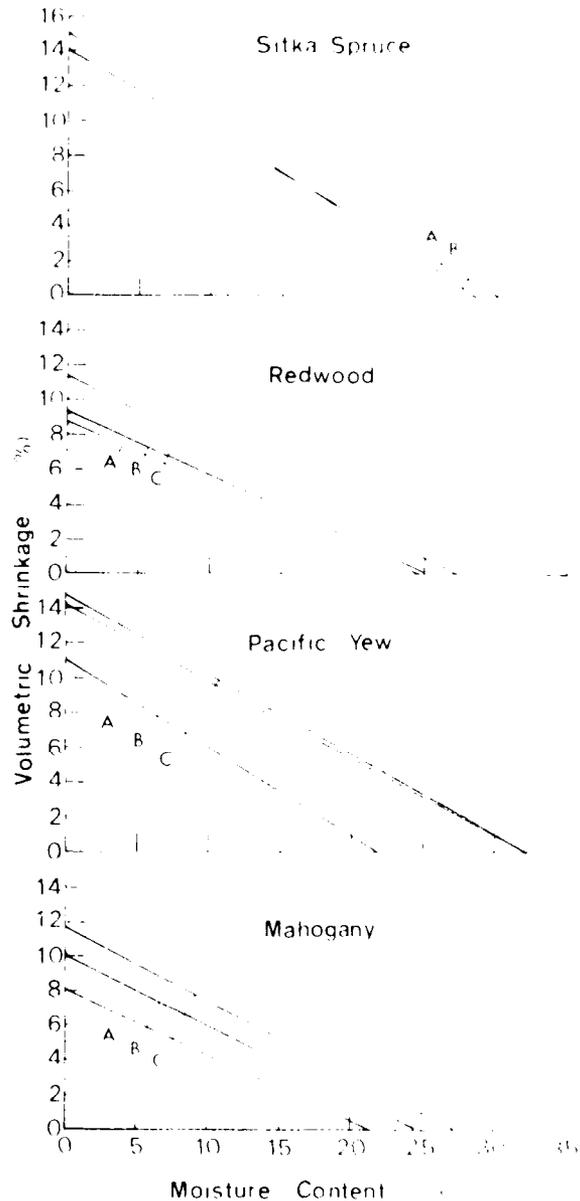


Figure 3.—Volumetric shrinkage-moisture content relationship for four woods tested unextracted (A), and after extended extraction in running cold water (B) and running hot water (C).

Figure 3 from Nearn (1955).

water content of the specimens but that it was the extractive content.

It is apparent from Figure 4 that extractives do not contribute to the stability of the wood. The dimensional change with increasing extractive content is about 1 percent greater for each percent of extractive content increase. Furthermore, when the data for wood extractives were plotted against the extractive content, the ones that were extracted at low pH values showed a lower vapor saturation.

Figure 5 shows, in the other hand, some data that are in close agreement with the results of Figure 4. The relationship with extractive content of the wood, as well as the amount of the extractive content, indicated the effect of extractive content. Lower and higher solubility of collapsed material in chloroform acetone showed that the collapsed material averaged 12.5 percent acetone solubility whereas non-collapsed material averaged only 1.2 percent. In the collapsed wood alone, the acetone soluble material is 48 percent. Collapsed material usually exhibits excessive shrinkage for its species (Table 1967).

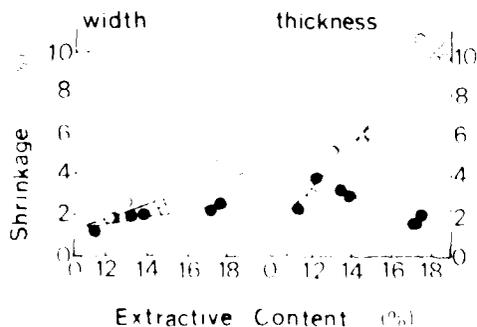


Figure 4. Relationship between extractive content and shrinkage in redwood with and without pretreating treatment preceding drying. Figures from Fricksen (1967).

- without pretreating treatment
- with pretreating treatment

The data work Demaree and Fricksen (1966) report that the volumetric shrinkage-extractive content relationship in redwood heartwood was temperature dependent (Figure 6). Shrinkage was inversely related to extractive content at 175°F. However, at 130°F and 110°F, shrinkage increased with extractive content. The authors explained these phenomena in terms of a dehydration-rehydration mechanism which is not applicable to high humidity

wood conditions. Some extractives are plasticized and are released by Demaree and Fricksen (1966) as existing in both the cell wall and the cell lumen as thin water films. If the temperature of wood rises in the film, the lumen sap was viewed as rehydrating and releasing materials diffuse into the cell wall where they are claimed to act as plasticizers that softened the cell wall rendering it cell-responsive. Collapsing cells would increase shrinkage.

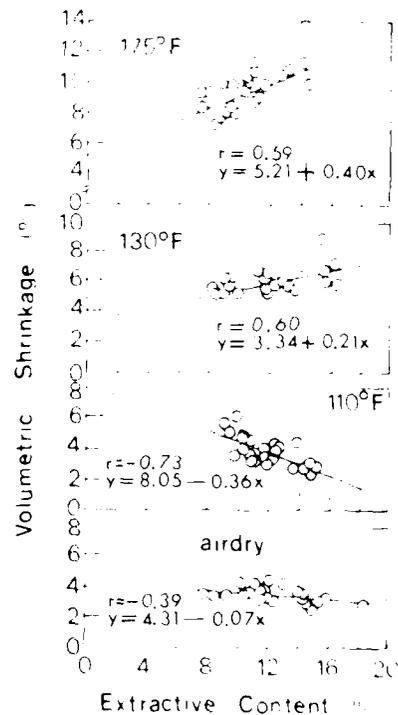


Figure 5. Relationship between volumetric shrinkage and extractive content in redwood. Extractive content and extractive content wood water of redwood dried at four different temperatures.

Figures From Demaree and Fricksen (1966).

The mechanism of plasticization by extractives or other sources of support. Nara and Smith (1957) found that unextracted wood specimens exhibited lower elastic modulus and were more than their extracted counterparts. Ammons (1942) reviewed the creep behavior of wood under using desorption or absorption under load. Desorption under load caused large creep deflections in all loadlines, especially in compression. Absorption, however, was claimed to produce only small creep deflections except where it was the first moisture change following load application. The largest creep deflections were

associated with the largest moisture content changes, by description.

Given this background, the plasticization of the cell wall by the adsorption of extractives is postulated by Demaree and Erickson (1970) as not only as it applies to the initial adsorption after loading. A more likely mechanism would be the movement of extractives out of the cell wall at high temperatures encountered in film drying. Extractives, especially those of low molecular weight, non-polymeric, non-lipid-phase solutions, if adsorbed water and move in response to concentration gradients. They may also evaporate and move in the vapor phase. The mechanism is that the extractives would be desorbed just as adsorbed water is as sorption shrinkage accompanies the desorption of water. The desorption of extractives would cause plasticization of the cell wall along a Arrhenius-like mechanism, and greater shrinkage and cell wall plasticization of extractive woods at high temperatures are expected to result in plasticization.

#### INFLUENCE OF THE TEMPERATURE DEPENDENCE OF WATER ADSORPTION

Most of the conventional studies on the effect of extractives on wood dimensional changes have been conducted at room temperature. Under these conditions, the extractives have been found to reduce the FSP of wood, especially at high relative humidities, and to lower the fiber saturation point of wood. Some minor reductions in green-to-oven-dry shrinkage of wood, however, the amount of dimensional change is only a few per cent change in volume. In general, the FSP was not changed by the presence of extractives. At ambient temperatures, extractives seemed to be benign. Low relative humidities in the cell wall that fill plasticized inter-fiber voids.

At temperatures above 100°C, the extractives in moist wood appeared to become more active adsorbates that moved in response to concentration gradients. In this case, they may have acted as plasticizers and increased the overall plasticity of the cell wall material. The extractives, if they are mobile in the cell wall, may cause plasticization of the cell wall and increase the plasticity of the wood. This is expected to result in plasticization of the wood.

At high temperatures, the extractives in wood are expected to be more active plasticizers. In fact, they are expected to be more active plasticizers than water, especially in the case of wood. The extractives are expected to be more active plasticizers than water, especially in the case of wood. The extractives are expected to be more active plasticizers than water, especially in the case of wood.

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MOISTURE MEASUREMENT PROBLEMS IN LUMBER DRYING<sup>1</sup>

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ABSTRACT

This paper discusses major needs for improved measurement of lumber moisture content prior to, during, and after drying. The need to define more clearly what is meant by moisture content in lumber in light of its inherent variability and to specify more precisely desired accuracies for green, partially dry, and completely air- or kiln-dried lumber is also discussed.

INTRODUCTION

The objective of lumber drying simply stated is generally to remove moisture from a board as quickly as possible with an acceptable amount of degrade. Inherent in the terms "moisture removal" is the concept of reducing the moisture level from some initial, often variable, value to a lower level that is dictated by either grading rules or mill yields.

The process of moisture removal remains one of the principal bottlenecks in lumber manufacturing with respect to time, equipment, capital investment, product value losses and, of more and more importance, energy costs.

Accurate knowledge of the moisture level in lumber at various stages of drying should enable our industry to overcome many of the existing problems inherent in lumber drying. Although the following discussion is specifically oriented to lumber, it should be generally applicable to many solid wood products.

DEFINITIONAL ASPECTS

Perhaps the initial problem encountered when considering moisture measurement in lumber involves clarifying exactly what is meant

by moisture content. The concept of moisture content as expressed as the weight or mass of water in terms of a percentage of wood's oven-dry weight is the standard definition of moisture content accepted and used by the solid wood products portion of the industry. One principal drawback to this expression is that two pieces of lumber having the same moisture content but differing densities will contain different absolute moisture levels, that is, on a grams-of-water-per-unit-volume-of-wood basis. This frequently means that when dealing with engineering calculations on moisture removal the density of the material has to be known or estimated. This direct interrelationship between moisture content, density and absolute water content often means that an estimation of one of these variables involves simultaneous estimation of the other. The importance of density in moisture measurement is further strengthened by the fact that many of the indirect electrical-property-based measurement techniques are strongly affected by density variations. In addition, the drying rate of lumber is also correlated with density of the piece. One might conclude from these facts that when speaking of moisture measurement problems in lumber drying one should consider both variables, or at least bear in mind the importance of density and its variations. Having touched upon the differences between absolute water content and percent moisture content, the latter concept will be used in the remainder of this text.

If lumber were a more homogeneous material many of the problems in lumber drying moisture measurement would be eliminated. Unfortunately,

<sup>1</sup>Paper presented at the Symposium on Wood Moisture Content-- Temperature and Humidity Relationships, Blacksburg, Virginia, October 29, 1979.

lumber exhibits considerable variability in its different physical and mechanical properties, including wide variability in moisture content.

The industry is therefore faced with estimating not only between-piece but within-piece moisture content variations, both in green and dried lumber. Within-piece variations can occur along the length of a piece, across the width, or with respect to the thickness. These can take the form of continuous sizeable zones of differing moisture content as a result of mixes of sapwood and heartwood tissue or discontinuous streaks or spots.

In examining any given board or set of boards, therefore, one might view moisture content in terms of:

1. the maximum value
2. the minimum value
3. the overall value
4. some measure of the variability present

This represents again a definitional problem, which is, what exactly do we mean when we speak of a board's moisture content? Up to the present time the industry has generally used the concept of *estimating average moisture content*—even though this may not be the limiting value important in processing or end quality.

The assessment of both between-piece and within-piece moisture content variability in both green and dry lumber needs to be quantified using a sound statistical basis for our principal commercial species. Such a study on kiln-dried lumber has been initiated by the U. S. Forest Products Laboratory in cooperation with the University of California Forest Products Laboratory and Louisiana State University.

The question of desired accuracy is a second aspect connected with defining exactly what is meant by lumber moisture content. As hopefully will be shown shortly, the moisture content accuracy needs of the industry may vary considerably depending on the moisture content level one is dealing with. It does not seem unreasonable that desired accuracy for moisture content estimations would be different for:

- a) green lumber;
- b) partially dry lumber;
- c) completely air- or kiln-dried lumber.

Taking into account the magnitude of inherent variability and the objectives for measuring moisture content, reasonably acceptable desired accuracies need to be established.

#### FACTORS AFFECTING MEASUREMENT

Various other factors that may affect the estimation of moisture content of lumber have been summarized in Table 1. In addition to the

Table 1.--Possible factors that may affect estimation of moisture content measurement in lumber. (Adapted from Olson, J. R. 1979.)

Variation in Material Properties	Variation in Moisture in Wood	Production Factors
Specific gravity	Between species	Feed speed
Thickness, width and length	Within species	Speed of measurement (dwell time)
Heart-sapwood content	Stand to stand	Total area sampled
Grain orientation	Tree to tree	Point sampling
Ring curvature	Within tree	Continuous sampling
Growth rate	Height	Board temperature
Structural direction	Radial	Hot after drying
Presence of defects	Within piece	Cold or frozen before and after drying
Knots	Moisture gradients	Board orientation when passing through measurement system
Checks	Moisture distributions	
Splits		
Wane		
Resin pockets		
Decay, etc.		
Uniformity of growth		
Surface roughness		

Inherent between- and within-piece variations already discussed, an effort has been made to identify the most significant factors with respect to variations in other material properties and to possible mill production influences. This array of variables, although probably incomplete, clearly shows the complexity of the problem.

a large daily output of lumber and hence a large number of individual pieces, many of the factors listed apply equally well to situations where only a small number of pieces are to be measured.

Attention is drawn to the suggested moisture measurement accuracies, which are as follows:

AN IDEALIZED MOISTURE CONTENT MEASURING SYSTEM

Based upon the previous discussion and consideration of the possible factors that may affect moisture content estimation the requirements of an idealized lumber moisture measurement system have been postulated and are listed in Table 2. While these requirements are based upon the anticipated needs of a mill producing

Green lumber	+ 5-10%
Partially dried lumber	+ 2-5%
Completely air- or kiln-dried lumber	+ 1-2%

Although obviously arbitrarily selected, these values should serve as a starting point and hopefully will stimulate establishment of general classes of appropriate accuracies.

Table 2.--Requirements of an idealized lumber moisture measurement system. (Adapted from Olsen, J. R. 1979.)

<u>System Requirement:</u>	<u>Comments</u>
Accuracy	Should be capable of the following accuracies: $\pm 5-10\%$ MC for green lumber, $\pm 2-5\%$ MC for partially dry lumber and $\pm 1-2\%$ for dry material
Speed	Speed of measurement - potentially very rapid (short dwell time) to allow for high feed speeds in some mills
Continuous	Maximize total area sampled - computerized output perhaps essential
Nondestructive	Both contact and noncontact should be feasible
Capital investment	Minimize investment - system should pay for itself in short period of time
Safety	Protection of mill personnel with necessary shielding, etc., essential
Ease of use	Mill personnel with proper training should be able to readily perform necessary measurements and evaluations
<u>The system should allow for variations in:</u>	
Mill and board temperature	Temperature independency necessary
Specific gravity	Must be accounted for, perhaps using another technique
Thickness	Must be accounted for, using lasers or other electrical/mechanical methods
Presence of defects	Should have capability for identifying and deleting these from determination of moisture content estimation of board
Moisture content	If a large enough volume of the board is sampled, it may be desirable to identify and take these into account

#### MEASUREMENT NEEDS PRIOR TO DRYING

There appear to be two general areas where better moisture content measurement prior to drying would lead to significantly improved drying practices. These are in the segregation of green lumber and the selection of kiln sample boards; these two aspects will be discussed separately.

#### Green Lumber Segregation

The desirability of separating lumber into special sorts or segregations prior to drying has been discussed in some detail by Arganbright (1973). Drying sorts can be classified into two main types. Sorts established on the basis of expected differences in rate of drying (drying-rate sorts) (Smith and Dittman, 1960), or sorts carried out on the basis of tendency to develop seasoning degrade (degrade-potential sorts) (Nicholson, 1973).

The objective, regardless of which sort is made, is to develop units of lumber in which all boards exhibit as uniform drying characteristics as possible. Such sorts can frequently be made on the basis of differences in moisture content as a result of sapwood and heartwood or the presence of wetwood (Ward *et al*, 1973). The former effect can be clearly seen in the data of Figure 1, which gives a frequency distribution of green weight per ft<sup>3</sup> for 5/4-inch thick ponderosa pine, mill classified sapwood and heartwood boards. Since weight per ft<sup>3</sup> is directly related to initial moisture content, one can see the two distinct moisture content populations of heartwood and sapwood material. The overlapping areas most likely represent boards containing both sapwood and heartwood. This points out one of the major problems encountered in drying rate segregation

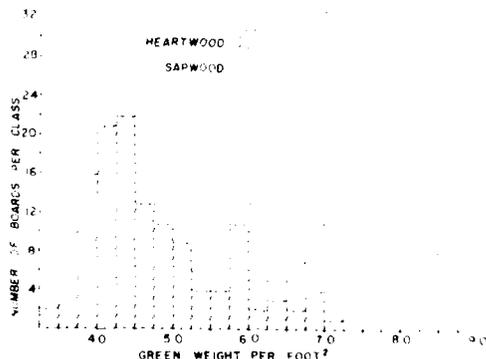


Figure 1.--Differences in Initial weight/ft<sup>3</sup> for mill segregated 5/4" ponderosa pine

and that is how to classify boards having different zones of moisture content, as the heartwood might normally be dried in 48 hours and the sapwood in 80-96 hours, although this is also related to grade differences in the material.

Examples of degrade potential sorts based upon moisture content differences would be the segregation of high-moisture-content sinker stock in redwood, hemlock, incense cedar, aspen and cottonwood to reduce collapse development. The work of Ward *et al* previously cited indicates that material susceptible to honeycomb and ring shake is associated with zones of higher-than-normal moisture content.

When drying a charge of lumber that contains significant quantities of material having either different drying rates or potential for degrade several different consequences may result, depending upon the nature of the drying schedule. The schedule being used may be based upon the response of the faster or easier to dry material or, as is more common, on the basis of the slower or more difficult to dry portion. This is equally true for time and/or moisture content type schedules.

If drying is controlled by the behavior of the easier to dry portion of the charge, the remaining portion of the charge may be subjected to kiln conditions which are too severe, thus causing excessive degrade. In addition, the slower drying portion may still be at too high a final moisture content at the end of the run.

If, on the other hand, drying is controlled by the response of the slower or more difficult to dry part of the charge, other problems can arise. In this case, the schedule being used is too mild for the easy to dry material and the end result is that the total through-put of the kiln is less than it could and should be. Because the charge is kept in the kiln longer than necessary, the direct drying costs are also greater than need be. This aspect is illustrated in Table 3, where potential savings in direct drying costs have been calculated for the example where lumber of two discrete drying rates might be segregated. These data show that greater possible saving can occur as total drying time becomes longer and as the ratio of the drying times for the two types of material increases. It should be noted that these calculations were based upon the assumption that a segregation can be made at no cost, which is obviously not true. Reliable data on the actual costs of unstacking, metering and re-stacking need to be obtained before the benefits of segregating green or partially dry material can be accurately assessed.

One of the most important consequences of drying material of mixed drying rates on the basis of the slower drying material is that the faster drying material is often brought to too low a final moisture content or it is overdried. This is particularly true for softwood lumber where the equalizing period is frequently not used. Some data on the high dollar losses resulting from increasing degrade as final moisture content decreases have been obtained, as shown by Figure 2 and Williston (1971). Although difficult to assess, the relationship between degrade and final moisture content needs to be much more fully evaluated.

The various benefits which might be expected from establishing or improving existing drying sorts or segregations are therefore:

1. Reduced overall drying times--greater kiln through-put;

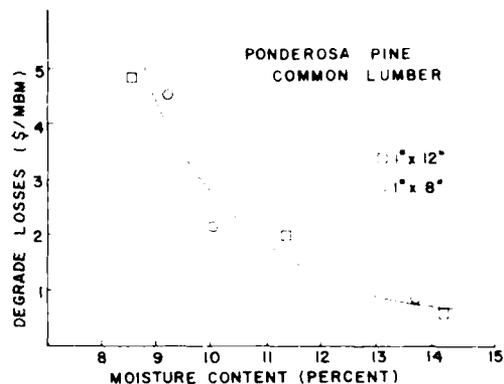


Figure 2.--Relationship between charge average final moisture content and degrade loss in 1960 dollars. (From Knight and Cook, 1960)

Table 3.--Calculated potential reductions in direct drying costs for different drying-rate sorts. (From Arganbright, 1973.)

Total drying time for slower drying sort (days)	Fraction of material in faster drying sort	Ratio of drying times of faster to slower sort	Reduction in total drying costs if material is dried as separate sorts \$/MBM
2	0.10	.95	0.008 <sup>2</sup>
		.75	0.041
		.50	0.081
	0.25	.95	0.021
		.75	0.102
		.50	0.203
	0.50	.95	0.040
		.75	0.202
		.50	0.404
8	0.10	.95	0.032
		.75	0.162
		.50	0.324
	0.25	.95	0.082
		.75	0.405
		.50	0.809
	0.50	.95	0.162
		.75	0.809
		.50	1.618

<sup>1</sup>Reduction in drying cost = (Total drying time for slower sort) x (kiln operating cost/hr) - ((fraction of material x (drying time for x (kiln cost/hr) + (fraction of material x in slowest sort) slower sort) (drying time of faster sort) x (kiln cost/hr))

<sup>2</sup>A fixed value of \$ 0.0337/MBM/hr was used for the kiln operating costs.

2. Reduced overall total drying times-- lower direct drying costs per Mfbm;
3. Improved uniformity in final moisture content-- less de-grade loss;
4. Better schedule suitability-- less defect development.

#### Kiln Sample Selection

When a kiln charge using kiln samples is run a number of different factors are considered in selecting the sample boards (Rasmussen, 1961). The estimated oven-dry weight of the kiln sample board is normally obtained by cutting roughly 1-inch long moisture content wafers from each end of the 2 - 4 ft. kiln samples for estimation of the sample's initial moisture content. Error in accurately assessing the initial moisture content can lead to significant errors in the calculated oven-dry weight and moisture contents of the sample boards during the run. This is shown by the data of Table 4 where estimated and actually determined oven-dry weights were determined for 10 California black oak kiln samples. Attention is drawn to the differences in actual and estimated moisture contents at the end of the kiln run. Moisture content errors of 3 percent or greater occurred as a result of initially incorrectly estimating sample board oven-dry weight.

Improved moisture measuring techniques would not only help reduce this type of error but would improve selection of sample boards when the criteria of difference on green or initial moisture content are used together with other factors.

#### MEASUREMENT NEEDS DURING DRYING

Accurate knowledge of the moisture content of a charge of lumber as it dries remains a real need in drying. While the use of kiln samples is still a useful means of estimating moisture content change, it is far from a perfect solution. In addition to the problems just discussed, this technique permits sampling only a small portion of the total charge, is relatively labor intensive, and gives data on the state of the charge at rather widely spaced time intervals.

With kilns using time schedules no such information is available and control of the kiln is adjusted on the basis of practice that has been found to yield acceptable results in the past. Time schedules do not permit our operator to adjust for between-charge variation in drying rate, regardless of whether the cause is a result of partial drying in the yard, variations in moisture content or whatever.

If the data on the changing moisture content of a charge were available this could be used as a reactive control mechanism and the kiln conditions could then be adjusted on a continuous basis. The use of load cells to measure weight changes of all or part of a charge is a step in this direction and some information on this approach is available for both hardwoods (Wengert and Evans, 1971) and softwoods (Holmes and Arganbright, 1976). In Wengert and Evans' work, adjustments were made using moisture content as calculated from charge weight and estimations of the charge's initial moisture content. The use of charge weight rather than moisture content as done by Holmes and Arganbright also necessitates the same a priori estimation of how moisture content correlates

Table 4.--A comparison of actual and estimated oven-dry weights for 3-foot long random width 4/4 California black oak kiln sample boards.

Kiln sample No.	Oven-dry weight estimated from moisture water (lbs)	Actual oven-dry weight (lbs)	Moisture at end of kiln run using	
			Estimated oven-dry weight (%)	Actual oven-dry weight (%)
1	5.10	5.13	8.43	7.79
2	3.98	4.10	9.54	6.34
3	4.24	4.21	8.01	8.78
4	3.03	3.17	5.61	9.46
5	3.19	3.21	4.38	3.74
6	4.46	3.44	9.86	42.44
7	3.87	3.86	7.49	7.77
8	3.60	3.63	10.00	9.09
9	6.33	6.25	14.37	15.84
10	3.20	3.34	11.56	6.88

to charge weight, at least for determining when to terminate the run.

Ideally, knowledge of not only average charge moisture content but the variation in moisture content between different boards within the charge is desired. This would permit kilns to be adjusted by either the fastest or slowest drying material or on the response of the average material. Development of the methodology to do this represents a very severe challenge.

The use of in-kiln meters such as the "kil-mo-trol" and "kiln-scan" techniques might be considered as early attempts at this problem. Such techniques, however, are generally considered to be primarily useful when the moisture content of the portion of the kiln they are sampling is below the fiber saturation point. Their existence does indicate a second real need for moisture content measurement during actual drying, which is becoming more and more important. This is the need to accurately determine when the charge has reached the desired average final moisture content or end point. Benefits from improved end-point determination would be reductions in degrade, as was noted under the discussion of degrade and final moisture content, total drying time and direct drying costs.

The much greater use of high-temperature kilns in the last several decades for softwood dimension lumber and its possible use with previously air- or kiln-dried hardwood lumber (Wengert, 1972) add to this need. This results from the fact that the use of high temperatures, with their faster drying rates, can lead to greater and more severe overdrying in much shorter times than in the case of conventional kiln temperatures.

#### MEASUREMENT NEEDS AFTER DRYING

As with the initial moisture content of lumber, a charge of dried lumber frequently exhibits considerable variation in final moisture content as a result of variability in drying rate or lack of uniformity within the kiln. Because of lumber standard requirements or potential problems in subsequent processing as with finger jointing, laminating, etc., lumber frequently must be measured for final moisture content after removal from the kiln.

There are at present various commercially available moisture meters for dry lumber in use throughout the United States. Major needs appear to lie in the areas of definitional aspects as previously noted, reducing the in-

fluence of density on meter readings, and improving the data recording and production management aspects (Carlson, 1977). Greater emphasis also needs to be placed on sensing for overdry stock in addition to redry.

Dry moisture metering also has great potential for use in lumber redrying. Redry lumber is that portion of a charge that is still at too high a final moisture content and must be dried further. Increasing the level of redry lumber rather than decreasing it, as is generally thought best in most mills, has been shown to have great potential for actually reducing overall drying costs by increasing kiln through-put and reducing degrade (Bassett, 1973).

Although most studies have involved kiln-dried lumber, the use of the redry concept in conjunction with air yards will undoubtedly have more and more potential as energy costs increase (Arganbright *et al.*, 1974). The influence of wide variability in lumber moisture content (as shown in Figure 3) and perhaps steeper moisture gradients in partially air-dried stock are problems that need to be evaluated. This problem is very similar to that of making green lumber moisture content segregations. In addition to the obvious sensing equipment problems, greater emphasis needs to be placed on the lumber handling that must be used, as the cost of rehandling may ultimately dictate whether such techniques are economically feasible.

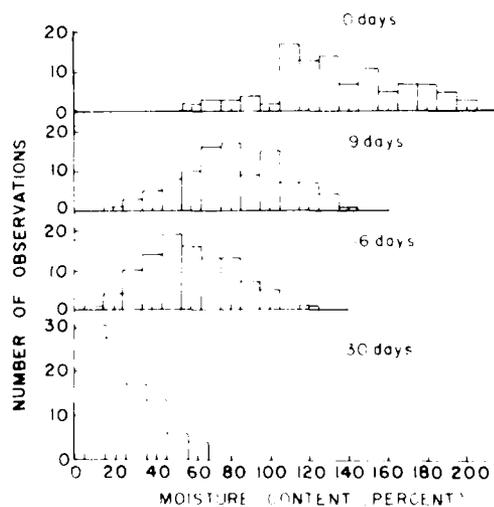


Figure 3.--Frequency distribution of moisture content for 1-inch thick heavy segregation redwood after varying periods of air drying.

## CONCLUSIONS

There is a definite need for better moisture measurement during the lumber drying process. The needs are diverse and frequently complex and include:

1. Clarification as to what is meant by lumber moisture content in light of normal within- and between-board variation;
2. Establishment of measurement accuracies for green, partially dry and completely air- and kiln-dried lumber;
3. Elimination of the influence of other material properties and production factors that now interfere with moisture measurement-- for example, density variations in lumber;
4. The development and technical and economic feasibility of the instrumentation, data recording and processing accessories and lumber handling equipment necessary for:
  - a. green lumber segregation
  - b. moisture measurement for kiln control systems
  - c. end point determination in kiln drying
  - d. moisture measurement after kiln drying or partial air seasoning for use in redry programs.

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SOME SURFACING DEFECTS AND PROBLEMS RELATED TO  
WOOD MOISTURE CONTENT<sup>1</sup>

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Abstract

Some common wood machining problems and their relation to moisture content and chip type are discussed. Methods to minimize the defects and some areas that require additional research are emphasized.

INTRODUCTION

The mechanical properties and the dimensions of wood vary as moisture content varies, so moisture content affects wood machining processes and products, particularly solid wood products. Wood machining problems associated with moisture content generally result in machining defects of the wood surface or tool wear. Because most of the problems are prevent or related to planing, the problems will be discussed as related to planing but could be related to wood machining processes where a wedge-shaped tool removes a chip from a workpiece by mechanical failure.

DEFECTS

The surfacing defects are described in detail in several references (Davis 1962, Koch 1964, Panshin and DeZeeuw 1964).

Raised grain is a roughened condition of the surface of wood in which part of the annual ring is raised above the surface. More distortion takes place in stock machined at a low moisture content and later exposed to air at a higher equilibrium moisture content (EMC). The corrugation of the surface may also be due to the transverse (across the grain) dimensional changes in the summerwood in comparison to those

of the winterwood. The raised grain is associated with a type of chip known as a "Machining chip" which is a chip that is produced by a planer and is characterized by its irregular shape and its tendency to break apart.

Another type of chip is the "planing chip" which is a chip that is produced by a planer and is characterized by its regular shape and its tendency to break apart. The planing chip is produced by a planer and is characterized by its regular shape and its tendency to break apart. The planing chip is produced by a planer and is characterized by its regular shape and its tendency to break apart.

Chip marks are shallow, irregular ridges or partial ridges on the surface of wood that are caused by chips that have been pressed into the surface. Chip marks will swell as they absorb water. Chip marks are result from an inadequate exhaust system that does not remove chips from the cutterhead. Chip marks tend to occur more frequently when low EMC conditions exist, such as in the winter.

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Crushing of the substrate may be known to occur after knives and cutters have passed (Jokinen and Stewart 1970, Hayes and Morrison 1974). The crushing is not localized and is

<sup>1</sup>Paper presented at the Symposium on Wood Moisture Content--Temperature and Humidity Relationships, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, October 29, 1979.

prints or raised grain between dense latewood and earlywood, but is a uniform layer of crushed wood below the surface and is a permanent deformation of the wood. Machining factors such as dull cutting tools and low rake angles cause crushing.

The aforementioned wood machining defects are affected to different degrees by moisture content in different species. For example, chipped grain and fuzzy grain increase as moisture content increases. Further, chipped grain occurs more frequently at moisture contents below 5 percent. Raised grain may occur from machining wood at a high or low moisture content and then changing moisture content; due to the uneven shrinkage and swelling of the earlywood and latewood. The defects often do not appear until after the product is finished and can affect the serviceability of the product. The machining defects can generally be minimized by reducing moisture content variation. Machining at an optimum wood moisture content (8-12 percent) and then maintaining the moisture content in service helps to minimize machining defects.

#### CHIP FORMATION

Surface quality and machining defects are related to chip formation. When machining along the grain, three distinct chip types have been observed (Franz 1958, Koch 1964, Kivimaa 195), and Voskresenkii 1955). The three chip types as described by Franz (1958) are:

Type I is formed when the wood splits ahead of the tool by cleavage until failure in bending occurs as a cantilever beam.

Type II is formed when wood failure in the chip is along a line extending from the cutting edge to the workpiece surface.

Type III is formed when compression and shear failures occur in the work ahead of the cutting edge.

The chip types are frequently associated with a particular wood machining defect. Similarities of tool geometry, wood properties, and moisture content for wood machining processes, especially knife cutting, produce similar defects whether simple orthogonal cutting or peripheral milling.

Chipped grain and chip type I are associated with the wood properties of low cleavage or tensile strength perpendicular to the grain, high compression strength parallel to the

grain, and high static bending strength. Very high or very low rake angles may increase the severity of chipped grain, especially when machining against slopes of grain up to 25° (Stewart, 1971a,b) (figs. 1, 2). Large depths of cut or machining conditions that increase the cut per knife also increase the severity of chipped grain.

Chip type III and defects such as raised grain, fuzzy grain, and a crushed subsurface are often associated with low or negative rake angles and dull tools, which cause excessively high cutting forces that increase crushing and do not cleanly sever the wood fibers. The situation is compounded when machining low density species or reaction wood.

A type II chip is generally associated with good surface quality. Selection of the tool geometry and cutting conditions for machining a particular species at a given moisture content can be balanced to produce a type II chip when machining along the grain. A type II chip is generally formed with moderate machining conditions.

#### RAKE ANGLE

Rake angle, the angle measured from the tool face to a perpendicular to the direction of tool travel, is the most important element of tool geometry controlling wood failure when machining. The wood failure determines formation of chip type, which is related to surface quality. Thus, selection of a rake angle to produce a satisfactory surface is paramount to efficient wood machining.

A technique was devised to approximate the optimum rake angle from the initial rake angle (Franz 1958). The technique demonstrated that an optimum rake angle for orthogonal wood-cutting parallel to the grain could be indirectly approximated from statistically determined mechanical properties of wood at various moisture contents and the cutting coefficient of friction.<sup>2</sup>

A simplified novel technique relates selected strength properties directly to the rake angle by means of an expression for the coefficient of friction and shows good correlation between strength properties of wood at various moisture contents and rake angles.

$$\mu = \frac{2}{\tan \left( \arctan \frac{\text{Normal tool force } (F_n)}{\text{Parallel tool force } (F_p)} \right) + \text{rake angle } (\alpha)}$$

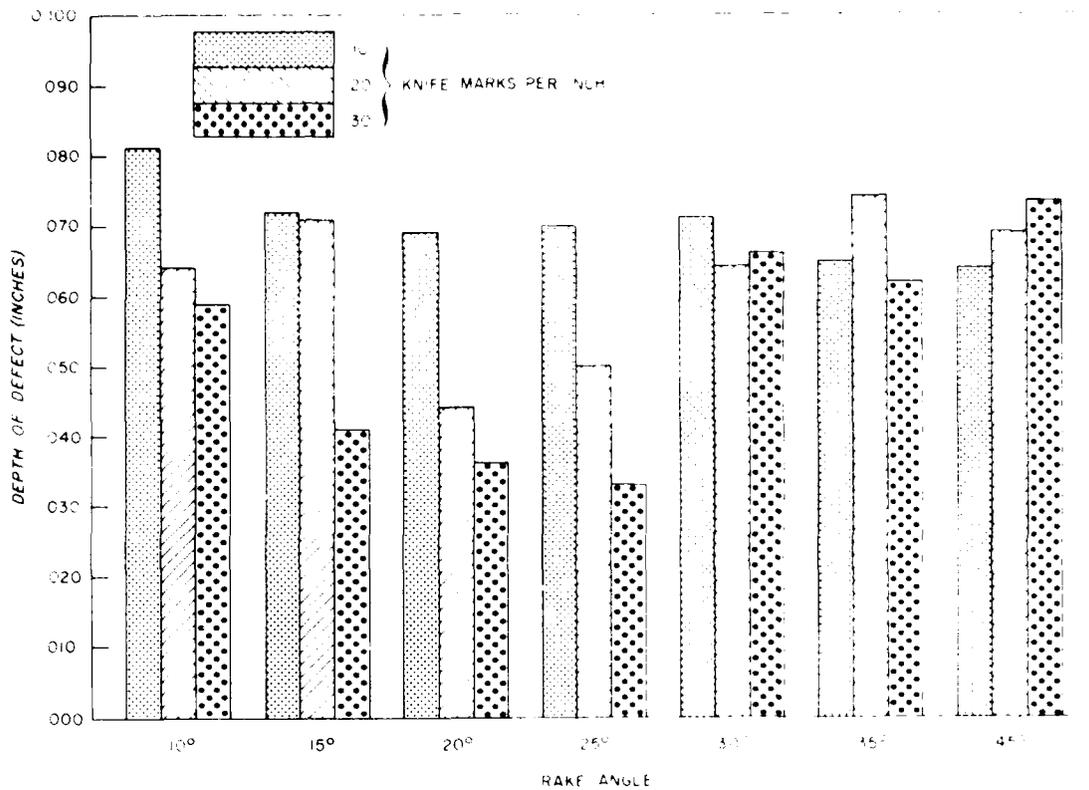


Figure 1.--Maximum depth of defect measured after knife sharpening on a lathe at rake angles of 10, 15, 20, 25, 30, 35, and 45 degrees with 10, 20, and 30 knife marks per inch with each rake angle. Maximum depth of defect measured at approximately 10-degree slope of grain.

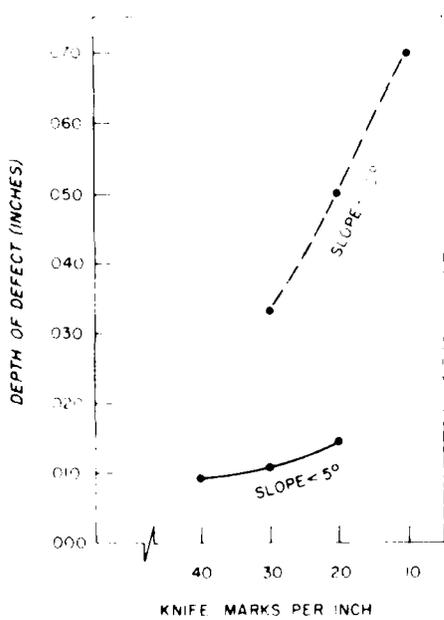


Figure 2.--Maximum depth of defect measured after knife sharpening on a lathe at rake angles of 10, 20, and 30 degrees and approximately 10-degree slope of grain.

(Stewart 1977). The cutting coefficient of friction was statistically related to the ratio of the tensile strength perpendicular to the grain (T) and the modulus of rupture in static bending (R). The relations were:

MC	Equation	r
1.5 percent	$\mu = 0.25 + 5.72 (T/R)$	0.97
9.3 percent	$\mu = 0.29 + 2.81 (T/R)$	0.99
Saturated	$\mu = 0.95 - 6.05 (T/R)$	-0.97

By assuming the normal tool force to be zero, the optimum rake angle could be equated directly to the strength properties at various moisture contents. The two methods for determining rake angle for orthogonal cutting parallel to the grain compare favorably (table 1).

#### PERIPHERAL MILLING

As indicated previously, the most severe cutting defects occur when peripheral milling against slopes of grain of 10° to 15°. Instead grain generally does not occur at angles of grain more than 20°. Although some evidence exists that lower rake angles may reduce the frequency of the defect chipped grain (Davis 1962) and moderate rake angles may produce the minimum depth of defect (Stewart 1974), a method for estimating an optimum rake angle for machining against the grain at various moisture contents has not been developed.

Considerable information relates moisture content to surface quality and cutterhead power requirements for Douglas-fir (Sack 1964) and hardwoods (Davis 1962). Generally, power requirements increase as feed rate, depth of cut, specific gravity, and moisture content increase (Davis 1962, Sack, 1964, Stewart, 1974). The additional power to machine as moisture content increases may be

due to the increase of force necessary to accelerate the heavier chip (Sack 1964). Further, wood is a viscoelastic material that absorbs more energy as it becomes wetter. The work to the proportional limit of the mechanical properties increases as moisture content increases.

#### GRAINING

In an attempt to prevent or remove knife cutting defects, grinding processes such as abrasive planing and sanding have been applied to wood surfaces. Grinding requires substantially more power than knife cutting. Generally, power increases as feed rate, depth of cut, specific gravity of wood, and moisture content increase for abrasive planing (Stewart 1974). The higher power requirement results from higher forces associated with many single point tools, which has the effect of a negative rake angle. The forces crush the wood below the surface (River and Miniatti 1975, Jeker and Stewart 1976). Additionally, heat is increased from the rubbing action between the coated abrasive belt and workpiece. Consequently, the defects commonly associated with grinding operations are fuzzy or raised grain and crushed, glazed, or burned surface. All of the defects except for grazing or burning tend to appear as moisture content increases after machining at a lower moisture content. An increase of moisture content after a material has been crushed and/or set after machining causes the compressed fibers to swell. Often the solvent of a finish or glue will raise the grain.

Abrasive belts tend to load more readily as the moisture content of the wood increases (Stewart 1974). Belt loading is probably the result of a complex relation among the physical, mechanical, and chemical properties of the wood and the pressures and temperatures developed during abrasive planing or sanding. Some

Table 1.—Rake angles (in degrees) calculated by the beam analysis and its correlation to selected mechanical properties for aspen, loblolly pine, yellow birch, and white pine at various moisture contents.

Moisture content	Aspen		Loblolly pine		Yellow birch		White pine	
	Beam analysis	Correlation						
1.5 percent	11	0.97	12	0.97	14	0.97	15	0.97
9.3 percent	13	0.99	19	0.99	21	0.99	22	0.99
Saturated	17	0.97	27	0.97	18	0.97	20	0.97

species such as yellow-poplar tend to load belts more and abrasive planing at high moisture contents can shorten belt life.

Methods to reduce belt loading are being developed. Belt loading has been shown to increase up to a point and then decrease as stock removal rate increases for red oak and yellow-poplar abrasive planed at moisture contents of 12 and lower. However, the belt cleaning effect was not observed after abrasive planing green yellow-poplar (figs. 3, 4).

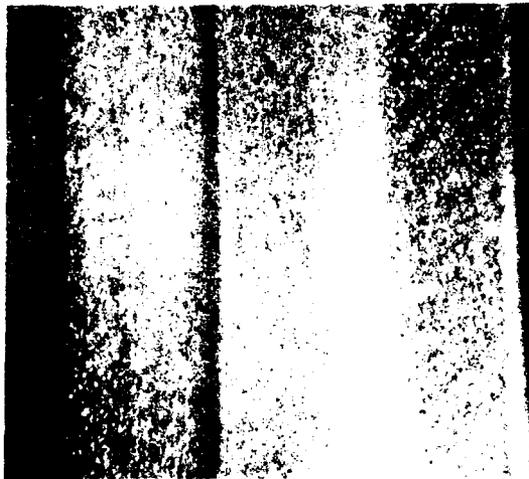


Figure 3.--Loading of Grit No. 36 abrasive planed belt as stock removal rate increases for yellow-poplar at 90° feed rate, 1.74-, 0.843-, and 0.129-inch depth of cut, and 40 percent moisture content.

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Another problem, rapid staining and etching of cutters, has been observed in slow linear cutting of green eucalyptus and radiata pine (Phillips and McKenzie 1964). Thus, corrosion may significantly accelerate the tool wear when cutting green wood. The wet wood provides an acidic environment for accelerating the tool wear by corrosion. Experiments on a yonker knife show a highly significant effect of potential (pH-value) in reducing rate of wear (McKenzie and McKenzie 1964). Thus, the wear of knives in wood cutting is electrochemical in nature, not corrosive as well as requiring more power on a fine wet wood. Generally, knife wear increases as the moisture content of the wood increases.

The solution of tool material, and a tool wear, a variety of tool steels and carbides have been developed that may be more



Figure 4.--Loading of grit No. 36 abrasive planed belt at all stock removal rates for yellow-poplar at 90° feed rate, 1.74-, 0.843-, and 0.129-inch depth of cut, and saturated moisture content.

resistant than the tools commonly used for wet cutting. However, the high tool wear program is still in the laboratory stage and will require further development. The use of a high speed abrasive planer with a high speed abrasive belt may be a solution to the problem of wet cutting.

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THE EFFECT OF TEMPERATURE AND MOISTURE CONTENT ON PHYSICAL CHANGES IN WOOD

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ABSTRACT

Electrical conductivity is extremely sensitive to changes in moisture content and temperature. The influence of moisture content and specific gravity on thermal conductivity and moisture movement are discussed with the use of a cellular geometrical model for wood. The use of alternate gradient in Fick's law for the calculation of unsteady-state and steady-state moisture movement are considered. The effect of moisture on wood permeability is described.

INTRODUCTION

The anisotropy and hygroscopicity of wood result in a unique complexity in the understanding of its physical properties compared with those of most other engineering materials. In the hygroscopic range of moisture contents, up to the fiber saturation point (FSP), the equilibrium moisture content (EMC) of wood is determined by its response to the relative humidity (RH) and moisture content (M) of its surroundings in accordance with the appropriate sorption isotherm [Staar (1977)]. The effects of temperature and moisture content on electrical resistance, dielectric constant, thermal conductivity, moisture movement, and permeability will each be discussed briefly.

ELECTRICAL RESISTANCE

The electrical resistivity of wood is extremely sensitive to changes in moisture content as revealed in Figure 1 which indicates a linear relationship between logarithm of resistivity ( $\log r$ ) and M up to 6 percent. Beyond this value there is progressively less change in  $r$  with M and beyond the FSP the change is relatively small. Figure 2 indicates a linear relationship between  $\log r$  and  $\log M$  from 6 percent to FSP.

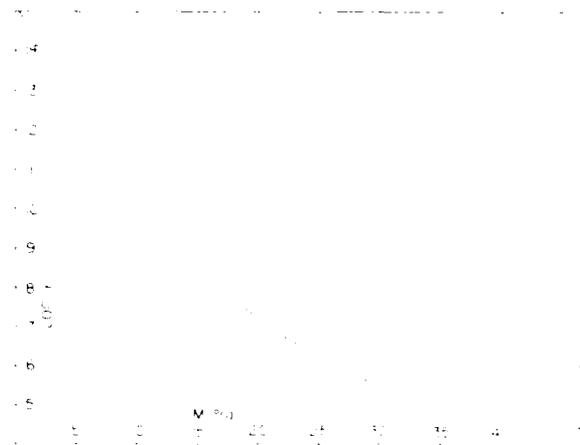


Figure 1.--Logarithm of resistivity, in ohm-cm, of wood as a function of moisture content at 20°C. From Brown et al. (1963). Courtesy of Forest Products Journal.

From Figures 1 and 2 it is possible to calculate the approximate increase in moisture content required to double the electrical conductivity (or to reduce the resistivity to one-half). These results are presented in Table 1.

Table 1.--Increase in moisture content required to double electrical conductivity.

Moisture Content Range	Increase in M to Double Conductivity
0 - 5	0.7
12 - 14	1.0
22 - 24	1.2

According to Fin (1965) the electrical conduction of wood is primarily ionic, accounting for the increase with moisture content, and it

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is a temperature-activated process, which accounts for the increase in conductivity with temperature. Plots of  $\log_e r$  against reciprocal temperature are usually straight lines, which can be analyzed according to the Arrhenius equation for the calculation of activation energies, as revealed in Figure 3. Activation energy is defined as:

$$E^* = 2.303 R \cdot d \log_e r / d (1/T) \quad (1)$$

where  $E^*$  = activation energy  
 $R$  = universal gas constant

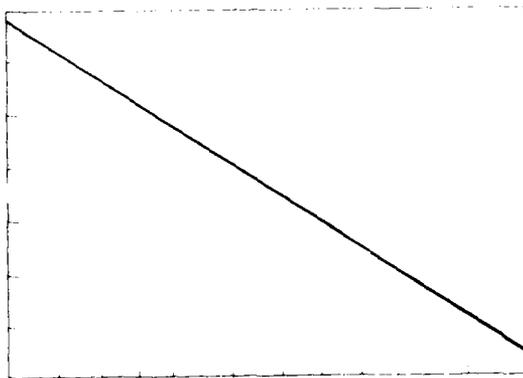


Figure 2.--Logarithm of resistivity of wood as a function of logarithm of moisture content from  $M = 0$  percent to FSP at 25°C.

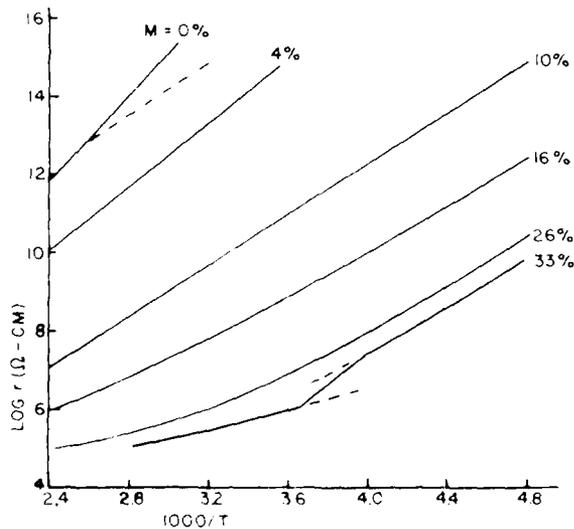


Figure 3.--Logarithm of resistivity as a function of reciprocal temperature in  $^{\circ}K$  at several moisture contents for yellow poplar wood. Adapted from Lin (1955). From Skar (1972). Courtesy of Syracuse University Press.

It is clear from Figure 2 that activation energies decrease as  $M$  increases, indicating a greater ease of displacement of ions under the influence of an electric field at higher moisture contents. Figure 4 reveals that activation energies may be as high as 28 kilocalories per mole under oven-dry conditions. At the  $E^*$  values, range from 3 kcal/mole at 97°C to 14 kcal/mole at ordinary temperatures to 14 kcal/mole at 46°C indicating the decreasing mobility of the ions as the temperature is reduced. From the activation energies it is possible to calculate the temperature rise required to double the electrical conductivity. These are listed in Table 2.

Table 2.--Temperature increases required to double electrical conductivity for various activation energies and temperatures

Activation Energy kcal/mole	Temperature $^{\circ}C$	Temperature Rise to Double Conductivity $^{\circ}C$
28.0	27	4.9
13.3	27	10.0
8.0	27	16.5
14.0	-46	5.5
4.0	97	55

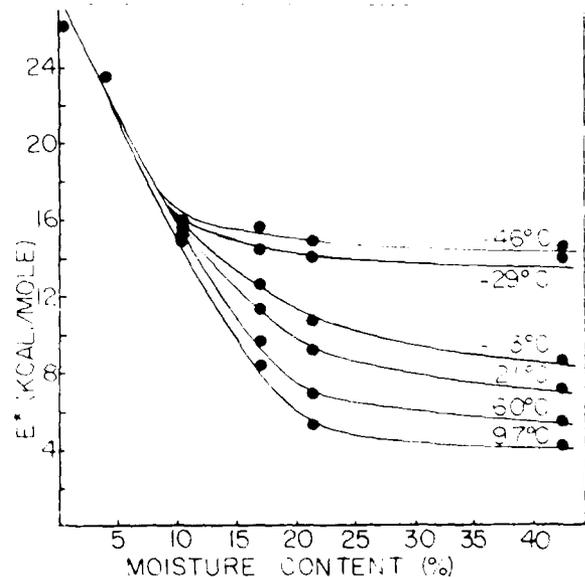


Figure 4.--Apparent activation energy versus moisture content at various temperatures for Douglas-fir. From Lin (1955). Courtesy of Forest Products Journal.

The resistance in the longitudinal fiber direction is lower than that in the transverse direction. Hart (1964) shows that the ratio of transverse to longitudinal resistivities can be as high as 2.5 assuming an isotropic cell-wall substance with the ratio decreasing with increased density and decreased misalignment of the cells in the tangential direction. Stamm (1927) measured the resistivities of four softwoods and

found longitudinal to transverse ratios from 1.5 to 2.5 with an average of 2.0, and with slightly higher tangential than radial resistivities.

#### DIELECTRIC CONSTANT

Dielectric constant is a measure of the electrical polarizability of a substance per unit volume. Water is highly polar and has a dielectric constant of 81 compared with a vacuum. Dry cell-wall substance, on the other hand, has a value of approximately 4 at a frequency of 2 MHz. The effect of the addition of moisture on the dielectric constant of wood is illustrated in figure 5. The relationship is curvilinear up to the FSP indicating a lower effective dielectric constant for bound water due to the forces of bonding to the cell wall. Beyond FSP the relationship is linear with the resultant representing the approximate sum of the components. This high sensitivity of dielectric constant to moisture content change is the basis for capacitance-type moisture meters. Dielectric-type meters, on the other hand, are based on the combined effect of dielectric constant and dissipation factor, both of which increase with wood moisture content.

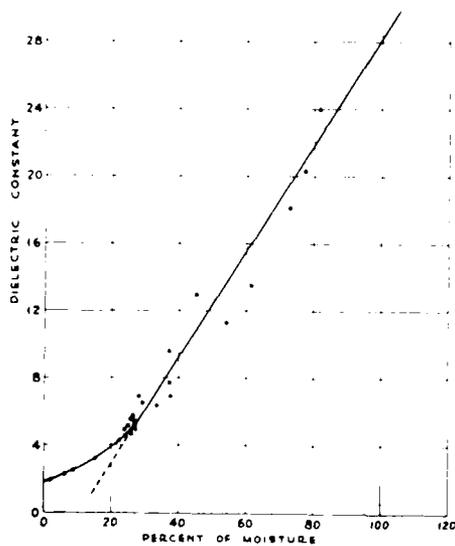


Figure 5.--The relationship between the dielectric constant at 2 MHz and moisture content of buckeye wood. From Skaar (1948). Courtesy of SUNY College of Environmental Science and Forestry.

Grain angle affects dielectric constant such that the dielectric constant of wood in the longitudinal direction is approximately double that in the transverse direction. Application of a cellular model to the analysis of dielectric constant indicates that the same ratio also applies to cell-wall substance signifying a greater ease of dipole displacement along the axis of the cellulose molecule.

AC resistivity may be calculated from the dielectric constant and dissipation factor at a given frequency by use of the following relationship based upon the reactive and resistive components of current in the dielectric material:

$$\rho = \frac{1.8 \times 10^{12}}{f \cdot E \cdot X} \quad (2)$$

where  $f$  = frequency, Hz  
 $E$  = dielectric constant  
 $X$  = dissipation factor

Measurements were made with basswood by Siau (1967) under oven-dry conditions and at  $M = 0.3$  and calculated values of resistivity at three radio frequencies are compared with dc resistivities in table 3.

Table 3.--Resistivity of basswood at various frequencies and moisture contents

Frequency	Vacuum-dry Resistivity, ohm-cm	0.3 Moisture Resistivity, ohm-cm
dc	$2.75 \times 10^{14}$	$1.15 \times 10^{11}$
$1.0 \times 10^5$ Hz	$9.63 \times 10^{10}$	$5.71 \times 10^8$
$1.0 \times 10^6$	$5.41 \times 10^9$	$1.15 \times 10^9$
$1.25 \times 10^7$	$2.71 \times 10^6$	$1.1 \times 10^6$

Table 3 reveals a significant decrease in resistivity with increases in frequency and moisture content, providing more favorable conditions for the dielectric heating of wood.

Measurements by Siau (1961) revealed a sharp decrease in dielectric constant of wood as the frequency was increased from  $10^5$  Hz to  $2.5 \times 10^7$  Hz. The dissipation factor, on the other hand, goes through a maximum at the resonant frequency of the dipoles. These resonant frequencies vary from 0.6 MHz at  $-30^\circ\text{C}$  to 35 MHz at  $25^\circ\text{C}$  for oven-dry wood. These frequencies increase as moisture content increases. Thus it was found that increasing either temperature or moisture content increased the resonant frequency indicating an increase in ease of polarization. It was possible to observe the effect of temperature on resonant frequency only under oven-dry conditions where a linear plot of the logarithm of frequency against reciprocal temperature was obtained in accordance with the Arrhenius equation indicating that the process is temperature activated. A calculation of the activation energy yields a value of 9.03 kcal per mole. This indicates that the resonant frequency at  $27^\circ\text{C}$  can be doubled by a temperature increase of  $14.4^\circ\text{C}$ .

Dielectric constant was observed to increase with temperature. For example, basswood with  $M = 7.1$  percent at 1 MHz had a dielectric constant of 1.75 at  $-60^\circ\text{C}$  and 2.5 at  $25^\circ\text{C}$ .

## THERMAL CONDUCTIVITY

The thermal conductivity of wood is not affected significantly by temperature. The influence of moisture content and specific gravity are accounted for empirically by equation of McLean and others [Siau (1970)] which treat wood as a parallel-slab model with the cell wall, lumen, and moisture as parallel conductances. Improved results over a wider density range can be obtained by use of a cellular model as depicted in Figure 6 and as previously proposed by Hart (1964). The application of this model to empirical data indicates that the thermal conductivities of bound water and cell-wall substance do not differ appreciably and therefore the conductivity of the moist cell wall is not affected greatly by moisture content. When it is assumed that the moist cell-wall conductivity is independent of moisture content, the increased conductivity at higher moisture contents is a result of the swelling of the cell wall and, therefore, lower porosity of the wood. In deriving the equation, the cross walls, lumens, and side walls are considered as separate conductances are represented in Figure 7. The equation for transverse thermal conductivity derived from the model has the form:

$$K_{WT} = \frac{(1-a) K_{WT}^2 + a K_a K_{WT}}{(1-a)^2 + a + (1-a) Ka + a K_{WT}} \quad (3)$$

where  $K_{WT}$  = transverse thermal conductivity of wood

$K_a$  = thermal conductivity of air in lumens

$K_{WT}$  = transverse thermal conductivity of cell-wall substance

$a$  = square root of wood porosity

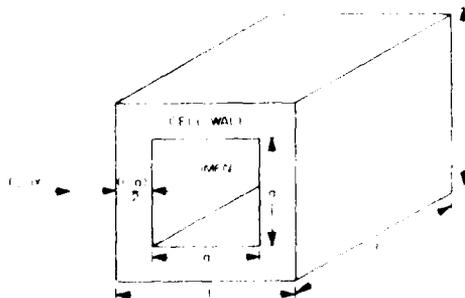


Figure 6.--Geometrical model for single wood cell. From Siau (1970). Courtesy of Wood and Fiber.

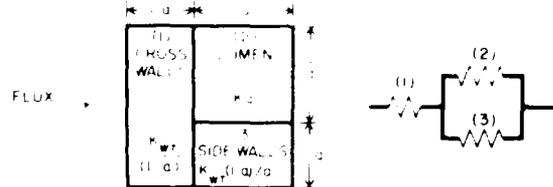


Figure 7.--Equivalent configuration of conductivity model showing conductivities of sections and the equivalent electrical circuit. From Siau (1970). Courtesy of Wood and Fiber.

Equation (3) has only been applied below 10%. It has been further refined to account for uneven flux distribution as advocated by Hart (1964). Equation (3) produces good agreement with the empirical equations when values  $1.0 \times 10^{-4}$  cal/(cm<sup>2</sup> °C sec) and  $10.5 \times 10^{-4}$  cal/(cm<sup>2</sup> °C sec) are used for  $K_a$  and  $K_{WT}$ . The model equation predicts that the thermal conductivity is nearly inversely linearly proportional to the square root of the porosity (Figure 8) for values of between 0.2 and 1.0 (corresponding to specific gravities from zero to 1.4) which would include all known woods. In fact the model equation may be closely approximated by the linear equation:

$$K_{WT} = (-11.3a + 12.2) \times 10^{-4} \quad (4)$$

where  $K_{WT}$  = thermal conductivity of wood, cal/(cm<sup>2</sup> °C sec)

The essential difference between the model equation and the other empirical equations is that in the former the conductivity is inversely proportional to "a" while in the latter is inversely proportional to the porosity or  $a^2$ .

The model equation has limitations related to the assumptions used in its derivation. For example the effect of pit openings, rays, and fibril angle are neglected. Wankaard (1942) has indicated that fibril angle can have a significant effect on thermal conductivity. Also the assumption has been made that the conductivity of the cell wall is independent of moisture content.

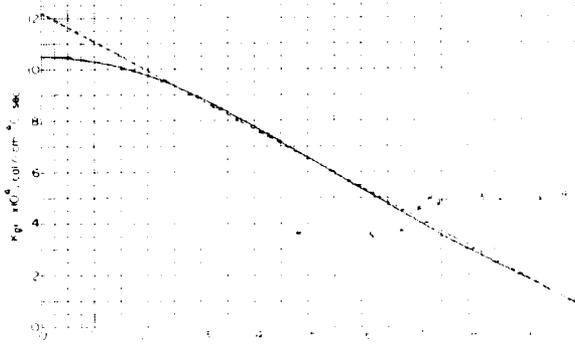


Figure 8.--Transverse thermal conductivity of wood versus "a" according to equation based on geometrical model compared with a linear regression equation of  $K_{qT}$  on "a". From Siau (1971). Courtesy of Syracuse University Press.

#### MOISTURE MOVEMENT

The movement of water vapor through wood is far more complex than that of heat due to its strong dependence on both temperature and moisture content. A family of curves relating the water-vapor diffusion coefficients of air in the lumens ( $D_V$ ) and the cell-wall in the transverse direction ( $D_{BT}$ ) to both T and M are depicted in Figure 9. The values of  $D_V$  are derived from the water-vapor diffusion coefficient through bulk air by conversion to a basis of a gradient in cell-wall substance through the sorption isotherm of wood. The values of  $D_{BT}$  are taken from values for cell-wall substance measured by Stamm (1959) in the longitudinal direction at 26.7°C at various moisture contents. They were converted to other temperatures by the assumption of a direct relationship with the saturated vapor pressure of water as suggested by Stamm (1959) and then converted to the transverse direction by dividing the values by 2.5. It is interesting to note that values of  $D_{BT}$  increase with wood moisture content due to decreased bonding of water molecules to sorption sites, while  $D_V$  decreases with increased M due to the increasing slope of the sorption isotherm at higher values of relative humidity. Therefore, lumen conductivity becomes more important at higher moisture contents.

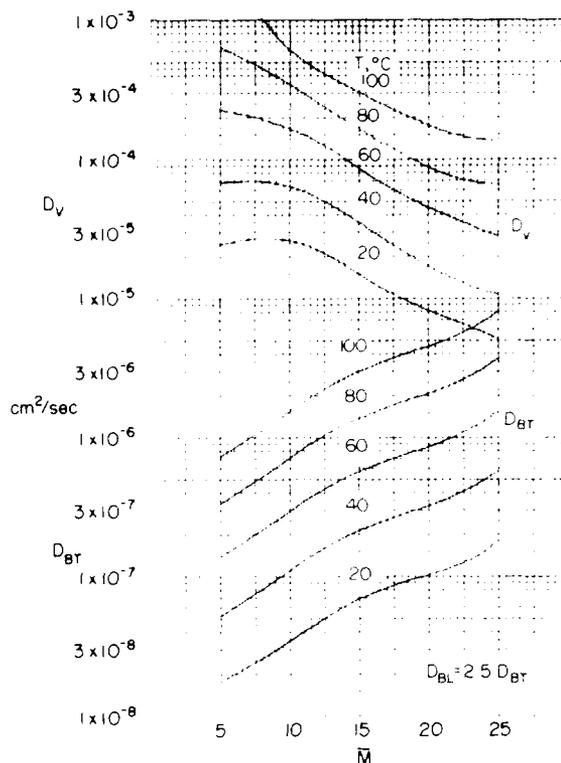


Figure 9.--Values of  $D_V$  and  $D_{BT}$  at various temperatures and moisture contents. From Siau (1971). Courtesy of Syracuse University Press.

The cellular model may be applied to moisture movement as well as to that of heat. When this is done for transverse flow, the conductivity of the lumen is much higher than that of the side walls in parallel with it making the latter negligible. When the lumens and cross walls are considered in series, the high conductivity of the lumen becomes negligible leaving the cross walls as the only part of the structure having significant resistance. This greatly simplifies the model equation which then has the form:

$$D_{qT} = \frac{D_{BT}}{(1-a^2)(1-a)} \quad (5)$$

where  $D_{qT}$  = transverse water-vapor diffusion coefficient of wood

In Equation (5), the  $(1-a)$  term in the denominator corrects the gradient to a basis of wood rather than cell-wall substance and the term  $(1-a^2)$  represents the length of the path through the cross walls. This equation neglects the effect of the pit openings on water-vapor movement which has not been mentioned by Starr (1967). This effect may indeed not be negligible at low moisture contents and high specific gravities.

The influence of  $M$  and  $T$  on the rate of vapor movement through wood with an oven-dry specific gravity of 0.5 is illustrated in figure 11. Equation (5) was used to calculate values of  $D_{gt}$  while a longitudinal model equation was used to determine  $D_{gl}$ . It is apparent, when comparing (11) with Figure 9, that  $D_{gl}$  is directly proportional to  $D_{gt}$  for the cell wall, while  $D_{gl}$  is dominated by the lumen conductivity,  $D_{gl}$ . Figure 11 indicates that an increase in moisture content of 5 to 8 percent is required to double the rate of diffusion in the transverse direction while temperature increases between 15.1 and 17.7°C are required for the same increase at temperatures of 30°C and 90°C.

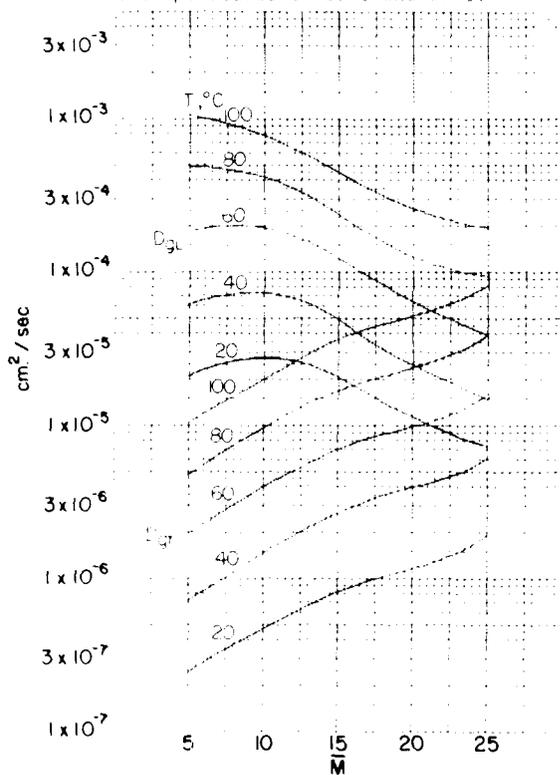


Figure 11.--Longitudinal and transverse diffusion coefficients of a wood with an oven-dry specific gravity of 0.5. From Siau (1971). Quoted by Siau, University Press.

The fact that the diffusion coefficient is highly sensitive to changes in  $M$  and  $T$  presents difficulties in the solution of practical problems involving unsteady-state moisture movement. The diffusion differential equation may be solved graphically in dimensionless terms when the diffusion coefficient is constant and  $M$  is in the same direction as heat flow. For moisture movement, the equation has the form:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left( D_{gt} \frac{\partial M}{\partial x} \right) \quad (6)$$

where  $t$  = time  
 $x$  = distance in the direction of flow

The solution of a practical problem may be simplified by the calculation of an average diffusion coefficient as suggested by Starb (1959). The relationship between  $D_{gt}$  and  $M$  at constant temperature is approximately parabolic. Therefore the average value of  $D_{gt}$  corresponds to a space and time average moisture content calculated as:

$$M = M_1 + 2/3 (M_2 - M_1) \quad (7)$$

where  $M_1$  = minimum moisture content over the range of values considered  
 $M_2$  = maximum moisture content

Equation (6) may then be written with a constant diffusion coefficient making it solvable by analytical or graphical methods.

$$\frac{\partial M}{\partial t} = D_{gt} \frac{\partial^2 M}{\partial x^2} \quad (8)$$

Equation (8) may also be derived by using vapor pressure or volume concentration as units of potential with an identical value of  $D_{gt}$  and an identical solution. The reason for this is the fact that the diffusion differential equation applies to a point within a specimen of wood which is at one temperature and, under these conditions, a differential change in moisture content, partial vapor pressure, and concentration are directly proportional to each other. The effects of changing moisture content and temperature can be accounted for in a practical problem if Equation (8) is transferred to a difference equation with the value of the diffusion coefficient adjusted continuously for changes of  $M$  and  $T$ . As an alternative, Equation (6) may be written in the form:

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x} \left( \frac{D_{gt}}{D_s} \frac{\partial M}{\partial RH} \frac{\partial p}{\partial RH} \right) \quad (9)$$

where

$p_s$  = saturated vapor pressure  
 $d^2p/dRH^2$  = slope of saturation isotherm  
 $p$  = vapor pressure

Complacation with changing  $M$  and  $T$  occur in steady-state moisture transfer problems. Starb (1959) has shown how Fick's first law can be expressed in these ways by using moisture content, volume concentration, or vapor pressure as gradients.

$$F = -D_m \frac{dM}{dx} \quad (10)$$

$$F = -D_h \frac{dp}{dx} \quad (11)$$

$$F = -D_{QT} \frac{dC}{dx} \quad (12)$$

where  $F$  = flux

$D_m$  = conductivity,  $gm^2/(cm \ sec)$   
 [ $k_d$  in Siau (1971)]

$D_h$  = conductivity,  $gm^2/(cm \ sec \ mm \ Hg)$

$C$  = concentration,  $gm/cm^3$  (wood)

The conductivities in Equations (10), (11), and (12) can be converted to one another. The conductivity for a concentration gradient is the same as the  $D_{QT}$  in Equation (6) with the units of  $cm^2/sec$ . All three of these forms will give equivalent results in an isothermal situation. Bramhall (1976) discusses the difficulty in the use of moisture content gradient, under nonisothermal conditions. Wemert (1976) favors the use of vapor pressure gradients in unsteady-state problems.

Two anomalous situations can arise in steady-state problems under nonisothermal conditions as illustrated in Figure 11 (a) and (b). In 11 (a) there is zero vapor pressure differential, but a moisture content differential of 12 percent. In 11 (b) the moisture differential is zero but there is a partial pressure differential of 110 mm of mercury. In 11 (c), which could be typical of a house with solid wood walls, there is a higher vapor pressure inside the house but a higher relative humidity and wood moisture content on the outside surface. The questions are raised as to what are the correct ways of calculating the vapor flux in these three cases.

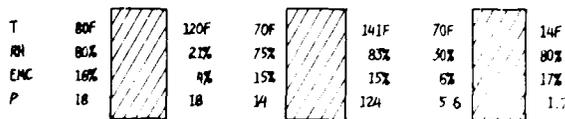


Figure 11.—Anomalies in steady-state moisture movement through wood. Partial pressures are expressed in millimeters of mercury.

## PERMEABILITY

Forstork (1964) has investigated the effect of moisture content change below the FSP on permeability of several species of wood. In the softwoods there was a moderate decrease in permeability as moisture content increased to overdry to 20 percent. This decrease in permeability could be explained in two ways: (a) a decrease in wood porosity, and (b) an increase in the size of the fibrillar strands in the range of the pit openings. The results for hardwoods were less consistent, with white oak heartwood exhibiting increases in permeability by factors of 5 to 20 with a decrease in  $M$  from 20 percent to zero. In the case of red oak, some specimens showed increased and some decreased permeability as the moisture content was increased. American elm showed consistent increases in permeability with increased  $M$ , sometimes as much as 50 percent. This could possibly be attributed to increases in cell sizes. With the exception of white oak heartwood these changes in permeability below FSP are minor and would not be expected to have a significant effect upon the pressure impregnation of liquids.

At moisture contents above FSP there is a drastic reduction in wood permeability due to the presence of liquid water in the cell lumens and the necessity of overcoming capillary forces as well as viscous forces to cause flow. This is the case with green wood of high moisture content. Air is always present in the lumens and the resulting capillary pressure will not be overcome to displace an air-liquid meniscus may be calculated from the following equation:

$$p_p = \frac{2\gamma \cos \theta}{R} \quad (13)$$

where  $p_p$  = pressure differential  
 $R$  = radius of opening  
 $\theta$  = contact angle

Capillary pressure, as defined by Equation (13) can reach hundreds of pounds per square inch for small openings. Stamm (1962) has calculated the maximum effective pore radius of wood specimens from the pressure required to overcome capillary forces.

One of the greatest difficulties in the measurement of wood permeability, with a liquid is the elimination of capillary forces by total saturation of the structure with liquid with the elimination of all air and particulates. This is difficult experimentally, as has discussed at length by Felby et al. (1966) and Forstork (1962, 1963). Forstork (1963) has been able to show that the permeability of several species of eastern hemlock saturated with nitrobenzene and a nonwetting liquid are equal as revealed in Figure 12.

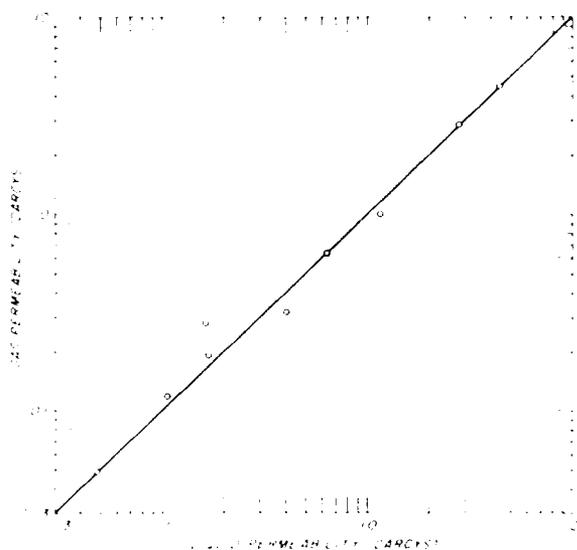


Figure 12.--Average gas permeability for nitrogen and helium at infinite pressure versus average liquid permeability for iso-octane and amyl alcohol. From Comstock (1967). Courtesy of Forest Products Journal.

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EFFECT OF MOISTURE ON STRENGTH PROPERTIES,  
PARTICLEBOARD AND COMPOSITE WOOD PANELS

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ABSTRACT

A review of literature is presented on the effect of moisture on dimensional and strength properties of three types of resin-bonded wood structural panels. Moisture affects dimensional and tensile strength properties of these panels. These changes can affect the performance of panels in use. There are several controlling variables among researchers.

SOFTWOOD PLYWOOD

Southern yellow pine provides presently the raw material for approximately 95% of the softwood plywood manufactured in the U.S.A. Plywood, like solid wood, is a hygroscopic material and readily absorbs or releases water, depending on moisture content, in relation to surrounding humidity and temperature. Swelling and shrinking properties of a wood are affected by moisture below fiber saturation point (FSP). Lee and Bellis (1) have established the relationship between relative humidity percent (RH%) and Equilibrium Moisture Content (EMC) in absorption for southern yellow pine plywood and for loblolly pine solid wood as shown in Figure 1. They found that the EMC values of plywood between 20% and 90% RH were approximately 1% lower than corresponding values of loblolly pine solid wood. The curve for plywood was based on average values of five different constructions. Average densities were  $0.60 \text{ g/cm}^3$  for plywood and  $0.54 \text{ g/cm}^3$  for solid wood. Thickness shrinkage of southern pine from the critical condition to moisture  $M_0$  averaged from 1.5 to 9%. Most plywood panels shrink less along the face grain than across grain, whereas solid wood shrinks equally in all directions. Moisture content always is higher than that of the surrounding atmosphere, and therefore, a sorption gradient exists between the two surfaces. Direction of moisture movement was also found that the rate of sorption is slow. However, the thickness of plywood is higher and permeability of the face and back surfaces is lower. Solid wood is a natural

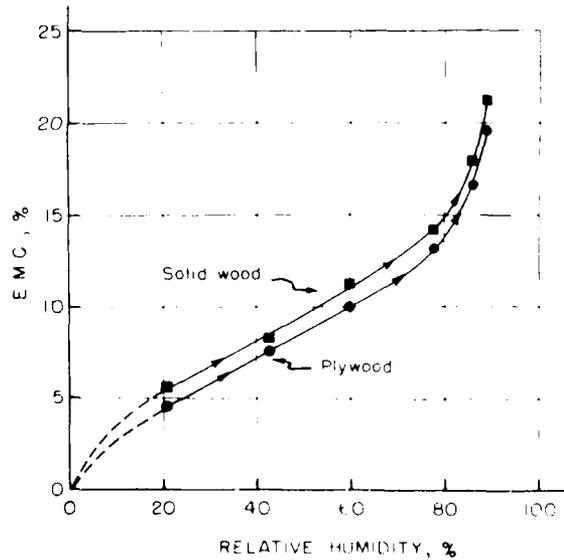


Figure 1. Moisture content of solid wood and plywood. (1) Lee and Bellis (2) Lee and Bellis (3) Lee and Bellis (4) Lee and Bellis (5) Lee and Bellis

product of the wood. The thickness of plywood is higher and permeability of the face and back surfaces is lower. Solid wood is a natural

pine plywood, determined by two Intersection point methods, were 28.7 and 21.3 MC. PSP values of loblolly pine solid wood determined by the same two methods were 31.0 and 27.5 MC. These PSP values for solid wood agree closely with published values (Choong (1969), Yao (1973)).

Plywood panels in service are subjected to fluctuations in relative humidity and temperature which, in turn, change the panel's moisture content (MC) and performance. It is commonly recognized that physical and mechanical properties of plywood are affected by MC below the fiber saturation point (FSP). Above the FSP, the properties of plywood are practically constant. The FSP values of solid wood of the southern yellow pines were found by Choong (1969) and Yao (1973) to range from 26% to 32%. Lee and Billis (1976) found the FSP value of southern pine plywood to be about 28% MC.

Drow (1957) investigated the effect of moisture on the compressive, bending, and shear strengths of western species plywood. He concluded that the exponential formula for moisture-strength adjustment was applicable to Douglas-fir and Sitka spruce plywood as well as to solid wood compression and static bending properties, if adjustment was limited to MC above 8%.

A series of studies concerning the effect of MC on the compression and shear strengths of Dens-lam-1R plywood was done by the Canadian Forest Service, Bohlen (1975), Longworth and Warren (1976), Palka and Billis (1977), Palka (1977). They indicated that, for compression and shear strengths of moisture-soaked Douglas-fir plywood, the exponential formula consistently overestimated the reduction in strength due to MC increase. It was recommended that the linear formula be employed for moisture-strength adjustment of plywood.

Lee and Billis (1976) studied the effect of moisture on flexural properties of 4-ply southern pine plywood. They determined the flexural properties (MOE, MOR, and PSP) of clear southern pine plywood at the following moisture contents: 8%, 10%, 13%, 16%, 19%, and water-soaked condition. Both MOR and MOE values were increased when moisture increased from approximately 13% to 19%. This behavior was also observed by King (1966) in solid timber species. The explanation is that the maximum values of flexural properties of timber occur at the MC attained immediately after saturation, which is between 6% and 8% MC. A general trend toward lower MC may induce a contraction of the wood, and therefore reduce MOE of plywood. The relationship between moisture content (from 8% to 19%) and flexural

properties were established for 3-ply, 4-ply, and 5-ply southern pine plywood. The formulas for the moisture-strength relationship were examined and compared with experimental results. One was a linear formula, strength = a - b(MC), and other was an exponential formula, strength = a - b(MC). It was found that the linear formulas fitted the experimental data equally well. It was recommended that the simple linear formula be used for moisture-flexure adjustment of southern pine plywood. The moisture-strength property reduction due to increase in moisture was approximately the same for all plywood constructions. In general, MOE, MOR, and PSP of southern pine plywood was reduced 1%, 3%, and 4% based on the strength value at 12% MC, respectively, in response to a 1% increase in MC. Relationships between moisture content and flexural properties of southern pine plywood of five constructions combined expressed as percentages of the properties at 12% MC are shown in Figure 2.

Chiu and Billis (1973) reported that 1.2" thick southern pine plywood after 24 hours of water immersion and drying at 90% RH retained 84.4% of the original MOE and 87.7% of the original MOR values.

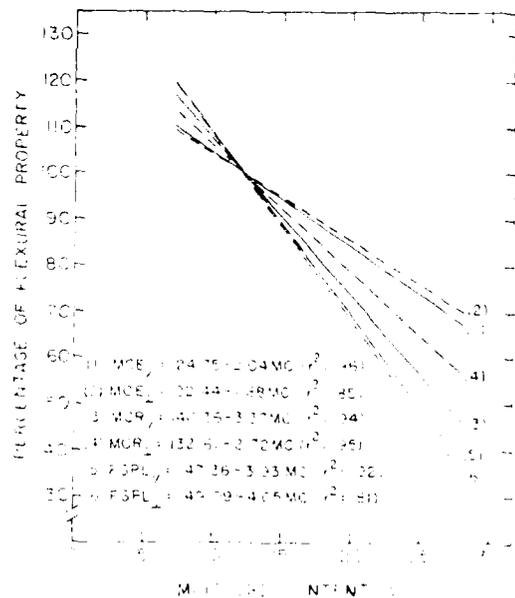


Figure 2. Relationship between MC and flexural properties of southern pine plywood expressed as a % of the properties at 12% MC (Chiu and Billis, 1976).



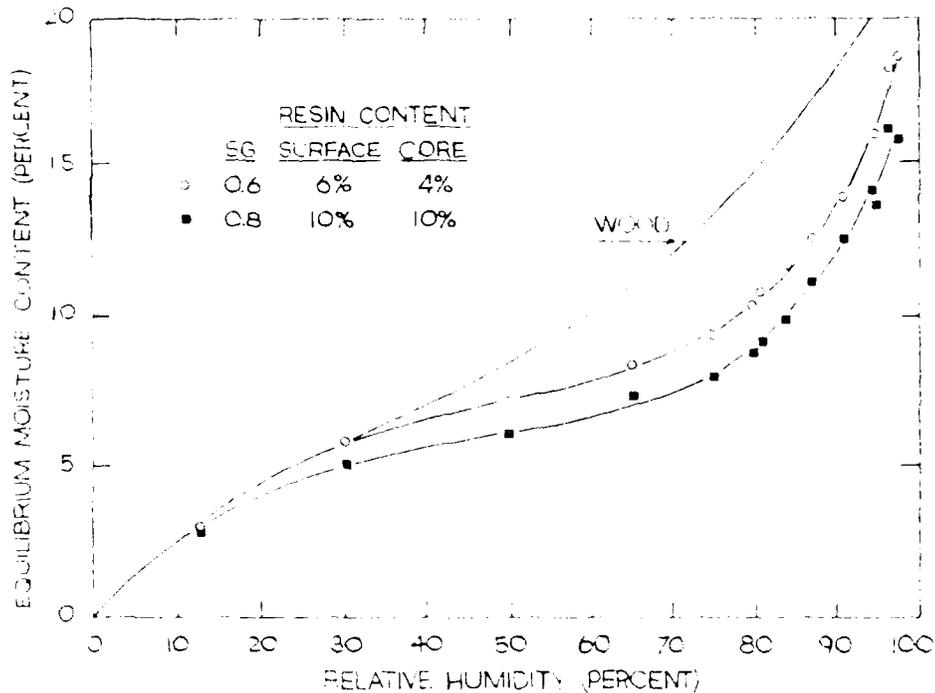


Figure 1. Relationship between RH and MC for particleboards and solid wood. (From Galligan and Schlotzky 1977)

and other two methods have been employed by researchers to study these changes, the ASTM method (ASTM 1981) and the ASTM D 1038 and the gravimetric method (Mitschke and Boffin 1987).

The moisture swelling of particleboard is a function of a number of several factors that include the material and manufacturing process, the thickness of the board, the water content, and the moisture content of the board. Higher density boards have more water absorption than lower density boards. In addition, higher density boards are characterized by a denser water absorption and therefore are expected to swell more than lower density boards. The relation of thickness, swelling, board density was found by several researchers, i.e., Mitchell (1963), Gonyea (1964) and Langer (1970).

Hill and Schlotzky (1977), Bunn et al. (1981) and Schlotzky (1987) have made correlations between thickness, swelling, and board density. They reported that, in general, other than board type, density, and height (Langer, Stewart, and Langer 1970; Bunn and Langer 1970), there are no significant differences between board density and thickness, swelling, or moisture content. The moisture content of a board is reported to be a function of board density and particle

density, and amount of resin and wax. In general, researchers agree that resin thickness is a function of board width, board density, and grain rather than board thickness. Researchers also agree that increasing the resin content increases thickness stability of particleboard (Langer 1970; Bunn and Langer 1970). However, prohibit the reduction in increasing the amount of resin used in order to obtain better thickness stability. The industry presently uses a 4 percent urea formaldehyde solution on a wet wood basis. Researchers have reached contradictory conclusions concerning the effect of wax on dimensional changes of particleboard. Inclusion of wax at higher than 1 percent rates interferes with adhesive bonding and reduces various strength properties. Boffin and Lee (1976) determined thickness changes of three commercial particleboards after subjecting them to 5 cycles of 65, 90, 65, 90, and 65% RH.

Swelling changes of particleboard with changes in relative humidity are greater than the dimensional changes and less than the thickness changes. The reason for the swelling changes is a function of the changes in the water content of the board. The changes in the water content are a function of the relative humidity





AD-A142 419

SYMPOSIUM ON WOOD MOISTURE CONTENT - TEMPERATURE AND  
HUMIDITY RELATIONSHIPS HELD AT BLACKSBURG VIRGINIA ON  
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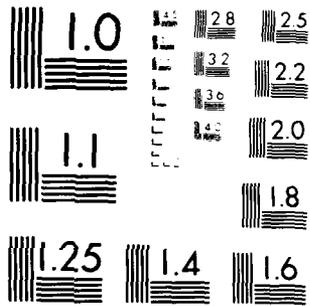
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AD-P003 445

EFFECT OF TEMPERATURE, HUMIDITY AND MOISTURE CONTENT

OF SOLID WOOD PRODUCTS AND END USE<sup>1</sup>

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ABSTRACT

Dimensional changes in response to normal climatic and seasonal variation in relative humidity in heated buildings is a predominant problem during both manufacture and consumer use of solid wood products. Environmental control should be considered in production, but for items in service, proper design and moisture retarding finishes offer best protection.

INTRODUCTION

There is little need to underscore the existence and importance of humidity-moisture content effects on wood products; countless examples are all too familiar to each of us even in our daily lives. These effects--usually detrimental--include the direct influence on dimensional behavior, strength and thermal properties as well as such indirect effects as biological deterioration and the failure of adhesion of glues and finishes. These effects prevail at every phase of end use from the storage and processing of stock in the plant through the eventual service life of the finished product in the consumer's possession. In reviewing this topic, the list of individual moisture related problems seems endless. In manufacturing, the all too common ones are misfitting parts, sunken or open glue joints, surface and end checks, and machining problems. The consumer experiences sticking of swollen drawers and doors, loosened tool handles and furniture joints, uneven joints and surfaces, cracked house walls, split panels, and so on. Rather than engage in a compilation, this paper will focus on a discussion of a few examples which typify the more common categories of problems and a discussion of the more urgently needed approaches for dealing with them.

In contemplating gaps in our technology which might be indicated by these moisture

related effects, it is tempting to re-echo the desirability for discovering economical ways to make wood dimensionally stable, fireproof and immune to biological deterioration. However, considering that the search for such alchemy has been with us almost as long as the problems, the prognosis for finding a panacea is not promising.

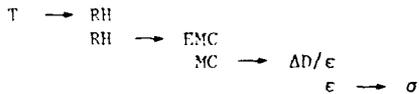
In considering this topic I have tried to view the resultant effects as they confront those directly involved with end use and products: e.g., the manufacturers, woodworkers and homeowners. From their viewpoints, the effects of moisture often seem mysterious, intangible, and insoluble. On the other hand, careful analysis of most problems suggest that a reasonable solution based on existing technology is possible which hasn't been taken advantage of or even recognized. My final conclusion then will be that even though some gaps in our technology can be identified, the greatest progress can be made by implementing existing technology rather than trying to fill the gaps. To be most effective this transfer of existing technology--or in simple terms "education"--must be expressed in language the worker or consumer can understand and must have relevance to specific problems.

RE-EXAMINING FUNDAMENTALS

Of all the moisture related effects on end use, the most infamous are those involving the dimensional change in response to bound water variation. While everyone knows that wood shrinks and swells, few can understand the

<sup>1</sup>Paper presented at the Symposium on Wood Moisture Content--Temperature and Humidity Relationships, VPI and SU, Blacksburg, Virginia, October 29, 1979.

interrelationships between the heating of the shop in the fall and the open glue joints which result. These interrelationships have been thoroughly reviewed during this conference and need not be repeated here in detail. But I always find it worthwhile to visualize the following progression:



as a reminder that temperature (T) can influence relative humidity (RH), relative humidity controls equilibrium moisture content (EMC), moisture content produces dimensional change ( $\Delta D$ ) or strain ( $\epsilon$ ), the restraint of which can cause stress ( $\sigma$ ), sometimes sufficient ( $\sigma_{max}$ ) to cause failure--that is, checks. In some cases only a portion of this chain of effects need be considered to resolve a particular problem.

#### TYPICAL PROBLEMS

A commonly encountered situation is the straightforward case of dimensional change which takes place when wood is used at a moisture content other than that which it will eventually assume in service. A routine example is the differential between the moisture content of the framing lumber installed in a building and the average equilibrium it will eventually reach after a period of occupancy and heating. In a study conducted in Amherst, Massachusetts, moisture meter readings of softwood structural lumber being delivered to job sites averaged 18-19% with a range of from 12 to 29%. Readings taken on equivalent interior framing members in houses occupied for a number of years averaged 8 to 9% moisture content. In a typical dwelling built with conventional light frame platform construction, the sills, joists, subfloors, base shoes, and rafters are vertically stacked; the perpendicular-to-grain dimensional changes are vertically cumulative. In a 2-story structure the cumulative dimensional change in the framing can exceed an inch from the time of construction to the attainment of eventual equilibrium. The consequences of tying part of the house to vertical masonry columns or plumbing can obviously cause uneven distortion, with cracked drywall, separated joints, and uneven floors. Builders always call this "settling"; I have never heard it called shrinkage. Many builders see the problem as inescapable. Since it seems unlikely that framing can economically be dried as low as 8% moisture content, the obvious way of dealing with the problem is to design the house framing so it can move vertically independent of the masonry. Wise builders do.

A more specific example is in framing of built-in kitchen counters, where the base is framed by nailing 2 x 4's on edge along the sub-floor. The countertop is constructed of plywood or particleboard. Since the rear edge of the countertop is anchored with a furring strip to the wall studs, its height is fixed above the floor. The front edge of the countertop responds to shrinkage of the base frame below it. In touring a house under construction, I noticed an obviously wet 2 x 4 being used for counter base framing. Sensing my concern, the builder assured me there was no problem in its high moisture content, since it would be nailed down and "can't go anywhere." But a quick mental calculation indicated that when the high moisture content (at or near the fiber saturation point) eventually reached equilibrium moisture content of about 8%, it would shrink an eighth inch or more; the front edge of the counter would drop an equal amount. That builder would never build a counter that was out of level by that much. Yet that's what the homeowner eventually got. (It's enough to make an egg roll off a Formica surface!)

In manufacturing plants where products such as millwork, flooring, cabinets, furniture or sporting goods are being produced, it should be routine that stock be kiln dried to an average moisture content the finished items will have in service. In most cases plants now do a reasonably good job in this regard. But still problems develop because moisture content is allowed to change during manufacture. A typical example is trouble with edge-glued furniture panels and chair seat blanks, where the end grain region of the stock is allowed to change moisture content. In dry weather, during the time interval between the edging and gluing operations, the end grain may loose enough moisture and result in enough shrinkage across the ends so that clamping pressure cannot fully close the joint. In damp weather, the ends of gluing stock may gain moisture and swell prior to machining. Edge jointing straightens the flared-end boards, which are then edge glued. When the panel ends eventually equalize back to their original lower moisture content, and attempt to shrink back to original condition, stresses are developed which may split the panels or open the ends of the glue joints.

#### FOCUS ON HUMIDITY

The above examples indicate typical problems associated with moisture content change. But more importantly, they reveal shortcomings in our traditional approach. Foremost is our preoccupation with the concept of moisture content, both in our thinking as well as in practice. In theory we know that moisture content responds to relative humidity. RH is the cause; EMC the effect. Yet in practice we

try to work mainly with moisture content, as if in doing so RH will in turn take care of itself. The result is that relative humidity has been almost universally ignored. I repeatedly meet manufacturers, woodworkers, and even hobbyists and homeowners who are very knowledgeable about the moisture content that wood should have for this purpose or that. Yet, they do not have an inkling of the relative humidity for establishing and maintaining such moisture levels, nor do they have even the simplest instruments for measuring relative humidity, nor the provision to regulate it in any way. It is quite apparent that there must be much more awareness of relative humidity and its relationship to moisture effects.

In a brief article entitled Some Thoughts on the Term "EMC"<sup>2</sup>, Bruce Heebink suggested an alternate term such as ERH or RHE (standing for "equilibrium relative humidity" or "relative humidity equilibrium") be adopted as a basis for specifying moisture condition. His suggestion was made primarily because so many modified wood products have different equilibrium moisture contents. By this reasoning, rather than specifying lumber to be dried to 8.0% MC, it

<sup>2</sup>SMST LOG. November, 1966. Mimeo 3pp. Society of Wood Science and Technology, Madison WI.

would be specified as being dried at an ERH of 42 percent. This same specification would be appropriate for various species whose EMC might range from 7 to 9 percent at this same 42 percent humidity level. Adapting an ERH philosophy would also focus needed attention on atmospheric conditions, namely relative humidity. It is obvious that greater humidity awareness and control would be especially important in manufacturing, for here the wood is as yet unprotected by finish and at this stage maintaining proper EMC is most critical. At the same time it is at this stage of end use that control would be most feasible.

#### IMPORTANCE OF VARIATION

It is common knowledge that wood shrinks and swells because of variation in atmospheric humidity. But in any actual situation, how much does the atmosphere change? How much does the moisture content vary? How much does wood really shrink and swell? What are the tolerable limits? Can we realistically stay within them? These questions deserve much more attention than they have been given.

We can get a general sense of the potential situation from figure 1, where examples of familiar RH-EMC and EMC-shrinkage relationships are plotted together; we can now read dimension change directly as a response to relative

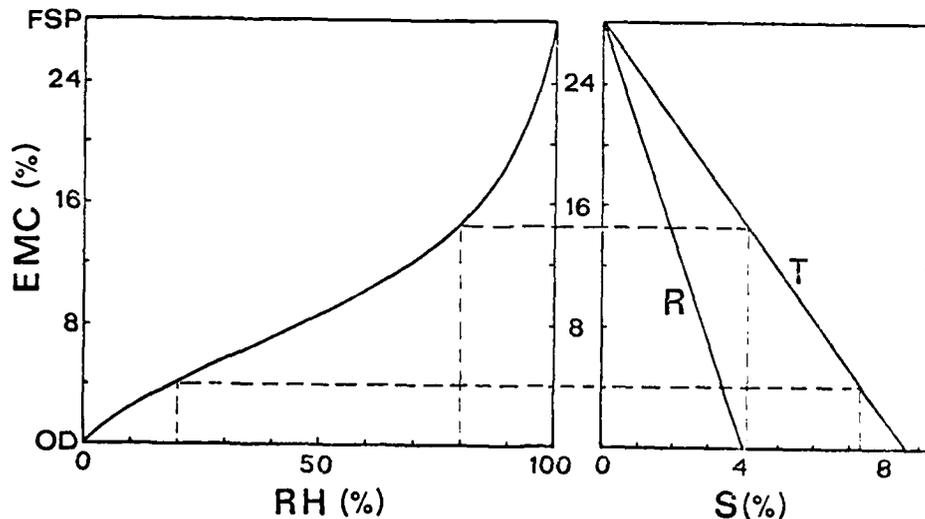


Figure 1.--Typical relationship between relative humidity (RH) and equilibrium moisture content (EMC) and between equilibrium moisture content and shrinkage (S). (T=tangential, R=radial). Average data for red oak are shown. Dashed lines show approximate winter-summer extremes for solid wood in winter-heated buildings in the Northeast.

humidity, more or less ignoring the EMC intermediate. For the user of wood or wood products, the notion of moisture content is a nebulous intermediate which is difficult to comprehend and seems academically remote. Correlating humidity directly with dimensional change--two tangible indicators of environment and wood behavior--would probably have far more relevance. But convention has traditionally ignored this approach.

For a typical situation in the Northeast, the humidity within heated buildings commonly drops to below 20 percent RH during periods of winter weather when the outdoor temperature is dipping below zero. In summer, indoor humidities commonly remain above the 80 percent mark for weeks at a time. Figure 1 suggests that unprotected wood of average species responding to these extremes will vary in tangential dimension by some three percent or more. Even greater extremes are not uncommon. (In my basement, spruce wafers have reached over 20 percent moisture content in summer, as low as three percent in winter.)

How tolerable is three percent variation in dimension? In some cases it may be insignificant, as in a piece of free-standing sculpture, a bread board, or the like. In drawers that stick or doors that won't close, it may be an aggravating problem, but seems to disappear harmlessly once the weather again becomes favorably dry.

In countless products, however, this three percent response to normal variation in humidity can be quite destructive. An example is any wood restrained from swelling, as the handle of a hammer in the head. If fitted tightly at a winter extreme, say 20-25% RH, and allowed to follow equilibrium to a summer high of 80-85% RH, the attempted swelling of three or more percent is restrained. Since the elastic strain limit in compression is commonly below one percent, most of the restrained swelling is sustained as permanent set. Upon redrying to the original relative humidity equilibrium, the socket of the handle shrinks to less than its original size and of course loosens in the head.

Similarly, longitudinal grain direction in a mortise restrains the tenon; and normal humidity variation can cause enough self induced compression set in a mortise and tenon joint to result in loosening and failure. The familiar loosening of chair joints, so commonly blamed on poor gluing or abuse of the chair, is probably most often the result of dimensional response to humidity variation.

Another result of the same mechanism is the splitting of wide members (such as table tops or side panels of case goods) which are fixed at their edges as seen in figure 2(A). After sustaining compression set in the swelling phase, splitting occurs during attempts to shrink back because the strain limit in tension perpendicular-to-grain is usually only 1-2 percent.

This mechanism can also develop checks in the ends of originally dry wood. For example, if the end grain surface of a dry board is wetted, its attempted swelling is restrained by the rest of the board and it takes on compression set of several percent. When redried, its attempted shrinkage exceeds the tensile strain limit and checking develops.

This destructive effect of moisture content cycling is also the source of a major misconception about wood which is common among woodworkers and consumers. Because the high end of the cycle is apparently without consequence, and because the visible problems emerge only when low humidity is reached, the deduction is that the problem occurred "because it was allowed to dry out." A corollary reaction is that "oh, we don't have any trouble with high humidity, it's low humidity that causes all our problems." Usually there is no recognition of the fact that the low humidity level was of consequence only because it was preceded by the high. People seem far more prone to humidifying during dry weather than dehumidifying during damp weather.

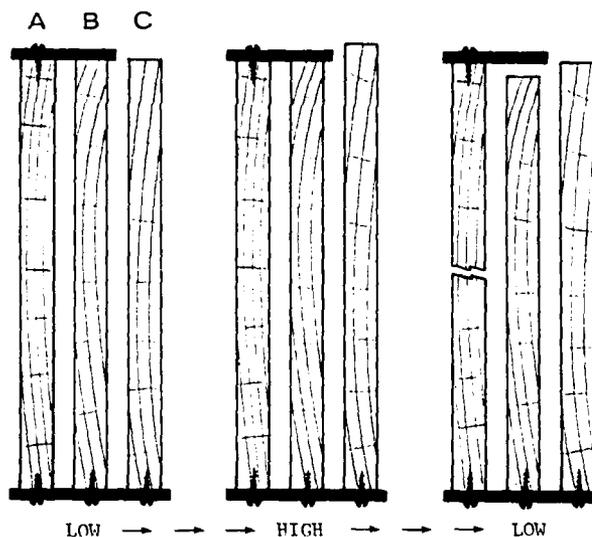


Figure 2.--Behavior of a wide board or panel under an extreme moisture cycle when (A) fastened at both edges and restrained from swelling, (B) restrained but not fastened, or (C) unrestrained and unfastened. During moisture gain, A and B may show no symptoms, although they accumulate compression set; the dimensional change in C may be quite apparent. During moisture loss, C returns to its original dimensions; B shrinks to a smaller dimension; A, restrained in its attempt to shrink (by an amount exceeding its strain limit in tension perpendicular to grain), may fail.

More awareness of the importance of variation is therefore necessary. Once understood, much more could be done to avoid the dangerous extremes.

There is also a notion that dryness is categorically detrimental to wood. Some museum conservators, for example, believe that wood should be stored at no lower than 50% RH and that 60-65% RH is optimum.

While controlling humidity might be a reasonable approach to controlling dimensional variation in the plant, it offers little promise for the consumer whose environment is inherently variable. The consumer must rely more upon finishes to provide a barrier which will retard moisture exchange and keep the total variation within harmless or tolerable limits. But I have found little useful information about the moisture excluding characteristics of current finishes. Likewise little has been reported about the relationship between actual atmospheric humidity and the actual moisture content of specific products finished with identified finishing materials. I feel quite strongly that this is an area where some practical applied research results would be most useful and welcomed by both manufacturers and consumers.

No small part of the problem of education is the many misconceptions about wood which prevail. We have all heard the notions that "wood has to breathe," or that wood is really living tissue and needs to be kept from drying out. In some cases misinterpretation is the obvious culprit. For example, in discussing the seasoning of wood, the author of one book on woodcarving boldly states, "If a log is kept in the dark, in for instance the cellar, and then suddenly exposed to the light, splitting will often take place."

#### CONDENSATION IN BUILDINGS

On a quite different topic, the problem of condensation in the walls of structures deserves mention. Although condensation has always been a concern in heated buildings, the onset of our national energy crisis has multiplied the frequency and consequences of this problem.

Here the role of temperature as it affects relative humidity is a key factor. In a heated building in cold weather, a drastic temperature gradient is established through the building wall from the inside to the outside. Since very cold air can hold virtually no moisture, even when the inside atmosphere seems quite dry it has more moisture than can be held by the outdoor air. Consequently the dewpoint line (that is, the temperature at which moisture vapor will condense to liquid) lies within the wall. Any vapor passing through the wall will eventually condense within the wall, usually within the insulation layer if the wall is insulated. This has the detrimental effects of increasing thermal

conductivity of the insulation and reducing its insulation efficiency as well as increasing the moisture content of any adjacent wood to a level that will support fungal activity or cause breakdown of paint adhesion.

Most buildings constructed in recent years have been well insulated with suitable vapor barriers installed to minimize condensation problems. However, a particularly serious problem has arisen since the energy crisis has prompted the insulating of many old buildings. Insulation is often blown or pumped into the empty walls of buildings without installation of a vapor barrier. The insulation not only establishes a dewpoint well within the wall, it also helps block escape of the condensation moisture when temperatures again rise. The result is rapid progress of fungal action in walls that have stood for centuries. Many historic houses are being badly damaged by this thoughtless use of insulation, and the problem, once created, is difficult to undo.

#### CONCLUSION

In most regions of the United States, especially in colder climates, the normal seasonal variation in indoor humidity can produce dimensional changes in wood which exceed tolerable limits. In manufacturing wood products, environmental control within the plant should be a primary consideration in controlling the effects of moisture variation in stock or in unfinished products. The in-service environment of most wood products is characterized by variation and beyond reliable control; therefore application of a moisture barrier finish must be relied upon to buffer the extremes of humidity variation.

In all cases, education must give greater emphasis to "Equilibrium Relative Humidity" in order to bring a greater understanding to both the producers and consumers of wood products.



AD-P003 446

FACTORS AFFECTING THE WATER

ADSORPTION OF PARTICLEBOARD AND FLAKEBOARD<sup>1</sup>

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ABSTRACT

The amount of water adsorption (WA) determines the dimensional stability of particleboard and flakeboard. Statistical regression models showed that WA is a function of exposure condition, resin type, and board specific gravity, as well as the thickness and slenderness ratio of the wood furnish. Those factors explained 95 percent of all variation in WA.

INTRODUCTION

Particleboard is the generic term for a panel manufactured from lignocellulosic materials. Wood-based particleboard is made from dry wood particles that have been coated with resin, formed into a mat, and pressed under heat; flakeboard is a particleboard composed of flakes. Processing parameters--wood species, reduction of solid wood to particles or flakes, drying temperature, amount and kind of resin and wax, moisture content of the mat, compression ratio, and pressing conditions--markedly affect the properties of the finished panels.

For example, because wood particleboard is hygroscopic, changes in relative humidity trigger complex responses by particleboard and flakeboard. The environmental moisture affects the moisture content of the board, measurably changing linear expansion (LE) in the plane of the panel and thickness swelling (TS) perpendicular to the plane. The amount of LE and TS depends on the processing parameters which also affect the amount of water adsorption (WA) and the equilibrium moisture content at

different relative humidities. In turn, WA and exposure conditions directly affect the amount of LE and TS.

Again due to the processing parameters, the amount of water particleboard adsorbs and, consequently, its equilibrium moisture content are not the same as those for solid wood (Halligan and Schniewind 1972, Suchsland 1972). Similarly, the "random" orientation assumed by the particles and flakes in the plane of the board during manufacture causes LE to be greater than normally would be expected for solid wood in the longitudinal direction.

TS has two components that affect dimensional change: the actual swelling of the wood and the release of compression stresses that develop during mat compaction. Because the amount of dimension change in a board can be critical for most uses, standards for commercial products of particleboard and flakeboard specify allowable dimensional properties (U.S. Department of Commerce 1966).

Vital (1980) established relationships between LE, TS, and WA (terms in the functions follow decreasing order of importance). For particleboard:

$$\begin{aligned}LE &= WA \times f(RT \times EC, SG, SR, TKN, SR \times EC, \\ &\quad RT, \text{ and } RT \times TKN) \\ TS &= f(EC, RT \times EC, SG \times EC, RT \times WA, \text{ and } RT)\end{aligned}$$

<sup>1</sup>Paper presented at the Symposium on Wood Moisture Content--Temperature and Humidity Relationships, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, October 29, 1979. FRL 1399, Forest Research Laboratory, Oregon State University, Corvallis.

And for flakeboard:

$$LE = WA \times f(FC, SAWT \times TKN, RT \times TKN, SG, TKN, TKN \times FC, SG \times FC, RT, \text{ and } TKN^2)$$

$$TS = f(WA, WA \times SG, RT, WA^2, RT \times TKN, FC, \text{ and } SAWT)$$

where FC = exposure condition (30-65 or 65-80%), TKN = furnish thickness (0.15-0.91 mm), SG = board specific gravity (0.53-0.78), RT = resin type (urea- or phenol-formaldehyde), SAWT = surface area by weight (50-400 cm<sup>2</sup>/g) and SR = slenderness ratio (10 to 300).

Thus, its relation to LE and TS makes WA an important characteristic of particleboard and flakeboard. Although processing variables are known to affect the amount of WA, this relationship has not been thoroughly established (Kelly 1977). Therefore we wanted to determine how furnish geometry, resin type, and board specific gravity (SG) affect WA when the relative humidity changes from 30 to 65 and from 65 to 80 percent.

#### MATERIALS AND METHODS

The raw material was green Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco], quarter-sawn into lumber with a nominal thickness of 25.4 mm and a density of 0.41 g/cm<sup>3</sup> (ovendry weight/green volume). The lumber was ripped across the grain into strips 12.7, 25.4, and 50.8 mm long. To generate the particles, we hammermilled flakes 4 mm wide and 25.4 mm long through a 12.7-mm screen, yielding thicknesses of 0.15, 0.41, 0.66, and 0.91 mm. Flakes of the desired thickness--0.15, 0.41, 0.66, or 0.91 mm--were generated with a laboratory disc-flaker. Flake width was determined by the thickness of the lumber. The green furnish, both particles and flakes, was dried at 85°C to a moisture content of approximately 3 percent, then sealed in plastic bags.

We manufactured a total of 96 homogeneous boards under constant conditions (table 1) according to a completely randomized single-replication factorial design. A laboratory-type, rotary drum blender was used to apply either phenol formaldehyde (PF) or urea formaldehyde (UF) resin to the furnish. Wax, resin, and water were applied sequentially with an air spray-gun. The mats were hand-telted and loaded in a single-opening hot press and pressed to specific gravities of 0.53, 0.66, or 0.78, corresponding to compression ratios of 1.30:1, 1.60:1, or 1.90:1. PF-bonded boards were stacked hot overnight, and UF-bonded boards were cooled immediately. All boards were conditioned at 32°C and 30-percent relative humidity.

Table 1. Processing conditions for particleboard and flakeboard

Factor	constant condition
Board size	1.5 x 46 x 56 cm
Resin solids content	5%, ovendry basis
Wax	0.5% Borden's BX-503B wax, ovendry basis
Mat moisture content	7.0 ± 0.1%
Press	temperature, 170°C; cycle, 11 min for PF and 8 min for UF; closing time, 60 sec; decompression time, 30 sec

Before testing, all boards were conditioned until about 13 mm thick. Three subsamples--25 mm long and 76 mm wide were taken from each board, then sequentially exposed to each of three relative humidities--30, 60, and 80 percent at temperatures of 32, 21, and 32°C, respectively--until the boards were equilibrated (about 2 months at each humidity). WA was determined by measuring the incremental change in weight to the nearest 0.1% for each change of relative humidity.

We used multiple regression analyses to correlate the WA increment with furnish geometry, board SG, and resin type. Using a step-wise procedure (Deter and Wasserman 1976), we selected the best set of variables for each equation. The regression equations were used to predict the increment in WA for the UF- and PF-bonded boards at the low and high relative humidities.

#### RESULTS AND DISCUSSION

Water adsorption is an important factor related to LE and TS of particleboard and flakeboard. However, as shown by Vital (1980), the relations between WA and LE and between WA and TS are nonlinear--in fact, several interactions occur between WA and other variables affecting LE or TS. The relationships between WA and the dimensional characteristics of the board are further complicated because variables affecting LE or TS also affect WA.

We derived these multiple regression equations relating furnish geometry, board SG, and resin type with the WA increment due to relative humidity increasing from 30 to 65 percent and from 65 to 80 percent. All terms in

the equation were significant at the 1-percent level. For particleboard:

$$\ln(WA) = 1.3146 + 0.4499 \times EC + 0.552 \times RT \\ - 0.1714 \times SG - 2.52 \times 10^{-3} \times SR$$

with  $Sy \cdot x = 0.0154$  and  $R^2 = 0.957$ . And for flakeboard:

$$\ln(WA) = 1.3854 + 0.2621 \times EC + 0.0948 \times RT \\ - 0.5032 \times SG + 2.40 \times 10^{-4} \times SR \\ + 0.0483 \times TKN^2 + 0.3654 \times SG \times EC$$

with  $Sy \cdot x = 0.0196$  and  $R^2 = 0.949$  where

$\ln(WA)$  = natural logarithm of the increment in water adsorption ( $WA = 1$ )

EC = exposure condition (0 for a relative humidity change from 30 to 65% and 1 for a change from 65 to 80%)

RT = resin type (assumes PF = 1 and PP = 2)

SR = slenderness ratio (furnish length/thickness)

TKN = furnish thickness

Regression analyses explained about 95 percent of all variation we observed in WA. As expected, exposure condition (EC in the model) was the most important variable affecting WA increment. Exposure condition alone explained 93 and 91 percent of all WA variation for particleboard and flakeboard, respectively. The increase in WA per 1-percent increase in relative humidity was larger at higher relative-humidity intervals.

Other experimental variables caused a relatively smaller variation in the WA increment. However, these small variations have an important effect on the amount of LE and TS (Vital 1980).

Because each exposure condition was the same for all boards, the variation in WA within each exposure condition was due to other variables. Once we considered exposure condition in the model, the most important variable affecting WA in flakeboard was board SG. However, board SG and exposure condition interacted to affect WA. An increase in SG generally decreased WA, but SG had less effect at high relative humidity. Apparently SG had little effect on WA once the board had adsorbed enough water to release the larger stresses from the compression set in the denser boards. Lehmann (1974) and Vital et al. (1974) also found that the amount of water adsorbed decreased if board SG increased.

Flakeboard made with phenolic resin generally adsorbed more water at both exposure conditions. Schneider (1973) found that the difference in WA due to resin type increased as the relative humidity increased. However, we

found no significant interaction between resin type and exposure condition. This tendency of phenolic-bonded boards to adsorb more water is associated with their high caustic content (Wittmann 1973).

WA in flakeboard was also affected by flake geometry, as indicated in the regression model by thickness squared ( $TKN^2$ ) and slenderness ratio (SR). The effect of flake or particle geometry on WA probably related to the change in the surface area covered by the resin and its bulking effect, as well as the change in the amount of end-grain surface as flake length and thickness changed. Geometry may also affect WA indirectly by causing a mechanical restraint in the board due to induced stresses from crushing and density variations. Increases in SG would also cause mechanical restraint in the board. Adsorption curves were similar for furnish, board, and solid wood, thus the belief that the effect of geometry was due to the mechanical restraint or resin distribution or both.

Figure 1 shows the surface responses for flakeboard ( $SG = 0.70$ ) as predicted by the equations we derived in the multiple regression analyses. The effect of changes in flake length and thickness for boards of other specific gravities can be estimated using these equations; the SG for each resin type and exposure condition should remain constant while flake length and thickness are increased slightly. Because board SG and flake geometry do not interact, response surfaces for other specific gravities will have shapes similar to those in figure 1. Figure 2 shows the predicted effect on WA when board SG is changed for a flakeboard made with 0.30- x 50-mm flakes.

The smallest increment in WA for each exposure condition and resin type (fig. 1) should occur with short 10-mm flakes between 0.30 and 0.50 mm thick. At this thickness, lengthening the flake slightly increased WA. Variable thickness of the short flakes also increased WA slightly. As flake length increased, WA became more sensitive to changes in flake thickness.

As observed with flakeboard, the WA increment in particleboard was also higher with boards made with phenolic resin. For particleboard, however, WA was more sensitive to changes in particle geometry than in board SG. Boards made with particles having a larger slenderness ratio (thinner particles) adsorbed less water.

Figure 3 predicts how changing particle thickness will affect WA for a PF- or PP-bonded particleboard with  $SG = 0.70$ . WA is more sensitive to changes in particle thickness between 0.15 and 0.30 mm. The smallest increment in

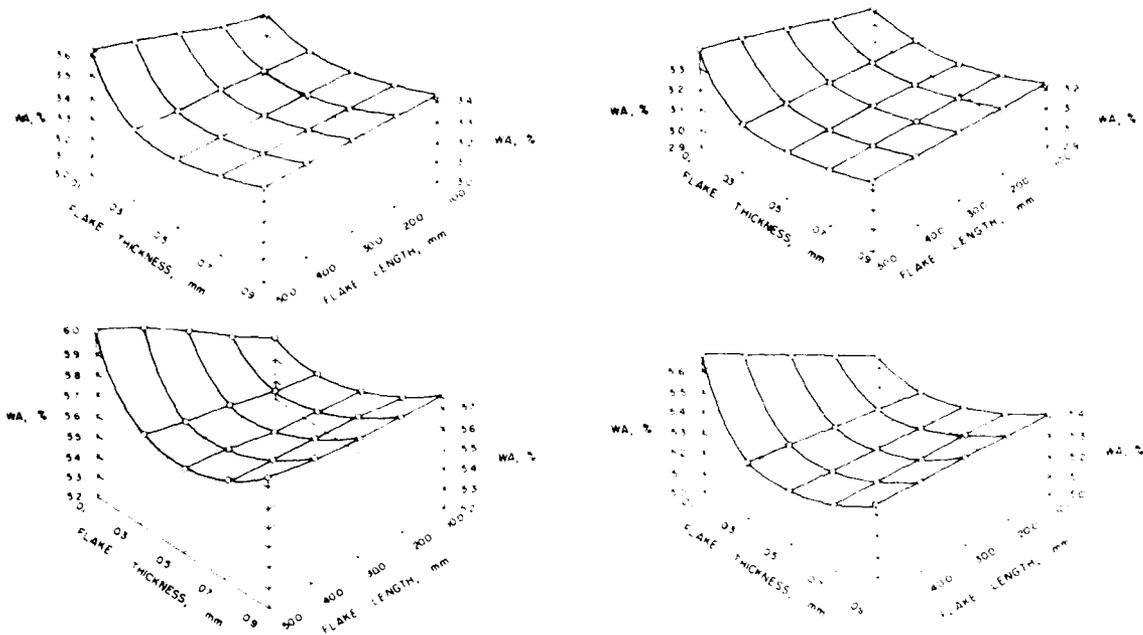


Figure 1. Predicted effect of flake length and thickness on the water adsorption (WA) for flakeboard (SG = 0.70) when relative humidity changes (A) from 30 to 65 percent in a PF-bonded board, (B) from 30 to 65 percent in a UF-bonded board, (C) from 65 to 80 percent in a PF-bonded board, and (D) from 65 to 80 percent in a UF-bonded board.

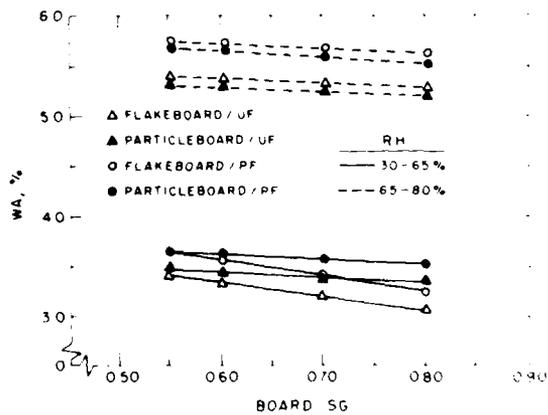


Figure 2. Predicted effect of board specific gravity (SG) on the water adsorption (WA) of flakeboard made with 50- x 0.30-mm flakes and particleboard made with particles 0.40 mm thick.

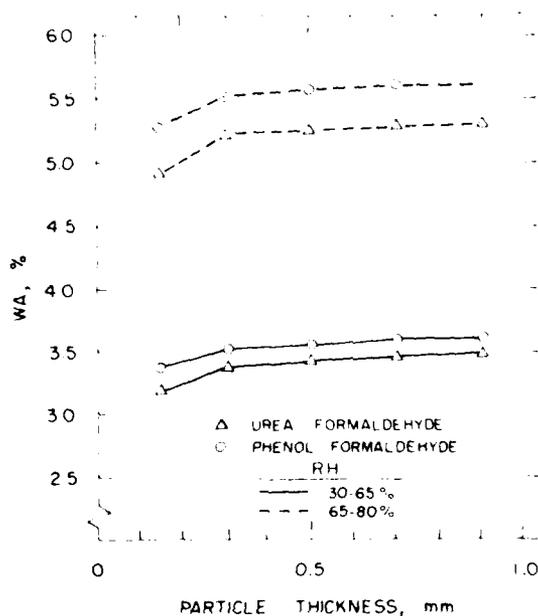


Figure 3. Predicted effect of particle thickness on the water adsorption (WA) of particleboard with a specific gravity of 0.70.

WA should occur with thin particles. The effect of particle thickness at other specific gravities can be calculated using the same technique we discussed for flakeboard.

Increasing particleboard SG decreased WA (Fig. 2). The effect was linear for both conditions but smaller than for flakeboard, consistent with other published reports.

#### CONCLUSIONS

1. For particleboard and flakeboard, the incremental change in WA is mainly a function of the exposure condition.
2. For particleboard and flakeboard, the increment in WA per 1-percent increase in relative humidity is larger at higher relative humidities.
3. In particleboard, WA is more sensitive to changes in particle thickness than to changes in board SG. In flakeboard, once exposure condition is considered, board SG is the most important variable affecting WA. WA decreases as SG increases, but the increment of decrease in WA due to increased SG is smaller at the higher relative-humidity interval.
4. Due to the high caustic content of the phenolic resin, boards made with PF resin adsorb more water than boards made with PF.
5. For particleboard of both resin types and relative-humidity intervals, the smallest increment in WA should occur with high density boards made with thin particles (0.15 mm).
6. For flakeboard of both resin types and both relative-humidity intervals, the smallest increment in WA should occur with high density boards made with short flakes (10.0 mm) between 0.30 and 0.50 mm thick.

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