High-Temperature Drying of Douglas Fir Dimension Lumber

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SUMMARY OF RESULTS

To avoid serious checking and honeycombing, 2- by 8-inch lumber had to be held 24 hours at 180 F dry-bulb temperature at conditions for EMC of 12 percent before elevating the temperature to 220 F. Time in the kiln was about 15 percent less than was needed with a conventional schedule.

Pieces 6 inches wide needed only 18 hours at 180 F dry-bulb temperature and conditions for EMC of 9 percent before raising the temperature to 220 F. Pieces 4 inches wide did not suffer serious degrade with temperature as high as 230 F at start of drying; uniformity in final moisture content was aided by separating lumber sawed from logs and peeler cores.

A warming period was necessary--5 hours for 8-inch widths, 4 hours for 6-inch widths, and 3+ hours for 4-inch widths. Wet and dry bulbs needed to be not more than 3 degrees apart.

Of many tested, only three coatings did well at preventing honeycombing and end-checking--silicone rubber (expensive!), urea with starch, and calcium chloride with starch.

High temperatures did not affect checking consistently, but were consistent in causing knots to loosen or to break when machined.

HIGH-TEMPERATURE DRYING OF DOUGLAS FIR DIMENSION LUMBER

INTRODUCTION

In the Pacific Northwest, commercial installations for high-temperature drying (above 212 F) have increased rapidly during the past 5 years. There has been extensive research in high-temperature drying (5),[1] but schedules for 2-inch Douglas fir dimension lumber have been proposed only in Canada (6). The study reported here was made to provide schedules suited to drying dimension lumber in Oregon.

High-temperature drying of Douglas fir dimension lumber appears feasible, but it has not been known whether all widths and lumber coming from different geographical areas would react similarly or differently when dried at temperatures above 212 F. Generally, with lumber 8 inches or more wide, warp is a problem; differences in rate of drying and amount of degrade in Douglas fir dimension from various geographical areas were illustrated in a study by Kozlik (1).

There are two methods of drying at temperatures above 212 F: in drying with superheated steam, the kiln is filled with steam to the exclusion of air; high-temperature drying requires a mixture of air and steam and resembles conventional drying where relative humidity is controlled.

High-temperature drying is not a new process; as early as 1867, a patent was granted in the United States for drying lumber by superheated steam. The process was first applied commercially during World War I, when several kilns for superheated steam were constructed in the Pacific Northwest. Rapid drying rates were reported for several of the western softwood species. The severe drying conditions, however, caused rapid deterioration of the kiln structure, and this method was abandoned after a few years.

Following World War II, German investigators revived the practice of high-temperature drying. Today, many commercial installations are successful in Europe, though the kilns are small compared with conventional kilns in western United States and Canada. European high-temperature kilns are generally constructed of metal and insulated against heat loss. Such kilns are vapor tight and heated electrically.

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[1] Numbers in parentheses refer to literature cited.

In the 1950's, the two Canadian forest products laboratories began studies in high-temperature drying and have published several excellent papers (4,5,6). Research in the United States on high-temperature drying has been less. In spite of apparent lack of information, a few companies have installed high-temperature kilns similar to the present conventional kilns but with higher air velocities and greater heating capacity. The development of drying schedules by individual companies has been haphazard, and many times the final product has had end-grain checking and poor uniformity of moisture content. Most commercial high-temperature drying in western United States has been limited to 2- by 4-inch studs of various softwood species.

GENERAL PROCEDURE FOR TEN SERIES OF CHARGES

All lumber in the study reported here was dried in the Forest Research Laboratory's experimental high-temperature dry kiln. The kiln has a holding capacity of 1,000 board feet of 4-quarter lumber, 8 feet long. The interior is welded aluminum construction with 6 inches of glass wool insulation and a plywood outer shell. The steam-heated kiln is equipped with a wide-band proportional recorder-controller with automatic reset at a maximum operating temperature of 270 F. All motor valves have wide-range proportional action except the valve regulating the steam pressure, which is operated by a narrow-band proportional controller. Two axial-flow fans (propeller type), driven by a motor with variable drive, can deliver air at velocities of 300-1,500 feet per minute. The fans can be reversed at intervals ranging from 15 minutes to 6 hours. A scale is installed in the kiln so that the weight of the lumber can be determined to compute moisture content without removing the charge or samples from the kiln.

All material in this study was 2-inch Douglas fir dimension lumber in 4-, 6-, and 8-inch widths. The grade of lumber was generally Construction or Standard, but occasionally Select and Utility were included. The lumber was collected in 10- and 18-foot lengths, except the 2- by 4-inch lumber, which was in 8-foot lengths to allow for determining moisture content and specific gravity and for matching boards.

Lumber was collected from mills in the mid-Willamette Valley in Oregon, except charges in series 8, which came from various geographic areas in Oregon.

The pieces of lumber ranged from all sapwood to inclusion of the pith and varied in growth rate from 5 to 56 annual rings per inch. In storage at the Laboratory, all unseasoned lumber was kept under water sprays.

Charges were divided into series, numbered 1-10. Each series was for an investigation of a particular phase of high-temperature schedules. The performance of each charge was rated on total kiln time, on final average moisture content and range of final moisture content, and on number of small, medium, large, and degrade checks. The size and depth of checks were rated as follows:

Small -- up to 4 inches long
Medium -- from 4 to 10 inches long
Large -- over 10 inches long
Degrade -- one-fourth the thickness or more in depth, depths of opposite checks to be combined; length to be equal to or more than one-half the width of the piece.

Individual charges were also evaluated for final moisture gradient from shell to core and effect of various schedules on loosening and breaking knots.

Small and medium checking do not influence the grades or appearance of softwood dimension lumber; but when a large percentage of boards has very many small and medium checks, the superficial appearance may cause concern to a buyer. If 70 percent, or more, of the boards in a charge have numerous small or medium checks, the pattern of checking is termed severe.

Occurrence of large and degrade checks can lower the grades for upper grades of dimension lumber. Presence of such checking in excess of 10 percent of the boards in a charge is termed severe.

Evaluation of checking is difficult, but arbitrary comparisons can be made between charges. In the tables presented in this report, checking (small, medium, large, and degrade) is given as percentage of boards affected in a charge and as total number affected in a charge.

DISCUSSION OF THE SERIES

Drying 2- by 8-Inch Dimension Lumber

Preliminary charges: series 1

Each of the four charges in series 1 contained about 300 board feet of 2- by 8-inch mill-run dimension lumber. These charges were dried to acquaint Laboratory personnel with the high-temperature kiln and to illustrate some of the problems encountered during high-temperature drying.

Charge 1A was dried at 260 F for 11 hours; final average moisture content was 18.4 percent. Charges 1B and 1C were dried at 225 F for 6 hours and then for 10 hours at 265 F. The final average moisture content was 16.8 percent for charge 1B and 18.8 percent for charge 1C. Charge 1D was dried at 220 F for 12 hours and for 24 hours at 230 F. The final average moisture content for charge 1D was 12.0 percent.

All lumber in series 1 exhibited excessive surface and end checking; occasional pieces had internal honeycombing. All pieces had a dry outer shell, as low as 9 percent moisture content, and the core was wet, averaging as high as 27 percent moisture content. Although kiln time was short, the appearance of excessive checking and the steep moisture gradient from shell to core showed that dimension lumber requires longer drying times with lower temperatures at higher conditions for EMC (equilibrium moisture content).

Various dry-bulb temperatures: series 2

Charges in series 2, with about 200 board feet per charge, tested the effect of longer drying times and different dry-bulb temperatures at a constant wet-bulb temperature of 210 F. The results are given in Table 1.

Table 1. Effects of Drying Time and Dry-Bulb Temperature with Constant Wet-Bulb Temperature of 210 F.

Charge	Dry-bulb temp	Final moisture content		Kiln time
		Shell	Core	
	Deg F	Percent	Percent	Hr
2A	220	9.2	15.2	54
2B	230	6.0	10.2	50
2C	240	6.6	11.3	30
2CC	240	8.1	16.0	27
2D	250	6.5	10.0	26
2E	260	5.9	10.1	23

Table 2. Effects of Higher Conditions for EMC and Total Kiln Time on Moisture Gradient from Shell to Core.

Charge	Final moisture content		Kiln time
	Shell	Core	
	Percent	Percent	Hr
3A	9.3	18.6	25
3B	8.6	13.1	35
3C	10.5	18.2	29
3D	8.1	15.9	34
3E	8.9	11.7	38
3F	9.9	14.8	35
3G	11.4	17.7	32
3H	9.6	13.2	38

Total kiln time decreased with increasing dry-bulb temperature. The gradient from shell to core was not so excessive as for charges in series 1, but charges 2A, 2C, and 2CC differed about 5 percent or more in moisture content. Both surface and end checking were severe for all charges: about 83 percent of the boards in each charge averaged 4.0 small checks per board; 24 percent of the boards averaged 1.4 medium checks per board; 7 percent of the boards averaged 0.8 large checks per board; and 6 percent of the boards averaged 1 degrade check per board. In addition, a large number of the boards in each charge dried at 240 F and higher had internal honeycombing. Most of the checking was confined to the ends of the boards.

Two stages in dry-bulb temperature: series 3

The charges in series 3, containing about 250 board feet per charge, were dried at higher conditions for EMC by maintaining the wet-bulb temperature at 212 F throughout the run and holding the dry-bulb temperature at 225 or 230 F from 6 to 12 hours before raising the temperature to 240 F. Table 2 shows the effects of different drying times with a 6-hour final steaming period at 215 F dry-bulb temperature and 212 F wet-bulb temperature to reduce the moisture gradient from shell to core. There were 24 boards in each charge, and two determinations of shell and core were taken on each board.

Short drying times, as for charges 3A, 3C, and 3G, produced shell-to-core moisture gradients ranging from 9.3 to 6.3 percent moisture content, but with longer drying times, as in charges 3E and 3H, moisture gradients ranged from 2.8 to 3.6 percent moisture content. Longer drying time reduced the moisture gradient but did not reduce the excessive surface and end checking. About 75 percent of the boards in each charge averaged 4 small checks per board; 27 percent of the boards averaged 3 medium checks per board; 22 percent of the boards

Table 3. Effect of End Coatings on End-Grain Honeycombing and End Drying.

Coating	Prevention of honeycombing	Prevention of end drying	Adhesion on wet wood	Appearance after drying
Aluminum paint	Poor	Poor	Good	Some flaking
Cupric oxide & phosphoric acid	Poor	Poor	Poor	Excessive flaking
Asphaltic kiln coating	Poor	Poor	Good	Excessive cracking
Silicone rubber gasket compound	Fair	Fair	Good	Small broken blisters
Aluminum flakes and gloss oil	Poor	Poor	Good	Excessive flaking
Two commercial natural varnishes	Poor	Poor	Good	Excessive cracking and flaking
Two commercial synthetic varnishes	Poor	Poor	Good	Excessive cracking
Calcium chloride and starch	Good	Good	Good	Some flaking
Sodium salt & silicone	Poor	Poor	Poor	- - -
Tygon in methyl ethyl ketone	Poor	Poor	Good	- - -
Portland cement & redwood bark fines	Poor	Poor	Poor	Excessive flaking
Sodium hydroxide	Poor	Fair	Good	- - -
Urea & starch	Good	Good	Good	Some flaking
Glycerin	Poor	Poor	Good	- - -
Epoxy resin	Poor	Poor	Good	Cracking
Ammonia dibasic phosphate	Fair	Fair	Good	- - -
Polyethylene glycol (mol. wt. 400 and 1,450)	Poor	Poor	Good	Completely melted off

Table 3. (Continued)

Coating	Prevention of honey-combing	Prevention of end drying	Adhesion on wet wood	Appearance after drying
Douglas fir bark wax	Poor	Poor	Good	Completely melted off
Silicone rubber bonding agent	Excellent	Excellent	Excellent	Some unbroken blisters
Asphalt mastic (remains soft under outer film)	Poor	Fair	Excellent	Many broken blisters
Neoprene-asphaltic bitumen compound	Poor	Fair	Excellent	Excessive broken blisters
Bitumen epoxy compound	Poor	Poor	Excellent	Excessive flaking
Polyoxyethylene fatty acid esters	Poor	Poor	Good	- - -
Six waste liquor by-products obtained from pulping	Poor	Poor	Poor	Completely flaked off

averaged 2 large checks per board; and 3 percent of boards averaged 0.5 degrade checks per board. As in previous charges, most checks were in the ends of the lumber, with many pieces having end-grain honeycombing.

End coatings

Since end checking and end-grain honeycombing were major problems in drying, a number of coatings were tested, and the results are presented in Table 3. The coatings were rated as follows:

Prevention of end-grain honeycombing

Excellent	-- checks extending into wood 1 inch or less
Good	-- checks extending into wood 1-2 inches
Fair	-- checks extending into wood 2-3 inches
Poor	-- checks extending into wood 3 or more inches

Prevention of end drying

Excellent	-- moisture gradient from board end to 2 inches or less in depth

Good -- moisture gradient from board end to 3 inches in depth
Fair -- moisture gradient from board end to 4 inches in depth
Poor -- moisture gradient from board end to 5 or more inches in depth

Adhesion to unseasoned board end
Excellent -- easy to apply, coating did not sag, and it adhered to wood without reapplication
Good -- easy to apply, coating sagged some, it adhered to wood after one or two applications
Poor -- hard to apply, coating sagged or flaked considerably and it did not adhere to wood after several applications.

Only three coatings were satisfactory in preventing end-grain honeycombing and end drying. Urea-starch coating and calcium chloride-starch had a good rating, and the cost of both coatings would be low. The silicone rubber bonding agent was excellent, but the cost of the silicone compound, at about $1.50 per board, is high. Although these three coatings prevented excessive end-grain honeycombing and end drying, end coating of Douglas fir dimension lumber for drying has not been favored by producers because it increases cost and adds another step to the process.

To determine some other means of reducing end-grain honeycombing and excessive surface checking, tests were made to gauge the effect on checking of a fast or slow elevation to initial dry-bulb temperatures, as shown in charges in series 4; internal board temperatures during drying were tested in series 5; and moisture content and length of drying time at which checking ceases were studied in series 6.

Heating rate: series 4

The charges in series 4, containing about 300 board feet per charge, were dried to determine the effect on checking of a fast or slow elevation to initial dry-bulb temperature from the wet-bulb temperature of 210 F . After a 9-hour warming period to the wet- and dry-bulb temperatures of 210 F, the dry-bulb temperature was elevated to 225 or 230 F in the time shown in Table 4.

The results of the test charges indicated no pronounced difference between a slow or fast rise to initial dry-bulb temperature from 210 F. Charge 4A, with a slow rise, had a larger percentage of medium checks, but charge 4AA, with a fast rise, had more small and degrade checks. Charge 4BBB, with a fast rise, had a larger percentage of medium and large checks than the matched charges 4B and 4BB, which had more small checks.

Internal temperature: series 5

Charges in series 5, each containing 8 boards, were tested for internal wood temperature from start to completion of drying. Copper and copper-constantan wire thermocouples were used to record temperatures. On a recording potentiometer, two stations measured dry- and wet-bulb temperatures and eight stations measured internal temperature of the wood. Of the eight stations, two stations each measured temperature of sapwood and heartwood samples and one station each, of samples with flat grain, vertical grain, coarse grain (less than five rings per inch), and fine grain (more than 15 rings per inch). All samples were coastal 2- by 8-inch Douglas fir. A thermocouple was placed in the wood at midthickness and midwidth. A 23/64-inch hole was bored into the test sample to the required depth. A 3/8-inch hardwood dowel had a shallow saw kerf cut along its length to hold the thermocouple wire, and one end of the dowel was rounded. The junction end of the thermocouple was bent over the rounded end of the dowel and

Table 4. Effect on Checking of Slow and Fast Heating to Initial Dry-Bulb Temperatures.

Charge	Dry-bulb temp	Time to temp[1]	Checks							
			Small		Medium		Large		Degrade	
			Boards	Total	Boards	Total	Boards	Total	Boards	Total
	Deg F	Hr	Percent		Percent		Percent		Percent	
4A	225 240	2.00	78	66	50	13	22	7	0	0
4AA	225 240	0.25	89	88	33	15	22	8	6	2
4B	230 240	3.00	83	69	17	3	11	2	0	0
4BB	230 240	1.25	89	89	28	9	0	0	0	0
4BBB	230 240	0.50	72	81	61	16	22	4	0	0

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[1] Following the warming period to initial wet-bulb temperature of 210 F, the time to attain dry-bulb temperatures of 225 or 230 F is shown.

returned along the length of the dowel in the saw kerf. Except for the soldered tip of the thermocouple and the rounded end of the dowel, their entire surfaces were spread with silicone rubber (room-temperature-vulcanizing bonding agent), and the dowel was driven into the drilled hole in the sample boards. This procedure was followed for all samples to eliminate as far as possible heat conduction to the thermocouple from the conditions inside the kiln. Thermal conductivity, expressed as calories per centimeter-degrees C-seconds, for wood parallel to the grain is approximately 0.000300 and for the silicone resin, 0.000495. With such low conductivity, the dowel or silicone resin would not materially affect internal temperature of the wood.

Figures 1, 2, and 3 illustrate relations of dry- and wet-bulb temperatures and internal temperature of the boards during drying. The board temperature shown in the figures is an average of measurements taken at the eight measuring stations. For the first 5-8 hours, the range of board temperatures was ± 3 F, but throughout the remaining time the range was only ± 1 1/2 F. Generally, sapwood samples recorded the low temperatures during the first stages of drying, but

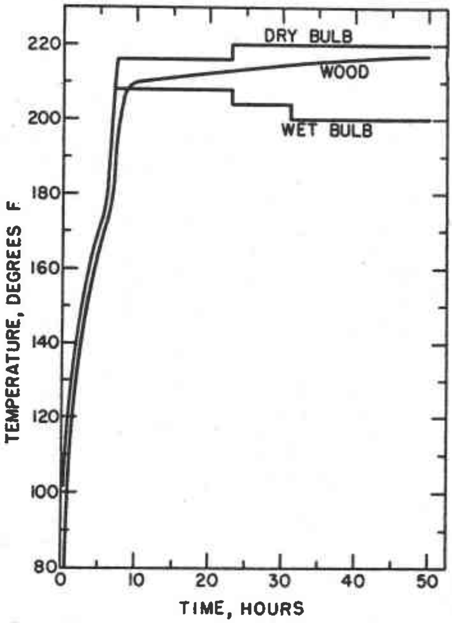


Figure 1. Relation of kiln temperature to internal temperature of wood being dried with a 7 1/2-hour warming period.

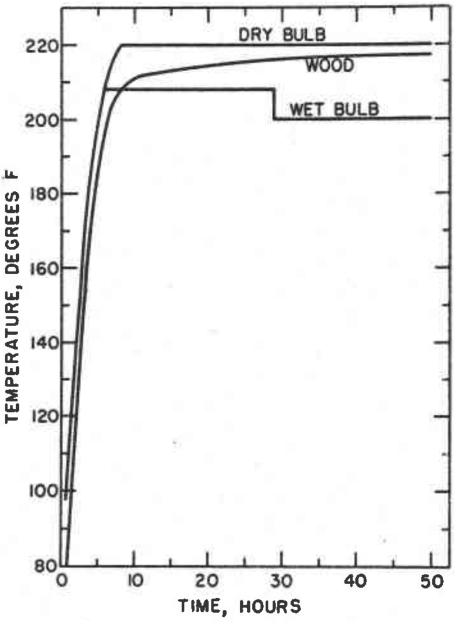
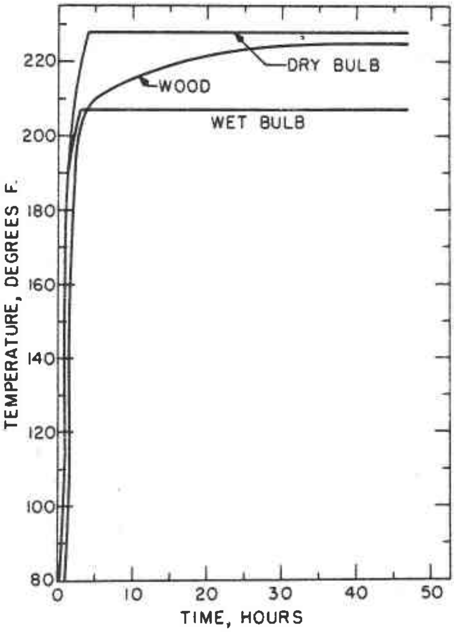


Figure 2. Relation of kiln temperature to temperature of wood being dried with an 8-hour warming period.

Figure 3. Relation of kiln temperature to temperature of wood being dried with a 4-hour warming period.



after 8 hours, no particular sample consistently had the lowest or highest temperature. Internal temperature of the board lagged about 10-15 F below the wet-bulb temperature during the warming period. After the wet-bulb temperature was reached inside the kiln, in 1-2 hours the internal temperature of the boards exceeded the wet-bulb temperature. Internal temperature of the boards increased slowly during drying, and after about 50 hours of drying the board temperature was 3-4 F below the dry-bulb temperature. The final moisture content of the wood core surrounding dowel and thermocouple wire ranged from 13 to 17 percent.

Regardless of the time used for the warm-up period, internal temperature of the boards followed wet- and dry-bulb temperatures in the same way, illustrated by Figures 1 and 2 with a slow warm-up period (7.5-8 hours) and Figure 3 with a fast warm-up (4 hours).

Checking cessation: series 6

Charges in series 6 were dried to determine at what average moisture content and length of drying time checking ceases to occur in both length and width.

For the six charges of series 6, matched samples (charges 6A to 6AAA and 6B to 6BBB) were cut from 14-foot lengths of clear flat-grain lumber sawed to 1 7/8-inch thickness, ± 1/16 inch. Each piece was 4 feet long, and both ends were sealed with silicone bonding rubber that vulcanizes at room temperature. Sections were cut from each 4-

foot piece to determine initial moisture content. The samples were dried at various combinations of temperature and conditions for EMC, including conventional and high-temperature schedules. At various intervals, the charges were taken from the kiln; each sample was weighed, and number of checks was recorded. (To be tallied during one of the observation periods a check had to be at least 0.01 inch wide.) A line was drawn with a marking crayon the full length of the check to enable the observer to determine if it lengthened and to tally new checks. Table 5 summarizes pertinent data for the charges in series 6.

Checking was visible after 7 hours of drying, regardless of kiln conditions (Table 5). If dry-bulb temperature was held below 212 F with conditions for EMC of 12 percent, checking was least severe. Although many small checks occurred, as in charges 6A and 6AA, most were not deep enough to appear in the wood after surfacing. With temperatures of 220 F at conditions for EMC of 12 percent or 210 F at conditions for EMC of 9 percent, as in charges 6BBB and 6BB, the checking pattern became severe after 7 hours of drying, and the final tally of checking was much higher than for the other charges. In all charges, except 6AAA with no checking, checks became wider, longer, and more numerous for the first 24 hours; after 48 hours, additional checking did not occur and previous checks became shorter. The most critical period in establishing the checking pattern, therefore, was the first 24 hours, regardless of kiln conditions.

Charges in series 6 showed that initial dry-bulb temperatures and conditions for EMC were critical in drying Douglas fir 8 inches or more wide. Test charges in series 7 were dried to determine near-optimum dry-bulb temperature and conditions for EMC required to reduce checking to an acceptable level.

Temperature and conditions for EMC: series 7

Series 7 contained 2- by 8-inch Construction-grade dimension lumber in 16-foot lengths cut into 8-foot lengths and randomly assigned to one of 14 charges. A section was cut from 12 percent of all pieces to measure specific gravity and moisture contents; the average moisture content was 41.1 percent and the average specific gravity, based on green volume and oven-dry weight, was 0.45. The boards averaged 18.6 growth rings per inch in the 12 percent sample. Fifty boards constituted a charge that was randomly assigned to one of five temperatures--180, 200, 210, 220, 225 F--with one of three conditions for EMC --6, 9, 12 percent--for each temperature, except that 225 F at conditions for EMC of 12 percent could not be obtained. Air velocity, measured on the leaving air side, for all charges was 800 feet per minute. After a charge reached an average moisture content of about 15 percent, the drying was stopped, although some charges had final moisture contents above or below the predetermined levels.

Table 5. Summary of Drying Schedules, Moisture Content, and Checking in Charges of Series 6.

Charge	Dry-bulb	EMC	Time	Init. MC	Checking[1] and moisture content after--									
					7 hours		16 hours		24 hours		48 hours		End of drying	
					Checks	MC	Checks	MC	Checks	MC	Checks	MC	Checks	MC
	Deg F	Percent	Hr	Percent		Percent		Percent		Percent		Percent		Percent
6A	200	12	33	60	11 s	44	22 s	39	--	--	No	--	11 s	17
	200	9	40		2 m		2 m				more		2 m	
	200	14	6											
6AA	200	12	43	57	11 s	46	21 s	37	35 s	34	No	--	18 s	16
	200	9	24		1 m		1 m		2 m		more		2 m	
	200	14	6											
6AAA	180	12	20	52	None	--	None	--	--	--	--	--	None	22
	220	12	24											
	220	9	24											
	211	20	6											
6B	180	12	24	44	None	--	--	--	3 s	27	No	--	3 s	22
	220	12	22						1 m		more		1 m	
	220	9	15											
	211	20	9											
6BB	210	9	71	36	Many	32	Many	--	--	--	No	--	14 s	15
	204	20	6		s,m		more				more		9 m	
					2 l		s,m						2 l	
6BBB	220	12	49	41	Many	--	--	--	--	--	No	--	15 s	13
	220	9	21		s,m						more		4 m	
	213	20	6		3 l, 1 d								3 l, 1 d	

[1] Small checks, s; medium, m; large, l; degrade, d.

Table 6. Effect of Temperature and Conditions for EMC on

			Checks							
			Small		Medium		Large		Degrade	
Charge	Dry-bulb	EMC	Boards	Total	Boards	Total	Boards	Total	Boards	Total
	Deg F	Percent	Percent		Percent		Percent		Percent	
7A	180	12	42	72	24	25	8	6	6	3
7AA	180	9	58	125	22	23	6	6	6	3
7AAA	180	6	62	101	28	37	18	16	6	3
7B	200	12	32	39	14	12	6	6	6	4
7BB	200	9	48	74	22	22	6	4	8	4
7BBB	200	6	72	125	40	46	10	13	0	0
7C	210	12	64	127	28	57	14	11	6	3
7CC	210	9	72	116	32	24	16	11	8	5
7CCC	210	6	68	141	22	26	10	8	6	3
7D	220	12	58	90	30	23	10	6	8	5
7DD	220	9	68	145	38	34	18	13	8	4
7DDD	220	6	80	177	34	37	12	10	6	4
7EE	225	9	58	118	30	37	18	12	6	4
7EEE	225	6	72	129	30	40	12	12	0	0

After drying, the lumber was surfaced in a commercial-size planer. Each board was tested for moisture content with a resistance moisture meter; number of small, medium, large, and degrade checks was recorded; 20 percent of the boards in each charge was sampled for moisture content of shell and core; numbers of loose and broken knots and depth of penetration of end-grain honeycombing were recorded. End-grain honeycombing was measured for depth by cutting back the end of the board until checking was no longer visible. A summary of the data is presented in Table 6, which shows that the percentage of boards with checks or with loose or broken knots varied from charge to charge regardless of temperature or conditons for EMC, so no one combination can be recommended.

Table 7 gives the average number of small, medium, and large checks, the average number of loose or broken black knots, and the average depth of honeycombing for each temperature and condition for EMC. The average number of degrade checks and loose or broken intergrown knots is not given in Table 7 since these data were nearly identical for all charges. Numbers of checks and knots and depth of

Checking, End-Grain Honeycombing, and Loose or Broken Knots.

Final moisture content			Kiln time	Loose or broken knots				Honeycomb depth
Meter[1]	Shell[2]	Core[2]		Black		Tight		
				Boards	No.	Boards	No.	
Percent	Percent	Percent	Hr	Percent		Percent		In.
17	13	15	115	40	42	4	2	0.7
16	13	16	104	46	45	0	0	2.2
16	13	15	82	30	22	4	3	3.4
15	12	15	135	52	57	4	5	1.4
15	12	14	119	40	45	8	5	2.4
17	13	17	66	34	34	0	0	4.1
17	13	16	110	48	52	8	4	1.4
18	14	18	68	34	36	0	0	2.0
16	12	15	66	44	44	0	0	3.8
13	11	13	111	34	34	6	3	1.0
16	12	16	72	44	50	0	0	3.0
15	12	14	62	48	46	10	8	3.9
12	9	12	94	58	62	6	3	1.0
14	10	12	60	44	60	10	6	3.3

[1] Determined with a resistance-type moisture meter.

[2] Determined by the oven-test method.

honeycombing for each test temperature at the different conditions for EMC were added separately and the average computed. The number of small checks occurring in charges dried at 180 F--7A, 7AA, and 7AAA--was totaled and averaged. Checks, knots, or depth of honeycombing for each condition for EMC were similarly totaled and averaged.

Checking tended to increase with increasing temperature, as shown in Table 7, where data indicate that least checking occurred in charges dried at 180 and 200 F and most checking was at drying temperatures of 225 F. As conditions for EMC were lowered from 12 to 6 percent, the amount of checking increased. Checking was least at conditions for EMC of 12 percent and most at conditions for EMC of 6 percent (Table 7).

Elevated drying temperature increased the number of black knots loosened in drying and broken in subsequent machining (Table 7). Drying temperature of 180 F averaged the fewest, with only 36 broken or loose black knots; temperatures of 200, 210, 220 F averaged 45, 44, and 43, respectively; but temperatures of 225 F averaged the maximum of 61. Effect of conditions for EMC on loosening and breaking black knots is not so obvious. Although conditions for EMC of 6 percent produced least effect and conditions for EMC of 9 percent, most effect, they were not really important in changing the number of loose or broken black knots.

Since end-grain honeycombing was a problem in drying 2- by 8-inch dimension lumber, the effect of temperature and conditions for EMC on end-grain honeycombing was studied. Conditions for EMC of 12 percent produced least depth of honeycombing (1.1 inches), but changing to conditions for EMC of 6 percent produced honeycombing that penetrated 2.2 inches. Effect of temperature on depth of honeycombing was not apparent because the least penetration occurred at 180 and 225 F and the most at 200 and 220 F.

Low temperature and conditions for high EMC required long drying times; high temperature and conditions for low EMC allowed shorter times in the kiln. The moisture gradient from shell to core was not steep in any charge, since the range in moisture content averaged from 2 to 4 percentage points. About 2-3 boards in a charge exceeded 19 percent moisture content.

Table 7. Effect of Temperature and Conditions for EMC on Average Number of Checks and Loose or Broken Black Knots, and Depth of Honeycombing.

Dry-bulb temp	EMC conditions	Checks			Loose, broken knots	Honeycomb depth
		Small	Medium	Large		
Deg F	Percent					In.
180	All[1]	99	28	9	36	2.1
200	All	79	27	8	45	2.6
210	All	128	36	10	44	2.4
220	All	137	31	10	43	2.6
225	All	124	38	12	61	2.2
All[1]	12	82	29	7	46	1.1
All	9	116	28	9	48	2.1
All	6	135	37	12	41	2.2

[1] Number of checks and knots and depth of honeycombing for each test temperature at the different conditions for EMC were added separately and the average computed with the effects of one variable combined.

Salamon's (6) studies and the results from series 7 showed that elevated temperature and lowered EMC tend to increase checking, the number of loose or broken black knots, and depth of honeycombing; series 8, therefore, was introduced to study drying by a conventional schedule for the first 24 hours, followed by high-temperature drying.

Lumber origin: series 8

For charges in series 8, 2- by 8-inch Construction-grade lumber in 16-foot lengths was collected from various areas in Oregon (Table 8). A section was sawed from the center of each 16-foot board to measure moisture content, and the two 8-foot sample boards were randomly assigned to the control charge (designated by double-letter suffix) or the test charge (designated by single-letter suffix). The kiln schedule for each charge is given below:

Control charge			Test charge		
Time	Dry-bulb temp	EMC conditions	Time	Dry-bulb temp	EMC conditions
Hr	Deg F	Percent	Hr	Deg F	Percent
0-24	180	12	0-24	180	12
24-48	180	9	24-44	220	8
48-65	180	6	44-56	220	6
65-72	180	19	56-62	214	16

The lumber was warmed for about 5 hours to the initial dry-bulb temperature. Total time in kiln was different for each charge, because time at conditions for EMC of 6 percent was varied slightly so that average final moisture content would be about 15 percent.

Total kiln time averaged 11 hours more for the control charges than for the test charges. Average final moisture content for each set of matched charges was very nearly equal, with the greatest difference occurring in charges 8E and 8EE, which had average final moisture contents of 15.3 and 13.6 percent. The range in final moisture varied considerably between sets of matched charges; moisture contents for charges 8D and 8DD, 8E and 8EE, 8G and 8GG, and 8I and 8II tested as significantly different at the 5 percent level of probability. Range in final moisture content for all charges is graphically presented in Figures 4 through 12.

Generally, more small checks occurred in the test charges than in the control charges, but medium, large, and degrade checks numbered much the same in control and test charges.

After 30-40 days' storage inside the Laboratory, the tight-piled lumber from all charges in series 7 was metered with a long-needled

Table 8. Comparison of a Low-High Temperature Schedule and a Conventional Schedule for Drying Lumber.

		Moisture content				Rings	Checks								Bds	
							Small		Medium		Large		Degrade			
Charge	Kiln time	Initial	Avg	Final core	Dif[1]	per inch	Boards	Total	Boards	Total	Boards	Total	Boards	Total	per charge	Regions
		Percent	Percent	Percent			Percent		Percent		Percent		Percent			
8A	62	38	16	20	Not	--	20	18	8	2	8	3	0	0	25	Dallas
8AA	80	39	14	17	sig	--	40	30	16	9	4	1	0	0	25	
8B	67	44	14	17	Not	--	27	62	14	17	8	8	8	10	79	Dallas
8BB	74	44	14	17	sig	--	20	28	10	25	4	3	2	2	79	
8C	67	45	15	18	Not	14	26	47	4	4	3	2	0	0	68	Foster
8CC	78	45	16	18	sig	14	31	28	0	0	2	2	0	0	68	
8D	67	39	16	19	Sig	19	28	18	8	3	5	3	0	0	39	Springfield
8DD	78	39	17	20		19	23	9	8	4	0	0	5	3	39	
8E	67	32	15	19	Sig	22	35	32	24	15	0	0	2	1	46	Mt. Hood
8EE	77	32	14	16		21	20	20	7	4	0	0	2	1	46	
8F	67	52	16	18	Not	8	44	64	13	8	4	2	7	3	45	Toledo
8FF	77	52	15	18	sig	7	38	36	9	4	4	3	0	0	45	
8G	67	44	16	20	Sig	15	27	19	0	0	2	2	2	1	45	Coos Bay
8GG	78	44	14	17		14	29	18	9	6	2	1	7	3	45	
8H	67	56	14	18	Not	10	38	48	13	7	2	2	2	1	45	Tillamook
8HH	78	56	14	17	sig	10	22	19	7	8	4	2	2	3	45	
8I	64	50	13	15	Sig	16	40	38	13	6	2	1	7	3	45	Prineville
8II	78	50	14	16		17	33	21	4	2	4	3	0	0	45	

[1] Significant at the 5 percent level of probability.

resistance meter. The average moisture content (taken at 1/5 the thickness) had been reduced by 1.0 percentage point. The moisture content of the core (taken at midthickness) had been lowered by 2.4 percentage points, which shows that the moisture gradient within each board levels out even though the lumber is tight-piled for a short period.

Drying 2- by 6-Inch Dimension Lumber

Each charge in series 9 contained about 500 board feet of 2- by 6-inch lumber. Control charge 9AAAA was dried below 212 F, and three other charges were dried above 212 F (Table 9). Specific gravity averaged 0.45, and initial moisture content ranged from 32.9 to 76.0 percent.

Each charge in series 9 had a 4-hour warming and a 6-hour final conditioning period. Total time in kiln was 60 hours for the control charge, 9AAAA, and ranged from 41 to 50 hours for the test charges.

The range in final moisture content in series 9 was not significantly different, at the 5 percent level of probability, for charges 9A, 9AA, and 9AAAA, all near 17.0 percent; but charge 9AAA was significantly different, at 12.1 percent. The moisture gradient from shell to core ranged from 4 to 7 percent moisture content in charges 9A, 9AA, and 9AAAA and from 2 to 5 percent in charge 9AAA.

Checking was more frequent in charge 9AA than in the other charges, but charge 9AAA and 9AA had about the same number of small checks. Although charges 9AA and 9AAA were dried at identical temperatures and conditions for EMC, the initial drying conditions were held only 13 hours for charge 9AA but 18 hours for 9AAA, which may account for the increased number of medium, large, and degrade checks in 9AA.

Charges dried at temperatures above 212 F in series 9 showed that drying times could be shorter than with conventional temperatures with range and average final moisture contents the same or better. The number of small checks tended to increase with temperatures above 212 F but, excluding charge 9AA, medium, large, and degrade checks occurred to the same extent as in conventional drying.

Drying 2- by 4-Inch Dimension Lumber

The 2- by 4-inch lumber in series 10 was collected from mills in the mid-Willamette Valley. The charges had a warming period of 3 hours and a final conditioning period of 4 hours. Charges 10A through 10AAAA, as shown in Table 10, had initial moisture contents ranging from 35.1 to 54.7 percent and included lumber cut from the sapwood to inclusion of the pith. Initial moisture content was not determined for

Table 9. Comparison of High Temperature and Conventional Schedules on 2- by 6-Inch Douglas Fir Dimension Lumber.

	Kiln cond			Moisture content			Checks							
							Small		Medium		Large		Degrade	
Charge	Dry-bulb	EMC	Kiln time[1]	Avg initial	Avg final	Range	Boards	Total	Boards	Total	Boards	Total	Boards	Total
	Deg F	Percent	Hr	Percent	Percent	Percent	Percent		Percent		Percent		Percent	
9A	200	9	18	40	17	12-22	42	56	20	11	10	8	5	2
	220	8	12											
	220	7	10											
9AA	225	8	13	44	17	12-23	55	98	22	21	15	14	2	1
	230	6	18											
9AAA	225	8	18	44	12	9-17	60	95	18	14	8	5	0	0
	230	6	20											
9AAAA	180	9	26	38	17	12-21	48	59	22	14	3	3	0	0
	180	6	24											

[1] Excluding the 4-hour warm-up period and 6-hour conditioning period.

charges 10B through 10E; lumber in charge 10E was cut only from veneer peeler cores.

Charges in series 10 were kiln-dried at various temperatures and conditions for EMC (Table 10). Charges 10AAAA and 10B were dried at conventional temperature of 180 F; charges 10A, 10BB, 10BBB, 10C, 10CC, and 10D had an initial temperature of 180 F followed by temperatures above 212 F; and charges 10AA, 10AAA, 10CCC, 10DD, 10DDD, and 10E had temperatures above 212 F during the entire drying cycle.

The fewest small checks were noted in charge 10BB, (conventional+high temperature schedule), and the most small checks occurred in charge 10E, with a high-temperature schedule. The fewest medium checks occurred in charges 10A and 10BB with conventional+high temperature schedules and in charge 10AAAA with a conventional schedule; the most medium checks occurred in charge 10D with a conventional+high temperature schedule. Large checks were fewest in charges 10AAA and 10CCC with a high-temperature schedule and in charge 10BBB with a conventional+high temperature schedule; large checks were most numerous in charges 10CC and 10D with a conventional+high temperature schedule. Fewest degrade checks occurred in charges 10A, 10BB, and 10D with a conventional+high temperature schedule and in charge 10CCC with a high-temperature schedule; most degrade checks occurred in 10CC with a conventional+high temperature schedule. Generally, small checks increased with high-temperature schedules, but medium and large checks were most numerous in charges with conventional+high temperature schedules. Degrade checks were not increased by any of the three different schedules. Charges 10B to 10DDD, containing lumber sawed from logs and peeler cores, had about the same proportion of small checks, but lumber sawed from logs had a greater number of medium and large checks. Degrade checks were in about the same proportion for lumber sawed from logs or peeler cores. The difference in checking pattern between lumber sawed from logs or from cores was not influenced by the type of schedule, so none of the three types of kiln schedules was more favorable than the others.

Total time in kiln ranged from 53 to 57 hours with a conventional schedule, 32 to 47 hours with a conventional+high temperature schedule, and 24 to 45 hours with a high-temperature schedule. Temperatures above 212 F can reduce total time in kiln by as much as 60 percent without additional degrade from checking.

Average final moisture content was generally from 13 to 15 percent, except in charges 10AAA and 10BBB, where it was 10.7 and 11.9 percent. Although the average final moisture content can be accepted,

Table 10. Comparison of High-Temperature and Conventional Kiln Schedules on 2- by 4-Inch Douglas Fir Dimension Lumber.

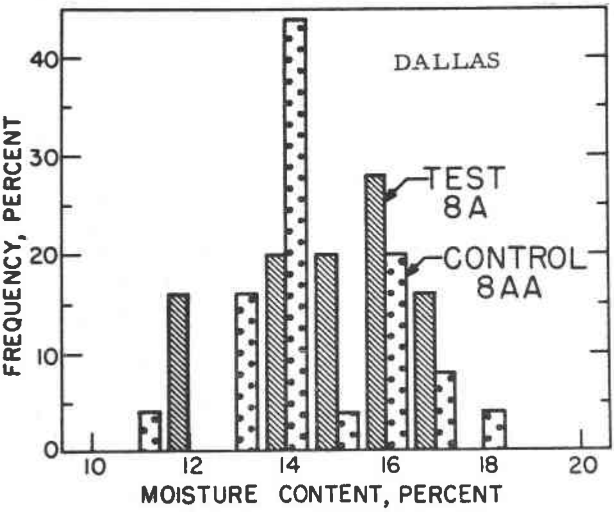
Charge	Kiln cond		Time	Moisture content			Checks								
							Small		Medium		Large		Degrade		
	Dry-bulb	EMC		Initial	Avg	Final Range	Boards	Total	Boards	Total	Boards	Total	Boards	Total	Boards
	Deg F	Percent	Hr	Percent	Percent	Percent	Percent		Percent		Percent		Percent		
10A	200	9	18	42	16	12-23	34	27	10	5	16	8	0	0	50
	220	8	12												
	220	7	10												
10AA	225	8	13	40	14	9-23	46	98	8	9	4	3	4	2	50
	230	6	18												
10AAA	225	8	18	45	11	7-15	52	84	0	0	0	0	4	3	50
	230	6	20												
10AAAA	180	9	26	38	16	13-20	28	21	8	5	4	2	2	1	50
	180	6	24												
10B	180	12	9	--	13	10-16	10	24	11	15	2	2	2	2	126
	180	9	17												
	180	6	20												
10BB	180	10	7	--	13	11-17	8	12	4	5	3	3	0	0	113
	220	8	17												
	230	6	7												
10BBB	180	6	7	--	12	10-14	16	25	6	8	0	0	1	1	125
	230	6	18												

10C	180	10	7	--	14	9-18	24	55	10	19	4	9	2	4	141
	220	8	17												
	230	6	7												
10CC	180	9	7	--	15	9-20	26	67	12	19	8	16	4	9	135
	230	6	18												
10CCC	230	6	17	--	13	10-16	25	61	9	21	0	0	0	0	137
10D	180	10	7	--	14	9-23	28	55	17	25	10	16	0	0	134
	220	8	17												
	230	6	7												
10DD	230	6	17	--	15	9-22	23	42	9	13	2	3	3	4	127
10DDD	230	6	17	--	15	8-22	49	102	8	11	1	1	2	6	130
10E	230	6	17	--	15	12-19	30	116	10	20	2	4	3	5	172

the range in moisture content was not desirable, as is especially evident in charges 10A, 10CC, and 10D with conventional+high temperature schedules, where the range was as great as 9-23 percent. Charges 10AA, 10DD, and 10DDD with high-temperature schedules had a range of 8-22 percent. This wide range, however, is attributable to the lumber, a total of 740 pieces sawed from logs, of which 24 pieces had a moisture content below 10 percent, and 14 pieces, above 19 percent. Eight hundred pieces of lumber sawed from veneer peeler cores had only 3 pieces with moisture content over 19 percent and no pieces below 10 percent. In charges 10B through 10DDD, the range in final moisture content between lumber sawed from logs or peeler cores was significantly different at the 5 percent level of probability in charges 10B, 10CCC, 10D, and 10DDD, showing that separation of lumber cut from logs and peeler cores would promote uniformity in drying. Total time in kiln for lumber sawed from peeler cores would average about 24 hours and for lumber sawed from logs, about 32 hours, for the lumber to average 15 percent final moisture content with range of 10-19 percent.

The range of final moisture content for charges 10B to 10E is shown in Figures 13-16.

Figure 4. Moisture content distribution for charges 8A and 8AA. Differences between moisture content of test charges and control were not significant at the 5 percent level of probability.



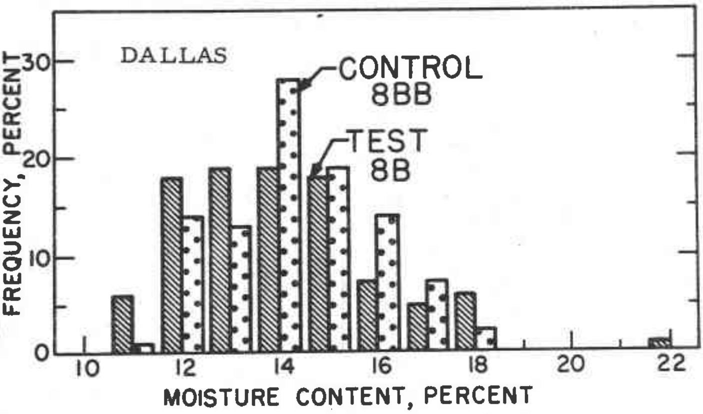


Figure 5. Moisture content distribution, charges 8B and 8BB--differences not significant.

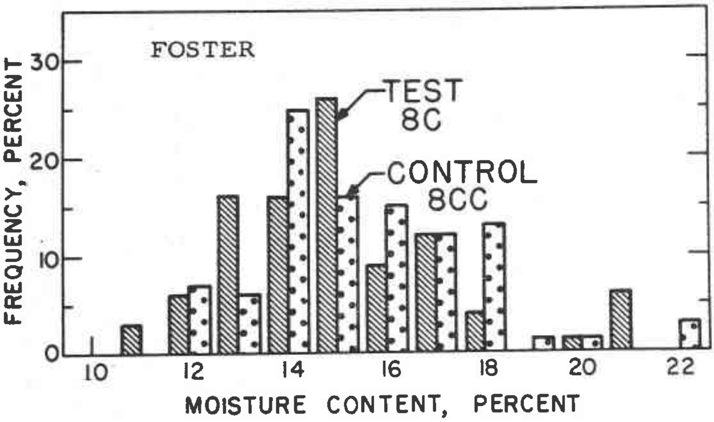


Figure 6. Moisture content distribution, charges 8C and 8CC--differences not significant.

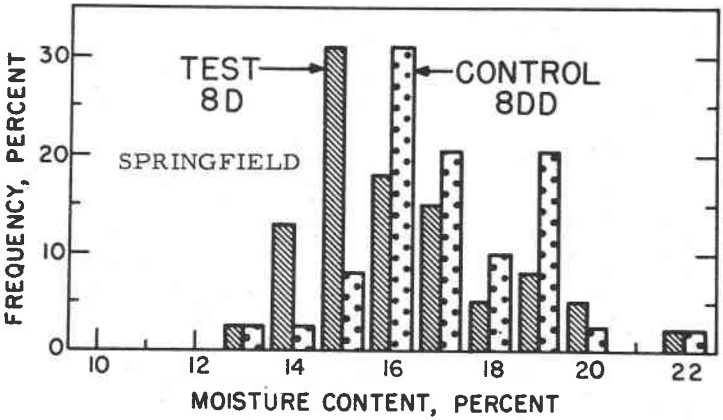
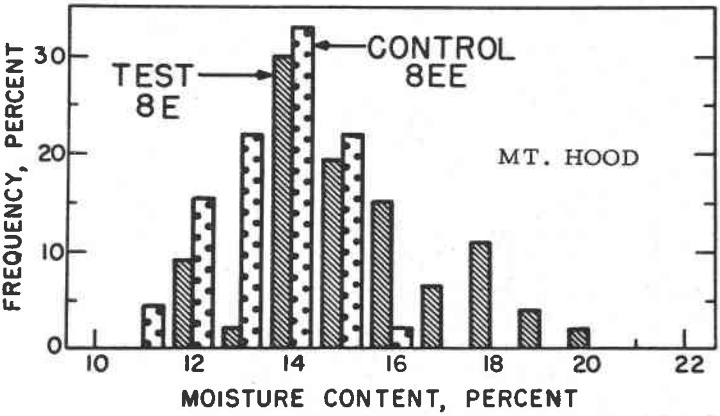


Figure 7. Control charges had significantly more pieces with higher MC than test charges.

Figure 8. Test charges had significantly more pieces with higher MC than control charges.



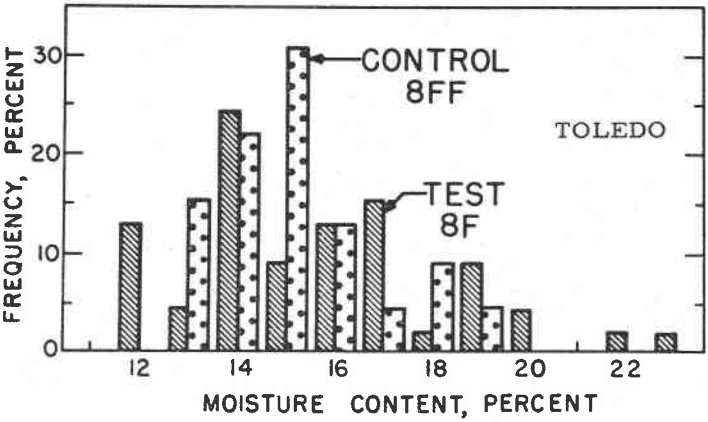
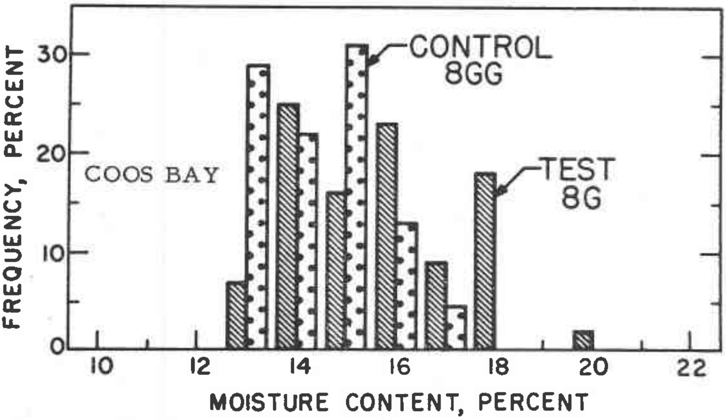


Figure 9. Differences between test and control charges were not significant.

Figure 10. Test charges had significantly more pieces with higher MC than control charges.



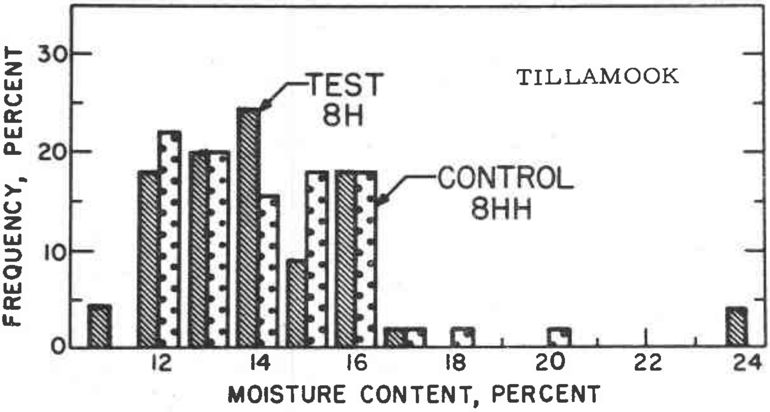


Figure 11. Above. Differences between test and control charges were not significant.

Figure 12. Control charges had significantly more pieces with high MC than test charges.

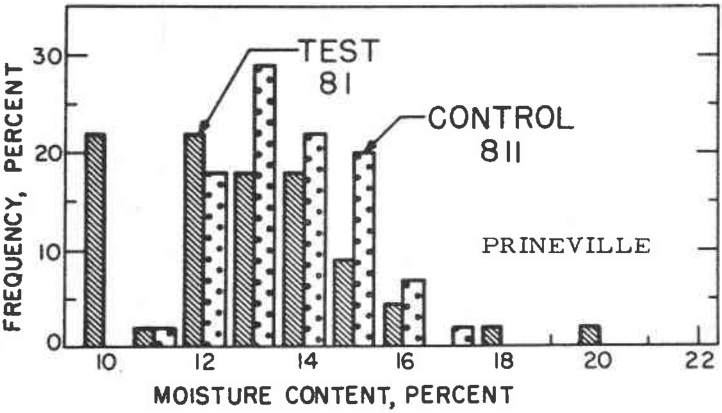


Figure 13.

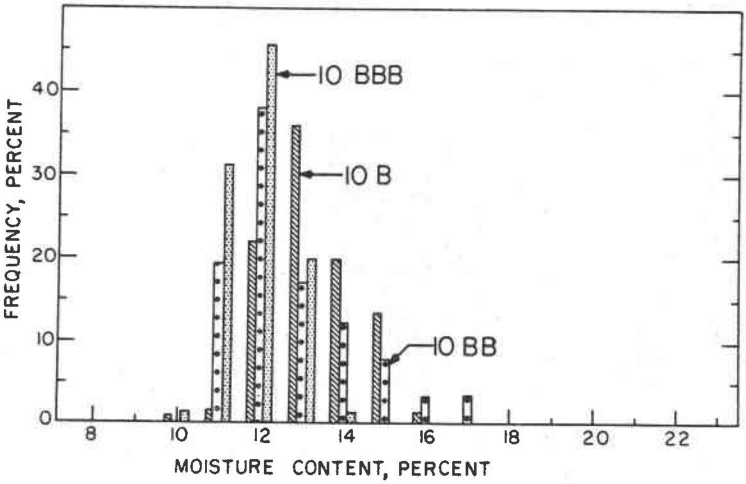
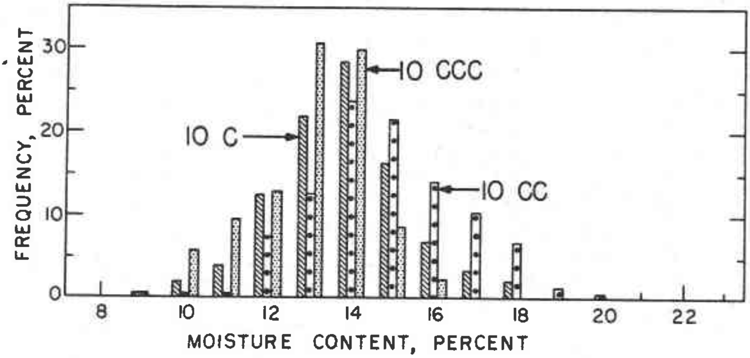


Figure 14.



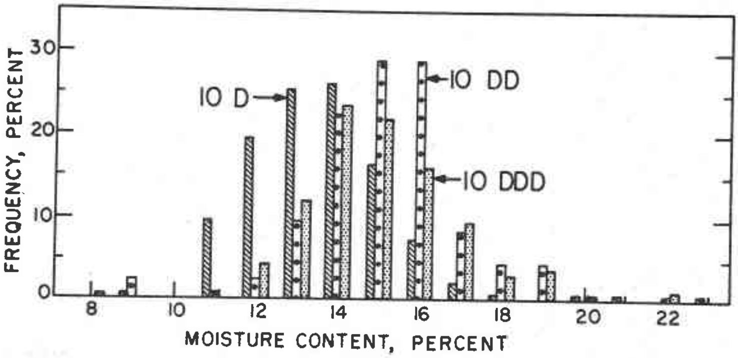
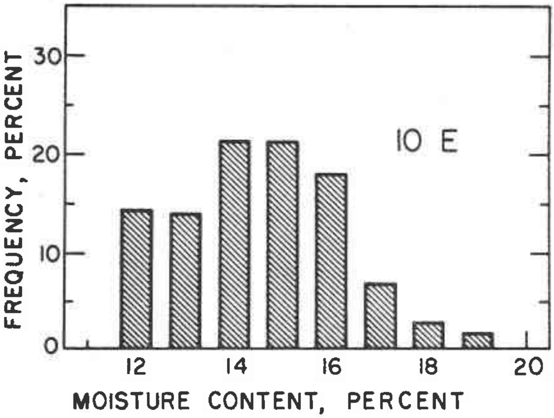


Figure 15.

Moisture content distribution for charges 10B, 10BB, and 10BBB; 10C, 10CC, and 10CCC; 10D, 10DD, and 10DDD. High-temperature drying produced about the same final moisture content as conventional drying but in a shorter time.

Figure 16. Moisture content distribution for charge 10E, showing that segregation of lumber cut from peeler cores promotes uniformity in drying.



General Considerations

Although different air velocities were not tested in this study, findings of other investigators (5) indicate that velocities of 600 feet per minute or better, measured on the leaving air side, are required for uniformity of final moisture content. With higher air velocities, good baffling practices are required. Fan reversal every 3 hours is recommended.

Cooling the lumber in the kilns after drying is suggested in areas having temperatures below freezing. A sharp change in temperature of wood causes thermal contraction that may induce splitting or checking in the wood surface.

The amount of warping was not measured, but a visual evaluation suggested that less twisting and cupping occur in lumber dried at high temperature than at conventional temperature.

The effect of high temperatures on the strength of Douglas fir is an important factor. Kozlik (2) showed that temperatures above 212 F reduced the shearing strength by 15-20 percent, modulus of rupture by 10-12 percent, modulus of elasticity by 4-5 percent, and toughness by 25-30 percent in 1 1/2-inch clear squares. Kozlik (3) illustrated that temperatures above 212 F affected the strength properties of 2- by 6-inch Douglas fir dimension lumber in 40, 60, and 80 percent strength-ratio classes as follows: modulus of elasticity was reduced by 1-2 percent, and modulus of rupture was reduced by 20-22 percent.

CONCLUSIONS

1. Douglas fir 2- by 8-inch dimension lumber cannot be subjected to temperatures above 212 F during the initial stages of drying without inflicting serious degrade from surface checks and end-grain honeycombing. Drying for at least 24 hours at 180 F dry-bulb temperature at conditions for EMC of 12 percent, followed by temperatures of 220-230 F, will produce lumber with degrade equivalent to that from commercial practices. Total time in kiln averaged 10-15 percent less for lumber dried with conventional-high temperature schedules than for lumber dried with a conventional schedule. Final average moisture content was 13-16 percent.

2. Douglas fir 2- by 6-inch dimension lumber can withstand temperatures above 212 F during the initial stages of drying without serious degrade. A few charges of 2- by 6-inch lumber were tested in this study, and it is suggested that such lumber be dried for at least 18 hours at 180 F dry-bulb temperature at conditions for EMC of 9 percent before raising temperature to 220-230 F. Total time in kiln will average about 50 hours with the average final moisture content about 16-17 percent.

3. Douglas fir 2- by 4-inch dimension lumber can be subjected to temperatures as high as 230 F at the start of the drying cycle without inflicting serious degrade. Total kiln time averages 24-32 hours with the average final moisture content 13-15 percent. Before drying, separation of lumber sawed from logs and from peeler cores insures increased uniformity in final moisture content.

4. A warming period to heat the lumber to wet-bulb temperature is advisable. During this period both the dry- and wet-bulb temperature should be held to a differential of 2 or 3 F. A 5-hour warming period is suggested for 8-inch widths, a 4-hour period for 6-inch widths, and a 3- to 4-hour period for 4-inch widths.

5. Final steaming or conditioning is recommended to reduce the moisture gradient from shell to core and soften the surface of the outer shell for machining. Lumber sawed to 8-inch widths should be conditioned for 6 hours, 6-inch widths for 5 hours, and 4-inch widths for 4 hours.

6. Many commercial end-coatings perform poorly at temperatures above 212 F. A solution of calcium chloride and starch prevented excessive end-grain honeycombing in lumber dried at high temperatures. A bonding agent of silicone rubber that vulcanizes at room temperature performed best of all coatings tested.

7. Number of small checks increased with elevated temperature, but number of medium and large checks increased slightly with higher temperature on 2- by 8-inch lumber only, and not on 4- and 6-inch widths. Degrade checks were not affected by elevated temperature in any of the lumber tested. Number of small, medium, and large checks in 8-inch width lumber increased as conditions for EMC of 12 percent changed to conditions for EMC of 6 percent. Depth of end-grain honeycombing was not affected by temperature but tended to increase when conditions for EMC of 12 percent were changed to conditions for EMC of 6 percent.

8. In all widths tested, temperatures above 180 F caused additional breaking and loosening of black knots during machining. Intergrown knots, 1 1/2 inches and wider, generally were partly broken or chipped out during machining.

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PROGRAM AND PURPOSE

The Forest Research Laboratory of the School of Forestry combines a well-equipped laboratory with a staff of forest and wood scientists in a program designed to improve the forest resource and promote full utilization of forest products. The extensive research done by the Laboratory is supported by the forest industry and by state and federal funds.

The current report results from studies in forest products, where wood scientists and technologists, chemists, and engineers are concerned with properties, processing, utilization, and marketing of wood and of timber by-products.

The PROGRAM of research includes

- identifying and developing chemicals from wood,
- improving pulping of wood and wood residues,
- investigating and improving manufacturing techniques,
- extending life of wood by treating,
- developing better methods of seasoning wood for higher quality and reduced costs,
- cooperating with forest scientists to determine effects of growing conditions on wood properties, and
- evaluating engineering properties of wood and wood-based materials and structures.

The PURPOSE of research on forest products is to expand markets, create new jobs, and bring more dollar returns, thus advancing the interests of forestry and forest industries, by

> developing products from residues and timber now wasted, and

> improving treatment and design of present wood products.

AN ADVISORY COMMITTEE composed of men from representative interests helps guide the research program in forest products. The following men constitute present membership:

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GEORGE C. FLANAGAN, Principal JOHN E. HANSEN, Alternate	Southern Oregon Timber Industries Association
J. R. GATES, Principal RAY L. TODD, Alternate	West Coast Lumber Inspection Bureau
DONALD W. PLEIER, Principal CHARLES W. BEST, Alternate	Western Wood Preservers Institute
W. J. RUNCKEL, Principal T. K. MAY, Alternate	Western Wood Products Association (WCLA)
FRED SOHN, Principal S. H. ELLINGSON, Alternate	Western Forest Industries Association

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