EFFECT OF AIR CIRCULATION ON DRYING*

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Systematic investigations are being undertaken in the Vancouver Forest Products Laboratory to evaluate factors influencing the rate of drying and the quality of lumber obtained. Some factors studied are related to the parameters of drying, including air-circulation rate, sticker thickness and power consumption. Others include the physical properties of different wood species, such as the permeability to liquids and vapors, modifications of permeability by steaming, and possible changes in the distribution of the water-soluble extractives during drying.

In a conventional dry kiln, after the initial heat-up time, the drying air moving across the charge supplies the necessary heat for evaporation of moisture and serves, at the same time, as a medium to remove the water vapor from the boundary layer -- a thin, saturated layer continuously forming over the drying surface. The transferred heat is proportional to the temperature difference between the bulk air stream and the wood surface. This boundary layer is initially at the wet-bulb temperature, but its temperature slowly rises toward the dry-bulb temperature as the wood dries.

This report shows the effect of three air-circulation rates -- 400, 600 and 900 fpm -- upon the rate of drying and the quality of western hemlock, Douglas fir and western white spruce dimension lumber. The conclusions are then applied to the drying of western white spruce dimension lumber.

SUMMARY OF EARLIER RESEARCH

Early work by the U.S. Forest Products Laboratory (Torgeson 1940) dealt with the effect of air-circulation rates from 400 to 1600 fpm upon 1-in. maple, and concluded in general that more air should be furnished at the beginning, followed by lesser amounts as the moisture content of the stock decreases and reductions are made in relative humidity.

Guernsey (1957) reported the effects of air-circulation and wet-bulb depression upon drying of 1-in. western hemlock in the range of 400 to 1100 fpm. Both factors seemed to have an effect on drying, but substantial savings in drying time were not shown.

Kollmann and Schneider (1961) intensively studied the effect of air-circulation rates in the range of 240 to 2170 fpm in super-heated steam using 3/4-in. beech and pine sapwood. Following the theory of the convection drying of hygroscopic material they found that the first drying period, where drying rate is constant, is influenced most by air circulation in both superheated steam and in superheated vapor. The effect of the high circulation rate diminished as drying progressed.

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Salamon reported preliminary results (1965a, 1966) and showed that savings can be made in drying 1-in. and 2-in. western hemlock lumber using a circulation rate of 900 fpm compared to 600 fpm. The use of high velocity in the early part of drying followed by a low velocity in drying below fiber saturation point (fsp) was suggested (Salamon 1965b).

It has been shown, under constant entering-air conditions, that a constant relative drying rate can be expressed as the wet-bulb depression multiplied by air velocity (Dedrick 1965, 1968). According to this relationship, a well-controlled kiln could achieve a constant specific drying rate by initially operating at a low depression with a high air-circulation rate, followed later by a high depression and a correspondingly low circulation rate.

This would be expressed by the equations:

$$\ln \frac{Mo}{M} = kt, \text{ where}$$

Mo = initial MC

M = observed MC

k = specific drying rate constant (hr^{-1})

t = time of drying from initial Mo, hours

and $k = f(T_d - T_w)$ (air-velocity)

where T_d = dry-bulb temp. (^{o}F)

T_w = wet-bulb temp. (^{o}F)

Studying the effect of a wide range of circulation rates, Sharp (1968) and Crews and Brown (1968) did not experience any noticeable increases in drying rate with increasing circulation rates. Unexpectedly, they found less degrade in lumber at the expense of increased cost.

The concept of having three different periods of drying is well known: (1) the constant rate, until the surface layer reaches the fsp; (2) the slightly falling rate, until the core passes through the fsp; and (3) the final period connected with vapor diffusion alone (Lykov 1955, Krischer/Kroll 1956). The first and last of these three drying phases are distinguishable with ease, but the boundaries of the second phase cannot be determined exactly.

EQUIPMENT USED IN STUDY

The kiln used was an experimental welded-aluminum kiln, which accommodates 160 board feet of 2-in. stock in 3-ft. lengths. The charge rests on the platform of a tared scale with a weight-print attachment so that moisture content changes can be noted at any time.

The kiln was designed and instrumented to permit the use of a wide variety of wet and dry-bulb temperatures and air velocities with precision and reproducibility. Provision was not made for reversal of air flow because of the narrow, 3-ft. width of the maximum load.

Temperature was measured by copper constantan thermocouples connected to a commercial chart recorder. Temperature controls were non-proportionating and manual, because moisture content schedules were used. The thermocouples located in the plenums were so arranged that only the air on the entering side of the lumber charge was monitored.

HOW THE STUDY WAS DONE

Two shipments each of western hemlock, western white spruce and Douglas fir 2 x 8-in. dimension lumber were obtained in lengths suitable to provide three matched charges of 3-ft. lumber. Each of the three charges was intended for use with one of the selected air-circulation rates of 400, 600 or 900 fpm. One western hemlock charge dried at high velocity was discarded because of kiln malfunction during drying and was, therefore, replaced by another charge from a third shipment.

The concept of three different periods of drying was accepted in this study. In all of the experiments, drying was carried out at the same moisture content schedule: 180°F dry bulb (DB) and 8°F depression (EMC 12.2 %) from green; 180°F DB and 11°F depression (EMC 10.6%) from 25% moisture content and finally 180°F DB and 15 degrees depression (EMC 9.0%) from 20% moisture content until an average of 15% was reached.

The changes of 25%, 20% and 15% moisture content was made on the basis of calculated weight of the total load. Using the above settings, time became a variable and thus an immediate measure of the influence of air-circulation upon drying rate. Two replications were made of each air-circulation rate.

In addition, another schedule using 170°F with 8, 11 and 15 degrees depression respecitvely was also used for Douglas fir because previous experience indicated that lower DB temperature might result in a similar drying rate to that obtained at higher (180°F) DB, but with less degrade.

Air-circulation rates were determined on the leaving-air side of the load from the average of three readings taken at room temperature with a hot-wire meter. Correction of these velocities for temperature and humidity changes experienced during drying was not attempted. Three-quarter inch aluminum stickers were used throughout the study.

The selection of lumber shipments was supervised by a qualified lumber grader. The moisture content ranged from 45.4% to 124.3% for western hemlock, from 29.8% to 74.2% for Douglas fir and from 30.7% to 95.9% for western white spruce.

Stratification was used in randomly assigning the macthed charges of each shipment to a schedule. The usual method described in detail elsewhere (Salamon 1963, 1965a) was used in the preparation of charges, and evaluation of moisture content, moisture distributions and quality changes.

RESULTS AND DISCUSSION

Table 1 presents information on charge, air-velocity, stepwise drying schedule, initial and final moisture contents and drying rate. Drying time was subdivided into three parts necessary to reach the corresponding approximate moisture contents of 25%, 20% and 15%. The appropriate breakdown of drying rate is shown in the table.

The lower range of final moisture content varied from 11.1% to 13.6% for western hemlock, while the upper range varied from 16.9% to 24.7%. Similar ranges, of western white spruce varied from 10.2% to 12.5% and from 14.7% to 17.8%, while those of Douglas fir varied from 10.9% to 13.1% and from 14.5% to 17.6%. The variation in final moisture content between pieces within a charge was about the same for all species at all levels of air velocity.

Drying rates as shown in Table 1 for each air velocity showed considerable variation, particularly between the three phases of drying. The data are self-explanatory and show the wide inherent variations to be expected between charges. Total drying rate between replicates varied from 1% to 5% for western hemlock, from 48% to 61% for western white spruce and from 7% to 43% for Douglas fir. Drying curves for averages of two charges of the three woods studied are shown in Figure 1. By showing averages, some of the individual variations were removed. For each species the actual drying time is shown and reductions in kiln-residence time can be read directly. They should be evaluated in conjunction with degrade (Figure 2) and MC differentials between cores and shells of individual boards.

Table 2 lists relative drying rates for moisture-content phases presented individually in Table 1. These phases are: green to 25%, 25% to 20%, 20% to 15% and finally green to 15%. The basis of calculating the effect of increasing air-velocity was 400 fpm and showed, for the green to 25% phase, 19% and 38% increase in drying rates at 600 and 900 fpm respectively for western hemlock, 25% and 42% increase for western white spruce and 155% and 100% for Douglas fir in similar order.

TABLE 1 - DRYING SCHEDULES FOR THREE SOFTWOOD SPECIES

Moisture Content Schedule Used: 180°F D.B. with depression of 8, 11, 15°F after the 25, 20, and 15 % M.C. was reached

Run No.	Air velocity ft. per min.	Drying Time Elapsed to reach M.C. Hrs.	% M.C. (Approx.)	Total Drying Time Hrs.	Initial M.C. Ave. %	Final M.C. Ave. %	Drying Rate % M.C./hr. Phase	Total
	WESTERN HEMLOCK							
111	400	109.0	25				.374	
		36.5	20				.137	
		30.5	15	176	65.8	15.2	.157	.288
131	400	104.0	25				.410	
		29.0	20				.172	
		43.0	15	176	67.6	14.2	.135	.303
132	600	94.5	25				.490	
		28.5	20				.175	
		38.0	15	161	71.3	14.4	.147	.353
112	600	86.5	25				.446	
		21.5	20				.233	
		30.0	15	138	63.6	15.3	.157	.350
133	900	77.5	25				.561	
		23.0	20				.217	
		33.5	15	134	68.5	14.8	.155	.401
123	900	87.5	25				.522	
		11.5	20				.435	
		27.0	15	126	70.7	18.7	.048	.413
	WESTERN WHITE SPRUCE							
211	400	66.0	25				.279	
		25.0	20				.200	
		36.0	15	127	43.4	13.6	.183	.235
221	400	42.0	25				.510	
		21.0	20				.238	
		32.0	15	95	46.4	12.7	.228	.355
212	600	43.0	25				.416	
		28.5	20				.175	
		40.5	15	112	42.9	13.4	.163	.263
222	600	35.0	25				.571	
		17.0	20				.294	
		29.0	15	81	45.0	13.4	.227	.390
213	900	46.5	25				.417	
		25.0	20				.200	
		40.5	15	112	44.4	12.7	.180	.283
223	900	32.5	25				.702	
		18.5	20				.270	
		26.0	15	77	47.8	12.6	.285	.457
	DOUGLAS FIR							
321	400	93.5	25				.171	
		29.0	20				.172	
		51.5	15	174	41.0	15.1	.095	.149
331	400	55.0	25				.245	
		25.0	20				.200	
		39.0	15	119	38.5	13.1	.177	.213
322	600	21.0	25				.771	
		52.5	20				.095	
		55.5	15	129	41.2	14.8	.094	.245
332	600	49.0	25				.292	
		26.0	20				.192	
		44.0	15	119	39.3	13.2	.155	.219
323	900	42.0	25				.381	
		21.0	20				.238	
		40.0	15	103	41.0	15.4	.115	.249
333	900	41.0	25				.451	
		24.0	20				.208	
		33.0	15	98	43.5	13.8	.188	.303

Table 2. Relative Drying Rates By Species For Runs Of Different Air Velocities (%).

Species	Air Velocity (f. p. m.)	Green to 25%MC	25 to 20%MC	20 to 15%MC	Green to 15%MC
Western hemlock	400	100	100	100	100
	600	119	132	104	119
	900	138	210	70	137
Western white spruce	400	100	100	100	100
	600	125	107	95	111
	900	142	107	113	125
Douglas fir	400	100	100	100	100
	600	255	77	92	128
	900	200	120	112	152

In the two moisture content ranges less than 25%, increase in air velocity did not produce a significant change in drying rates, with the exception of western hemlock and Douglas fir drying from 25% to 20%. In the last phase, from 20% to 15% with each of the species studied, lower and higher rates than those noted at 400 fpm were found with 1-in. lumber earlier (Salamon 1966).

EFFECTS OF DRYING ON DEGRADE

The overall drying rates from green to 15% moisture content for each species showed a general increase with increasing air velocity, but these results must be assessed in conjunction with the amount of degrade.

The method used for grading was developed and reported earlier (Salamon 1963, 1964a). Using this technique, the surfaced lumber was divided into three categories based on number and severity of defects resulting from drying. These categories were: A--no or slight defects; B--medium defects, which normally do not cause change in the lumber grade; C--heavy defects, which would usually result in lower lumber grade. A summary of quality changes for each charge, based upon individual defects, is shown in Figure 2.

In general, it appeared that the degrade from drying at 180°F DB temperature was greatest at 900 fpm air velocity for spruce and Douglas fir. Western hemlock was a special case. It did not show defects when dried at 400 fpm and exhibited heavy but variable degrade at 600 and 900 fpm velocity. Western white spruce showed increasing degrade with increase in air velocity. The proportion of heavy defects in spruce was higher than 10% with the 900 fpm velocity.

Douglas fir followed a pattern similar to spruce, but exhibited defects to a greater degree. The higher amount of degrade was probably caused by a high evaporation rate from the lumber surface, unaccompanied by corresponding moisture movement from the core. Thus the moisture difference resulted in unequal stress and shrinkage development causing defects to develop.

Those Douglas fir charges which were dried at 170°F constant DB temperature exhibited no C degrade at the highest air velocity and only 4.5% B degrade at this velocity. No defect whatsoever was evident at lower air velocities. These results underline the importance of applying lower DB temperatures initially.

In a minimum of 83% of the Douglas fir and western white spruce pieces from all schedules but one, the moisture differential between core and shell was found to be less than 5%. However, in the highest air-velocity run number 323 of Douglas fir, only 21% of the pieces had a moisture differential less than 5%. This 5% value is the boundary between acceptable quality and casehardened wood. In the western hemlock runs, the percentage of

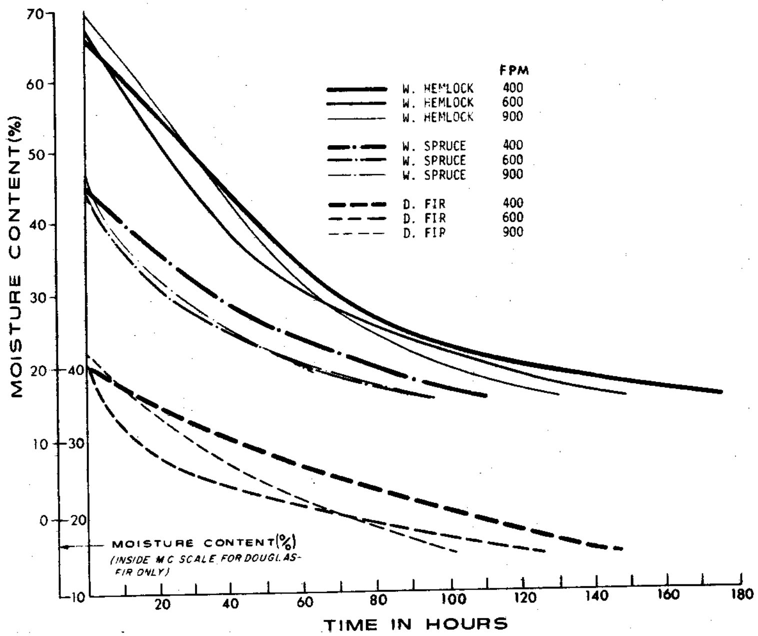

Figure 1. Drying curves for averages of 2 charges for three species.

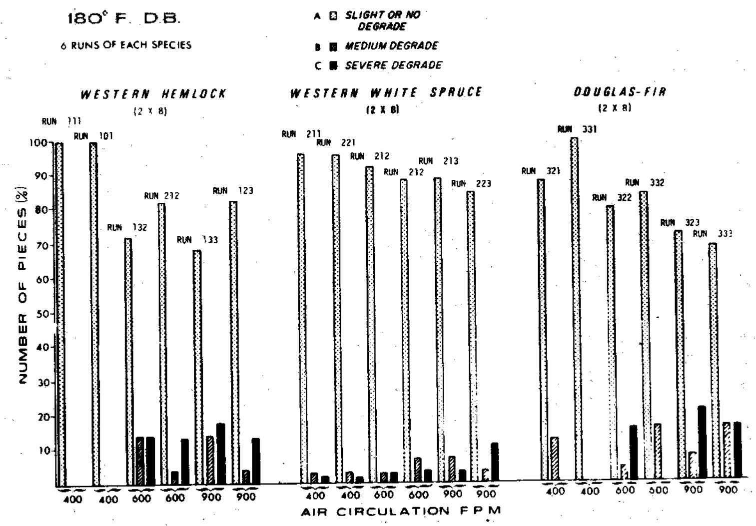

Figure 2. Effect of air circulation on lumber quality is shown by grading result of 3-ft long lumber.

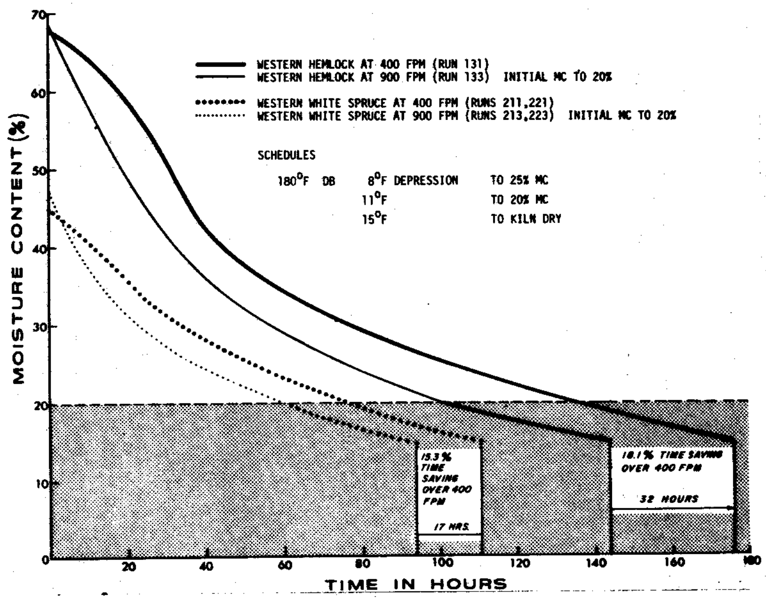

Figure 3. Combination drying curves made up by two air velocities.

pieces with a moisture differential less than 5% ranged from 36% (Run 123) to 96% (Run 112). This once again illustrates the wide variability in the drying properties of Douglas fir and western hemlock and emphasizes the advantage of segregation into moisture classes, possibly into sapwood and heartwood with greatly differing permeabilities. Conditioning treatments could also be used with an additional extension of the schedules.

DRYING TIMES REDUCED

On the basis of these experimental results, a definite saving in drying time is indicated for all species studied. Figure 3 summarizes these results for western hemlock, western white spruce and Figure 4 for Douglas fir. Two curves are shown for each species, the low-velocity control curve (400 fpm) and a curve designed to include high velocity (900 fpm) in the initial part and a low velocity (400 fpm) after the fsp is reached.

The aim of changing air velocity from 900 to 400 fpm is to achieve an acceptable lumber quality in addition to the shortening of the kiln cycle, without unduly increasing power consumption of the fans. To test the possible saving, a shipment of western white spruce dimension lumber was selected, subdivided into three charges and each randomly assigned to an elevated temperature or one of two low-high temperature schedules. During the first 20 hours of the elevated-temperature schedule, the initial air-circulation rate was maintained at 900 fpm, which was switched subsequently to 250 fpm. The two low-high temperature schedules differed only in their velocities and were run at air-circulation rates of 900 and 500 or 900 and 250 fpm. The changes in all three schedules were made at the time, established by continuous remote-control readings, when the fsp at the core of lumber was passed. The drying curves are shown in Figure 5.

Table 3 shows data and evaluation of drying schedules used in Figure 5. The basis of comparison is the elevated temperature schedule, the settings of which are shown stepwise together with the air velocity measured in the slots. Final moisture contents of the three charges show that the upper limits were well within the acceptable range of the new kiln-dry standard except for one piece in Run 1-4 which had a final MC of 24%. This piece was not the highest in initial moisture content. The range and average moisture-content differential between shell and core increased with severity of treatment; however, the average values were acceptable and reasonable.

During a recent study in the pilot kiln it was found that 2x8-in. western white spruce required 75 hours of drying at 250 fpm to achieve an acceptable moisture distribution (Salamon 1969). Using this time schedule as a basis, the elevated-temperature Run 4-4 achieved a saving of 28% in the time and the low-high temperature Runs 1-4 and 5-4, 47%. Run 1-4 showed slightly more degrade than Run 5-4.

The power required by the combination circulation rates for these schedules can be estimated from data accumulated in runs in our pilot kiln which is capable of circulation rates of 250, 500 and 900 fpm. Run 4-4 scheduled at 900 and 250 fpm would require about 15.5 kwh/Mfbm, which is the consumption determined for the 75-hour control schedule at 250 fpm (Salamon 1969). The low-high temperature Run 1-4 schedules at 900 and 500 fpm would require 16% more power. Run 5-4, the low-high temperature schedule at 900 and 250 fpm would require 13% less than the control. The calculations are based on a maximum moisture-content loss of 40% from green to dry.

SUMMARY OF CONCLUSIONS

1. The study showed that under the same moisture-content schedule, residence time decreased with increased air velocity, and resulted in similar ranges of final moisture content.

2. Least amount of degrade was experienced with wood dried at the lowest level of air circulation regardless of species. Degrade increased in western white spruce and Douglas fir with increase in air velocity. No trend was indicated for western hemlock.

3. If a combination is used, of 900 fpm air velocity from green to fsp and 400 fpm to the end of the drying reductions in kiln-residence time in the order of 18% for hemlock, 15% for spruce and 25% for Douglas fir are indicated.

4. By using a combination of air-circulation rates of 900 and 250 fpm in conjunction with an elevated-temperature schedule or a low-high temperature schedule, a substantial saving in drying time of western white spruce was achieved when compared to an industrial schedule of 75 hours at 250 fpm air velocity.

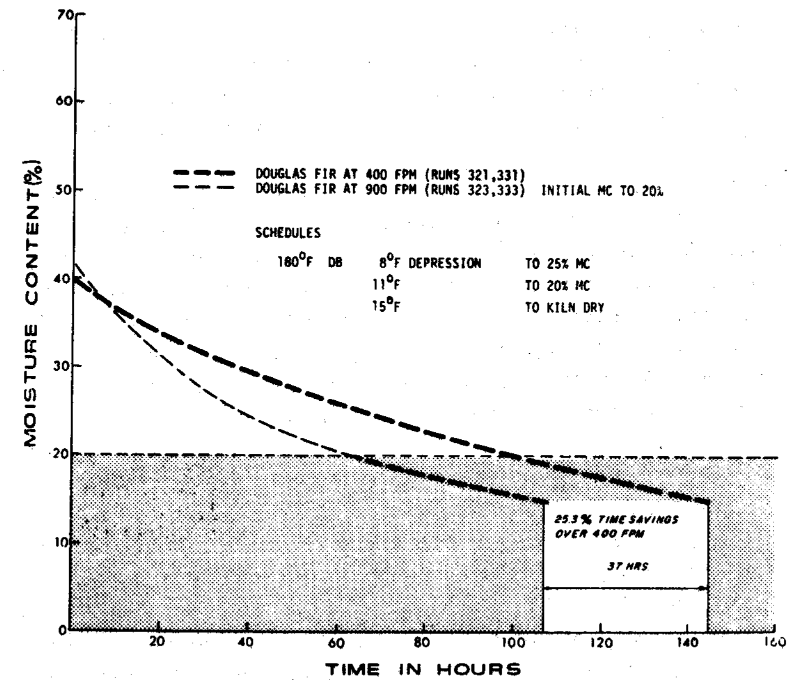

Figure 4. Combination drying curves made up by two air velocities.

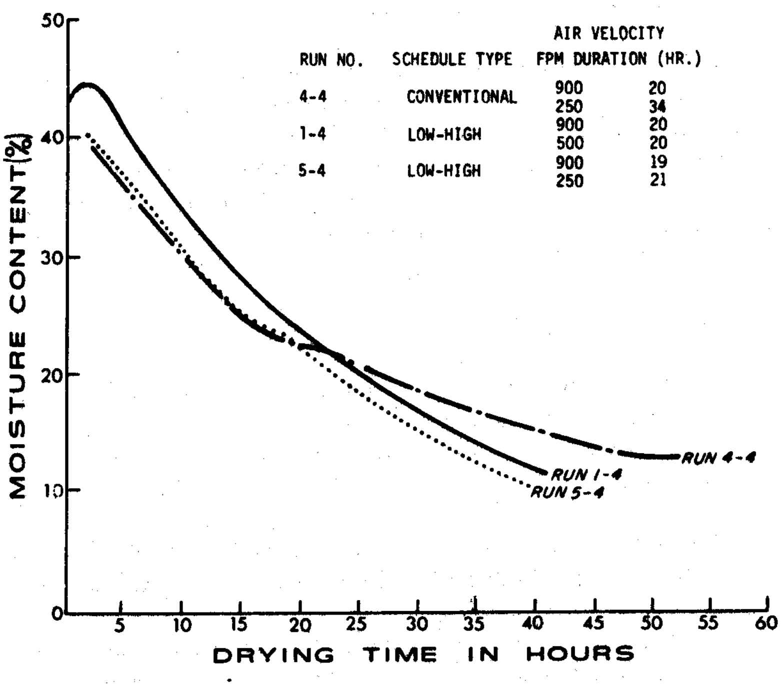

Figure 5. Drying curves of western white spruce lumber employing different heating rates and varied combinations of air velocities.

TABLE 3. DRYING SCHEDULE OF WESTERN WHITE SPRUCE LUMBER AT VARYING AIR VELOCITIES

Schedule	Run No.	Air velocity maintained (f.p.m.)	Hrs.	D.B. Temp. °F	W.B. Dep. °F	Drying time elapsed to reach M.C. Hrs.	Drying time elapsed to reach M.C. % M.C.	Total drying time Hrs.	Drying Rate % Hr. Ind.	Drying Rate % Hr. Total	Initial M.C. Min.	Initial M.C. Ave.	Initial M.C. Max.	Final M.C. Min.	Final M.C. Ave.	Final M.C. Max.	% M.C. difference between Shell and Core Min.	% M.C. difference between Shell and Core Ave.	% M.C. difference between Shell and Core Max.	Degrade (%) A	Degrade (%) B	Degrade (%) C
Elevated Temp.	4-4	900	20	170	10	16.0	25		0.92													
				180	20																	
				190	30	27.0	20		0.45													
		250	34	200	40																	
				180	10	54.0	13.4	54	0.24	0.49	27.6	39.7	99.7	8.3	11.5	13.7	-1.0	2.8	4.7	89.4	5.3	5.3
Low-high Temp.	5-4	900	19	170	10	15.5	25		0.93													
				180	20																	
				190	30	23.0	20		0.67													
		250	21	232	27	40.0	10.0	40	0.59	0.73	31.5	39.4	93.1	5.5	9.8	13.5	-0.2	3.3	7.4	89.4	5.3	5.3
Low-high Temp.	1-4	900	20	170	10	17.0	25		1.10													
				180	20	25.0	20															
				190	30				0.62													
		500	20	232	27	40.0	12.0	40	0.53	0.79	29.3	43.7 (43.0)	86.6	7.0	10.8 (10.4)	24.0 (14.1)	0.0	4.5 (4.1)	19.5 (7.9)	84.2	10.5	5.3

( ): Values after removal of one high final moisture content piece
Ind.: Individual drying rate for each step of schedule
A = None; B = Medium; C = Severe

5. Drying degrade of a western white spruce charge was the same, regardless of whether an elevated temperature or a low-high temperature schedule is used in conjunction with a combination of 900 and 250 fpm air velocities.

6. Energy consumption was estimated to be about the same in the conventional kiln charge with combination of 900 fpm velocity for 20 hours and 250 fpm velocity for 34 hours, as compared to 250 fpm constant air velocity for 75 hours. Moisture distribution and lumber quality was comparable.

7. Further work is needed for Douglas fir and western hemlock to show the economic advantages of the above combination of air velocities.

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