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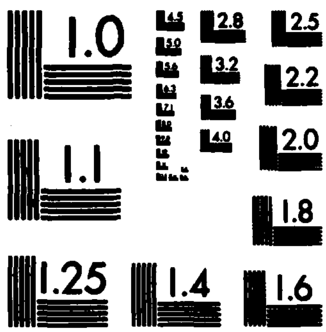

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Empirical Equations for Estimating Drying Times of Thick Rotary-Cut Veneer in Press and Jet Dryers

John L. Tschernitz

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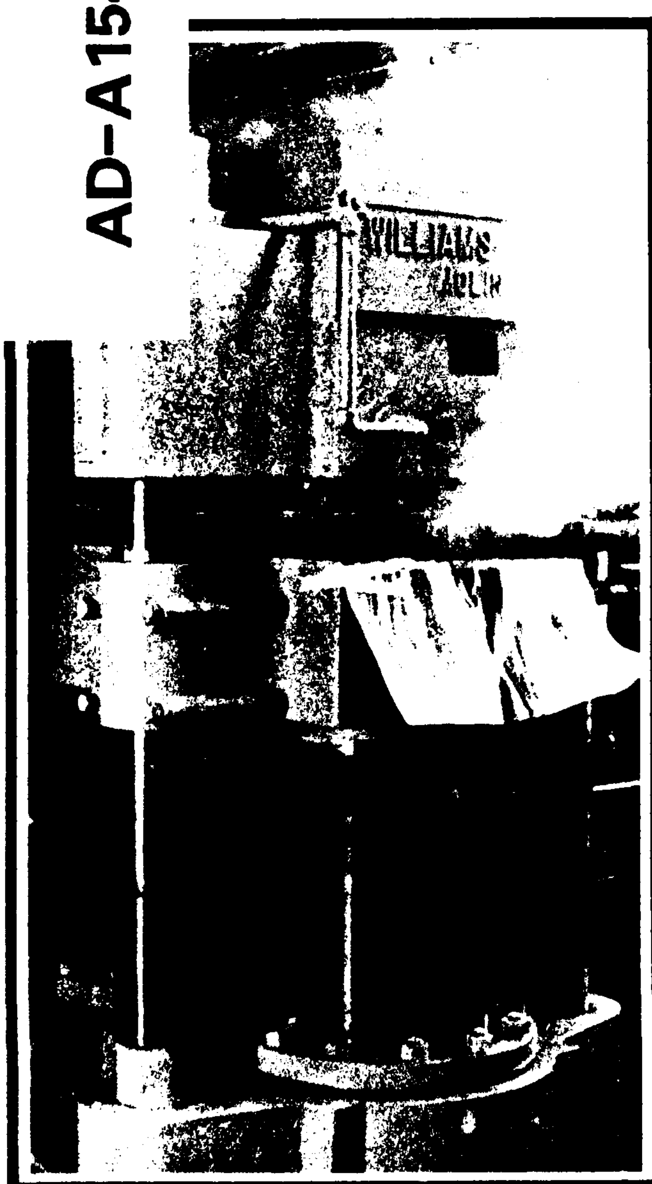

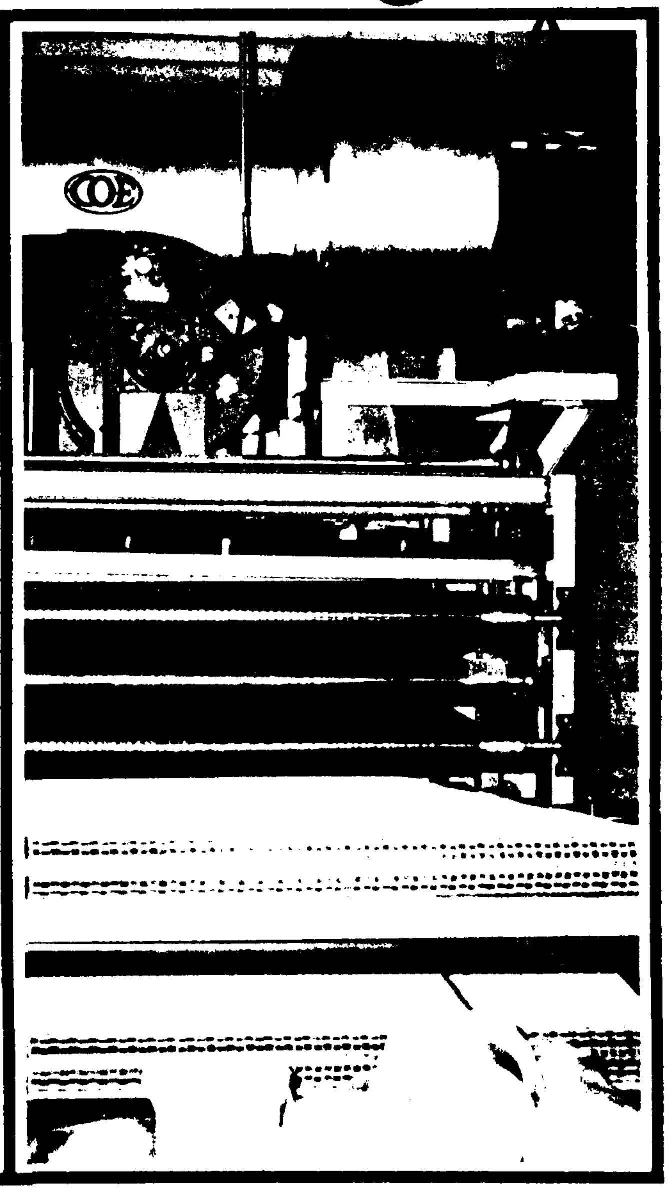

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Abstract

Drying time determinations for thick veneers have not generally been analytically described. With the advent of computers, it is now possible to evaluate coefficients for empirical equations of a form that, in the past, was not readily amenable to traditional analysis.

The drying rates of rotary-cut Douglas-fir veneers 1/8 to 1/2 inch thick were determined for press and jet dryers. Drying rates for southern pine veneers 1/8 to 1/2 inch thick were determined only for press drying. The variables considered for the two wood groups were temperature, thickness, and moisture content. In the case of press drying, miscellaneous observations of the effects of press pressure and caul design were made. An empirical equation was derived from a simple physical model and used to correlate this data. Such correlations are useful in dryer selection and operation.

Keywords: Drying rates, thick veneer, platen, jet, empirical equation.

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The Laboratory is maintained in cooperation with the University of Wisconsin.

Acknowledgment

Because this paper is a by-product of an extensive team research program, it is not feasible to name all the individuals who contributed to this work. The author thanks those many people for their efforts.

Empirical Equations for Estimating Drying Times of Thick Rotary-Cut Veneer in Press and Jet Dryers

John L. Tschernitz, Chemical Engineer
Forest Products Laboratory, Madison, Wis.

Introduction

During the period 1970-72 the Forest Products Laboratory (FPL) explored the feasibility of producing structural lumber products from laminated parallel-grain rotary-cut thick veneers. One important feature of one such process—termed Press-Lam—is the rapid (2-4 min) cure of laminating resins utilizing the residual high (180° F) temperature of the veneers after drying.

To explore the economics of the process it was necessary to establish drying times for veneer up to 1/2 inch thick, dried in different dryers (Hann et al. 1971; Schaffer et al. 1972, 1977). At the same time, to manipulate the drying time data better, we developed an analytical correlation of drying times for various temperatures, species, and veneer thicknesses. Other than Comstock's (1971) summary of past correlations of veneer drying rates and his own study of jet drying rates, studies on veneer drying rates have not been extensive and the author is not aware of any additions to the literature. Drying times have not generally been analytically described because of the complexity of physical events. Empirical equations developed from a highly simplified physical model can be easily used to estimate drying times for varying conditions.

The model that forms the basis for our equations assumes that, at temperatures above 212° F, the drying rate is heat-transfer controlled by an internal mechanism. With simplifying assumptions, our equation is derived on the basis of the concept of a retreating evaporating zone, which correlates drying time with temperature, thickness, and moisture content. Because of the limitations of this model, it has been necessary to construct an empirical form of the derived equation specific to the dryer type and veneer species.

This paper describes the use of empirical equations for the analytical correlation of the drying variables—time, temperature, green thickness, and moisture content—for drying southern pine and Douglas-fir thick-cut veneers in two dryer types.

Drying Methods, Materials, and Procedures

To develop a broad basis for drying time equations, we ran veneers of two species and four green thicknesses through three types of dryers at times and temperatures that were typical for those dryers or were necessary for complete drying of the veneers. Each time-temperature curve formed part of the data base for the equations.

Drying Methods

Three methods of drying were considered as practical for drying thick veneer to moisture levels low enough for gluing. Heated-platen, or press, drying utilizes rapid solid/solid heat transfer from platens to veneer. Heated impingement air, or jet, drying utilizes gas/solid heat transfer by high-velocity perpendicular air flow. Roller drying also utilizes gas/solid heat transfer; air flow is of low velocity and parallel to the veneer surface.

The major drying rate data in this study were obtained from steam- and oil-heated presses and a jet gas-fired experimental dryer at Coe Manufacturing, Painesville, Ohio.[1] Minor drying observations were made on a steam-heated Coe roller dryer.

Press Drying

The advantages of press drying veneer are:

1) Highest rate of drying,

2) Greater uniformity of veneer thickness from the dryer,

3) Flattening of the rough veneer surface, producing greater areas of effective contact in gluing.

[1] The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture of any product or service to the exclusion of others that may be suitable.

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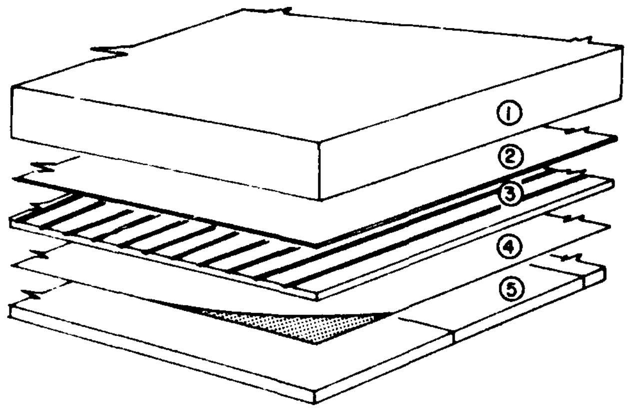

Figure 1.—Caul designs for drying presses. Components are (1) steam- or oil-heated platen, (2) aluminum sheet metal insert, (3) aluminum vented caul with 1/8-inch holes on 1-inch centers and a back channel (1/8- x 1/8-in.) vent, and (4) 60-mesh fourdrinier bronze wire screen. Specimen is (5). (ML 84 5658)

The primary disadvantage is the lack of a commercially available continuously heated press-dryer system. After this study was completed, Weyerhaeuser developed and patented a press-drying system consisting of a series of presses operated on a carousel base for continuous product flow (Brookhyser and Pierson 1980). A press-drying system for veneer, consisting essentially of a multi-opening press, was also developed in Finland (Mustakallio and Paaki 1977).

Three slightly different presses were used. Presses A (26 x 205 in.) and B (48 x 48 in.) were steam-heated with a maximum platen temperature of 375° F, and press C (36 x 36 in.) was oil-heated with a maximum platen temperature of 500° F. Loading pressures were maintained at 50 $lb/in.^2$.

A caul system (Heebink and Compton 1966) was modified by removing the 60-mesh fourdrinier bronze screen (fig. 1). Operating without this screen decreased drying time by 10%. No excess pressure was indicated, either by a significant temperature rise above 212° F within the veneer thickness center or by blowup of the veneer upon press openings.

Several phenomena regarding press drying should be noted:[2,3]

1) Vented cauls or screens are essential.

2) The principal path of vapor and/or liquid flow is in the radial direction (perpendicular to the surface).

3) No difference in drying rate is observed for varying sizes and shapes of veneer—e.g., 12 inches wide by 24, 48, or 96 inches long; or 48 inches long by 6, 12, 18, or 24 inches wide.

4) Rotary knife checks have surprisingly little effect on drying rates—i.e., drying rates are the same for sawn boards and peeled veneer of equal thickness.

Jet Dryer

The advantages of conventional jet drying over press drying include:

1) Commercial availability,

2) Continuous operation,

3) Lower capital equipment costs.

The disadvantages of jet drying as compared with press and roller drying include:

1) High operating costs for electric power,

2) No appreciable increase in drying rates for thicknesses greater than 1/4 inch,

3) Not-as-high-quality veneer as from press dryers.

A cooperative agreement was made with the Coe Manufacturing Company to perform drying tests on a pilot, gas-fired, jet dryer. These plant-site tests were conducted on Douglas-fir heartwood. Because the experimental unit was only about 16 feet long and was only single-tiered, a complete drying curve for any given temperature and veneer thickness was established by making multipasses of a veneer through the dryer, with intermediate weighings after each pass. The speed of the chain was continuously variable over a wide range. The temperature was controllable (direct gas fire) with an upper limit of 800° F, and was regulated by conventional process control recorder/controllers.

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[2] Tschernitz, J. L. Feasibility of producing a high yield laminated structural product, Appendix IIA, Press Drying. Unpublished report. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1971.

[3] Tschernitz, J. L. Douglas-fir thick veneer drying studies. Unpublished report. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1972.

The drying air was directed onto the veneer by top and bottom vertical impingement from a manifold of jets. For our tests, the jets were located for the middle veneer thickness (0.389 in.) of the three tested. Jet size, spacing in the manifold, and separation from the veneer were considered to be proprietary information. Jet velocity was about 3,500 feet per minute. Weight loss was determined by a calibrated scale to an accuracy of ±0.01 pound.

Roller Dryer
A limited number of tests of Douglas-fir heartwood was made in the FPL steam-coil-heated Coe roller dryer for purposes of comparison. Advantages of the roller dryer are:

1) Continuous operation,

2) Commercial availability,

3) Lower operating cost than press or jet dryers.

Of the three dryers, the roller unit has the lowest drying rates. Temperature is variable to a maximum of 335° F, but because the purpose of these observations was to establish the relative drying rates, only one temperature—300° F—was used. A drive speed was chosen so that a smooth curve of MC over time could be obtained with about six passes per curve.

Materials

Log Selection
Southern pine.—Fifty loblolly pine logs, 17 feet long and 12 to 23 inches in diameter, were purchased from a plywood mill in east Texas. The grade request had been "woods run," but the quality of these logs was high (grade unknown). All the wood for veneer was sapwood, since the heartwood core was 5 inches or less. Because of the high quality of the logs, no selection or grading of the veneers was necessary.

Douglas-fir.—Thirty old- and new-growth coastal Douglas-fir logs were obtained from the Pacific Northwest. They were 17 feet long with diameters from 14 to 34 inches; sapwood thickness was from 1 to 4 inches. The log grade was 4 (sawlog, PNW grading scale) (Lane 1972), which presented problems in selecting material for drying rate determinations. The criteria for selection of material was to have knots no larger than 1 inch and no more frequent than three per piece of veneer. Thus in a 12- x 48-inch veneer the total knot volume would be less than 0.5%. Pieces with pitch pockets were also eliminated. Because of the difficulty in selecting "clear" material from this low-grade group of logs, a new set of six grade No. 1 logs was obtained, and these were used as source material for jet drying tests.

Log Preparation and Veneer Cutting
All logs were stored outside in Madison, Wis., in winter, when the temperature was consistently below 40° F. The logs were cut, as needed, into 48- to 52-inch bolts and heated by water immersion prior to cutting. Southern pine was heated at 100° F for 16 hours and Douglas-fir at 140° F for 64 hours.

Veneer was cut from these bolts to selected thicknesses of 1/8 to 1/2 inch on the FPL 4-foot-long experimental industrial-type rotary lathe. The veneer was clipped to a width of 12 inches, squared to 48 inches long, and then wrapped in plastic and cold stored at 36° F as inventory for the press drying tests. Prior to drying, the veneer was allowed to reach room temperature.

The selection of clear veneer for establishing the drying characteristics of these veneers is necessary in order to reduce the variation in drying rate data. Because low-grade logs have different volumes of knots from one area to another in the log, and because knots generally have low initial MC, average MC calculations are confounded. Note that the use of clear wood in no way lessens the value of using these data to establish the drying rates of knotty boards since the final MC of the clear areas of knotty veneer would be the same for both.

All sapwood and heartwood were segregated and separate drying tests were made for each group.

Inasmuch as the materials for these drying rate studies were randomly selected from a larger population, we had the advantage of obtaining veneer from several different logs used for Press-Lam lumber construction. Consequently, the number of veneers for any one test was variable.

Procedures

Critical variables in correlating drying rates and developing a model were veneer moisture content, temperature, thickness, and time of drying.

Moisture Content
Because the use of an average observed initial MC causes large error in the final MC computation for individual veneers, a destructive determination of MC of each veneer was necessary. The "ovendry" weights of the individual pieces of veneer were determined by returning them to the dryers at temperatures greater than 300° F for predetermined times. This procedure was checked against conventional gravimetric methods and found to be accurate.

Table 1.—Typical drying data for Douglas-fir multipasses of heartwood veneer[1] in a jet dryer.

Veneer No.	Moisture content at time θ				
	0 min	1.63 min	3.26 min	4.89 min	6.52 min
	%				
1	31.4	24.7	17.3	11.0	6.37
2	30.1	24.5	16.4	11.2	6.39
3	29.5	23.3	16.3	9.66	5.10
4	31.0	24.4	17.1	11.7	6.30
5	28.3	22.1	15.5	9.70	6.30
Average	30.0	23.8	16.5	10.6	6.09

[1]Thickness = 0.259 in.; temperature = 400° F.

Press dryer.—The MC's at various times were established by three weighings: 1) initial weight for green MC before drying; 2) weight at the end of fixed time intervals during drying; 3) "ovendry" weight after return to the press at 375° F. Each drying coordinate represents an average of data obtained from four separate veneers.

Jet dryer.—Because these tests were performed in Ohio on Douglas-fir heartwood veneers sent from FPL it was necessary to modify the test procedures to conserve materials. Each veneer was weighed initially, and then weighed after each pass through the jet dryer until the MC was reduced to about 5% (table 1). After the last pass, the veneers were weighed and wrapped in plastic for return to FPL. The final determination of "ovendry" weights was made by heating to dryness in the roller dryer. Five replicates were run in groups for each drying curve.

Roller dryer.—These tests were similar to those run in the jet dryer in that weight loss measurements were made on one set of five veneers after each pass through the dryer, again because of a limited veneer source. The final weights were established by drying in a press dryer.

Temperature

Press drying.—Platen temperatures were maintained and measured by process controllers. Veneer temperatures were measured with 30-gage copper-constantan, cotton-covered, enameled wire. The surface couple was placed between caul and wood. Internal temperatures were obtained by inserting thermocouples into 3/4-inch-deep holes drilled in the ends and sides of the veneer and sealed with a wooden toothpick plug.

Temperature measurements at interfaces—i.e., metal-wood boundaries and at internal positions in veneers—are subject to experimental errors of large magnitude. Even with these limitations, temperature measurements were made that provided some insight into heat transfer efficiency, uniformity of heating, and pressure rise within the wood caused by insufficient venting.

Jet dryer.—With the jet dryer it was not possible to measure internal temperatures in the boards, only operating air temperatures.

Roller dryer.—Again, air temperatures but not internal board temperatures were measured.

Thickness

All references to thickness are green measurements, termed $\underline{\ell}$ and expressed in decimals, or are thickness classes expressed as fractions.

Because of surface roughness and/or shelling in certain veneers, a special technique and apparatus (Peters and Mergin 1970) was used to facilitate thickness measurements. A 1-1/2-inch-diameter contact pad under 40 lb/in.^{2} flattened the veneer to provide a regular surface for measurement. The veneer thickness, green and dry, was measured to an accuracy of ±0.001 inch. Readings were observed at three to five marked positions along the axis of the veneer and averaged.

Time

Drying times for press drying are actually platen contact times and, for jet drying, are cumulative residence times.

Derivation and Application of Empirical Equations

Derivation of Equations

We can now develop a model for the drying event, from which the empirical equations may be derived.

The physics of drying for either press or jet drying are the same. Reduced to its simplest form, each drying method can be interpreted as a heat transfer phenomenon. In both cases, surface temperatures are considered to be above the normal boiling point of water (212° F). Since water at atmospheric pressure can boil at only 212° F, the driving force for water evaporation must be the difference between the gas/solid or solid/solid surface temperature and 212° F. This type of drying process can be treated as a one-dimensional heat transfer phenomenon with phase change (Kreith 1965).

While many observations of the temperatures in veneer boards were made during press drying, the time/temperature functions of wood can be approximately represented by the curves in figure 2. (One set of actual time-temperature data is given in table 2.) Ideally, in a homogeneous, porous, nonhydroscopic, insoluble-media removal of water by evaporation from an infinite slab of finite thickness,

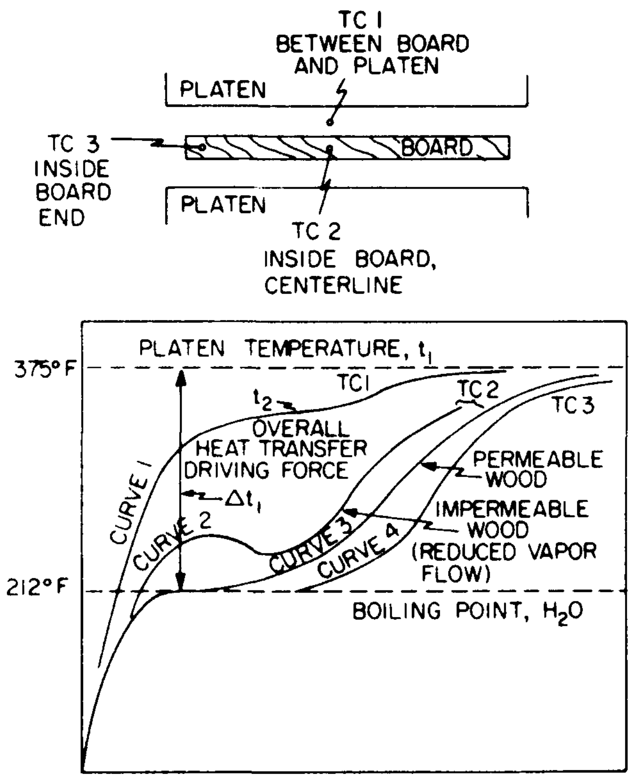

Figure 2.—Thermocouple (TC) locations and schematic temperature-time response of veneer in press drying. (ML 84 5661)

Table 2.—Typical southern pine veneer temperatures in press drying at various times[1]

Time	Temperature[2]		E x 100[3]
	Center, TC 2	Platen, t_1	
Min		*°F*	*%*
1	134	314	85
2	218	314	72
3	220	318	60
4	218	326	49
5	218	332	39
6	218	337	32
7	217	348	25
8	218	354	20
9	220	361	15
10	220	366	12
11	222	367	9
12	230	368	7
13	240	370	5
14	254	371	4
15	266	371	3
16	285	373	2.2
17	306	374	1.7
18	325	375	1.3
19	341	376	1.0
20	347	376	
21	359	377	

[1]Veneer = 0.5 x 12 x 24 in.; temperature = 375° F; *pressure = 50 lb/in.²; vented caul.*

[2]See fig. 2.

[3]As from fig. 5.

one would expect the center temperature (liquid water) to rise to the normal boiling point and remain constant until all of the water evaporated, and then rapidly rise to the surface temperature (fig. 2, curve 4). Because free water and bound water exist in wood, and because wood is an inhomogeneous, anisotropic material of limited permeability, this idealized stepped temperature/time function is not observed. For more permeable woods (e.g., southern pine) one observes a plateau temperature slightly above the normal boiling point of water when a low press pressure of 50 lb/in.², with sufficient venting is used. Curve No. 3 (fig. 2) is typical of the permeable wood centerline temperature, and shows some elevation above No. 4 due to a slight pressure buildup (pressure drop in vapor flow). Curve No. 2 would occur under conditions of low wood permeability or excessive press pressure. Curve No. 1 represents the temperature of the interface between the wood and the caul, which is difficult to determine experimentally. The overall temperature driving force for heat transfer is the difference between the platen and centerline temperature. An exact mathematical analysis of this unsteady state event would be extremely difficult and unnecessary. However, with simplifying assumptions a useful model can be derived.

The following simple model is proposed to describe high-temperature drying of thick veneers (fig. 3). It is assumed that heat transfer occurs at two sides of the infinite slab (veneer) and the corresponding vapor flow proceeds in the opposite direction, perpendicular to the surface.

Drying can be considered to proceed as an expanding dry zone (ε) formed by a retreating evaporating interface (surface) resulting in a symmetrically shrinking wet zone ($l/2 - \varepsilon$, where l = green thickness).

If one ignores the superheating of the escaping water vapor, the temperature rise of the dry wood in the dry zone, and the surface resistance between t_1 and t_2, then a simplified heat balance can be written over a differential section:

$$\frac{dQ}{d\theta} = C_{H_2O} \lambda A \frac{d\varepsilon}{d\theta} \quad (1)$$

where Q = heat transferred

θ = time

C_{H_2O} = weight of liquid water per unit volume of wood

λ = latent heat of evaporation of water

A = area of contact

ε = depth of evaporating zone from surface at any time θ

But

$$\frac{dQ}{d\theta} = \frac{kA}{\varepsilon}(t_2 - t_{212}) \quad (2)$$

where k = thermal conductivity of dry wood

t_2 = surface temperature of wood

t_{212} = normal boiling point H_2O.

Combining equations (1) and (2)

$$C_{H_2O} \lambda A \frac{d\varepsilon}{d\theta} = \frac{kA}{\varepsilon}(t_2 - t_{212}) \quad (3)$$

Rearranging

$$\int_0^{\varepsilon} C_{H_2O} \lambda A \varepsilon \, d\varepsilon = \int_0^{\theta} kA(t_2 - t_{212}) d\theta \quad (4)$$

Equation (4) can be integrated assuming all quantities except θ and ε are constants.

Rearranging and integrating provides us with a solution for time, θ:

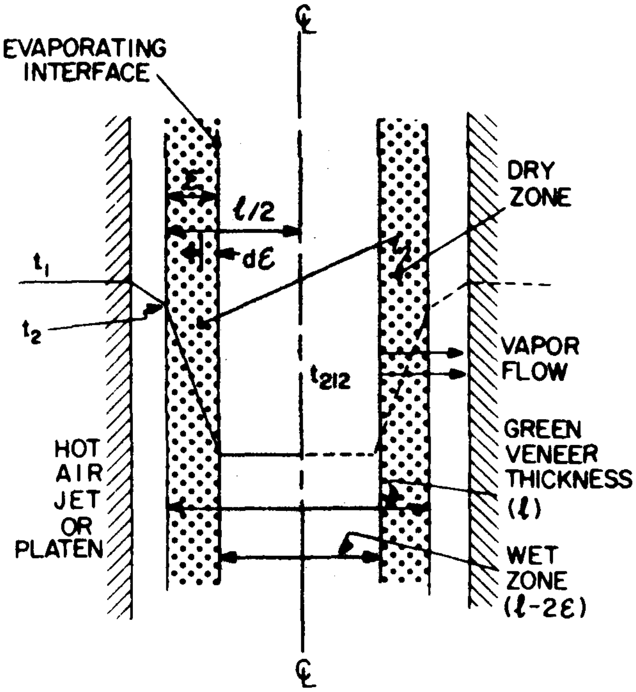

Figure 3.—Model for heat transfer and vapor flow in press drying thick veneer. (ML 84 5664)

$$\theta = \frac{C_{H_2O} \lambda \varepsilon^2}{2k(t_2 - t_{212})} \quad (5)$$

If

$$C_{H_2O} = \frac{W_{H_2O}}{V}$$

and

$$\rho_{wood} = \frac{W_{DW}}{V}$$

where W_{H_2O} = weight H_2O;

W_{DW} = weight dry wood

V = unit volume wood

then

$$C_{H_2O} = \frac{M_0 W_{DW}}{100 V} = \frac{M_0 \rho_{wood}}{100} \quad (6)$$

Since this model proposes an evaporating interface within the wood, at any time θ, two zones exist:

Dry zone, MC = 0

Wet zone, MC = M_0

if ϵ = thickness of dry zone, and

$\ell/2$ = total distance surface to centerline

and if M_i = average moisture content of zone 1 + zone 2

then

$$\frac{\ell}{2} M_i = \left(\frac{\ell}{2} - \epsilon\right) M_0$$

Then

$$\epsilon = \frac{\ell}{2}\left(1 - \frac{M_i}{M_0}\right) \quad (7)$$

Substituting equations (6) and (7) into equation (5)

$$\theta = \frac{M_0 \rho_{DW} \lambda \left(\frac{\ell}{2}\right)^2 \left(1 - \frac{M_i}{M_0}\right)^2}{100 \cdot 2k(t_2 - t_{212})} \quad (8)$$

Application of Equation to Southern Pine Sapwood (Press-Dried)

Assuming no heartwood veneer, M_0 can be taken as 100%. Substituting M_0 into equation (8)

$$\theta = \frac{\rho_{DW} \lambda (100 - M_i)^2 \left(\frac{\ell}{2}\right)^2}{100 \cdot 2k \cdot 100(t_2 - t_{212})} \quad (9)$$

Ideally, the internal pressure in the veneer is at atmospheric pressure, then $t_{212} = 212°$ F. However, this value is not observed experimentally (see TC 2, table 2). In addition, if we substitute the physical properties shown in equation (9) as:

ρ_{DW} = 0.42 x 62.4 lb/ft^3

k = 0.1 Btu/hr · ft · °F

λ = 1000 Btu/lb H_2O evaporation

and assume

M_0 = 100%

M_i = 5%

ℓ = 0.5 in./12

t_2 = 400° F

and solving for θ

θ = 0.27 h or 16.4 min.

However, from figure 5

θ = 11.3 min.

Obviously, the calculated value is 50% too high. Therefore, an empirical form of equation (9) is needed. By inspection of equation (9), grouping terms, the following empirical equation is proposed:

$$\theta = \frac{(C_1 - C_2 M_i^{C_4}) \ell^{C_3}}{(t_1 - C_5)} \quad (10)$$

assuming $t_2 = t_1$, for platen or jet air temperature.

An equation in this form has three variables: average MC (M_i, %; or, for southern pine, M_i = E x 100), veneer thickness (ℓ, in.), and platen or air temperature (t_1, °F).

The coefficients $C_1 - C_5$ are empirical and therefore must be derived from experimental data for any wood species/dryer system.

Applications of Equation to Douglas-Fir Heartwood and Sapwood (Press- and Jet-Dried)

The same empirical equation (10) was used for Douglas-fir heartwood in both press drying and Coe jet drying. The initial MC's were 35% in press drying and 32% in jet drying.

Most Douglas-fir veneer is heartwood, but some sapwood veneer is recovered. Press drying data for heart and sapwood were combined and fitted with a modified empirical equation. Rearranging equation (8):

$$\theta = \frac{M_0 \rho_{DW} \lambda (M_0 - M_i)^2 \left(\frac{\ell}{2}\right)^2}{100 \cdot M_0^2 2k(t_2 - t_{212})} \quad (11)$$

By inspection, the following empirical equation is suggested:

Assume $t_2 = t_1$

$$\theta = \frac{(C_1 M_0^{C_2} - C_3 M_i^{C_4}) \ell^{C_5}}{(t_1 - C_6)} \quad (12)$$

Use of Empirical Equations

All the drying data have been plotted as integral drying curves on semi-log paper. The choice of these coordinates follows from past drying practice and has the distinct advantage of expanding the scale for the lower MC's, which are of particular interest. For veneer drying, the semi-log plot and the two observations, an initial and one drying time coordinate, can rapidly establish a first estimate of a drying curve. Original data points and the calculated values from these empirical correlations (figs. 4-9) show the closeness of fit over a wide range of operating variables.

Fitting of Model to Experimental Data

The coefficients of equations (10) and (12) cannot be derived from known physical properties of the elements of the system, and therefore are only to be considered empirical. Coefficients in equations (10) and (12) were obtained by use of a nonlinear least squares analysis (table 3) (University of Wisconsin Computer Center statistical packages: Gauhaus and NREG). For ease of analysis the following data were used for the routine:

Southern pine (sapwood, press)—Curve smoothed

Douglas-fir (heartwood, press)—Data points

Douglas-fir (heartwood and sapwood, press)—Data points

Douglas-fir (heartwood, jet)—Curve smoothed.

(Roller dryer data were insufficient to be correlated in this manner.) Unfortunately, because of the way in which these data were treated, no statistical description of the degree of fit can be presented.

A comparison with some of the derived coefficients of equation (9) is interesting: The boiling point coefficient, t_{212}, has a spread of 182 to 239 for the four values (table 3) and the thickness exponent ranges from 1.43 to 1.94, both of magnitudes similar to the derived numbers, 212 and 2. It is interesting to note that for conventional kiln drying of sawn boards, the thickness coefficient has been observed to be between 1.5 and 2.0 (Kroll 1959).

Use of Equation with Southern Pine

Because extreme variation occurs in moisture content in southern pine, it is desirable to use a relative basis for expressing MC in the correlation of drying times.

The green MC of the southern pine used in these experiments was about 100%, and variability within and between trees was great (table 4). Variation in initial MC will produce variation in final MC for veneers dried on an equal area/equal time base. For example, the initial MC of sapwood of 72 veneers from 7 logs ranged from 85% to 129%; press dried under the same conditions and time, their final MC's were 5.4% and 8.3%, respectively.

Each of the four individual veneers per experimental condition used here varied between wide limits. For the press drying shown in figure 4, initial moisture content ranged from 75% to 134%, with an average of 103%. For the temperature runs shown in figure 5, initial moisture contents ranged from 67% to 108%, with an average of 87%.

The variation in the green MC was primarily due to variation within and between trees and not due to process operations. There is some water removed mechanically by the knife-pressure bar in veneer cutting and some by evaporation during cutting and storage of the sheets, but this loss was less than 5%.

Heartwood MC is only about 35%, and when heartwood was present it was removed from the drying tests.

Because of these variations in green MC, moisture contents to be correlated are presented on a relative basis, E:

$$E = \frac{M_i}{M_0} \qquad (13)$$

where

M_i = dried MC, %

M_0 = green MC, %.

Therefore, E x 100 = % MC, if M_0 = 100. This implies that a veneer with an initial MC of 120% would require a greater drying time to a fixed MC than a 100% one, which on the average was found to be true.

The closeness of fit of the equation to the smoothed drying curves for southern pine is shown in figures 4 and 5 where predicted values are overlayed upon actual drying curves. Because of the nature of the least squares analysis used, the percentage deviation is greater at shorter drying times.

Table 3.—Coefficients for equations (10) and (12)

Coefficient	Press dryer			Jet dryer
	Southern pine (Eq. 10)	Douglas-fir (heart) (Eq. 10)	Douglas-fir (heart/sap) (Eq. 12)	Douglas-fir (heart) (Eq. 10)
C_1	20.900	88.790	24.863	35.675
C_2	11.610	78.364	0.1859	19.009
C_3	1.429	1.942	23.946	1.465
C_4	0.1238	0.0321	0.1796	0.1774
C_5	181.8	239.4	1.823	204
C_6	—	—	233.0	—

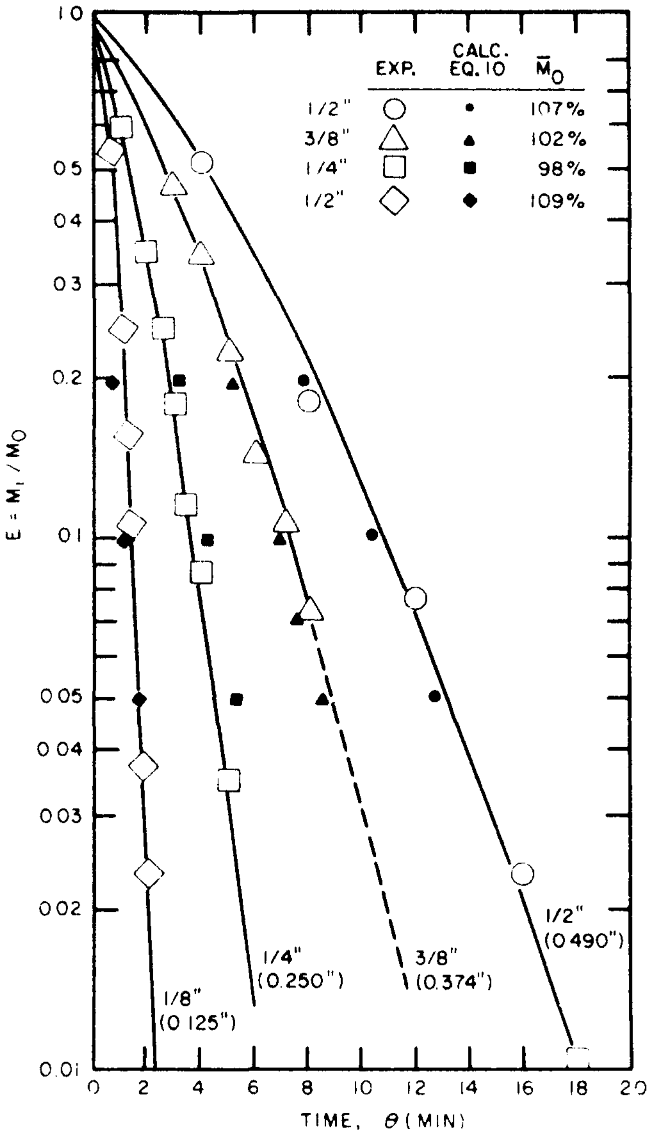

Figure 4.—Southern pine integral press drying curves at various thicknesses. Temperature = 375° F; pressure = 50 lb/in.²; veneer = ℓ x 12 x 48 inches (ℓ (decimal) = actual average measured thicknesses; fraction = thickness class); vented caul. (ML 84 5663)

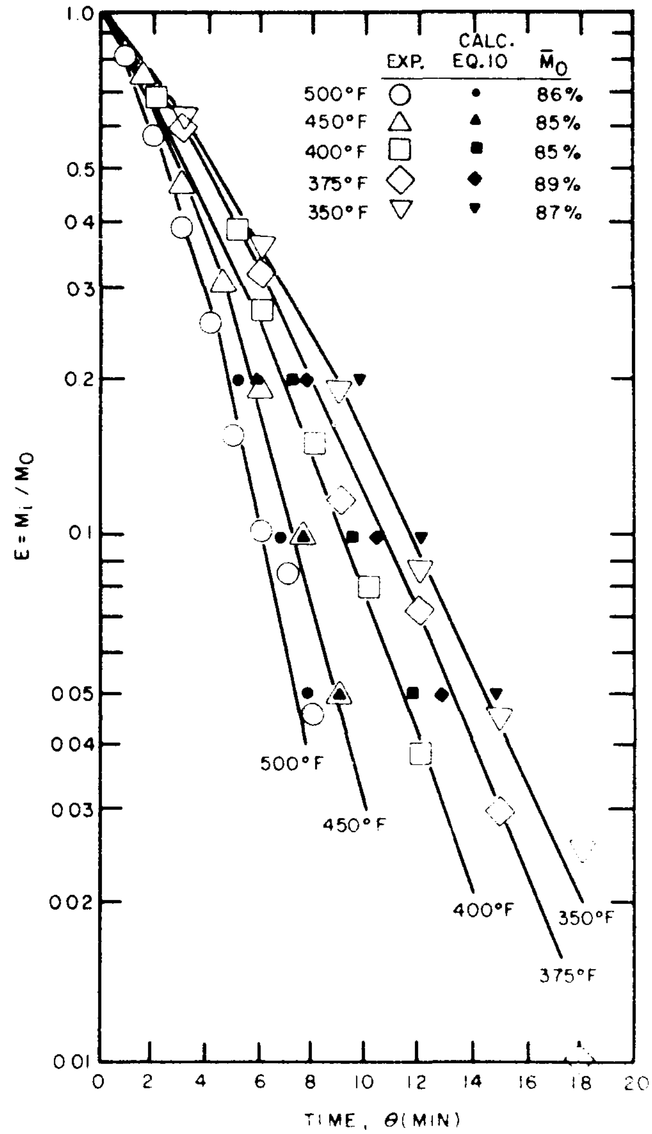

Figure 5.—Southern pine integral press drying curves at various temperatures. Pressure 50 lb/in.²; veneer = 0.5 x 12 x 24 inches; unvented caul. (ML 84 5662)

Table 4.—Scatter in southern pine veneer moisture contents before and during press drying and calculation of relative moisture content E[1]

Data set	Initial MC, M_0, for specimen No. 1	2	3	4	[2] $\overline{M_0}$	MC at time θ, M_i (and relative MC, E) for specimen No. 1	2	3	4	[2] $\overline{M_i}$	[2] $\overline{E}$
[illegible]	[illegible]	[illegible]	84.4	95.4	95.4	66.7 (.654)	60.2 (.604)	44.3 (.525)	63.7 (.668)	[illegible]	[illegible]
[illegible]	81.5	[illegible]	[illegible]	[illegible]	89.2	22.0 (.270)	[illegible] (.325)	26.5 (.316)	33.6 (.362)	28.6	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	90.4	[illegible] (.142)	11.8 (.144)	10.7 (.115)	11.2 (.128)	12.0	[illegible]
12	[illegible]	[illegible]	[illegible]	77.9	87.6	7.08 (.0659)	5.54 (.0709)	7.38 (.0849)	5.17 (.0664)	6.29	.072
[illegible]	79.5	97.9	80.1	85.7	85.8	2.08 (.0262)	2.62 (.0268)	2.87 (.0358)	2.64 (.0308)	2.55	.0299
[illegible]	[illegible]	87.0	91.9	88.4	87.7	.90 (.0108)	.81 (.0093)	.97 (.0106)	.94 (.0106)	.91	.0103

[1] [illegible] x 12 x 24 in; temperature = 375° F; pressure = 50 lb/in.²; vented caul.

[2] Average of four values (N = 1, 2, 3, 4).

Table 5.—Calculated press-drying times (from eq. (10)) for southern pine veneers of various thicknesses[1]: M_0 = 100%; M_i = 5%

Green thickness	Drying time at temperatures of 300° F	325° F	350° F	375° F	400° F	425° F	450° F	475° F	500° F
In	*Min*								
0.10	2.12	1.75	1.49	1.29	1.14	1.03	0.93	0.85	0.78
.12	2.75	2.27	1.93	1.66	1.49	1.33	1.21	1.10	1.02
.14	3.42	2.83	2.40	2.09	1.85	1.66	1.51	1.38	1.27
.16	4.15	3.42	2.91	2.53	2.24	2.01	1.82	1.67	1.54
.18	4.91	4.05	3.45	3.00	2.66	2.38	2.16	1.97	1.82
.20	5.70	4.71	4.01	3.49	3.09	2.77	2.51	2.30	2.12
.22	6.54	5.40	4.59	4.00	3.54	3.17	2.88	2.63	2.43
.24	7.40	6.11	5.20	4.53	4.01	3.60	3.25	2.98	2.75
.26	8.30	6.85	5.83	5.08	4.49	4.03	3.66	3.34	3.08
.28	9.23	7.62	6.48	5.64	5.00	4.48	4.06	3.72	3.43
.30	10.19	8.41	7.16	6.23	5.52	4.95	4.49	4.10	3.78
.32	11.17	9.22	7.85	6.83	6.05	5.43	4.92	4.50	4.15
.34	12.18	10.05	8.56	7.45	6.60	5.92	5.37	4.91	4.52
.36	13.22	10.91	9.29	8.09	7.16	6.42	5.82	5.33	4.91
.38	14.28	11.79	10.03	8.74	7.73	6.94	6.29	5.75	5.30
.40	15.37	12.68	10.80	9.40	8.32	7.47	6.77	6.19	5.71
.42	16.48	13.60	11.58	10.08	8.92	8.01	7.26	6.64	6.12
.44	17.61	14.54	12.37	10.77	9.54	8.56	7.76	7.10	6.54
.46	18.77	15.49	13.19	11.48	10.16	9.12	8.27	7.56	6.97
.48	19.94	16.46	14.01	12.20	10.80	9.69	8.79	8.04	7.41
.50	21.14	17.45	14.86	12.93	11.45	10.27	9.31	8.52	7.85
.52	22.36	18.46	15.71	13.68	12.11	10.87	9.85	9.01	8.30
.54	23.60	19.48	16.58	14.44	12.78	11.47	10.40	9.51	8.76
.56	24.86	20.52	17.47	15.21	13.46	12.08	10.95	10.02	9.23

[1] Pressure = 50 lb/in.²; vented caul.

It is easy to construct tables of press drying time for various thicknesses, press temperatures, and final MC's by substituting the coefficients in table 3 into equation (10) (table 5). The times are calculated for an initial MC of 100% and a final MC of 5%. The following correlation can be made for other initial MC's:

If, from table 5, we chose a platen temperature of 375° F and a veneer thickness of 0.5 inch, the cycle time is 12.93 minutes from 100% to 5%, and

$$E = \frac{M_i}{M_0} = \frac{5}{100} = 0.05$$

However, if M_0 is actually 105.3% instead of 100%, then after 12.93 minutes the predicted final MC would be:

$$M_i = (105.3)(0.05) = 5.3\%$$

With M_0 values higher or lower than 100, equation (10) can be used to calculate times required to reach fixed moisture levels.

Because these drying tests were part of a larger project (Schaffer et al. 1972), it was possible to check the correlation by press drying southern pine under one set of conditions to two different moisture levels. For this check, we removed a sample of 144 sheets of veneer from seven logs from the original 50-log population (4 bolts per log) which had been press dried, one-half to 6% and the other half to 16%. The closeness of prediction and observed average final MC of 72 boards in each class is apparent in table 6.

Table 6.—Predicted and actual average moisture content for press-dried southern pine veneers

Drying set[1]	Predicted								
	Ideal			Corrected for observed M_0			Actual for θ		
	M_0	M_i	θ[2]	M_0	M_i	θ_i	M_0	M_i	θ
	— % —		*Min*	— % —		*Min*	— % —		*Min*
1	100	5	12.9	105.3	5.3	12.9	105.3	5.89	13
2	100	15	8.96	107.5	16.1	8.96	107.5	15.97	9.0

[1] 72 veneers per set; veneer = 0.5 x 12 x 48 in.; temperature = 375° F.

[2] θ for M_i's are taken from constructed tables similar to table 5.

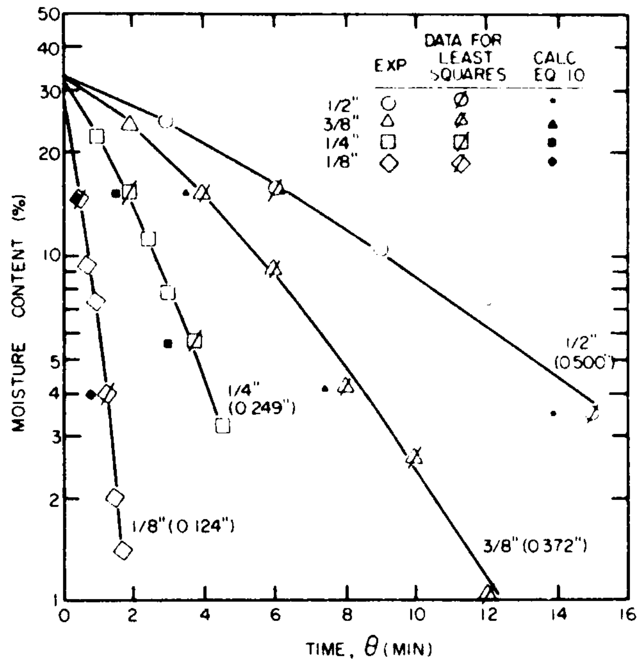

Figure 6.—Douglas-fir heartwood integral press drying curves at various thicknesses. Temperature = 375° F; pressure = 50 lb/in.²; veneer = t x 12 x 48 inches; vented caul. (ML 84 5659)

Use of Equation with Douglas-Fir

Press-Dried

Heartwood was the material of primary interest in these drying tests since this represents the major fraction of veneer when the log was peeled. The initial MC variation of Douglas-fir heartwood is relatively narrow compared to that of southern pine sapwood—i.e., initial heartwood MC's ranged from 30 to 36% (table 1); sapwood showed green moisture levels of 100 to 160%. Therefore the heartwood data were not put on the relative basis E, as had been done with southern pine. Actual initial MC was used in the treatment of the combined heartwood and sapwood.

Evidence of the closeness of fit using the heartwood data alone (eq. (10)) can be observed in figures 6 and 7. The estimates for combined heartwood and sapwood (eq. 12)) are shown in figure 8. Using equation (10) with five coefficients (table 3), one can construct press drying times for heartwood as dried to various MC's. One such table for Douglas-fir heartwood with platen contact times in minutes is shown in table 7.

Jet-Dried
The integral jet drying curves for heartwood at four temperatures and three thicknesses are given in figure 9. The actual data points and the values calculated from equation (10) are shown. With press drying and jet drying data now in analytical form, it is possible to construct tables of drying rates for any thickness and temperature. An illustration of this is table 8.

Comparison of Press, Jet, and Roller Dryers
For Douglas-fir heartwood veneers of equal thickness and the same dryer temperature, jet drying requires 1.5 to 4.5 times as long to dry to equal MC as a press dryer (represented as a ratio in table 9). These calculations were made from the empirical equations previously derived. In thick veneers jet dryers have little advantage over roller dryers. Plots of the jet, roller, and press dryers at 300° F (fig. 10) show graphically that the advantage of jet drying is minimal.

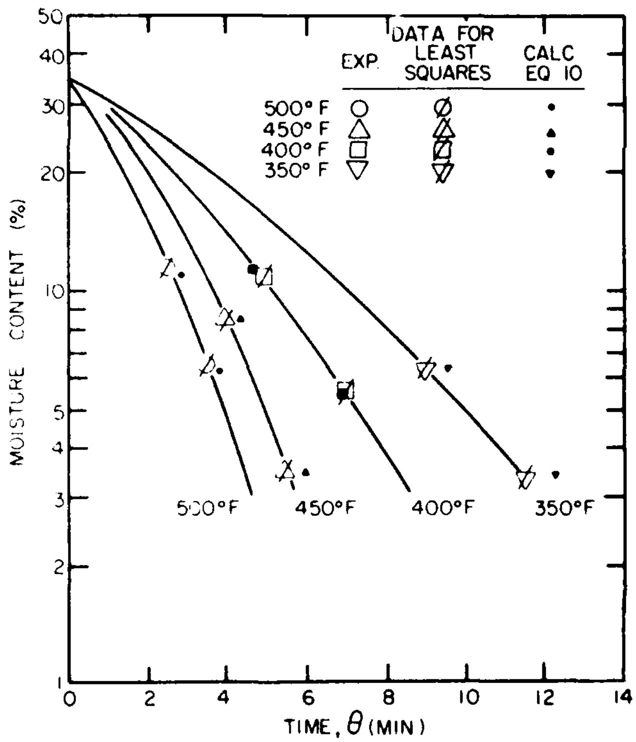

Figure 7.—Douglas-fir heartwood integral press drying curves at various temperatures. Pressure = 50 lb/in.²; veneer = 0.42 x 12 x 24 inches; unvented caul. (ML 84 5660)

Table 7.—Calculated press-drying times (from eq. (10)) for Douglas-fir heartwood veneers of various thicknesses: M_o = 100%; M_f = 5%[1]

Green thickness	Drying time at temperatures of			
	300° F	375° F	400° F	500° F
In.	*Min*			
0.1	1.18	0.52	0.44	0.27
.2	4.55	2.03	1.71	1.05
.3	10.00	4.46	4.27	2.32
.4	17.48	7.81	7.25	4.06
.5	26.96	12.04	10.17	6.26

[1]Pressure = 50 lb/in.²; vented caul.

Table 8.—Calculated jet-drying times (from eq. (10)) for Douglas-fir heartwood veneers of various thicknesses: M_o = 100%; M_f = 5%.

Green thickness	Drying time at temperatures of			
	300° F	400° F	500° F	600° F
In.	*Min*			
0.1	3.70	1.81	1.20	0.89
.2	10.23	5.01	3.32	2.48
.3	18.54	9.08	6.01	4.49
.4	28.26	13.84	9.16	6.85
.5	39.18	19.19	12.70	9.50

Table 9.—Calculated ratio (from equation (10)) of jet- to press-drying times for Douglas-fir heartwood veneers of various thicknesses: M_o = 100%; M_f = 5%

Green thickness	Ratio at temperature of			
	300° F	400° F	500° F	600° F
In.	*Min*			
0.1	3.12	4.06	4.36	4.51
.2	2.24	2.91	3.13	3.24
.3	1.85	2.40	2.58	2.67
.4	1.61	2.09	2.25	2.33
.5	1.45	1.88	2.02	2.09

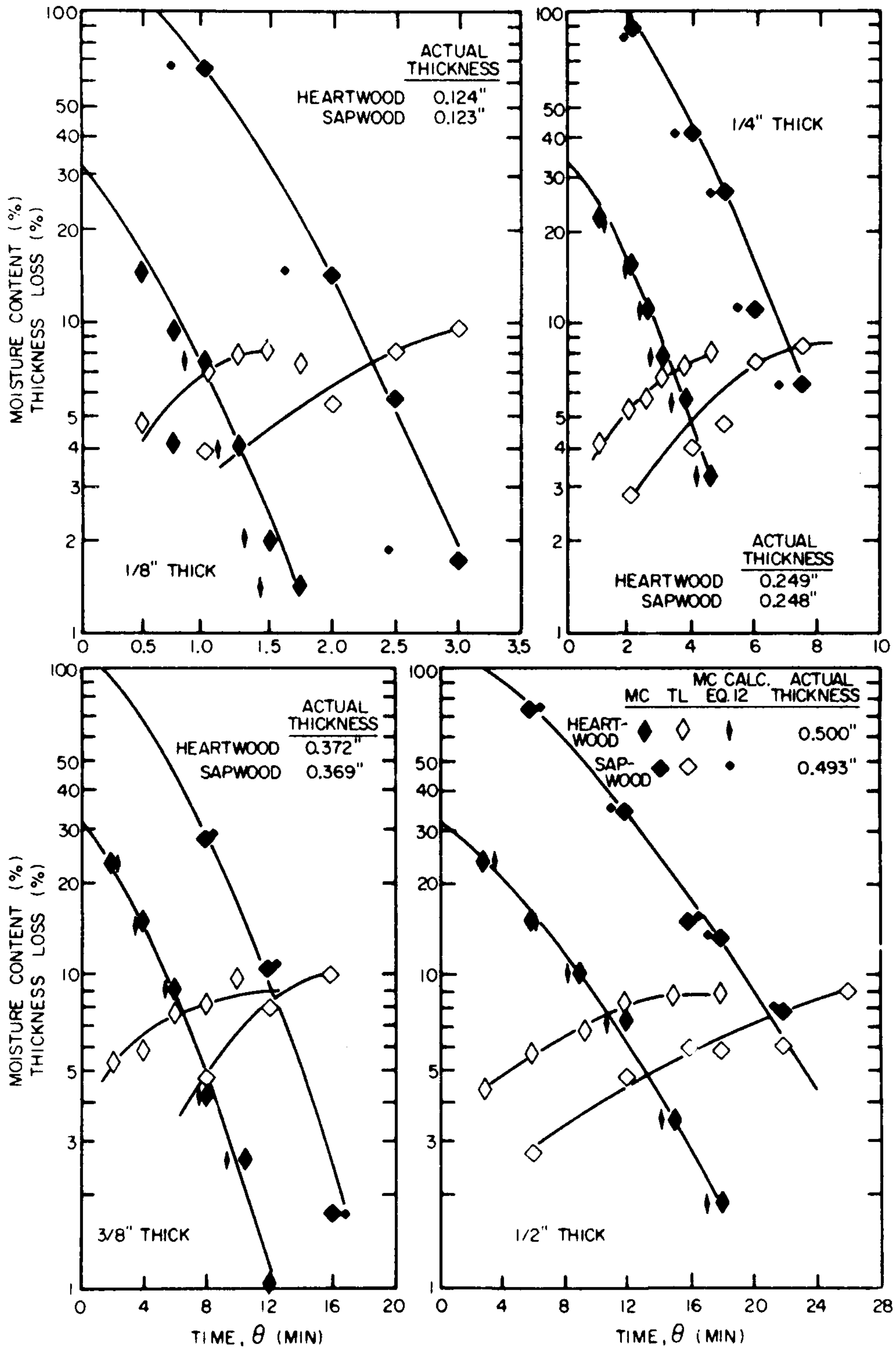

Figure 8.—Douglas-fir integral press drying curves (moisture content) and percent thickness loss, for heartwood and sapwood, for four thickness classes. (ML 84 5666)

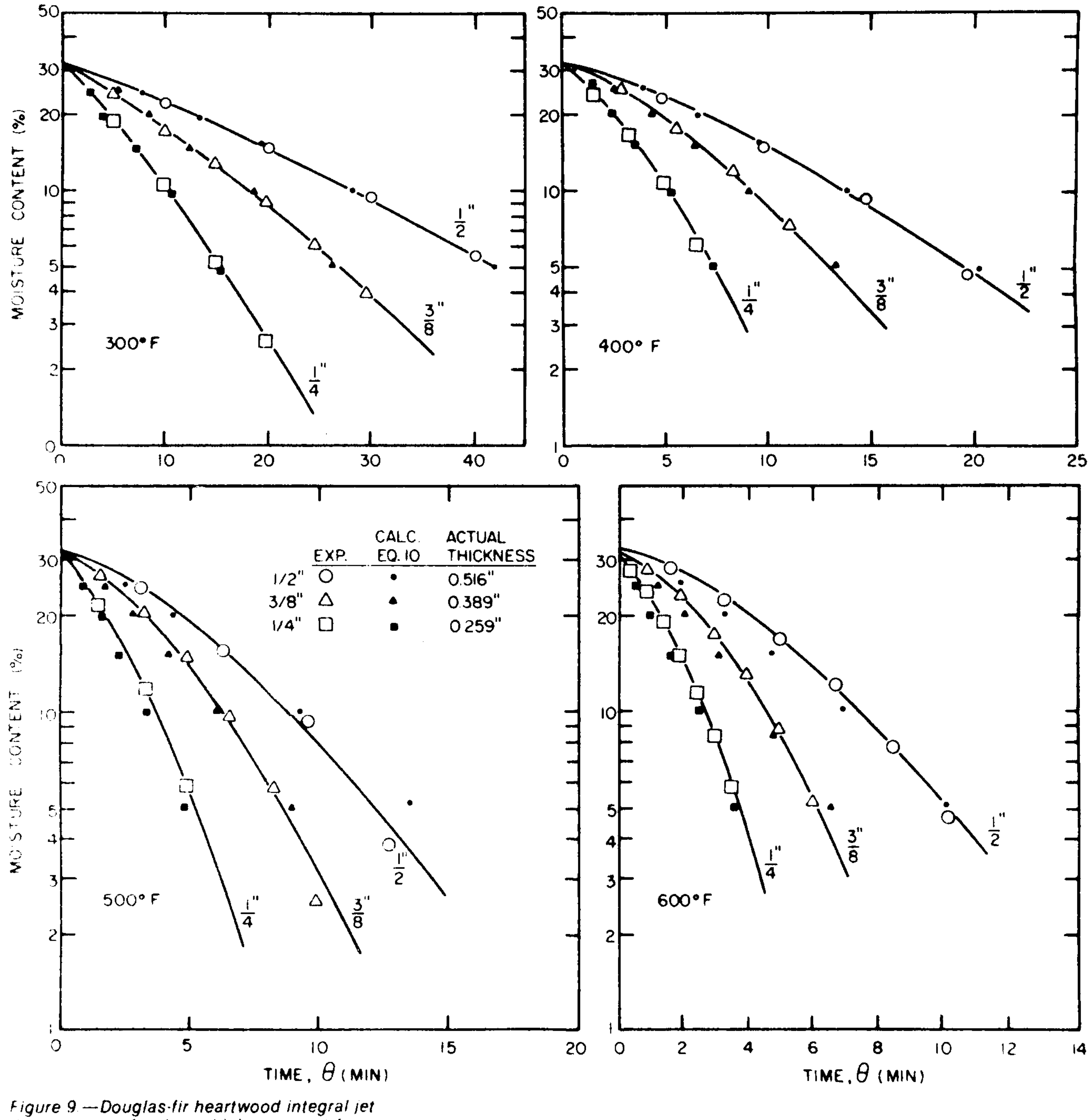

Figure 9.—Douglas-fir heartwood integral jet drying curves, for three thicknesses, at four temperatures. (ML 84 5667)

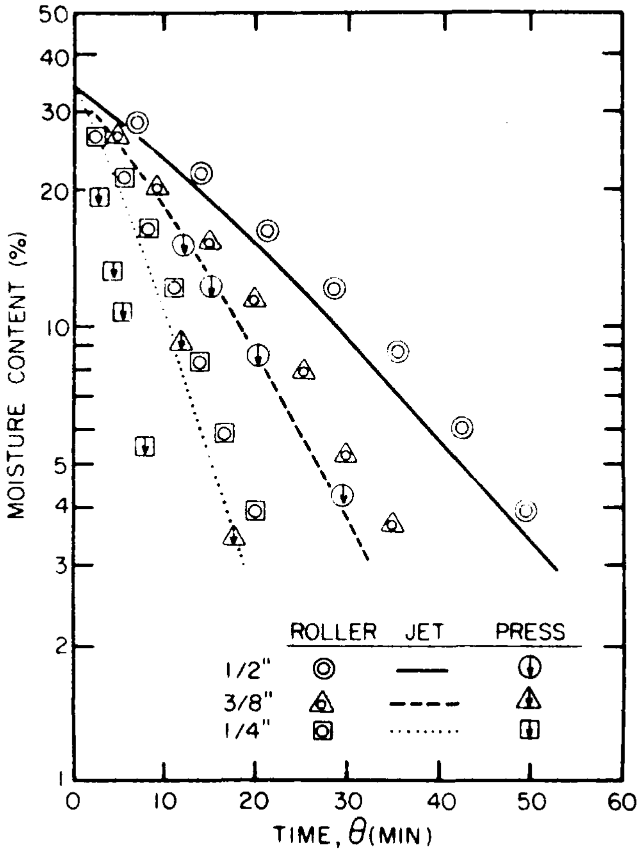

Figure 10.—Douglas-fir heartwood integral drying curves for a single group of veneers dried in roller, jet, and press dryers. Actual average thicknesses were: 1/4" = 0.259"; 3/8" = 0.389"; and 1/2" = 0.516". (ML 84 5665)

Conclusions

The author describes ~~In this paper we have developed~~ a method of fitting veneer drying data to an empirical equation of a form applicable to both jet and press drying for veneers 1/8 to 1/2 inch thick across a wide range of temperatures. With drying rate data represented by an empirical equation, it is possible to interpolate drying times with some certainty and to extrapolate beyond experimental observations for a limited range. If the basic form of the equations developed in this paper are found to be applicable to other species, the amount of experimentation necessary to characterize a given dryer/species system would be reduced, making cost analysis more efficient.

Additional Keywords: Tables (data); charts; experimental data

Literature Cited

Brookhyser, B. B.; Pierson, D. W. Veneer drying and handling. U.S. Patent No. 4,192,079. March 11, 1980.

Comstock, G. L. The kinetics of veneer jet drying. Forest Products Journal 21(3): 104-111; 1971.

Hann, R. A.; Jokerst, R. W.; Kurtenacker, R. S.; Peters, C. C.; Tschernitz, J. L. Rapid production of pallet deck boards from low-grade logs. Res. Pap. FPL 154. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1971.

Heebink, B. G.; Compton, K. C. Paneling and flooring from low-grade hardwood logs. Res. Note. FPL-0122. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1966.

Kreith, Frank. Principles of heat transfer. 2nd Ed. Scranton, PA: International Textbook Co.; 1965.

Kroll, K. Dryers and drying techniques. Berlin: Springer-Verlag; 1959.

Lane, Paul H. Logs selected by Lane. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; 1972.

Mustakallio, Kai; Paaki, Matti. Finns leading way in eliminating hot-air methods in veneer drying. World Wood 18(12): F18-19; 1977.

Peters, C. C.; Mergin, A. F. Unpublished test equipment development. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1970.

Schaffer, E. L.; Jokerst, R. W.; Moody, R. C.; Peters, C. C.; Tschernitz, J. L.; Zahn, J. J. Press-lam: Progress in technical development of laminated veneer structural products. Res. Pap. FPL 279. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory; 1977.

Schaffer, E. L.; Tschernitz, J. L.; Peters, C. C.; Moody, R. C.; Jokerst, R. W.; Zahn, J. J. FPL Press-Lam process: Fast, efficient conversion of logs into structural products. Forest Products Journal 22(11): 11-18; 1972.

Appendix— Pressure Phenomena in Press Drying

Increased platen pressures result in increased thickness loss during press drying; the loss plateaus at pressures approaching 200 lb/in.². (Corollarily, increased pressure increases the drying rates.) The maximum loss is greater for southern pine (35%) than for Douglas-fir (20%). Plotting thickness loss versus press pressure (at constant M_i) generates an "S"-shaped curve—slow initial rise (25 lb/in.²), rapid intermediate rise (100 lb/in.²), and plateau (200 lb/in.²). Thickness loss is permanent, with no springback detected for southern pine; Douglas-fir was not tested. At pressures above approximately 50 lb/in.², thickness loss accelerates and insufficient venting causes popping of the veneer even when vented cauls are used. From limited observations, at 50 lb/in.² the percent thickness loss appears to be independent of initial thickness and temperature in the range explored in these tests.

To check the necessity for vapor venting, we press dried veneers between aluminum sheets (with no vented caul). The following observations were made:

1) Rate of drying is about the same as with vented cauls.

2) No vapor can flow from the face of the veneer because there are no channels.

3) High temperature rises are observed in the center of the veneer (265° F, equivalent to 30 lb/in.², g).

4) Excessive sap flows from the end grain of the veneers.

5) "Blow up" occurred during drying and/or when the press opened.

In a later project, large quantities of thick Douglas-fir veneer were press-dried substituting used fourdrinier screen for the vented caul, which did provide for adequate vapor flow.

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