1973

High-Temperature Kilning of Southern Pine Poles, Timbers, Lumber, and Thick Veneer

Peter Koch
Chief Wood Scientist
Southern Forest Experiment Station, USDA Forest Service, Pineville, La.

At dry-bulb temperatures above the boiling point of water, with large wet-bulb depressions and high air velocities, southern pine products can be dried quickly. In an impingement-jet kiln at 300° F., veneer 3/8- to 5/8-inch thick can be brought to 10 percent moisture content in 40 to 75 minutes. Drying times for lumber are linearly related to thickness, e.g., at dry- and wet-bulb temperatures of 240° and 160° F., time required is 10.4, 15.8, and 20.7 hours for thicknesses of 1.0, 1.5, and 1.9 inches. Under similar conditions, planks or timbers 2, 3, and 4 inches thick can be dried to 10 percent moisture content in 22.4, 35.6, and 45.3 hours; surface checks in timbers so dried are absent or minor, but in 3- and 4-inch pieces end-checking may be moderate to severe. At 225° F., with 50° wet-bulb depression, poles 8 to 10 inches in diameter can be reduced to 30 percent moisture in about 44 hours.

It is becoming increasingly apparent that economies in manufacture can be accomplished by drying southern pine at temperatures above the boiling point of water. Such drying procedures are standard practice in the plywood industry, and are gaining considerable acceptance by lumber producers. Pole manufacturers are also experimenting with the idea.

The purpose of this paper is to note some principles of high-temperature drying, and then to summarize experimental data specific to southern pine. Readers desiring further reviews of the literature on high-temperature drying should consult Lowery et al. (23) and Salamon (28).

Hart (7) has summarized the difference between low- and high-temperature drying. His explanation, somewhat paraphrased, is as follows. When wood is dried at a dry-bulb temperature exceeding the boiling point of water, the wet-bulb temperature will be less than the boiling-point temperature if a steam–air (i.e., vapor–air) mixture is used; it will reach its maximum value, the boiling point, if a pure steam atmosphere is employed. In either atmosphere, pressure is built up in the wood when the free water above fiber saturation is heated beyond the boiling point. The slight steam pressure thus created results in hydrodynamic flow of water vapor from the wet line to the wood surface. In low-temperature drying, by contrast, moisture moves from the wet line to the wood surface by diffusion. This is the fundamental difference between low- and high-temperature drying. Pit pores, which are very ineffective for diffusion, become quite adequate as passageways for pressure flow of vapor (7).

There are two processes of high-temperature drying. The first uses superheated steam, i.e., steam above the boiling point of water. In this system, the steam occupies the kiln to the complete exclusion of air. The process is controlled solely by manipulation of dry-bulb temperature. Under such circumstances, Kauman (8) reported that equilibrium moisture content (e.m.c.) of the heated wood was about 20 percent at 212° F., and approximately 5 percent at 240° F., as shown in figure 1. During World War I, this process was used in the Pacific Northwest to dry 4/4 softwoods to 10 percent moisture content in about 24 hours. Since the high-temperature steam reacted with wood of some western species to cause rapid kiln deterioration, the process is not used currently in the United States.

The other process of high-temperature drying uses mixtures of air and steam at atmospheric pressure. Air is brought into the kiln in the conventional manner; any steam present (apart from low-pressure steam injected for deliberate humidification) is moisture expelled from the lumber. The process is controlled by wet- and dry-bulb thermometers, since e.m.c. of the heated wood is determined by dry-bulb temperature and the relative humidity. At any given dry-bulb temperature, whether above or below the boiling point of water, the relative humidity is:

$$100 \times \left(\frac{\text{partial pressure of water vapor in the atmosphere}}{\text{pressure of saturated water vapor}}\right)$$

The partial pressure of water vapor in an air–vapor mixture at any dry-bulb temperature (whether above

Reprinted from Proceedings, American Wood-Preservers' Association, Volume 69, pp. 123 to 140, 1973.

or below the boiling point) is the vapor pressure at the prevailing wet-bulb temperature. For example, at a dry-bulb temperature of 240° F. and a wet-bulb temperature of 160° F., the partial water vapor pressure is 4.739 p.s.i. absolute, and the pressure of saturated water vapor is 24.97 p.s.i. Therefore, the relative vapor pressure is 0.19, and the relative humidity is 19 percent.

In 1926 the USDA Forest Products Laboratory (37) prepared curves which, when mathematically extrapolated, provided e.m.c. data to 248° F. Kauman (8, p. 330) has provided graphs showing the e.m.c. for wood in steam–air mixtures above the boiling point of water; from these curves (based on data of A. J. Stamm, W. K. Loughborough, and R. Keylwerth) the Forest Products Laboratories of Canada have published the data shown in Table 1.

From the table it is seen that, at a dry-bulb temperature of 240° F., e.m.c. values for wood at various wet-bulb temperatures are about as follows:

Wet-bulb temperature		*Equilibrium moisture content*
°F.	*°C.*	*Percent*
168	76	2
189	87	3
203	95	4
212	100	5

By 1954 over a hundred small kilns specifically designed for this process were in service (25); their acceptance in Europe prompted research on high-temperature drying of softwoods at the Forest Products Laboratories of Canada (21, 22, 5, 2, 3, 30, 29, 31), in the United States (13, 14, 15, 16, 17, 11, 12), and in Australia (4).

There is not complete agreement on the manner in which moisture moves out of wood during high-temperature drying. Kollmann and Schneider (20) classify three stages of drying. The first stage, in which rate of drying is constant, occurs only if the initial moisture content is above fiber saturation point; evaporation takes place at the wood surface. The second stage occurs when free water is no longer present over all the surface and the surface temperature rises above the wet-bulb temperature. During this stage the rate of drying declines. The third and final stage—also a falling rate period—begins when the wettest portion of the wood drops below fiber saturation point and continues until all of the wood is in equilibrium with the drying conditions. Hann (6) has also described stages two and three. A general description [after Hart (7)] of the mechanism of high-temperature drying is given by Koch (18, p. 326–328).

With the foregoing in mind, let us review some data specific to the drying of southern pine in steam–air mixtures at temperatures above the boiling point.

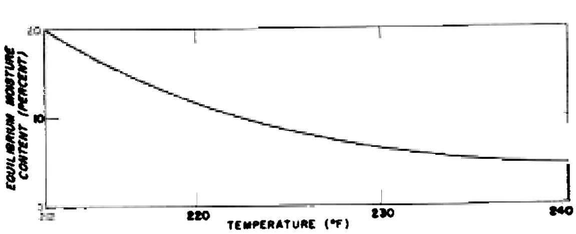

Figure 1.—Equilibrium Moisture Content of Wood in Superheated Steam at Atmospheric Pressure. (Drawing after Kauman 1956.)

Thick Veneers

Readers interested in high-temperature drying of thin southern pine veneers for plywood should consult the review by Koch (18, p. 1004–1009). The present discussion is limited to veneers at least ⅜-inch thick.

Koch (13) studied the drying of sawn southern pine veneers planed to 7/16-inch thickness. The veneers ranged in moisture content from 45 to 180 percent and averaged about 117 percent. Three high-temperature treatments were tried: a conventional roller-veneer dryer at 300° F.; an impingement-jet dryer at 300° F.; and the same jet dryer at 350° F.

A 90-minute pass through a conventional roller dryer at 300° F. brought the moisture content to an average of 4.4 percent with a range from 0 to 17.6 percent (Fig. 2). The veneer was continuously fed longitudinally, as in a jet dryer, but the air was circulated in a counter-flowing horizontal direction instead of impinging vertically. Nominal air velocity was 600 f.p.m. Resin exudation was light but solid over a considerable portion of the veneers.

A 60-minute pass through an impingement-jet dryer at 300° F. with air velocity of about 3,500 f.p.m. brought the 7/16-inch veneers to an average moisture content of 5.1 percent with range from 0.2 to 14.3 percent (Fig. 2).

When the impingement-jet dryer was raised to 350° F., all of the veneers were dried to less than 10 percent moisture content in 40 minutes (Fig. 2). In both the jet dryer trials, resin exudation was heavy and solid over part of the surface of many of the veneers.

Kimball (10) made a comparative evaluation of drying times for sawn and sliced loblolly pine veneers in the thickness range from 3/16- to 9/16-inch. Figure 3 shows that the sliced veneer dried somewhat faster than the sawn veneer in an impingement-jet dryer at 300° F. Impingement velocity was approximately 4,000 f.p.m. The 3/16-inch veneer dried to 10 percent average moisture content in about 20 minutes, the ⅜-inch in about 40 minutes, and the

Table 1.—Relationship of Equilibrium Moisture Content to Temperature and Relative Humidity of Air-Steam Mixtures at Atmospheric Pressure and Above 212° F. (Data from Ladell 1957)[1]

Wet-bulb temperature (°F.)	Dry-bulb temperature (°F.) 260	255	250	245	240	235	230	225	220	215	212
	Percent										
212	42 3.1	45 3.4	49 3.8	53 4.2	59 5.0	65 5.8	70 6.9	77 8.7	85 11.3	94 15.5	100 19.5
210	40 2.9	43 3.3	47 3.6	51 4.0	56 4.7	61 5.4	67 6.3	74 8.0	82 10.4	90 14.0	98 17.0
205	36 2.7	39 3.0	43 3.4	47 3.8	51 4.2	55 4.7	61 5.5	67 6.6	74 8.3	82 10.7	88 13.0
200	32 2.4	36 2.8	39 3.1	42 3.4	46 3.8	51 4.3	55 4.9	62 5.8	67 6.9	74 8.7	79 10.0
195	30 2.2	32 2.5	35 2.8	38 3.1	42 3.5	46 3.9	51 4.5	56 5.1	61 5.9	66 7.0	69 7.6
190	26 2.0	28 2.2	30 2.4	34 2.8	37 3.1	40 3.4	44 3.8	48 4.3	52 5.0	58 5.7	61 6.2
185	23 1.8	25 2.0	28 2.2	30 2.5	32 2.7	35 3.0	39 3.4	42 3.7	47 4.3	52 5.0	55 5.4
180	20 1.6	22 1.8	24 2.0	27 2.3	29 2.5	31 2.7	35 3.1	38 3.4	42 3.9	47 4.5	50 4.9
175	19 1.5	20 1.6	22 1.8	24 2.0	26 2.2	29 2.5	32 2.8	35 3.2	38 3.5	43 4.0	45 4.4
170	17 1.3	18 1.5	20 1.7	22 1.9	24 2.1	26 2.3	28 2.5	31 2.9	34 3.2	38 3.5	40 3.8
165	15 1.2	16 1.3	17 1.4	19 1.6	21 1.9	23 2.1	25 2.3	28 2.5	31 2.9	34 3.3	36 5.5
160	13 1.0	14 1.2	16 1.3	17 1.5	19 1.7	21 1.8	23 2.1	25 2.3	27 2.6	30 2.9	32 3.1

[1] In body of table, the upper figure is percent relative humidity, and the lower is percent e.m.c.

9/16-inch in approximately 70 minutes. These times were averages; to achieve a uniform final moisture content, Kimball concluded, either the original (green) moisture content must be uniform, or the dried veneer must be equalized.

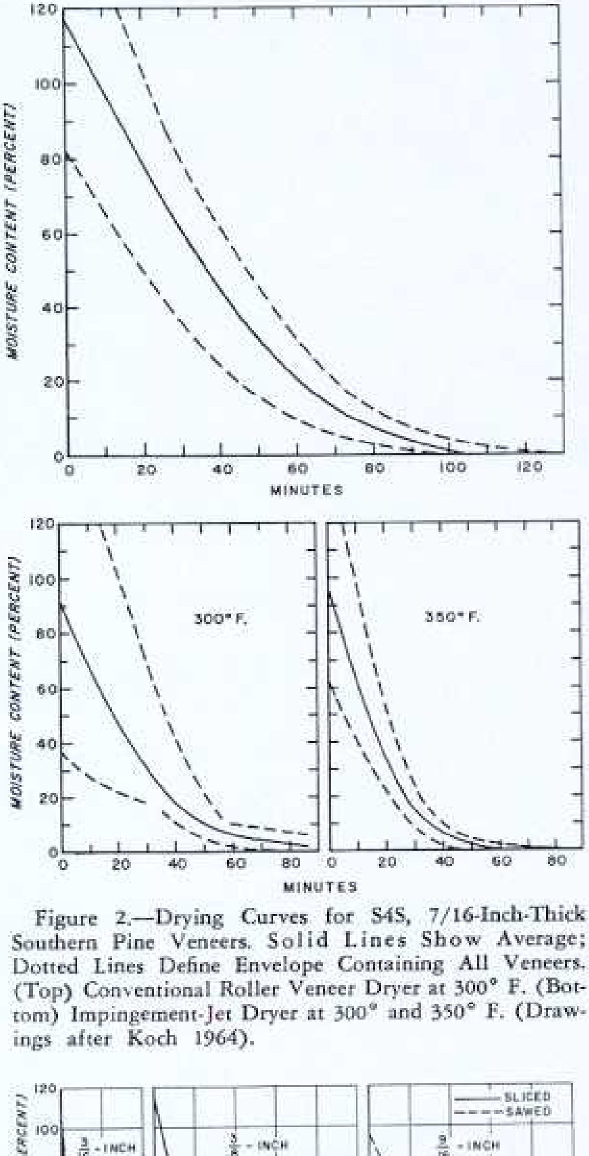

Figure 2.—Drying Curves for S4S, 7/16-Inch-Thick Southern Pine Veneers. Solid Lines Show Average; Dotted Lines Define Envelope Containing All Veneers. (Top) Conventional Roller Veneer Dryer at 300° F. (Bottom) Impingement-Jet Dryer at 300° and 350° F. (Drawings after Koch 1964).

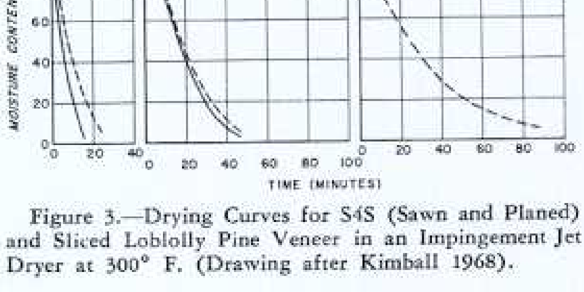

Figure 3.—Drying Curves for S4S (Sawn and Planed) and Sliced Loblolly Pine Veneer in an Impingement Jet Dryer at 300° F. (Drawing after Kimball 1968).

Lumber

Koch (14, 15, 16, 17, 18A) has provided data specific to the drying of southern pine lumber in a steam–air mixture at 240° F.

Drying at High and Low Temperatures

In the first of two experiments, Koch (15) compared 2 by 4 studs conventionally stacked and kiln-dried on a mild schedule (temperatures not exceeding 180° F. and air velocity of 500 f.p.m.) with studs dried on a high-temperature schedule.

The 24-hour, high-temperature schedule was simple. The green lumber was clamped rigidly in aluminum frames, in almost total mechanical restraint against crook, bow, and twist (Fig. 4). Still in frames, the studs were wheeled into the preheated kiln and dried for 21 hours at a dry-bulb temperature of 240° F. and a wet-bulb temperature of 160° F. Then, to relieve case-hardening, they were steamed for the last 3 hours at a dry-bulb temperature of 195° F. and a wet-bulb temperature of 185° F. Throughout the 24 hours, air was cross-circulated at 1,000 f.p.m.; direction of airflow was reversed every 75 minutes. Weight of charge and energy consumption for heat, humidity control (steam spray), and fan were continuously charted against time. With the schedule completed, the studs were wheeled from the kiln and cooled under restraint for 48 hours in an atmosphere that ranged from 40 to 60 percent relative humidity and 70° to 80° F.

To insure inclusion of juvenile wood in the kiln charges, half the lumber to be dried was cut from cores residual from steamed veneer logs and the

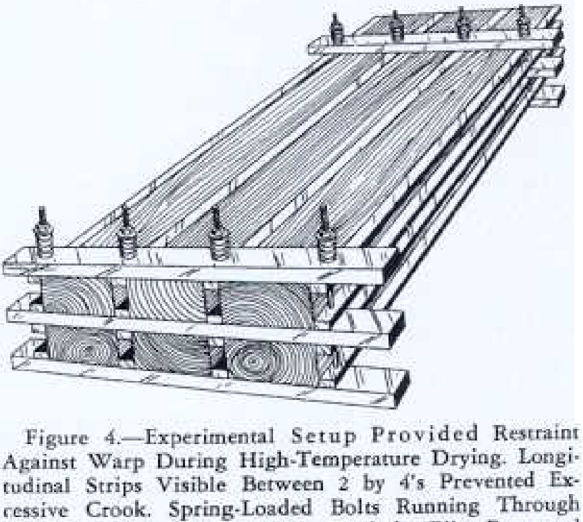

Figure 4.—Experimental Setup Provided Restraint Against Warp During High-Temperature Drying. Longitudinal Strips Visible Between 2 by 4's Prevented Excessive Crook. Spring-Loaded Bolts Running Through the Strips, from Top to Bottom of the Pile, Prevented Excessive Twist and Bow. The Studs Were 8 Feet Long. Aluminum Cross Stickers Were Spaced 2 Feet Apart and Measured ¾-Inch Thick and 1½ Inches Wide. (Drawing after Koch 1971a.)

remainder cut from very small logs. Lumber from these two sources was dried separately. Prior to drying, the green studs were planed to uniform thickness (1⅞ inches) and width (4 inches).

Ending moisture content for the low-temperature charges averaged 11.8 percent, whereas the high-temperature charges averaged 9.1 percent at the finish (Fig. 5).

	Moisture content 48 hours after discharge from kiln	
	High-temperature schedule	*Low-temperature schedule*
	Percent	
Studs from veneer cores		
Average	9.3	11.8
Standard deviation	3.3	2.4
Range	5.4–21.2	2.1–21.7
Studs from small logs		
Average	8.9	11.7
Standard deviation	3.2	2.7
Range	5.2–21.2	5.3–21.3

In general, the high-temperature schedule took less than one-fourth the time and about one-half the energy required for the low-temperature schedule (Table 2).

While cheaper energy sources are available to most commercial kilns, the electric power used in the study for both heating and air circulation afforded valid and convenient comparisons of energy required. Largely because it took less time, the high-temperature schedule required less energy. Thus power for fan motors was about halved, despite the 1,000-f.p.m. circulation rate. The low-temperature schedule, with its high initial humidities, required five times as much energy for humidity control and more than 1½ times as much for heat.

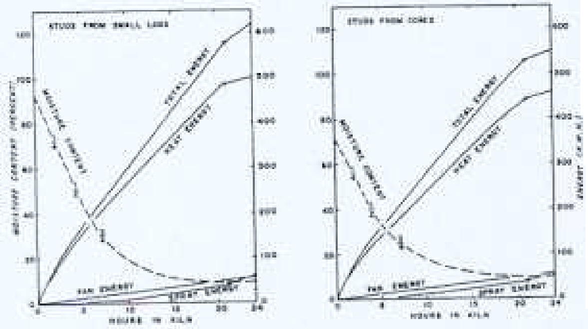

Figure 5.—Moisture Content Change and Kilowatt-Hour Demand by 24-Stud Charge First Dried 21 Hours with Dry- and Wet-Bulb Temperatures of 240° and 160° F., and Then Steamed 3 Hours with Dry- and Wet-Bulb Temperatures of 195° and 185° F. Air Cross-Circulated at 1,000 f.p.m. Lumber was 1⅞ Inches Thick. Moisture Contents Were Calculated from the Green and Ovendry Weights of Each Entire Charge. Data from Three Charges Were Averaged to Derive Each Curve. Numbers Inset in Moisture Content Curves Indicate Time to One-Fourth, One-Half, and Three-Fourths of Total Moisture Loss. (Drawings after Koch 1971a.)

Results with this very small experimental kiln cannot be scaled directly to a commercial kiln, but the trends are evident. In Europe, Keylwerth (9) found that a high-temperature kiln using air–steam mixtures required 1.2 to 1.5 kilowatt-hours per kilogram (2.2 pounds) of water evaporated; this compared with 2 to 4 kilowatt hours for low-temperature drying. The lower energy requirements were attributed to smaller heat loss, lesser heat capacity of the construction materials, and shorter drying time.

Koch (15) found that studs dried under restraint at high temperature warped significantly less than

Table 2.—Time and Energy Expended to Kiln-Dry Each Charge of 24 Southern Pine Studs Cut From Veneer Cores and Small Logs[1] (15)

Expenditure	High temperature		Low temperature[2]	
	From cores	From small logs	From cores	From small logs
Time, hours	24	24	102	113
Energy, k.w.h.				
Heat[3]	442	500	700	790
Humidity control[4]	54	61	295	290
Fan	55	57	107	119
Total	551	618	1102	1199

[1] Each figure is the average for three charges.
[2] Not exceeding 180° F.; approximately Schedule T12-C5 from Rasmussen (27).
[3] Supplied by electric resistance-type heating coils.
[4] Steam for humidification was provided by electric immersion heaters in a water bath.

those conventionally stickered and dried at low temperature. Warp was measured 48 hours out of the kiln, just before planing, after planing, after a 20-day humid cycle (81° F. dry-bulb and 78° wet-bulb temperature) during which the studs were individually and freely suspended from hooks placed in one end, and after a 20-day dry cycle (130° F. dry-bulb and near 80° wet-bulb temperature). The differences charted in Figure 6 were significant at all stages of manufacture.

Warp measured immediately after planing largely determines the mill grade and selling price of studs. Average values at this stage were:

Warp	*High temperature, restrained*	*Low temperature, unrestrained*
	Inch	
Crook	0.12	0.23
Bow	.21	.29
Twist	.09	.24

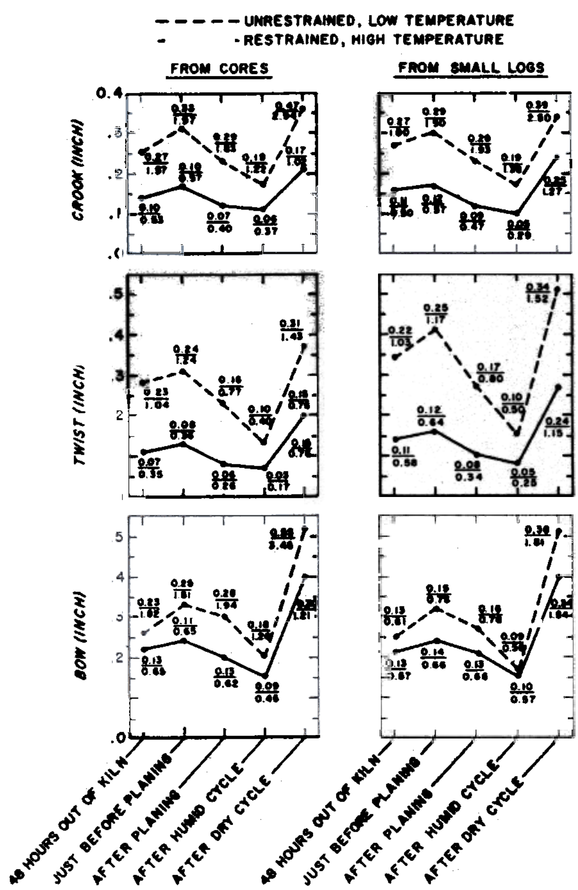

Figure 6.—Warp in 8-Foot Southern Pine 2 by 4's Cut from Small Logs (Right) and Steamed Veneer Cores (Left), when Kiln-Dried at High Temperature Under Restraint and at Low Temperature Stacked Conventionally. Each Plotted Point Is the Average for 72 Studs; Adjacent to Each Point, the Standard Deviation is Printed Just Above the Maximum Value of Warp Observed at that Point. (Drawing after Koch 1971a.)

When studs are incorporated in buildings, they are frequently exposed to high humidities until the roof is in place and the heating or air conditioning system is activated. Exposing planed studs to high humidity for 20 days simulated this situation; average warp after exposure was least in wood dried at high temperature:

Warp	*High temperature, restrained*	*Low temperature, unrestrained*
	Inch	
Crook	0.10	0.17
Bow	.15	.18
Twist	.08	.14

Studs built into upper walls may first go through a period of high humidity as described above, and then be subjected to extremely dry atmospheres when heat is turned on in winter. At the end of the 20-day dry cycle following the humid cycle, average warp was severe in all studs, but less extreme in those dried under restraint at high temperature:

Warp	*High temperature, restrained*	*Low temperature, unrestrained*
	Inch	
Crook	0.23	0.35
Bow	.42	.52
Twist	.23	.44

When measured just after planing and after the dry cycle, studs cut from cores twisted significantly less than those cut from small logs. Pooling data from both schedules gave average values as follows:

Time of measurement	*Twist in studs from veneer cores*	*Twist in studs from small logs*
	Inch	
Just after planing	0.14	0.19
After dry cycle	.28	.39

With these exceptions, warp in studs from cores did not significantly differ from that in studs from small logs.

In general, studs dried under restraint at high temperature graded substantially better after planing than those dried at low temperature (Table 3). Because 8-foot 2 by 4's of Stud grade or better have approximately twice the value of studs in grades 3 and 4, a tabulation is of interest:

SPIB Grade	*High temperature*	*Low temperature*
	Percent	
No. 1, No. 2, and Stud	91	59
No. 3 and No. 4	9	41
Total	100	100

With data from both schedules pooled, cores yielded more No. 1 Common and less No. 3 and 4 Common than small logs:

SPIB Grade	*Studs from cores*	*Studs from small logs*
	Percent	
No. 1	37	19
No. 1, No. 2, and Stud	80	70
No. 3 and No. 4	20	30

Table 3.—Grade Distribution of Studs Immediately Following Planing[1] (15)

Grade[2]	High temperature		Low temperature	
	From cores	From small logs	From cores	From small logs
	Number			
No. 1 Common	31	17	22	11
No. 2 Common	21	17	18	19
Stud Grade	17	28	6	9
No. 3 Common	1[3]	6[4]	20	23
No. 4 Common	2[5]	4[4]	6	10
Total	72	72	72	72

[1] The 72 studs in each category represent three kiln-charge replications of 24 studs apiece.
[2] Southern Pine Inspection Bureau (35).
[3] Had crook of 0.38 inch.
[4] Three of the 10 studs in grades 3 and 4 were within Stud Grade limitations on warp.
[5] Warp was within Stud Grade limitations on both of these pieces, but both were downgraded to No. 4 because of readily identifiable compression wood.

As Table 3 indicates, the higher grade-yield in studs cut from cores was particularly evident with the high-temperature schedule; studs from cores yielded only 4 percent in grades 3 and 4, while studs from small logs yielded 14 percent.

The 24-hour schedule brought considerable resin to the surface of the rough, dry 2 by 4's, but planing to final thickness removed all traces of resin and discoloration. All studs dried on the 24-hour schedule developed end checks that ranged from 1.5 to 2.1 inches in depth. In no case, however, were the checks a cause for degrade.

Since studs cut from very small logs and veneer cores contain juvenile wood of low specific gravity, as well as defects such as knots and cross grain, they vary greatly in strength. By analysis of variance, edgewise bending properties of modulus of elasticity, proportional limit, and modulus of rupture did not differ significantly between the two drying treatments. In all three strength properties, however, the studs from veneer cores were stronger than those from small logs (Table 4).

Studs from small logs had the same specific gravity as those from cores (0.51, basis of ovendry volume and weight). It is likely, however, that knots in the cores were smaller than those in small logs. In the southern pines, the butt log (source of most veneer cores) tends to shed its limbs at an early age, whereas tops of mature southern pines (probably the source of most of the small logs) may have fairly large, live branches; large knots reduce the strength of studs containing them.

Toughness and specific gravity of clear wood cut from the studs did not differ significantly between the two drying treatments. Each value in the following tabulation represents data from 72 studs (two replications per stud); average moisture content at test was 8.6 percent with standard deviation of 0.5 and range from 7.1 to 11.4 percent.

Property	High temperature		Low temperature	
	From cores	From small logs	From cores	From small logs
Toughness, inch-pounds				
Average	202	191	200	183
Standard deviation	71	73	77	63
Range	56–402	59–355	79–268	61–339
Specific gravity (basis of volume at test and ovendry weight)				
Average	0.52	0.52	0.52	0.52
Standard deviation	.06	.08	.08	.10
Range	.41–.70	.38–.72	.40–.85	.37–.89

Clear wood in studs from veneer cores was significantly tougher (201 inch-pounds) than clear wood in studs from small logs (187 inch-pounds). Since the specific gravities did not differ significantly, an explanation of this result is not readily seen.

Effects of Lumber and Kiln Factors

In further experiments, Koch (16, 17) obtained information about the effects of air velocity, lumber

Table 4.—Comparison of Edgewise-Bending Properties of Southern Pine Studs Cut From Small Logs or Veneer Cores When Kiln-Dried for 24 Hours at Temperatures Not Exceeding 240° F. or For About 100 Hours at Temperatures Not Exceeding 180° F.[1,2] (15)

Property[3]	High temperature		Low temperature	
	From cores	From small logs	From cores	From small logs
	P.s.i.			
Modulus of elasticity				
Average	1,624,000	1,457,000	1,630,000	1,510,000
Standard deviation	393,000	433,000	498,000	496,000
Range	812,000-2,585,000	594,000-2,828,000	550,000-2,692,000	584,000-2,858,000
Proportional limit				
Average	5,050	4,650	5,390	4,740
Standard deviation	1,850	1,770	2,190	1,950
Range	1,490-9,130	1,090-9,600	1,180-10,000	1,100-10,220
Modulus of rupture				
Average	6,980	6,520	7,540	6,560
Standard deviation	3,330	3,020	3,620	3,290
Range	1,600-17,100	1,960-13,820	1,450-16,725	1,630-18,210

[1] Each average value shown represents data from 72 studs. Average moisture content at test was 7.6 percent with range from 6.1 to 9.6 percent.
[2] Studs cut from cores or small logs, dried at either high or low temperatures; all averaged 0.51 specific gravity (basis of ovendry volume and weight).
[3] For all three properties, values for studs from cores were significantly higher than values for studs from small logs; the kiln schedules, however, did not significantly (0.05 level) affect values. Interactions were not significant.

thickness and specific gravity, and wet-bulb depression. A total of 108 kilnloads (24 boards per load) of southern pine lumber was dried for 24 hours in an air–steam mixture at 240° F. Boards were 8 feet long, 4 inches wide, and planed green to exact thicknesses of 1.9, 1.5, and 1.0 inches; they were dried under mechanical restraint, approximately as shown in Figure 4. Prior to drying, the lumber was stored in water, and therefore green moisture content was somewhat above normal, averaging about 120 percent.

Air velocity.—Air velocities tested were 510 and 930 f.p.m. In the early stages of drying, moisture content was reduced most rapidly at the high velocity (Fig. 7). For example, at 80° wet-bulb depression the 1.9-inch lumber (stud thickness) was brought to about 60 percent moisture content after 5 hours in high-velocity air. In low-velocity air similar boards were near 80 percent after 5 hours. This early advantage is reflected in the number of hours required to reach 10 percent moisture content—that is, 21 hours at the high velocity and nearly 25 hours at the low velocity (Fig. 8, bottom right and left).

Since Koch's (17) experiment had only two levels of circulation velocity (510 and 930 f.p.m.), a mathematical relationship with drying rate could not be established. On the thicker lumber, high velocity most effectively reduced drying time at 40° and 80° depression.

Kollmann and Schneider (20) found that, in the velocity range from 230 to 2,100 f.p.m., the first-stage drying rate increased as the 0.5 to 0.6 power of velocity. In the next stage of falling drying rate, the effect of flow velocity became steadily smaller but was still discernible at 20 percent moisture content.

Board thickness and wet-bulb depression.—In Koch's (17) experiment, time to dry to 10 percent moisture content was approximately proportional to board thickness. With high air velocity and large wet-bulb depressions, the relationship was nearly linear (Fig. 8, top right).

The relationship between drying time, board thickness, wet-bulb depression, and air velocity is further

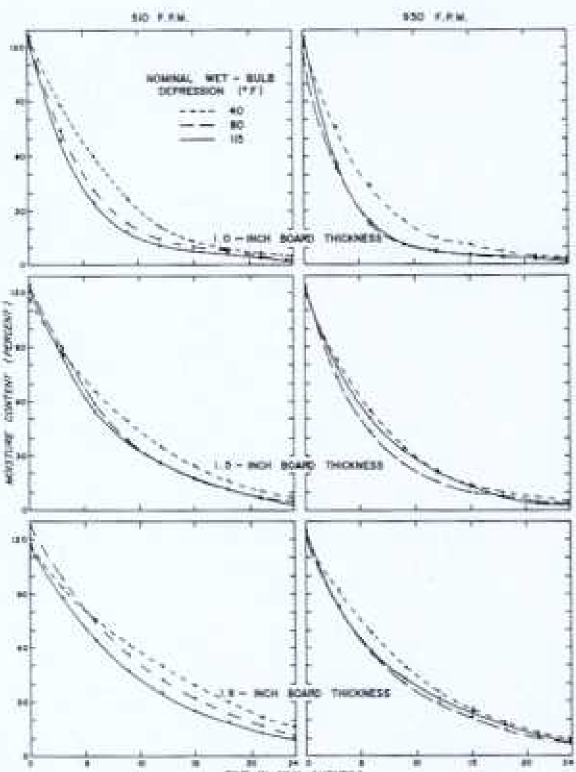

Figure 7.—Effect of Board Thickness and Wet-Bulb Depression on Moisture Content Changes in 24-Board Charges of 4-Inch-Wide Southern Pine Lumber Dried for 24 Hours at 240° F. in Air-Steam Mixtures Circulated at 510 f.p.m. (Left) and 930 f.p.m. (Right). Circulation Velocities were Measured at 70° F. Each Curve Is Based on Data from Six Kilnloads. (Drawing after Koch 1972a.)

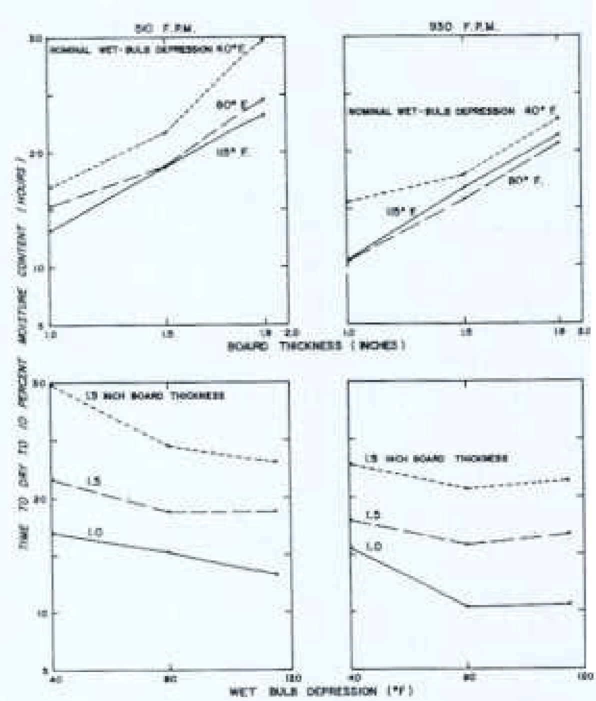

Figure 8.—Effect of Board Thickness and Wet-Bulb Depression on Time Required for 4-Inch-Wide Southern Pine Lumber to Dry at 240° F. from about 122 to 10 Percent Moisture Content. Data Beyond 24 Hours Were Obtained by Extrapolation of Figure 7. Drying Was in an Air-Steam Mixture Circulated at 510 f.p.m. (Left) and 930 f.p.m. (Right). Circulation Velocities were Measured at 70° F. Each Point Is Based on Data from Six Kilnloads. (Drawing after Koch 1972a.)

shown by the following tabulation, which shows hours required for loads to reach 10 percent moisture content. The experimental design did not permit measurement of the range and standard deviation of moisture content within loads.

Board thickness and air velocity (f.p.m.)	Wet-bulb depression, degrees F. 40	80	115
	Hours		
1 inch			
510	17.0	15.4	13.2
930	15.5	10.4	10.5
1.5 inches			
510	21.7	18.9	18.8
930	18.0	15.8	16.8
1.9 inches			
510	29.8	24.5	23.2
930	22.7	20.7	21.4

At both air velocities a wet-bulb depression of 80° caused substantially faster water loss than a depression of 40°. A depression of 115° was slightly better than 80° in slow air, while in fast air it was no better and may have been slightly inferior (Fig. 8, bottom left and right).

For drying at 240°, then, the combination of 80° wet-bulb depression and the 930-foot air velocity proved faster than all other schedules tested. The times required to dry 1-, 1.5- and 1.9-inch lumber to 10 percent moisture content were 10.4, 15.8, and 20.7 hours.

Neither initial moisture content of the kilnloads (range 90 to 140 percent) nor load specific gravity was strongly correlated with drying time. The experimental design did not permit firm conclusions about the effect of moisture content and specific gravity as isolated factors. Average initial moisture contents of the loads in the three gravity classes were:

Gravity class	Moisture content Percent
Low (avg. 0.43)	140
Medium (avg. 0.47)	124
High (avg. 0.52)	105

At dry-bulb temperature of 240° F., time to dry to 10 percent moisture content could be expressed by regression formulas in terms of air velocity, board thickness (inches), and wet-bulb depression (° F.):

At air velocity of 510 f.p.m.:

Time in hours = 10.83
+ 11.69 (board thickness)
− 0.1503 (wet-bulb depression)
+ 0.0005776 (wet-bulb depression)^2

This expression accounted for 84 percent of the observed variation, with a standard error of the estimate (square root of the error mean square) of 2.14 hours.

At air velocity of 930 f.p.m.:

Time in hours = 10.77
+ 10.56 (board thickness)
− 0.2354 (wet-bulb depression)
+ 0.001283 (wet-bulb depression)^2

This expression accounted for 83 percent of the observed variation, with a standard error of the estimate of 1.89 hours.

Boards of low gravity had a greater percentage of moisture content than those of high gravity, and they lost water more rapidly during drying. This generalization was true for boards of all three thicknesses at the three humidities and two air velocities tested; pooled data were as follows:

Load specific gravity class	Initial water content per load	Average water loss per load after various times in the kiln 6 hours	12 hours	24 hours
	Pounds			
Low	284	156	224	271
Medium	275	148	213	260
High	258	143	201	243

Energy required to dry to 10 percent moisture content.—In the electrically powered and heated experimental kiln, energy was required for three purposes: heat, air circulation, and humidification by steam spray.

Two factors that significantly affected heat energy—because they affected time in kiln—were lumber thickness and wet-bulb depression.

Lumber thickness Inches	Average heat energy per 24-board load Kw.-hr.
1.0	294
1.5	385
1.9	509
Wet-bulb depression °F.	
40	435
80	366
115	387

There were no significant interactions; i.e., the generalization that heat energy was minimized with thin lumber and 80° depression held true for wood of all three specific gravities dried at both air speeds.

Predictably, fan energy consumed per load was positively correlated with board thickness and air velocity, as follows (there were no significant interactions):

Board thickness Inches	Average fan energy per 24-board load Kw.-hr.
1.0	23.7
1.5	31.8
1.9	43.4
Air velocity F.p.m	
510	26.2
930	39.7

Humidification energy was significantly affected only by wet-bulb depression. At a depression of 115° F., it averaged less than 1 kw.-hr. per load; at 80° depression it averaged 17 kw.-hr., and at 40° depression it was 83 kw.-hr. There were no significant interactions.

When the three energy components were summed, only board thickness and wet-bulb depression proved significant by analysis of variance. Total energy required per load was minimum with 80° wet-bulb depression:

Wet-bulb depression	*Total energy per 24-board load*
°F.	*Kw.-hr.*
40	552
80	415
115	421

Of course, thin lumber required less energy than thick lumber:

Board thickness	*Total energy per 24-board load*
Inches	*Kw.-hr.*
1.0	348
1.5	446
1.9	593

These values are averages for load data with all factors pooled except the one listed. Load specific gravity and air velocity proved not significant. There were no significant interactions.

Shrinkage.—Since the boards emerged from the kiln at varying moisture contents, there was no basis for computing relative shrinkage. Sections of the boards were therefore ovendried and percentages of shrinkage from green condition noted. In the following tabulation all data are pooled except for the factor of interest; in those categories omitted, values did not differ significantly. There were no significant interactions.

Factor and level	*Shrinkage from green to ovendry*		
	Width	*Thickness*	*Volume*
Specific gravity		*Percent*	
Low	4.5	5.4	9.8
Medium	4.9	5.7	10.4
High	5.1	6.0	11.0
Wet-bulb depression, °F.			
40	5.1		10.6
80	4.9		10.4
115	4.7		10.1
Board thickness, inches			
1.0	4.9	6.0	10.8
1.5	4.9	5.6	10.3
1.9	4.7	5.5	10.0
Air velocity f.p.m.			
510		5.8	10.5
930		5.6	10.2

From these data it is evident that the greatest percentage of shrinkage from green to ovendry occurred in dense, thin boards dried in low-velocity air with a 40° F. wet-bulb depression. Conversely, least percentage of shrinkage occurred in thick boards of low density dried in high-velocity air with a 115° F. wet-bulb depression.

Mechanical properties.—No significant differences in modulus of elasticity, proportional limit, modulus of rupture in bending, or toughness were detected in clear wood dried by the six schedules (two air velocities and three wet-bulb depressions). Pine dried at 80° F. or 115° F. wet-bulb depression had slightly greater end hardness than that dried at 40° depression; side hardness was unaffected by schedule.

Timbers

Published information on high-temperature kiln-drying of southern pine timbers is limited to that from a single study by Koch (19A).

In this study, 10 kilnloads of green southern pine (species unidentified but probably loblolly, *Pinus taeda* L.) were dried in a kiln held at 240° F. with wet-bulb depression of 80° F. and air-circulation velocity of 1,000 feet per minute. Direction of air circulation was reversed every 75 minutes. Kiln charges were given a top load but were not otherwise restrained against warp. Stickering was conventional.

Each of the 10 kilnloads was comprised of eighteen 100-inch-long S4S planks in a replicated factorial combination of three thicknesses (2, 3, and 4 inches) and three widths (4, 8, and 12 inches).

Specific gravity (basis of green volume and ovendry weight) averaged 0.49, and green moisture content averaged 119 percent.

Drying Rates

Time to dry was positively correlated with both board width and thickness (figs. 9, 10, and 11). When data for all widths were pooled, time to dry to 10 percent moisture content had a near-linear correlation (table 5 and fig. 10). Average times (width data pooled) to reach 10 percent moisture content were as follows.

Lumber thickness	*Time in kiln*
Inches	*Hours*
2.0	22.4
3.0	35.6
4.0	45.3

These data further confirm results obtained in earlier experiments (17), which yielded the following near-linear relationship between board thickness and time to dry 4-inch-wide southern pine under nearly identical conditions (fig. 10).

Lumber thickness	*Time in kiln*
Inches	*Hours*
1.0	10.4
1.5	15.8
1.9	20.7

Analysis of variance, and visual inspection of figure 10, show that the 4-inch widths differed significantly from the 8- and 12-inch widths in the relationship between thickness and time to dry to 10 percent moisture content. In brief, 4-inch-thick narrow lumber appears to dry more quickly than a linear relationship would suggest. This interaction

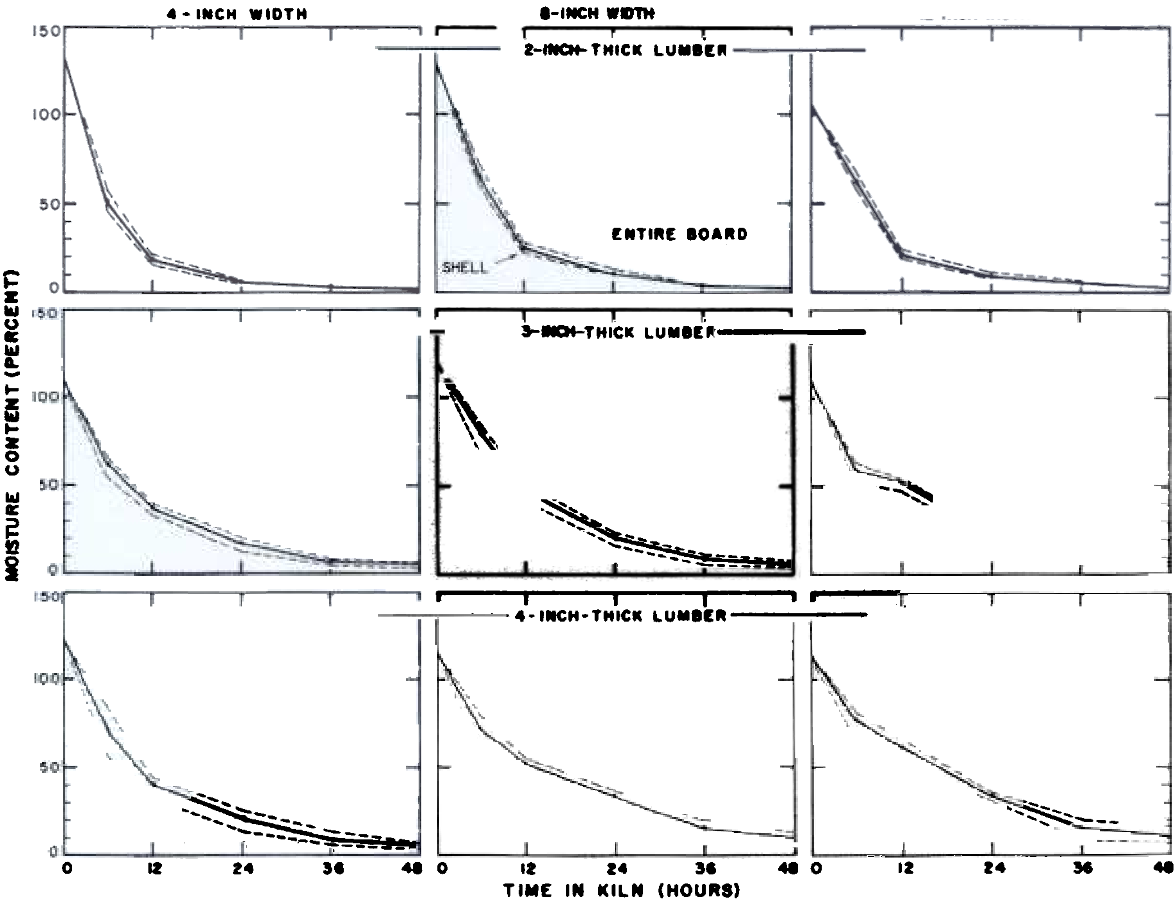

Figure 9.—Moisture content change in three widths of southern pine of 2-, 3-, and 4-inch thickness dried at 240° F. with 80° wet-bulb depression and air circulation velocity of 1,000 f.p.m. Each data point is the average of values from four boards.

Table 5.—Time to dry (at 240° F. with 80° wet-bulb depression) southern pine from green to 10 percent moisture content

Lumber thickness and width (inches)	*Kiln time*
	Hours
2-inch thickness	
4	19.5
8	24.5
12	23.2
	$\bar{X} = 22.4$
	32.6
	34.7
	39.6
	$\bar{X} = 35.6$
	35.8
	47.3
	53.0

between width and thickness was also evident at target moisture contents of 15 and 30 percent (fig. 11). With width data pooled, times to dry to various moisture contents were as follows:

Lumber thickness	*Drying time* To 10%	To 15%	To 30%
Inches		*Hours*	
2	22.4	17.9	10.7
3	35.6	29.7	18.5
4	45.3	34.8	23.7

During the early hours of drying, moisture contents in the core (innermost 0.66 inch of thickness) were greater than those in the shells (outermost 0.66 inch of thickness at top and bottom surfaces), but as board averages approached 10 percent, the core and shell values converged (fig. 9). In 3- and 4-inch pieces, both core and shell dried more slowly as width increased (table 6). In all thicknesses, times to dry both core and shell were positively correlated with thickness, as shown in the following tabulation:

Portion and lumber thickness (inches)	*Kiln time* To 10%	To 15%	To 30%
		Hours	
Core			
2	24.8	20.3	11.2
3	40.4	33.4	20.0
4	57.1	45.2	25.9
Shell			
2	21.3	16.3	10.1
3	31.4	26.0	16.9
4	33.1	29.5	20.1

Shrinkage When Dried From Green To 10 Percent

Width shrinkage from green to 10 percent moisture content differed significantly (0.05 level) with width, but not with thickness.

Board width, green *Inches*	*Width shrinkage* *Inch*
4	0.13
8	.23
12	.37

Thickness shrinkage varied with both board width and thickness in a significant interaction. Four-inch-wide boards had less thickness shrinkage than 12-inch boards.

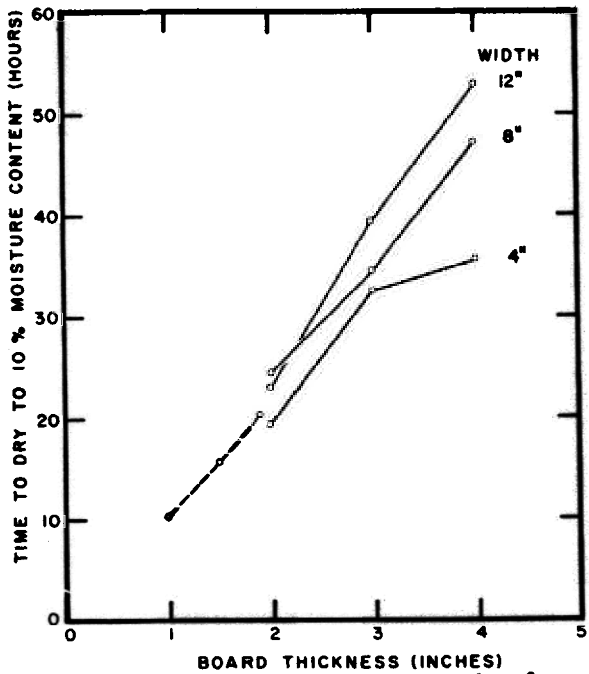

Figure 10.—Time to dry (at 240° F. with 80° wet-bulb depression) various thicknesses and widths of southern pine lumber from green to 10 percent moisture content. Dotted line shows data from previous experiment (17) with 4-inch-wide lumber.

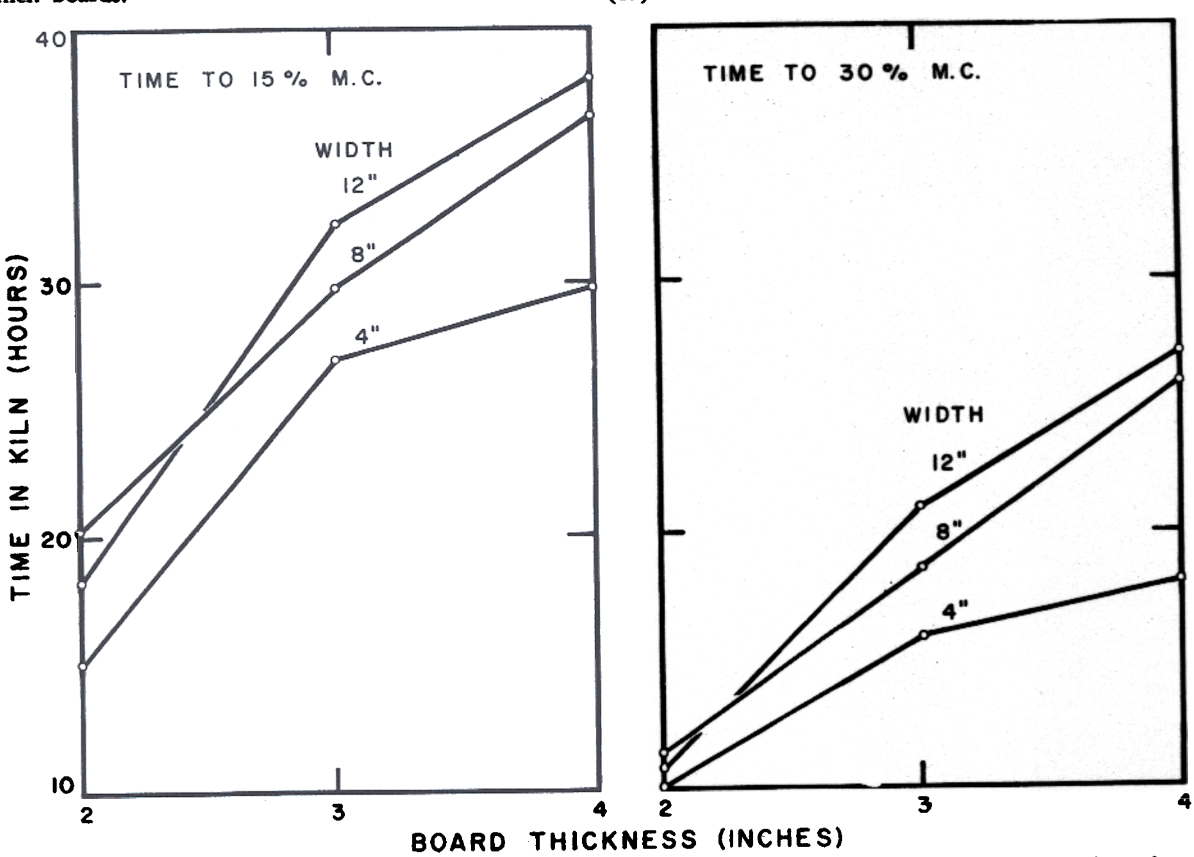

Figure 11.—Time to dry (at 240° F. with 80° wet-bulb depression) various thicknesses and widths of southern pine lumber from green to 15 and 30 percent moisture contents.

Board thickness and width (inches)	*Thickness shrinkage* *Inch*
2-inch thickness	
4	0.07
8	.10
12	.10
3-inch thickness	
4	.14
8	.13
12	.17
4-inch thickness	
4	.13
8	.18
12	.19

All boards were 100 inches long when green. Average length shrinkage in drying to 10 percent was 0.08 inch, with no significant differences attributable to width or thickness.

Warp in Wood at 10 Percent Moisture Content

Crook averaged 0.20 inch and varied significantly with board width but not with thickness. Crook was greater (0.25 inch) in 4-inch widths than in 8- and 12-inch pieces (0.18 and 0.17 inch).

Bow in dry boards also averaged 0.20 inch, but was not significantly correlated with board thickness or width.

Table 6.—Time to dry cores and shells (at 240° F. with 80° wet-bulb depression) of southern pine from green to 10, 15, and 30 percent moisture content

Lumber thickness and width (inches)	*Kiln time* *To 10%*	*To 15%*	*To 30%*
	Hours		
CORE			
2-inch thickness			
4	19.6	17.2	10.6
8	28.6	22.9	11.8
12	26.3	20.7	11.2
3-inch thickness			
4	35.2	30.4	18.2
8	40.7	32.8	19.9
12	45.4	37.1	22.1
4-inch thickness			
4	42.2	34.6	20.4
8	57.8	46.5	28.4
12	71.3	54.5	28.8
SHELL			
2-inch thickness			
4	20.0	13.2	9.1
8	22.9	19.1	10.9
12	21.7	16.7	10.3
3-inch thickness			
4	28.2	23.1	14.4
8	31.9	26.3	16.9
12	34.1	28.5	19.3
4-inch thickness			
4	29.0	23.7	13.7
8	35.1	31.8	21.3
12	35.2	33.1	23.3

Twist averaged 0.23; it was not significantly related to thickness or width. Cup was slight or absent.

Checking At 10 Percent Moisture Content

Surface checks.—The surface of wood dried to 10 percent moisture content showed few checks; on average, only one check was observed for each 28 inches of sample line drawn perpendicular to the grain on the face or back. Frequency of checks was not significantly related to board thickness or width.

Surface checks averaged 1.4 inches in length and 0.09 inch in depth. Checks were longest and deepest in thick wide stock as follows:

Board thickness and width (inches)	*Surface check* *Length*	*Depth*
	Inches	
2-inch thickness		
4	0.3	0.01
8	.0	.00
12	1.3	.08
3-inch thickness		
4	.2	.01
8	1.7	.11
12	2.1	.13
4-inch thickness		
4	.3	.01
8	2.2	.23
12	4.2	.27

End checks.—The most severely checked end of each board was evaluated to obtain data on frequency of occurrence and length along the grain (average and maximum length observed). These data were recorded from checks visible on the outer surface.

One end check was observed for each 9.4 inches measured across the grain on the top or bottom surface of board ends; this frequency was not significantly related to board thickness or width. The checks averaged 1.6 inches in length; the longest check in each board averaged 2.4 inches. Visible end checks were longest in wide thick lumber:

Board thickness and width (inches)	*Length of end check on board surface* *Average*	*Maximum*
	Inches	
2-inch thickness		
4	0.4	0.5
8	.4	.5
12	1.4	1.7
3-inch thickness		
4	.2	.2
8	1.4	1.9
12	3.2	5.7
4-inch thickness		
4	.4	.5
8	2.0	2.9
12	5.5	7.8

In addition to checks visible on board ends, substantial checking was found in interiors adjacent to the ends. In general, the 2-inch-thick lumber had minor end-checks, although the board pictured (fig. 12, top) had checks extending in 3 to 4 inches. Three-inch lumber, when dried to 10 percent, had more severe checks, which in some cases extended 5 or 6 inches (fig. 12, middle). Lumber 4 inches thick in some cases had checks that extended 7 to 9 inches in from board ends (fig. 12, bottom).

After the main experiment was concluded, three 4 by 8's were dried for 48 hours at 240° F. with 80° wet-bulb depression and then conditioned for 4 hours at 195° with 10° wet-bulb depression to yield an average moisture content of 10 percent (shell about 8 percent and core about 11 percent when the timbers were dissected). After cooling and equilibrating in the laboratory for about a week, checks were observed to extend about 9 inches into each end of each timber. Case hardening was minimal.

In the entire experiment, only two internal checks were observed at a distance from board ends; both were found in 4 by 4's dried to less than 10 percent moisture content in 48 hours (fig. 13).

Poles

Steaming and vacuum process.—When southern pine poles are not air-dried or kiln-dried prior to preservative treatments, a steaming and vacuum process is frequently used to condition them under limitations stipulated by the American Wood-Preservers' Association. Southern pine poles and piles are steamed in a treating cylinder, at a maximum permitted temperature of 245° F. (about 12.5 p.s.i.). The temperature must be reached in less than 1 hour.

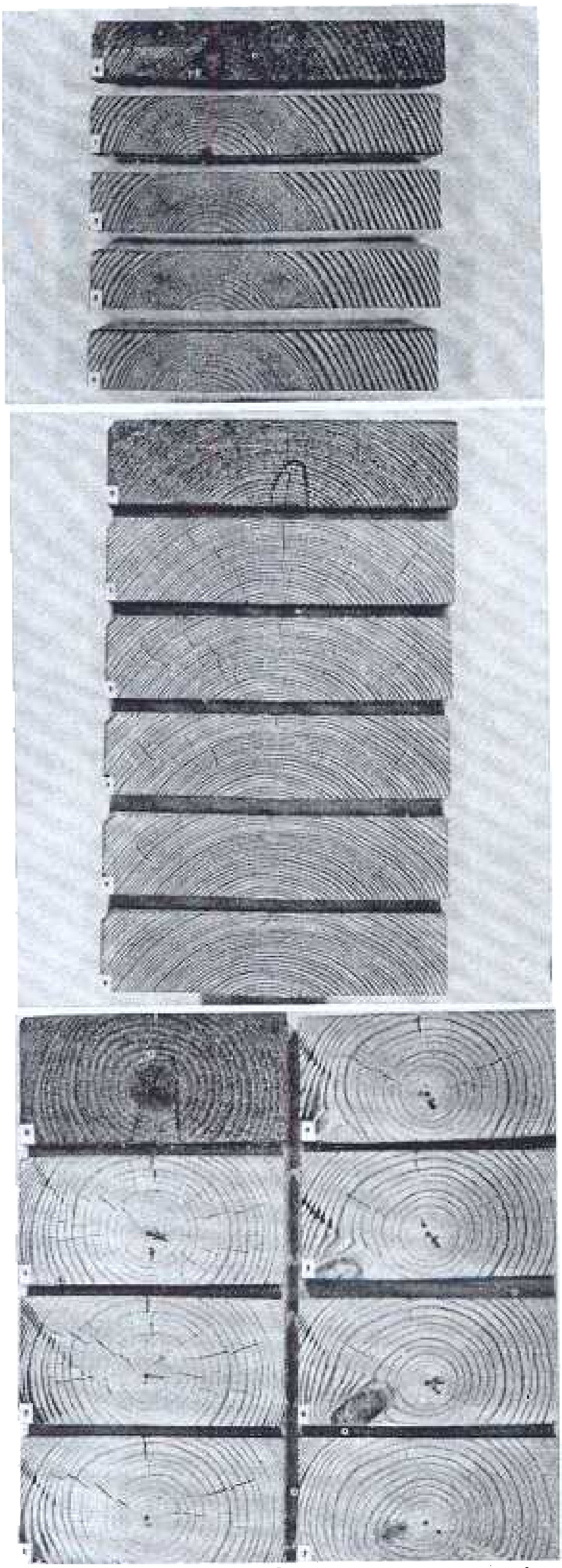

Figure 12.—With boards near 10 percent moisture content, some checks penetrated several inches into the ends. The numerals on each section indicate distance in inches from board end. Top: 2 by 12 after 24 hours in kiln. Center: 3 by 12 after 36 hours. Bottom: 4 by 8 after 48 hours. The specimens illustrated had the worst checks observed.

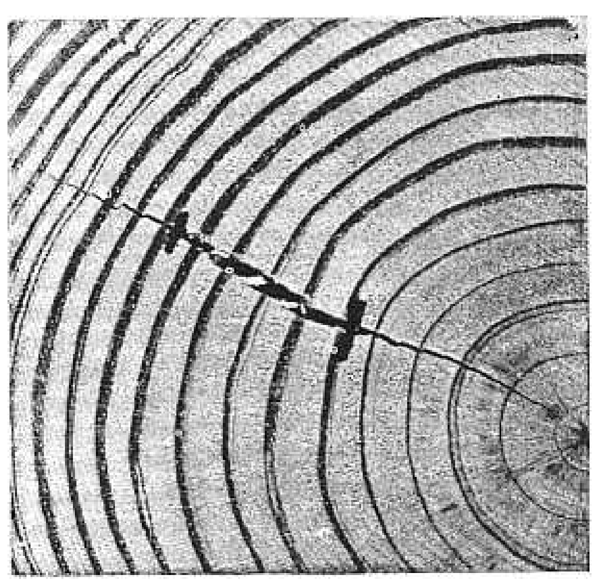

Figure 13.—One of two observed internal checks in 4 by 4's dried to less than 10 percent moisture content in 48 hours. When first dissected, the check was limited by the ink marks; by the time it was photographed 2 days later, it had extended considerably.

During the steaming period, usually 6 to 15 hours, water condenses on the surface of the poles and there is practically no loss in moisture content. When the steam pressure is released, moisture at temperatures above 212° F. moves rapidly under slight pressure from the wet line to the wood surface.

Vacuum is then applied to lower the boiling point and speed the flow of moisture to the surface. The wood is cooled rapidly by the evaporating moisture. When green, round, southern pine poles are subjected to a 5- to 6-hour vacuum after steaming, 50 to 60 percent of the total moisture removed is taken out during the first hour and 70 to 80 percent during the first 2 hours (24). Approximately 5 to 6 pounds of water are removed per cubic foot of sapwood by the average steaming and vacuum treatment; smaller amounts are removed from timbers, particularly if they contain considerable heartwood. Little, if any, water will be withdrawn from partially seasoned wood (24).

Steaming affects the properties of wood. In brief, wood subjected to prolonged exposure in a steam atmosphere loses weight and strength, becomes discolored, and undergoes chemical degradation. It is for these reasons that limitations are placed on the severity of steam-drying schedules.

The steaming and vacuum process has several disadvantages. It requires a retort—thus reducing retort time available for treating. It removes only a limited amount of water from the poles, and may adversely affect wood mechanical properties. Moreover, the water removed from poles by this method poses a pollution problem. For these reasons, there is substantial interest in development of accelerated schedules for kiln-drying southern pine poles.

Kiln-drying in steam–air mixtures.—Schedules for rapid kiln-drying of southern pine poles prior to creosoting were tested around 1940 by Segelken (33). To dry class 5 poles (25 and 40 feet in length) to 25 percent moisture content in 130 hours, the initial dry-bulb temperature of 140° F. was increased more or less linearly to 195° F. during the first 95 hours and then maintained at 195° F. for the final 35 hours; relative humidity was raised to 90 percent in the first 24 hours and then decreased more or less linearly to 30 percent by the end of the 130-hour run. During this time moisture content dropped from 66 percent to 25 percent. Weight per cubic foot dropped from about 54 pounds to about 41 pounds, i.e., water loss per cubic foot was 0.10 pound per hour. In this particular test, 5 pounds of steam were required to evaporate 1 pound of water. The dry poles were a dark straw color and free of gummy deposits. Checking was uniform over the whole surface, individual checks measuring 0.10 to 0.15 inch in width and 12 to 36 inches in length.

The following year, Segelken (34) used a different kiln to dry a mixture of shortleaf and longleaf pine poles of classes 1 to 7 in lengths from 20 to 45 feet. The poles were brought from about 83 to 30 percent moisture content in 100 hours by holding the dry-bulb temperature constant at 232° F. and the wet-bulb constant at 142° F. During the 100 hours, weight per cubic foot dropped from about 55 to 40 pounds, i.e., a weight loss per cubic foot of 0.15 pound per hour. In this well-insulated, cross-circulating kiln, only 2 to 2½ pounds of steam were required to evaporate one pound of water from the poles. Both stickered and unstickered charges were dried; evidence of faster drying in stickered loads was not conclusive. Checks in the dry poles averaged 30 inches long, 0.12 inch wide, and 1.75 inches deep. The poles were successfully treated with creosote. No evaluation of strength loss was made; however, it is probable that pole temperature did not exceed 212° during most of the drying period.

More recently, Thompson and Stevens (36) reported on accelerated drying of green loblolly and longleaf pine poles averaging 8 to 10 inches in diameter and about 60 percent moisture content. In air circulated at 300 f.p.m. with dry-bulb temperatures of 225°, 212°, and 160° F. (with corresponding wet-bulb depressions of 50°, 42°, and 40° F.) poles required about 44, 66, and 90 hours, respectively, to reach 30 percent moisture content. These times were substantially less than the 177 hours required with the low-temperature control, a conventional schedule utilizing a wet-bulb temperature of 120° F. and initial and final dry-bulb temperatures of 130° and 160° F., with the latter reading attained in 10° increments over several days.

Maximum wood temperatures, reached at radial depths of 1 to 3 inches, were approximately equal to the average of the wet- and dry-bulb temperatures. Modulus of rupture of clear wood samples taken from poles dried at 225° F. was 14 percent lower than that of control samples. Strength of clear wood from poles dried at 212° F. was not significantly reduced.

When the poles were pressure-treated, penetration and retention of creosote were adequate (36).

Discussion

It is virtually certain that the technology of high-temperature drying will be increasingly applied by manufacture of southern pine. The nature and the rate of application will vary somewhat by product.

Thick veneers.—Techniques are being developed for laminating dimension lumber from thick veneers (1, 19, 26, 32). Methods for drying such pieces are accordingly receiving considerable attention. Although some will probably be press-dried, it is also quite practical to use impingement-type roller veneer dryers at temperatures ranging from 300° to perhaps 400° F. Resin exudation may or may not be troublesome. Koch (13) observed severe exudation, while Kimball (10) did not. In thicknesses less than ⅝-inch, time in the dryer is of such short duration (approximately an hour) that diminution of strength should not be a problem.

Lumber.—Most published research on high-temperature drying of southern pine lumber has been restricted to 4-inch widths. In a kiln providing a cross-circulation velocity of 1,000 f.p.m. at dry- and wet-bulb temperatures of 240° and 160° F., drying time to 10 percent moisture content is linear with thickness. Thus, for thicknesses of 1.0, 1.5, and 1.9 inches, drying time is 10.4, 15.8, and 20.7 hours. Case-hardening can be relieved by steaming for 1 to 3 hours at dry- and wet-bulb temperatures of 195° and 185° F.

If the lumber is held under mechanical restraint during drying, conditioning, and cooling, warp will be less than in low-temperature operations. High-temperature schedules take only about one-fourth the time and half the energy required by conventional methods, and normal planing procedures remove all resin exudation and surface discoloration.

Eventually this new technology is likely to alter industry drying practices. At present, manufacturers grade and ship southern pine studs at moisture contents of 12 or 13 percent. Most of the studs find use in air-conditioned or heated buildings, however, and in service their moisture content declines to 9 or 10 percent. Experience and research have shown conclusively that the additional drying causes studs to deform considerably. High-temperature drying under restraint would enable manufacturers to reach the desired 10 percent moisture level without undue degrade from warp.

Timbers.—High-temperature kilns have not yet been widely adopted for drying southern pine thicker than two inches. As with thinner lumber, time required to dry at 10 percent moisture is linearly related to thickness. With 240° F. dry-bulb temperature, 80° wet-bulb depression, and air cross-circulated at 1,000 f.p.m., thicknesses of 2, 3, and 4 inches attained 10 percent moisture content in 22.4, 35.6, and 45.3 hours. Although surface checks were absent or minor, end-checking may be moderate to severe in pieces 3 and 4 inches thick. End coating of such timbers may be desirable. Shrinkage and warp do not appear to present difficulties, and case-hardening can be relieved by a 3- or 4-hour conditioning period. In some pieces, resin exudation may cover a substantial portion of the timber surface; when objectionable, it can be removed by light planing. Minor strength losses are likely but have not been quantitatively appraised in southern pine timbers dried at 240°.

Poles.—Because of the short drying times achievable, high-temperature schedules will probably find increased use in the pole industry. Evidence to date is that checking patterns and treatability are acceptable in poles so dried. Some loss in strength is likely to occur, however. Additional research is needed to establish maximum permissible dry-bulb temperature.

Literature Cited

1. Bohlen, J. C. 1972. LVL Laminated-veneer lumber—development and economics. Forest Prod. J. 22(1):18–26.
2. Calvert, W. W. 1958. High-temperature kiln-drying of lumber—a summary of Canadian progress. Forest Prod. J. 8:200–204.
3. Calvert, W. W. 1965. High-temperature kiln-drying of eastern Canadian species. Can. Wood Prod. Ind. 5(7):34–39.
4. Christensen, F. J. 1970. Breakthrough in drying softwoods. CSIRO Forest Prod. Newsl. 377, p. 3–5. Melbourne, Aust.
5. Guernsey, F. W. 1957. High-temperature drying of British Columbia softwoods. Forest Prod. J. 7:368–371.
6. Hann, R. A. 1964. Drying yellow-poplar at temperatures above 100° C. Forest Prod. J. 14:215–220.
7. Hart, C. A. 1965. The drying of wood. N. C. State Univ. Sch. For. Tech. Rep. 27, 24 p.
8. Kauman, W. G. 1956. Equilibrium moisture content relations and drying control in superheated steam drying. Forest Prod. J. 6:328–332.
9. Keylwerth, R. 1952. [High-temperature drying installations.] Holz als Roh- und Werkst. 10: 134–138.
10. Kimball, K. E. 1968. Accelerated methods of drying thick-sliced and thin-sawed loblolly pine. Forest Prod. J. 18(1):31–38.
11. Kimball, K. E., and Lowery, D. P. 1967a. Methods for drying lodgepole pine and western larch studs. Forest Prod. J. 17(4):32–40.
12. Kimball, K. E., and Lowery, D. P. 1967b. Quality of studs kiln-dried by high and conventional temperatures. Forest Prod. J. 17(9):81–85.
13. Koch, P. 1964. Techniques for drying thick southern pine veneer. Forest Prod. J. 14:382–386.
14. Koch, P. 1969. At 240° F. southern pine studs can be dried and steam-straightened in 24 hours. South. Lumberman 219(2723):26, 28–29.
15. Koch, P. 1971a. Process for straightening and drying southern pine 2' by 4's in 24 hours. Forest Prod. J. 21(5):17–24.

16. Koch, P. 1971b. One-day kilning dries pine studs to 10% moisture. Forest Ind. 98(12): 70–71.

17. Koch, P. 1972a. Drying southern pine at 240° F. —effects of air velocity and humidity, board thickness and density. Forest Prod. J. 22(9): 62–67.

18. Koch, P. 1972b. Utilization of the southern pines. USDA Agric. Handb. 420, 1663 p.

18A. Koch, P. 1972. Process for steam straightening and kiln drying lumber. (U. S. Pat. No. 3,680,219.) U. S. Pat. Off., Wash., D. C.

19. Koch, P. 1973. Structural lumber laminated from one-quarter inch rotary-peeled southern pine veneer. Forest Prod. J. 23 (in press).

19A. Koch, P. 1973. Time to dry 2-, 3-, and 4-inch southern pine at 240° F., as related to board width. Forest Prod. J. 23(7):17–25.

20. Kollmann, F., and Schneider, A. 1961. [The influence of flow velocity on the drying of sawn timber in superheated steam.] Holz als Roh- und Werkst. 19:461–478.

21. Ladell, J. L. 1955. High temperature drying of lumber. Timber Can. 15(11):19, 22, 46.

22. Ladell, J. L. 1957. High-temperature kiln-drying of eastern Canadian softwoods: drying guide and tentative schedules. Forest Prod. Lab. Can. Tech. Note 2, 18 p. Ottawa.

23. Lowery, D. P., Krier, J. P., and Hann, R. A. 1968. High-temperature drying of lumber—a review. USDA Forest Serv. Res. Pap. INT-48, 10 p. Intermt. Forest and Range Exp. Stn., Ogden, Utah.

24. MacLean, J. D. 1960. Preservative treatment of wood by pressure methods. USDA Agric. Handb. 40 rev., 160 p.

25. Mathewson, J. S. 1954. High-temperature drying: its application to the drying of lumber. J. Forest Prod. Res. Soc. 4:276–280.

26. Moody, R. C., and Peters, C. C. 1972. Feasibility of producing a high-yield laminated structural product: strength properties of rotary knife-cut laminated southern pine. USDA Forest Serv. Res. Pap. FPL-178, 12 p. Forest Prod. Lab., Madison, Wis.

27. Rasmussen, E. F. 1961. Dry kiln operator's manual. USDA Agric. Handb. 188, 197 p.

28. Salamon, M. 1969. High-temperature drying and its effect on wood properties. Forest Prod. J. 19(3):27–34.

29. Salamon, M. 1970. White spruce kiln schedule employs mixed air velocities. Can. Forest Ind. 90(9):48–50.

30. Salamon, M., and McBride, C. F. 1966. High temperature drying: a comparison of western hemlock and balsam fir dried at high and conventional temperatures. Br. Columbia Lumberman 50(11):44, 46, 48–52.

31. Salamon, M., and McIntyre, S. 1970. Combination schedule improves drying of western white spruce lumber. Forest Prod. J. 20(7):41–42.

32. Schaffer, E. L., Jokerst, R. W., Moody, R. C., Peters, C. C., Tschernitz, J. L., and Zahn, J. J. 1972. Feasibility of producing a high-yield laminated structural product: general summary. USDA Forest Serv. Res. Pap. FPL-175, 18 p. Forest Prod. Lab., Madison, Wis.

33. Segelken, J. G. 1941. Kiln drying longleaf southern pine poles. Am. Wood Preserv. Assoc. Proc. 37:135–154.

34. Segelken, J. G. 1942. Kiln drying southern pine poles. Am. Wood Preserv. Assoc. Proc. 38:251–262.

35. Southern Pine Inspection Bureau. 1968. Standard grading rules for southern pine lumber. 171 p. South. Pine Insp. Bur., Pensacola, Fla.

36. Thompson, W. S., and Stevens, R. R. 1972. Kiln-drying of southern pine poles: results of laboratory and field studies. Forest Prod. J. 22(3): 17–24.

37. USDA Forest Products Laboratory. 1957. Special methods of seasoning wood. High temperature drying: its application to the drying of lumber. USDA Forest Serv. Forest Prod. Lab. Rep. 1665-1, 6 p. Madison, Wis.