Drying Southern Pine at 240°F. -- Effects Of Air Velocity and Humidity, Board Thickness and Density

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Abstract

Kiln time to reach 10 percent moisture content was shortened by circulating air at high velocity, but was little affected by board specific gravity. A wet-bulb depression of 80°F. provided faster drying than depressions of 40 or 115°F. At 80° depression and with air circulated at 930 f.p.m., kiln time was directly proportional to board thickness. Under these optimum conditions, 1 by 4's required 10.4 hours to reach 10 percent moisture content; boards 1.5 and 1.9 inches thick required 15.8 and 20.7 hours respectively. Total energy expended in drying to 10 percent moisture content was affected by board thickness and specific gravity; air circulation velocity did not significantly affect total energy. Boards kilned for 24 hours at 240°F. and then ovendried showed significant variation in shrinkage according to the drying schedule used. No significant differences in modulus of elasticity, proportional limit, modulus of rupture in bending, or toughness were detected in clear-wood specimens cut from lumber dried by the six schedules.

THE LITERATURE CONTAINS numerous theoretical discussions of the effect of kiln and wood variables on time to dry lumber. Statistically valid observations of these effects are difficult to make because a factorial experimental design is required; the several-day length of normal kiln schedules has generally discouraged execution of such experiments.

Here, the purpose is to report a factorial experiment designed around the very short, high-temperature kiln schedules for southern pine described by Koch.[1] These short schedules permitted evaluation of four major drying variables: wet-bulb depression, velocity of cross-circulating air, and thickness and specific gravity of boards.

In all, 108 kiln loads (24 boards per load) of southern pine lumber were dried at 240°F. in an air-steam mixture. Boards were 8 feet long, 4 inches wide, and planed green to exact thicknesses. The lumber was stored in water prior to drying, and therefore green moisture content was somewhat above normal, averaging 122 percent. The range in individual boards was from 35 to 201 percent; standard deviation was 28.8 percent.

Factors in the experiment were:

1) Wet-bulb depressions of 40, 80, and 115°F.
2) Cross-circulating air and steam velocities of 510 and 930 f.p.m.
3) Board thicknesses of 1, 1.5, and 1.9 inches.
4) Board specific gravities (ovendry weight and green volume) of 0.34 - 0.45 (avg. 0.43), 0.45 - 0.48 (avg. 0.47), and 0.49 - 0.75 (avg. 0.52).
5) Two replications of kiln charges.

Procedure

Source of Studs

To fill the requirement for two replications of each kiln load, two 1,296-board samples were randomly drawn from a sawmill in central Louisiana. The second replication was collected after the first replication had been dried. Boards were green, mill-run, and initially 2 inches thick. From each replication of 1,296, one-third of the boards were planed—on a random selection basis—to 1.9 inch thickness, one-third to 1.5 inch, and one-third to 1.0 inch. The 432 boards in each thickness category were then segregated into the three gravity classes (based on 1-inch wafers cut from each end of each green board). Since each class contained an equal number of boards, normal distribution caused the range of the central class to be considerably less than that of the high and low classes. The 144-board classes were randomly subdivided into 48-board groups for the three wet-bulb depressions. Finally, the boards in each group were randomly divided into two kiln loads of 24 boards each for drying at high and low air velocities.

Boards in each replication were stored under water until charged into the kiln. Selection of factor combinations for each day's kiln charge was made randomly. Usually four kiln loads were dried per week, and thus it was necessary to hold the last-dried load of each replication in water (with anti-fungicide) for about 4 months.

Measurements Prior to Drying

In addition to board specific gravity, measurements

[1]Koch, P. 1971. Process for straightening and drying southern pine 2 by 4's in 24 hours. Forest Prod. J. 21:17-24.

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made just prior to kiln-drying included the weight, length, width, and thickness of each green board.

Kiln Schedule

The green lumber was clamped rigidly in aluminum frames, in almost total mechanical restraint against crook, bow, and twist (refer to Fig. 1 of publication cited in footnote 1). The frames permitted conventional cross-circulation of air. Still in frames, the lumber was wheeled into the preheated kiln and dried for 24 hours at a dry-bulb temperature of 240°F. and a wet-bulb temperature of 200°, 160°, or 125°F. Time for the kiln to re-attain a dry-bulb temperature of 240°F. averaged 88 minutes Time to reach wet-bulb temperature averaged 25 minutes. Thoughout the 24 hours, air was cross-circulated at constant velocity (930 or 510 f.p.m.); direction of airflow was reversed every 75 minutes. Weight of charge together with energy consumption for heat, humidity control (steam spray), and fan was continuously monitored against time.

Computations of kiln time and energy to dry loads were based on the weight and energy curves and knowledge of green and ovendry load weights. When the 24-hour kiln run did not bring boards to 10 percent moisture, weight and energy curves were extrapolated.

Measurements on Dry Lumber

With the schedule completed, loads were immediately wheeled from the kiln, and individual boards were weighed and measured for crook, bow, and twist. Boards were then restacked on conventional sticks and conditioned for 24 hours at 72°F. and 50 percent relative humidity. Following this conditioning, each board was measured for length, width, thickness, crook, bow, and twist. Cup was not evaluated; prior observations indicated that cupping is not extensive in 4-inch boards of the thicknesses under test. Three 1-inch slices were then removed at quarter points of each board, weighed, ovendried, reweighed, and measured for volume. From these data, board moisture content and specific gravity (ovendry weight and volume basis) were computed. Width and thickness of the ovendry slices were also recorded.

Strength Evaluation

From the 1.5- and 1.9-inch-thick dry boards in replication 2, specimens were removed and tested for mechanical properties. Removal of the 1-inch slices at quarter points reduced each board to three pieces. The least defective piece from each board was saved for mechanical testing.

This operation yielded 36 sets of 24 pieces each—each set representing a kiln load of 1.5- or 1.9-inch boards. From each set of 24, the eight most defective pieces were reserved for hardness evaluation and the remaining straight-grained and knot-free pieces were randomly assigned for either bending or toughness evaluation. Thus 288 (36 x 8) specimens were made for each property evaluation.

Bending specimens were machined to 1 by 1 by 16 inches, toughness specimens to 0.79 by 0.79 by 11 inches, and hardness specimens to 6-inch lengths 4 inches wide and either 1.5 or 1.9 inches thick. Prior to test, the specimens were stacked on sticks and equilibrated for at least 3 weeks in an atmosphere held at 72°F. dry-bulb temperature and 50-percent relative humidity.

Equilibrated bending specimens were evaluated for modulus of elasticity, proportional limit, and modulus of rupture over a 14-inch span with single-point loading. The apparatus and speed of loading followed ASTM D 143-52, Testing Small Clear Specimens of Timber.

Toughness specimens were evaluated according to ASTM D 143-52, paragraphs 71-75; hardness was measured on both top and bottom faces and on both ends according to ASTM D 143-52, paragraphs 84 and 86.

Following the tests, specific gravity and moisture content of each specimen were determined from two cross-sectional slices taken near the failure, one from each end of the piece.

Results

Moisture Contents and Kiln Times

In the early stages of drying, moisture content was reduced most rapidly at the high velocity (Fig. 1). For example, the 1.9-inch lumber (stud thickness) at 80° wet-bulb depression had 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. 2, bottom right and left). Since only two circulation velocities (510 and 930 f.p.m.) were tested, the mathematical relation between drying time and velocity could not be established. On the thicker lumber, high velocity most effectively reduced drying time at 40° and 80° depressions.

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. 2, top right).

The relationship between drying time, board thickness, wet-bulb depression, and air velocity is further shown by the following tabulation, in which data for all three specific gravity classes have been pooled. Numbers in the body of the tabulation show 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. Readers desiring such data are referred to page 21 of the article previously cited.

Board thickness and air velocity (f.p.m.)	Wet bulb depression (°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

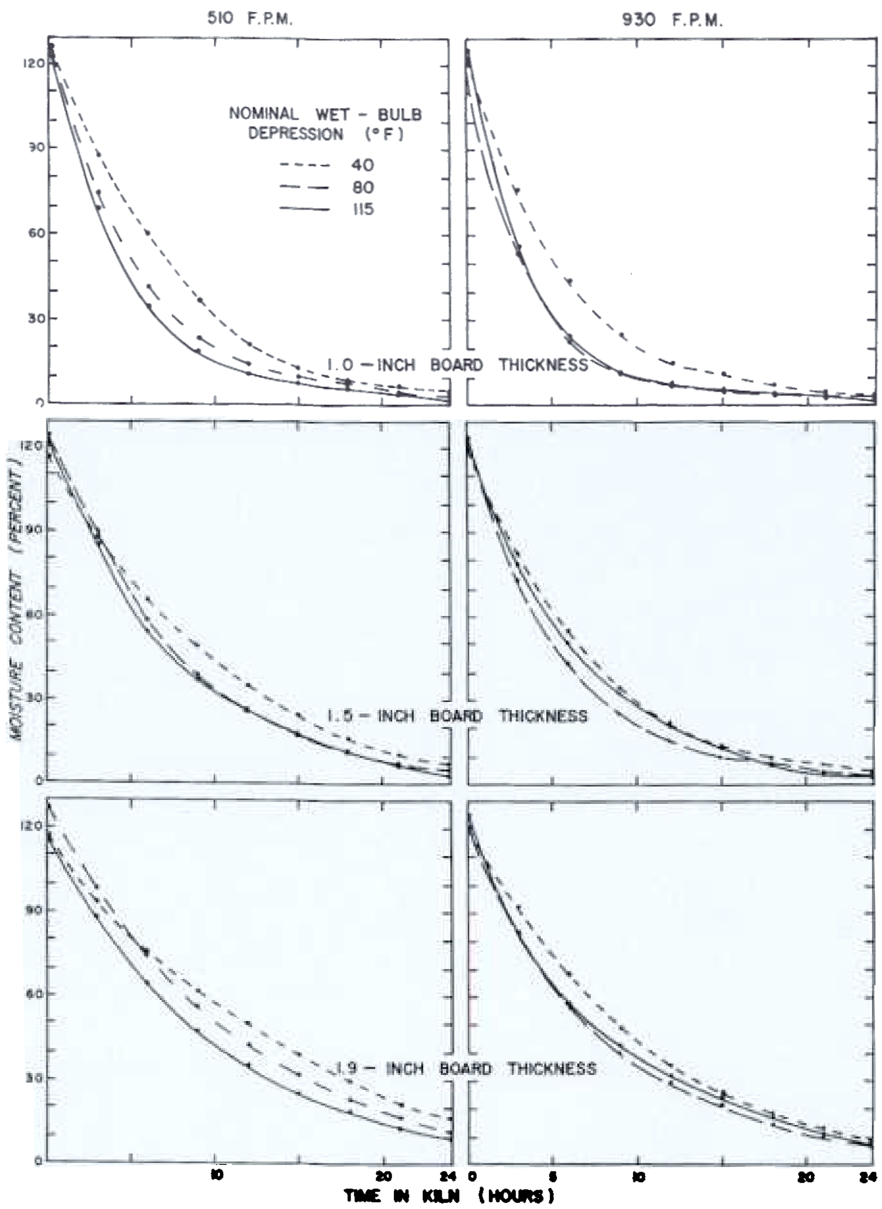

Figure 1. — Effect of board thickness and wet-bulb depression on moisture content changes in 24-board charges of 4-inch-wide southern pine lumber dried at 240°F. in air-steam mixtures circulated at 510 f.p.m. (left) and 930 f.p.m. (right). Circulation velocities were measured at 70°F. Each curve is based on data from six kiln loads.

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. 2, 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.

In this study neither initial moisture content of the loads (range 90 to 140 percent) nor load specific gravity was strongly correlated with drying time. The design did not include moisture content as one of the main factors, and therefore data are insufficient to draw 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
	(%)
Low	140
Medium	124
High	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.):

For 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.

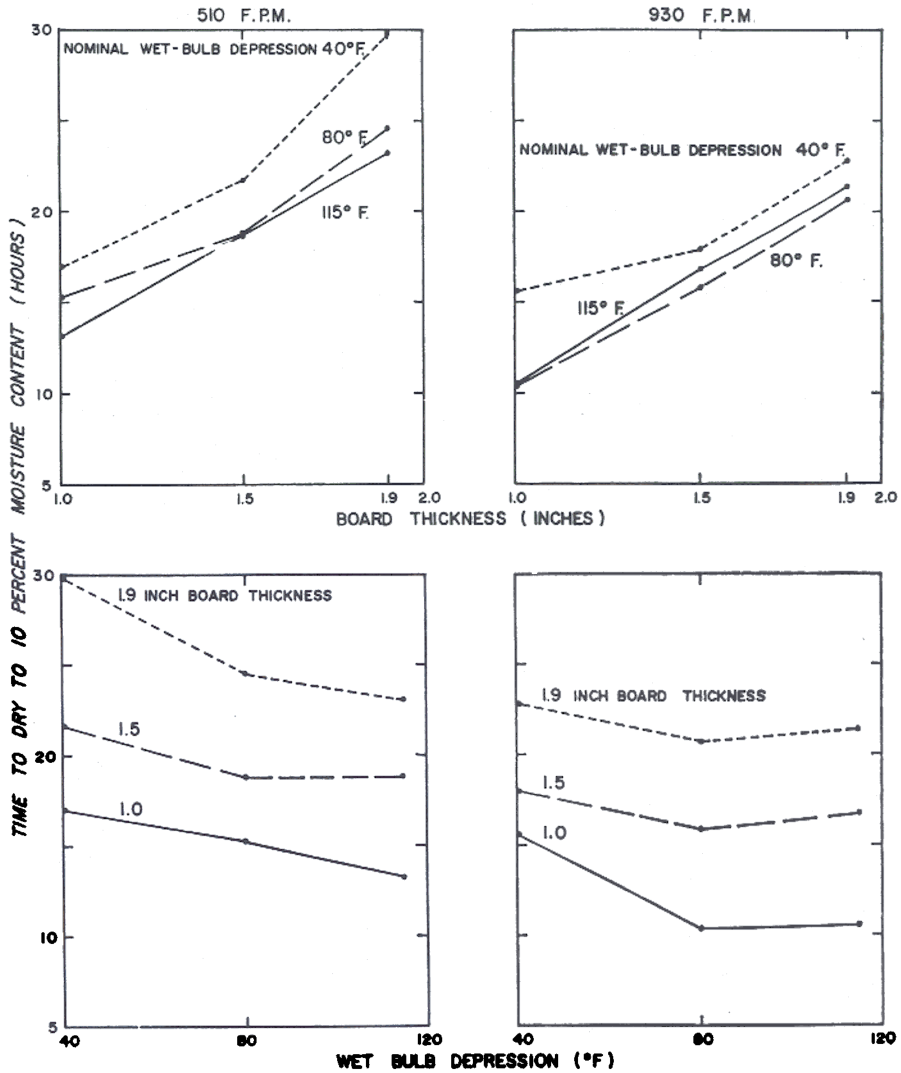

Figure 2. — Effect of board thickness and wet-bulb depression on time required for 4-inch-wide southern pine lumber to dry at 240°F. from about 122 to 10 percent moisture content. Drying was in an air-steam mixture circulated at 510 f.p.m. (left) and 930 f.p.m. (right). Circulation velocities were measured at 70°F. Each point is based on data from six kiln loads.

For 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 84 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.

Heat energy expended per load is dependent on time in kiln. Two factors that significantly (0.05 level) affected heat energy—because they affected time in kiln—were lumber thickness and wet-bulb depression.

Lumber thickness	Average heat energy per load
(In.)	(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 foregoing generalization was 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	Average fan energy per load
(In.)	(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., energy for humidification averaged less than 1 kilowatt hour 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 load
(°F.)	
40	
80	
115	

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

Board thickness	Total energy per load
(In.)	(Kw.-hr.)
	348
	446
	593

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

Warp

Warp of each board was measured immediately when loads were discharged from the kiln, and again 24 hours later. In general, the driest boards warped most, but useful statistics are difficult to extract because board moisture contents varied widely at the end of the kiln run. Thin boards dried under optimum conditions were near ovendry, whereas some of the 1.9-inch boards dried at 40° depression with low air velocity were near fiber saturation. Overall statistics describing warp of the 2,592 boards can be summarized as follows:

Type of warp and time at which measured	Average	Standard deviation	Maximum
		Inch	
Crook			
On discharge from kiln	0.176	0.124	0.76
24 hours later	.192	.137	1.27
Bow			
On discharge from kiln	.158	.124	1.84
24 hours later	.195	.156	2.08
Twist			
On discharge from kiln	.094	.063	.47
24 hours later	.104	.071	.59

Crook, bow, and twist all averaged greater after the boards had cooled (unrestrained on sticks) for 24-hours following discharge from the kiln. It is likely that restraint should be maintained during the cooling period if warp is to be minimized.

Shrinkage

Shrinkage in width, thickness, and volume was measured 24 hours after lumber was discharged from the kiln, and again when board sections were ovendried. Length shrinkage was measured only once, *i.e.*, 24 hours after kiln discharge.

As with the data on warp, variation in moisture content renders it difficult to draw conclusions from shrinkage measurements made 24 hours after discharge. Predictably, the driest boards showed most shrinkage, as is evident from the length data taken 24 hours after kiln discharge:

Lumber thickness (In.) and moisture content	Average length shrinkage from green condition
	(%)
1.0 (at 4.2 percent)	0.145
1.5 (at 5.5 percent)	.122
1.9 (at 10.3 percent)	.104

More meaningful are percentages of shrinkage from green to ovendry. 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
	— Percent —		
Specific gravity			
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 (In.)			
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 wood dried by the six schedules. 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.

Discussion

The original study[1] was exploratory, and only one 240° schedule was tested, *i.e.,* lumber was dried at 240°F. with wet-bulb depression of 80°F. and cross-circulation velocity of about 1,000 f.p.m.

The study here reported examined the effect of a range of wet-bulb depressions and two levels of air velocity. Of the six 240° schedules tested, the originally selected schedule was best; *i.e.,* it resulted in the most rapid drving and the least energy consumption. With this optimum schedule, times to dry 1-, 1.5-, and 1.9-inch lumber to 10 percent moisture content were 10.4, 15.8, and 20.7 hours.

The prior research showed that casehardening resulting from the foregoing schedule can be relieved in stud-thickness lumber by steaming for an additional 3 hours at dry- and wet-bulb temperatures of 195° and 185°F. Thinner lumber should require less steaming time.

The prior work also gives data on grade yield and warp for 8-foot stud-thickness lumber dried with the optimum schedule, conditioned, and cooled—all under positive mechanical restraint against warp. In brief, the planed, dry studs graded 91 percent in SPIB grades 1, 2, and Stud; crook, bow, and twist averaged 0.12, .21, and .09 inch.

To date, the schedule selected as best has not been evaluated on lumber wider than 4 inches.

From these data, and from impressions formed in other high-temperature drying studies conducted at Pineville, Louisiana, from 1963 to 1971, I draw three conclusions:

- Southern pine studs should be graded and shipped at a moisture content of 9 to 10 percent.
- Studs can be advantageously dried to this moisture content at 240°F., provided they are restrained against warp while in the kiln.
- By 1977 it is likely that most southern pine studs will be dried in high-temperature kilns.