

THE EFFECT OF WETWOOD ON LUMBER DRYING TIMES AND RATES: AN EXPLORATORY EVALUATION WITH LONGITUDINAL GAS PERMEABILITY

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(Received March 1985)

ABSTRACT

Lumber containing wetwood, or sinker heartwood, cannot be dried as rapidly as lumber with normal wood. To determine why wetwood dries more slowly, measurements of longitudinal gas permeability (LGP) were made in sapwood, heartwood, and wetwood from white fir (*Abies concolor*) and aspen (*Populus tremuloides* and *P. grandidentata*). The LGP values were then compared with drying times, drying rates, and anatomical characteristics of matched wood samples. Sapwood had highest average LGP values (11 to 38 Darcys) and fastest drying rates. Heartwood had lowest average LGP values (0.2 to 0.8 Darcys) and slow drying rates, but short drying times because of low green moisture content. Wetwood had longest drying times and slowest drying rates, but higher average LGP values (0.2 to 2.5 Darcys) than heartwood.

Scanning electron micrographs (SEM) show that low LGP values and slow drying rates for heartwood and wetwood are due largely to aspiration of bordered pits in white fir tracheids and to tyloses formation in aspen vessels. Scanning electron microscopy suggests that wetwood drying rates may be further reduced by deposits of bacteria and extraneous material that block transverse moisture diffusion and increase moisture holding capacity of the wood. Concurrently, wetwood bacteria may increase LGP by destroying tori in aspirated pits of white fir and by aborting tyloses development in aspen.

Keywords: Bacterial wetwood, lumber drying, longitudinal gas permeability, aspen, white fir.

INTRODUCTION

The presence of wetwood, or sinker heartwood, in softwood dimension lumber slows drying times, resulting in losses of energy and higher manufacturing costs (Ward and Pong 1980). At the end of a conventional kiln-drying cycle, most wetwood boards will be above a maximum allowable moisture content (MC) of 19% and must usually be separated from normal lumber of the dry chain and redried. Redry operations can increase kiln-drying costs by 40% or more (Ward and Shedd 1981).

This paper reports results from an exploratory study to determine if measurements of permeability can be related to the slow drying of wetwood. Permeability is a measure of the ease with which a fluid (liquid or gas) flows through wood under the influence of a pressure gradient and thus is considered an indicator of drying rates (Siau 1971). It is generally assumed that wetwood is less permeable than normal wood because lumber and veneer containing wetwood usually take longer to dry (Ward and Pong 1980). Nevertheless, few studies have actually measured permeability in wetwood. Most permeability studies have been con-

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cerned with factors contributing to differences in fluid flow between sapwood and heartwood. There is a need to compare the permeability factors of sapwood and heartwood with those of wetwood, and then determine how they influence drying rates of lumber.

LITERATURE REVIEW

Both conifers and hardwoods can develop wetwood that will decrease drying times for lumber. A review of the literature indicates that permeability of conifers and hardwoods is influenced by different anatomical features. In conifers, fluid flow is essentially through interconnected bordered pit pairs in the tracheids, while in hardwoods the flow is mainly through open-ended vessels (Siau 1971). Consequently, any discussion of permeability influences on drying rates must consider normal anatomical differences between conifers and hardwoods as well as the unique features of wetwood.

Permeability of conifers

The sapwood of conifers is much more permeable than either heartwood or wetwood. Any severe reduction in permeability of coniferous sapwood can be largely attributed to aspiration of tori in bordered pit pairs either with heartwood formation or by drying (Petric 1971). In the living tree the permeability of sapwood is much higher than that of heartwood and is not influenced by season of the year (Markstrom and Hann 1972).

Both air-drying and oven-drying will cause aspiration of tori in sapwood that results in severe reductions of permeability (Bramhall and Wilson 1971; Comstock and Côté 1968; Liese and Bauch 1967; Petty and Puritch 1970). After drying, the permeability values for sapwood will match the low permeability values of heartwood which are not affected by drying (Arganbright and Wilcox 1969; Markstrom and Hann 1972).

Before sapwood is dried, fluid flow is greater through the earlywood tracheids because of the larger number of bordered pit pairs per tracheid (Liese and Bauch 1977; Petty and Puritch 1970). Because latewood tracheids have fewer pits and are thicker walled than earlywood tracheids, Comstock (1965) was able to correlate a decrease in permeability of eastern hemlock with an increase in specific gravity and volume of latewood. After air-drying, permeability within the annual ring becomes reversed with latewood now being more permeable than earlywood. This is due to complete aspiration of earlywood pits while some latewood pits remain unaspirated (Booker 1977; Liese and Bauch 1967; Petty and Puritch 1970).

Permeability of hardwoods

Plugging of vessels with tyloses or with excess amounts of extractives is the main cause of permeability reduction in hardwoods (Petric 1972). Measurements of longitudinal water permeability in trembling aspen (Knutson 1968) showed sapwood to be very permeable, while most samples of wetwood and heartwood were completely impermeable. Kemp (1957) found that the rate of tangential moisture loss from trembling aspen sapwood was distinctly greater than from heartwood and wetwood and he attributed this to plugging of vessels in heartwood and wetwood by tyloses which were absent in sapwood vessels.

Characteristics of wetwood

Wetwood forms in the living tree and is an abnormal, water-infused, type of heartwood that can invariably be associated with infestation of the trunk by bacteria (Bauch et al. 1975; Brill et al. 1981; Hartley et al. 1961; Schink et al. 1981a; Ward and Zeikus 1980). Two general types of wetwood have been described by Ward and Zeikus (1980). One type of wetwood forms directly from dying sapwood that has been colonized by bacteria and is known variously as sap-transition wetwood, heavy wetwood, or heavy sinker heart. The second type known either as wetheart or light sinker heart develops in normally formed heartwood by invasion of bacteria from adjacent wetwood.

Drying times and rates can vary by type of wetwood. Sap-transition wetwood (heavy sinker heart) usually takes longer to dry than wetheart (light sinker heart) when it occurs in lumber from western hemlock (Kozlik and Ward 1981) and white fir (Ward and Shedd 1981). When drying western hemlock dimension lumber, Ward and Kozlik (1975) observed that from green to 30% MC light sinker heart dried at a faster rate than heavy sinker heart. Below 30% MC, heavy and light sinker heart dried at similar rates. White fir can also have a heavy type of sapwood which is usually adjacent to wetwood in butt logs. Heavy sapwood requires an extra 12 to 24 hours kiln-drying time, but still dries faster than wetwood (Ward and Shedd 1981).

Low permeability of never-dried wetwood to longitudinal water flow was related to aspiration of bordered pits in western hemlock (Lin et al. 1973) and silver fir (Bauch et al. 1979). Aspirated bordered pits are quite characteristic of wetwood in western hemlock (Kozlik et al. 1972; Lin et al. 1973; Ward and Kozlik 1975), white fir (Wilcox and Schlink 1971) and silver fir (Brill et al. 1981; Frühwald et al. 1981), but apparently not of wetwood in Todomatsu fir (Takizawa et al. 1976).

Longitudinal water permeability of never-dried wetwood from western hemlock was found to be slightly higher than heartwood (Lin et al. 1973), despite observations that the wetwood dried at a slower rate (Kozlik et al. 1972).

Added influence of extractives

Wetwood can have greater amounts of extractives than sapwood and heartwood (Schroeder and Kozlik 1972) and this could influence permeability and drying rates. Encrustation of extractives on aspirated pits adds to the reduction of permeability in heartwood of conifers (Bramhall and Wilson 1971; Comstock 1965; Resch and Ecklund 1964). Plugging of vessels with excess extractives was related by Bauch et al. (1982) to impermeability of bacterial wetwood in African limba. Lin and Lancaster (1973) found that the permeability of western hemlock wetwood decreases during drying. Their tests suggest that western hemlock wetwood contains excess amounts of soluble extractives that migrate toward the board surface during drying, and reduce permeability by being deposited on aspirated pit membranes and in interstitial openings when the wood reaches fiber saturation point.

The importance of soluble wood extractives for retarding moisture loss from wetwood and refractory heartwood can be derived from experiments on the presteaming of green lumber. Presteaming increased the drying rates of wetwood in dimension lumber of white fir (Simpson 1975) and western hemlock (Kozlik et al. 1972), but had little effect on drying rates of normal wood. Mackay (1974)

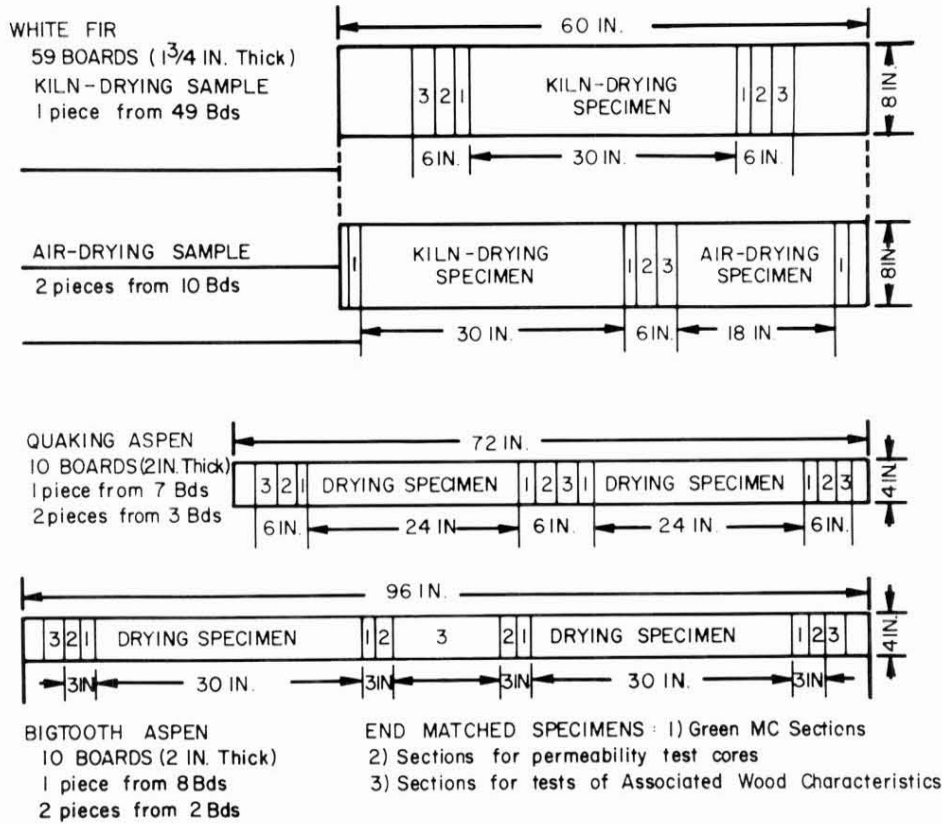


FIG. 1. Diagram of sample boards showing size and location of test specimens.

was able to reduce drying times and wet pockets in aspen dimension lumber with wetwood by intermittent periods of high humidity (essentially steaming) during high-temperature kiln-drying. Steaming appears to improve the rate of moisture loss in impermeable, slow-drying woods by removing or breaking up extractives that block moisture diffusion through the cells (Comstock 1965; Kininmonth 1973; Kozlik et al. 1972; Mackay 1971).

Wetwood extractives may slow drying rates in a manner not entirely due to plugging of vessels and tracheids. The absorptive capacity of wetwood for liquids was found to be greater than normal wood for white fir (Arganbright and Wilcox 1969; Wilcox and Schlink 1971), silver fir (Frühwald et al. 1981), and Scots pine (Lagerberg 1935). Worrall and Parmeter (1982) found that white fir wetwood has a higher osmotic potential than normal wood. These reports suggest that wetwood may hold water more tenaciously than normal wood and will thus dry more slowly.

EXPERIMENTAL

Drying times and drying rates were determined for sapwood, heartwood, and wetwood in softwood dimension lumber by experimental drying of sample board sections from white fir and aspen (graded under softwood dimension rules). The

TABLE 1. Kiln schedule used to dry 7/4 white fir and 8/4 aspen in this study.

Drying time	Kiln temperature		Relative humidity	Equilibrium moisture content
	Dry-bulb	Wet-bulb		
<i>h</i>	°F		%	%
0 to 24	180	170	79	11.1
24 to 48	180	165	70	9.0
48 to 72	180	157	57	7.0
72 to final moisture content	180	150	38	4.6

drying data were compared with LGP measurements taken in samples matching the drying samples. To facilitate interpretation of data from permeability and drying tests, supplemental measurements were made of the following wood properties: specific gravity, electrical resistance, growth rate, and fine wood structure.

Materials

All tests were made with green samples from logs and lumber of white fir, *Abies concolor* (Gord. and Glend.) Lindl. ex Hildebr., bigtooth aspen, *Populus grandidentata* Michx., and quaking aspen, *P. tremuloides* Michx. White fir samples consisted of 59 green boards (1¾ in. thick by 8 in. wide by 5 ft long) that were selected in the Roseburg Lumber Co. mill at Anderson, California. The first aspen samples were taken from butt logs (8 ft long) of five bigtooth aspen trees growing in Oneida County, Wisconsin. There was wetwood but very little heartwood in these trees, so a second sample of four logs (6 ft long) were taken from two quaking aspen trees growing in Larimer County, Colorado. All aspen logs were sawn into 2- by 4-in. boards at the Forest Products Laboratory. All sample boards were cut into specimens for the various tests according to the method illustrated in Fig. 1.

Each test specimen for drying contained at least 70%, by volume, of either sapwood, heartwood, or wetwood. Wood types were initially identified on the basis of appearance, odor, and resistance to a pulsed electric current. Wetwood has a grayish water-soaked appearance, which can be distinguished from sapwood and heartwood with the help of past experience. Wetwood has distinct fermentative odors that are due to fatty acids that are not found in sapwood and heartwood (Bauch et al. 1975; Schink et al. 1981a; Ward and Pong 1980; Ward and Zeikus 1980; Worrall and Parmeter 1982). Resistance to a pulsed electric current is lower in wetwood than in sapwood and heartwood (Bauch et al. 1979; Kozlik and Ward 1981; Ward 1984; Ward and Kozlik 1975; Ward and Shedd 1981).

Drying procedures

There were four separate kiln-drying tests: two for white fir and one each for bigtooth aspen and for quaking aspen. A white fir subsample was air-dried in conjunction with one of the white fir kiln-drying tests. The drying schedule for all four kiln charges is outlined in Table 1. The white fir subsample was air-dried from green to 12% MC in two stages. Green air-drying samples were first placed in a 12% equilibrium moisture content (EMC) room (temperature = 80 F, relative humidity = 65%) until they had dried to approximately 20% MC. They were then

transferred to a 6% EMC room (temperature = 80 F, relative humidity = 30%) until 12% MC was reached. Board sections for drying tests (Fig. 1) were end-sealed and weighed immediately after being crosscut from longer boards. All drying samples were weighed throughout the course of drying, and interim MC values were later calculated from oven-dried weights of the samples.

Permeability tests

Flow of nitrogen gas along the grain was determined for cylindrical test cores of sapwood, heartwood, and wetwood from white fir and the two aspen species. The cores were taken from green board sections and end-matched to the drying test specimens (see Fig. 1). At selected positions on the end-grain surface of the board sections, a pair of cores (end-matched along the grain) were extracted using a drill with hollow core bit. Each green core, measuring 1.27 cm in diameter and 1.9 cm along the grain, was microtomed across the end-grain diameter to a length of 1.6 cm, and then dried by either one of two methods. For each pair of end-matched test cores, one core was oven-dried at 160 F to 6% MC, while its mate was solvent-dried in ethanol according to the method of Sachs and Kinney (1974) and reconditioned to 6% MC.

Measurements of nitrogen gas permeability were made using the apparatus and methods developed by Comstock (1965, 1967, 1968). Comstock (1967) found that gas permeability measurements in wood yield a "superficial gas permeability," which is slightly higher than the true permeability because of slip flow. However, Comstock (1968) also found a consistent relationship exists between the permeability of green wood to water and its permeability to nitrogen gas after drying. With proper preparation of test specimens, such as solvent-drying and microtoming, longitudinal gas permeability provides an estimation of the permeability properties of green wood as it occurs in the tree, while avoiding the problem of air embolism encountered in measurements of liquid permeability (Booker 1977). The flow of gas through each test specimen is expressed in Darcys as calculated from the relationship used by Comstock (1967):

$$\text{Darcys} = K_g = \frac{QL\eta}{A\Delta P} \frac{p}{p'}$$

where

- K_g = superficial gas permeability (Darcys)
- Q = flow rate (cubic cm per sec)
- A = flow area (square cm)
- L = flow length (cm)
- ΔP = pressure drop (atmospheres)
- η = viscosity (centipose)
- p = pressure flow rate Q (atmospheres)
- p' = mean absolute pressure within the specimen (atmospheres)

Associated wood characteristics

Measurements and observations were also made of electric resistance, specific gravity, growth rate, latewood (white fir only), and fine wood structure. These wood characteristics were determined mostly on test specimens taken from end-

TABLE 2. Average moisture content, drying times, and rates for the kiln-dried samples of white fir and aspen, and drying times and rates for the air-dried subsamples of white fir.

Wood type	Total kiln sample			Subsample			
	Moisture content at end of kiln cycle ¹	Drying time to 15% moisture content	Rate of moisture content loss ²	Kiln-dried ³		Air-dried	
				Drying time to 15% moisture content	Rate of moisture content loss ²	Drying time to 15% moisture content	Rate of moisture content loss ²
	%	h	%/h	h	%/h	h	%/h
White fir							
Sapwood—normal	15.0	96	1.54	96	1.70	432	0.38
Sapwood—heavy	19.0	106	1.80	120	1.58	504	0.37
All sapwood	15.5	98	1.63	103	1.67	468	0.36
Heartwood	8.0	67	0.58	68	0.68	408	0.11
Wetwood—sapwood trans.	40.0	170	0.80	155	0.87	1,056	0.13
Wetwood—wetheart	29.0	150	1.06	140	0.79	816	0.13
All Wetwood	36.0	163	0.88	152	0.84	996	0.13
Bigtooth Aspen							
Sapwood	16.5	104	0.84				
Heartwood	20.0	116	0.57				
Wetwood—sapwood trans.	39.0	192	0.59				
Quaking aspen							
Sapwood	15.0	94	0.95				
Heartwood	20.5	122	0.51				
Wetwood—wetheart	35.0	180	0.48				

¹ Conventional kiln cycles were 96 hours for all samples.

² Based on total moisture content loss from green to 15% moisture content.

³ Part of total kiln sample (see Fig. 1, Air Drying Sample).

matched board sections (Fig. 1), but some additional measurements of electric resistance were made on the green drying specimens.

Resistance to a pulsed electric current.—These measurements help to identify wetwood and normal wood and were made with a Shigometer Model 7950 (North-east Electronics Corp., Concord, NH). Needle electrodes spaced 1/2 inch apart (and attached to the Shigometer) were inserted 1/4 inch into the side grain surfaces of green drying specimens, and into the end-grain surfaces of green specimens used to determine specific gravity.

Specific gravity (SG).—The volume of small green wood specimens was determined by water immersion and SG calculated on the basis of oven-dry weight and green volume.

Growth rate and latewood.—The number of annual growth rings per inch was calculated from green SG specimens of aspen and white fir. Latewood was measured on each white fir specimen at the same time as the growth rate measurements. The proportion of latewood was expressed as a percent of the annual ring width. Latewood could not be readily determined for aspen because of the diffuse porous annual ring growth.

Scanning electron microscopy (SEM).—SEM was employed to evaluate fine wood structure. Wood sections, 2 mm by 7 mm by 7 mm, were cut from: a) selected permeability cores after testing, b) green board sections end-matching

TABLE 3. Comparative properties of aspen and white fir study material.

Wood type	Drying samples ¹				End-matched specimens (average values)					
	Moisture content			Resis- tance ²	Num- ber	Mois- ture content (green)	Resis- tance ³	Specific gravity (green volume)	Growth rate	Late- wood
	Num- ber	Aver- age	Range, minimum- maximum							
			K- ohms			K- ohms		Rings/ in.		
		%						%		
Aspen										
Bigtooth-sapwood	5	102	98–126	119	14	107	116	0.42	9	—
Quaking-sapwood	4	104	95–115	121	18	110	129	0.34	26	—
All sapwood	9	103		120	32	108	122	0.38	18	
Bigtooth-heartwood	3	81	73–88	107	6	77	108	0.39	8	—
Quaking-heartwood	3	77	71–80	119	10	69	122	0.36	12	—
All heartwood	6	79		113	16	72	115	0.37	10	
Bigtooth-wetwood (sapwood- trans.)	4	129	120–136	25	18	138	22	0.37	8	—
Quaking-wetwood (wetheart)	6	101	94–114	62	12	102	71	0.38	12	—
All wetwood	10	113		47	30	124	51	0.38	9	
White fir										
Sapwood—light	15	163	128–192	151	27	187	134	0.35	20	21
Sapwood—heavy	6	206	174–233	170	18	212	141	0.35	18	18
All sapwood	21	175		157	45	197	136	0.35	19	20
Heartwood	19	54	45–78	112	45	55	126	0.32	9	14
Wetwood (sapwood-trans.)	12	151	133–171	13	30	157	15	0.43	11	20
Wetwood (wetheart)	7	174	100–262	22	15	145	24	0.40	10	19
All wetwood	19	159		16	45	152	18	0.42	11	20

¹ Green wood board sections.² Pulsed current resistances measured on board surfaces (average of both sides).³ Pulsed current resistances measured on end-grain of specimens.

the drying test specimens, and c) a few drying test specimens after drying. Green wood sections were solvent-dried with ethanol by the critical point method of Sachs and Kinney (1974) to preserve the original condition of never-dried wood. All dried SEM specimens were mounted on specimen holders, vacuum-coated with approximately 100–200 Å of gold, and examined with a Cambridge Stereo-scan Electron microscope at 20 kV.

RESULTS AND DISCUSSION

Drying times and rates

Drying times.—Wetwood board samples from both aspen and white fir took longer to dry to 15% MC than did normal wood (Table 2). Aspen sapwood dried in a shorter time than heartwood, while white fir sapwood took longer to dry than heartwood, yet the total rate of moisture loss for sapwood of both species was faster than the total rate of moisture loss for their respective heartwoods. The longer drying time for white fir sapwood can be attributed to an initial green MC that averages more than 100% higher than heartwood MC (Table 3). The green MC of aspen sapwood averages 30% higher than heartwood MC and is not enough to offset the advantages of a faster drying rate for sapwood. Drying times in Table

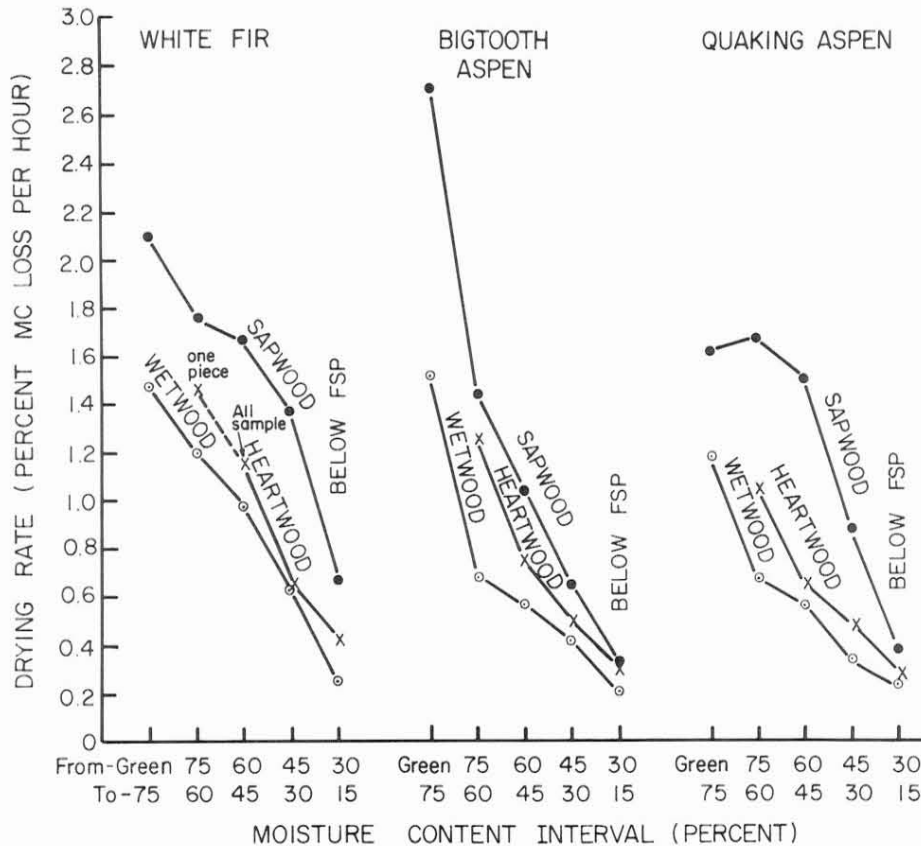


FIG. 2. Comparison of average kiln-drying rates for 7/4 white fir and 8/4 aspen lumber according to wood type and moisture content interval.

2 for the three white fir board sorts are comparable to those reported by Smith and Dittman (1960) and Pong and Wilcox (1974) for white fir dimension lumber of similar thickness. There are no comparable drying times in the literature for aspen because different kiln schedules were used.

Drying rates.—Total drying time is not a good criterion for evaluating ease of drying lumber because the initial green MC differs with wood type. When the total amount of moisture loss from green to 15% MC is considered, then drying rates for wetwood and heartwood are similar and much slower than drying rates for sapwood (Table 2).

To properly evaluate differences in rate of moisture loss among the three wood types, attention must be given to changes in the rate of moisture loss at different MC levels during the course of drying. The rate of moisture loss progressively decreased from green to final MC during the kiln-drying of white fir and aspen (Figs. 2 and 3B), and air-drying of white fir (Fig. 3A).

Sapwood dries at the fastest rate throughout the entire drying cycle, while wetwood dries at the slowest rate when kiln drying aspen and white fir (Fig. 2), and air-drying white fir (Fig. 3A). Heartwood does not dry as fast as sapwood but always faster than wetwood at each MC level. Because wetwood starts drying at

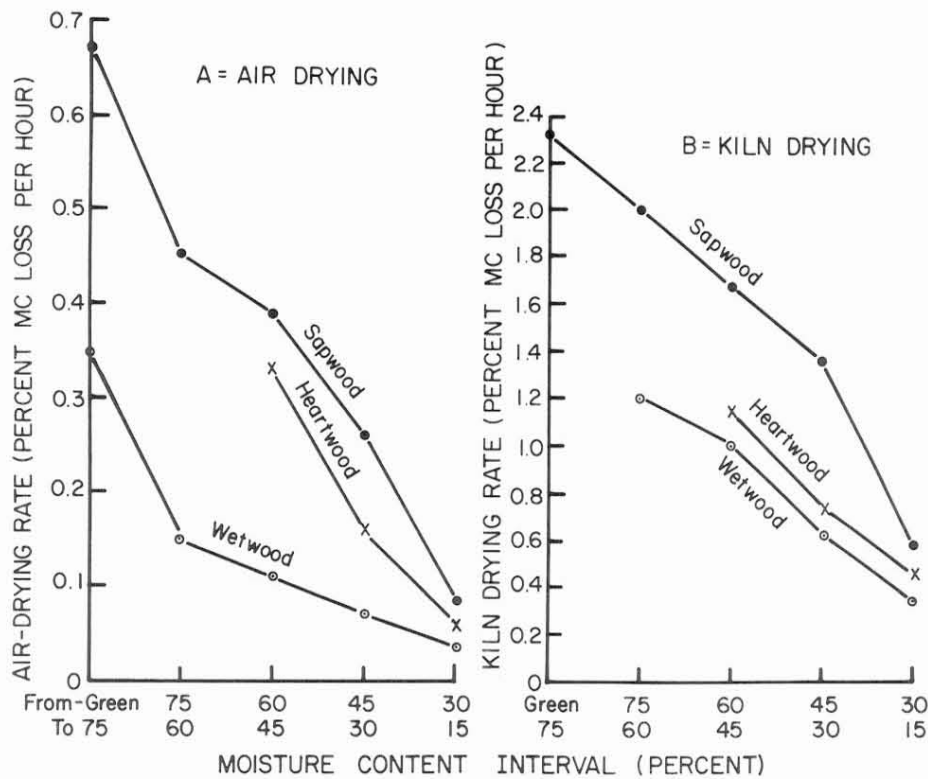


FIG. 3. Comparison of air-drying rates (A) and kiln-drying rates (B) by moisture content interval and wood types for subsample of 7/4-inch thick white fir.

a higher MC than heartwood, it can appear that the overall drying rate of wetwood is faster than heartwood. This may explain why Lin and Kozlik (1971) believed that wetwood in western hemlock dries at a faster rate than heartwood during the initial stages of drying.

Air-drying does not appear to be more advantageous than kiln-drying for improving the drying rate of wetwood in white fir lumber. Kiln-drying increased the drying rate for white fir wetwood with respect to the drying rates of sapwood and heartwood (Fig. 3B). Air-drying also extends total drying times, 4.5 to 6.6 times longer than kiln-drying (Table 2).

Longitudinal gas permeability

Sapwood of both aspen and white fir was much more permeable than either heartwood or wetwood. Results from the permeability tests in Table 4 for white fir and aspen show that the oven-drying method greatly reduced the permeability of white fir sapwood, but had little or no effect on the other samples. The distribution of permeability values by wood types is illustrated in Figs. 4 and 5 respectively for ethanol-dried cores of white fir and aspen. Oven-drying also caused some cores, particularly wetwood, to check seriously so that abnormally high permeability values occurred. Permeability values for checked samples together with the values from their end-matched mates (even though sound) were omitted

TABLE 4. Longitudinal gas permeability of white fir and aspen according to species, wood type, and method for drying test cores.

Species	Wood type	Permeability					
		Ethanol-dried			Oven-dried		
		Number of cores	Mean	Standard deviation	Number of cores	Mean	Standard deviation
	 Darcys Darcys		
White fir	Sapwood—light	57	13.83	5.65	57	1.12	0.81
	Sapwood—heavy	23	11.45	7.84	23	1.84	1.74
	All sapwood	80	13.14	6.40	80	1.33	1.19
	Heartwood	55	0.78	0.44	55	0.60	0.39
	Wetwood ¹	48	1.76	1.68	48	1.03	0.58
	Wetwood ²	27	2.39	3.70	27	3.54	4.79
	All wetwood	75	1.98	2.59	75	1.93	3.12
Bigtooth aspen	Sapwood	14	37.91	4.35	14	39.94	4.17
	Heartwood	6	0.50	0.51	6	0.43	0.31
	Wetwood ¹	18	2.53	7.23	18	4.63	6.32
Quaking aspen	Sapwood	17	24.05	2.11	17	23.29	1.59
	Heartwood	10	0.20	0.18	10	0.16	0.14
	Wetwood ²	10	0.25	0.19	10	0.18	0.12

¹ Mostly sapwood-transition type of wetwood.² Mostly wetheart type.

from Table 4. Excess checking caused a loss of 12 white fir test cores and 6 aspen cores.

Anatomical influences on permeability

White fir.—Scanning electron micrographs show that low permeability values in white fir test specimens (Table 4) can be associated with aspirated tori that presumably obstruct the longitudinal flow of gas. Bordered pits in earlywood and latewood of ethanol-dried sapwood were unaspirated (Fig. 6A–C), but all pits in oven-dried sapwood were aspirated (Fig. 6D–F). On the average, there was a tenfold decrease in the permeability of sapwood with oven-drying (Table 4), but individual differences between paired cores could be much greater. Heartwood was impermeable even with ethanol drying (Table 4), and this can be associated with tight aspiration of tori in both earlywood and latewood pits (Fig. 6H, I).

Average permeability values for wetwood (combined oven-dry and ethanol-dry) cores were about 1.5 times higher than oven-dry sapwood covers and 2.8 times higher than all heartwood cores (Table 4). These differences in comparative permeability values can be explained by SEM, which revealed that most, if not all, bordered pits in the tracheids of oven-dried sapwood cores (Fig. 6D–F) and green heartwood cores (Fig. 6H, I) are tightly aspirated. The permeability of ethanol-dried wetwood is usually quite low because many bordered pits are aspirated (Fig. 7B, D) and coated with extraneous material, but relatively high permeabilities also occur and can be associated with presence of unaspirated pits (Fig. 7C) or with aspirated pits that have been disintegrated by bacterial action (Fig. 7E, F). Schink et al. (1981a, b) isolated bacteria from wetwood populations that are capable of producing pectinases and hemicelluloses which can disintegrate the torus.

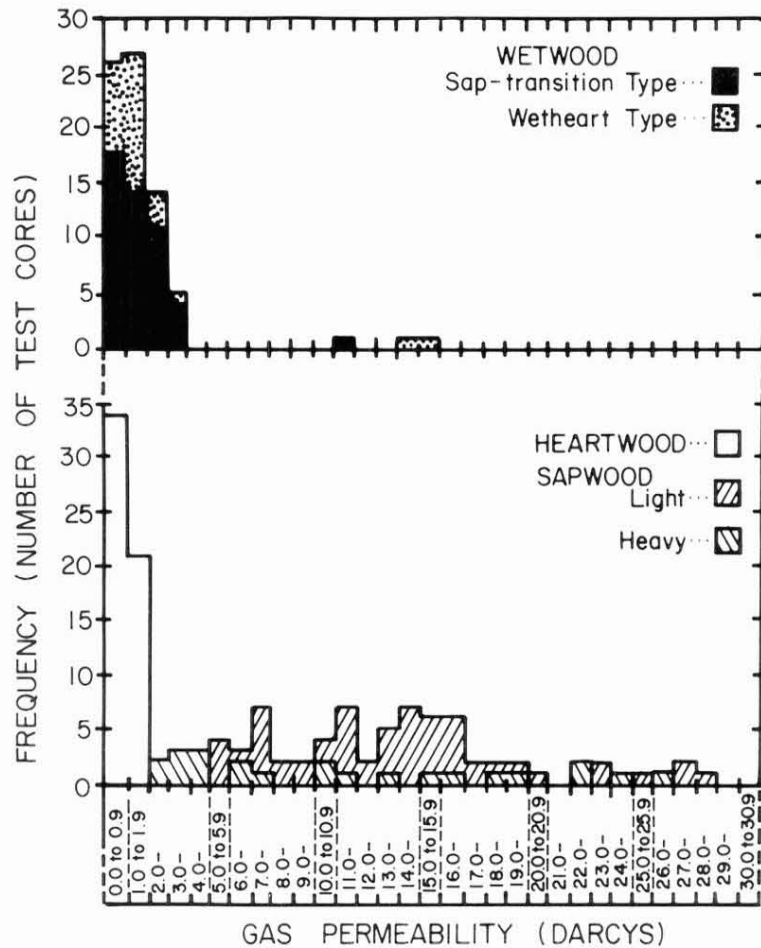


FIG. 4. Frequency distribution of LGP values for white fir test cores after ethanol dehydration and air-drying.

Unusually high permeability values sometimes occurred in oven-dried cores of wetwood, while their ethanol-dried mates had very low permeability. This could be explained by the presence of ruptures in aspirated tori of these unusually permeable specimens (Fig. 7G). Bacterial weakening of the torus may contribute to ruptures in oven-dried wetheart, but similar ruptures have been observed under the SEM in apparently normal wood. Western hemlock that was kiln-dried at elevated temperatures had ruptured tori in both heartwood and bacterial wetwood but not in sapwood (Ward and Kozlik 1975). Banks (1971) suggested that damage by the electron beam may be responsible for ruptures in aspirated tori of air-dried Parana pine, but considered the possibility that splitting may occur during drying because there is apparently no thickening of the torus in this species.

Two specimens of wetheart had abnormally high permeability values for both ethanol-dried cores (Fig. 4 at 15 Darcys) and their oven-dried mates. All four cores contained holes in the aspirated tori and cell walls that were caused by wood decay fungi (Fig. 7H, I). Fungi are rarely encountered in wetwood because of the anaerobic atmospheres that generally prevail (Ward and Zeikus 1980) and these

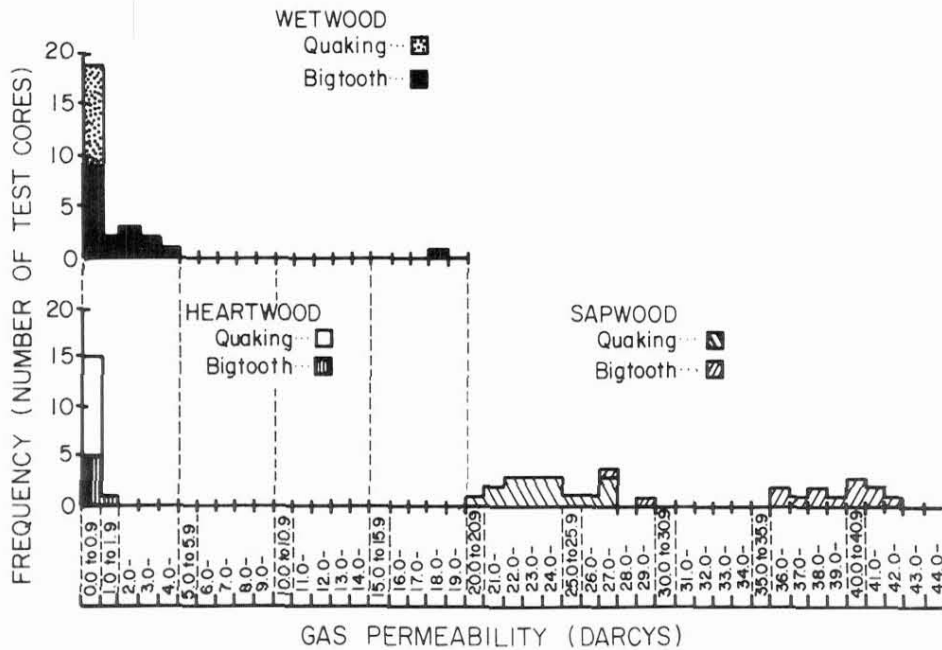


FIG. 5. Frequency distribution of LGP values for quaking aspen and bigtooth aspen test cores after ethanol dehydration and air-drying.

specimens may represent heartwood that was infected by decay fungi before wetwood formation.

Most bordered pits were aspirated in sapwood test specimens that had been air-dried and kiln-dried, but their permeability was not measured in this study. Bordered pits in the kiln-dried sapwood boards of this study tended to be more tightly aspirated than the air-dried boards. Some bordered pits in the latewood of air-dried sapwood remained unaspirated.

Aspen. — A comparison of longitudinal permeability values (Table 4) with scanning electron micrographs shows that tyloses formation in the vessels is mainly responsible for the low permeability of heartwood and wetwood from bigtooth and quaking aspen (Fig. 8B–D). Sapwood that did not have tyloses (Fig. 8A) was many times more permeable than either heartwood or wetwood. The sapwood of quaking aspen was less permeable than the sapwood of large tooth aspen. This will be discussed in the section concerned with influences of SG and growth rate.

There is some evidence that wetwood bacteria may interfere with the formation of tyloses. During normal physiological formation of heartwood from sapwood, tyloses often balloon out from living ray parenchyma cells into the lumens of adjacent vessels to become a regular feature of normal heartwood in aspen. Bigtooth aspen had wetwood (sap-transition wetwood) that formed directly from sapwood, while quaking aspen wetwood formed largely in existing heartwood (wetheart). Permeability values for the wetheart in quaking aspen are similar to the values for normal heartwood and are 10 to 25 times lower than the permeability of the sap-transition type wetwood in bigtooth aspen (Table 4). Examination by SEM indicated that tyloses formation was apparently aborted in many vessels of

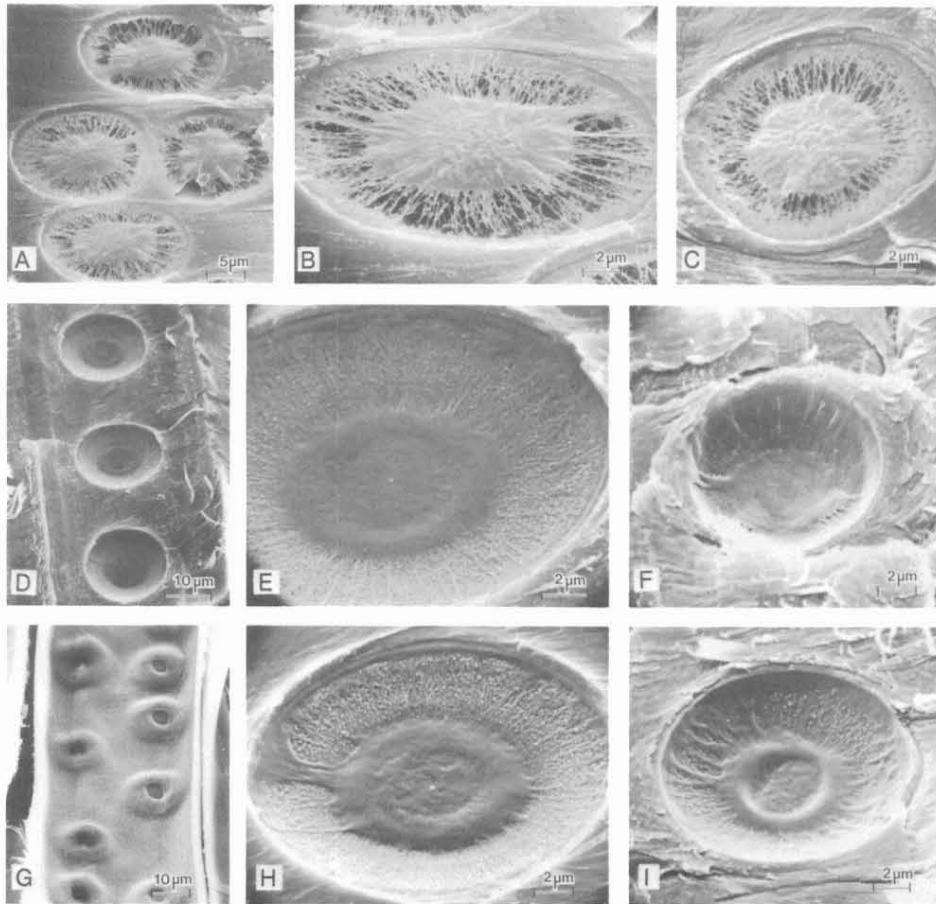


FIG. 6. Scanning electron micrographs of tracheids and bordered pits in normal wood of white fir taken from permeability test specimens. Ethanol-dried sapwood showing unspirated tori in earlywood (A, B) and latewood (C). Oven-dried sapwood showing aspirated tori in earlywood (D, E) and latewood (F). Ethanol-dried heartwood showing earlywood lumen with bordered pits and warty layer free of extraneous material (G) and aspirated tori in earlywood (H) and latewood (I).

sap-transition wetwood from bigtooth aspen (Fig. 8F), yet the permeability of this wetwood averaged much lower than the permeability of sapwood (Table 4).

One sample of wetwood from bigtooth aspen had unusually high permeability values (Fig. 5 at 18 Darcys). Figure 8G reveals bore holes by decay fungi are probably responsible for the high permeabilities in this sample.

Influence of other wood characteristics

Comparative values of green MC, electrical resistance, SG, and growth rate are listed in Table 3 for aspen and white fir. Also listed are percent latewood values for white fir. Of the five wood characteristics listed in Table 3, wetwood could only be consistently distinguished from sapwood by measurements of pulsed-current resistance and from heartwood by measurements of MC.

Resistance to a pulsed-electric current.—Wetwood of both aspen and white fir

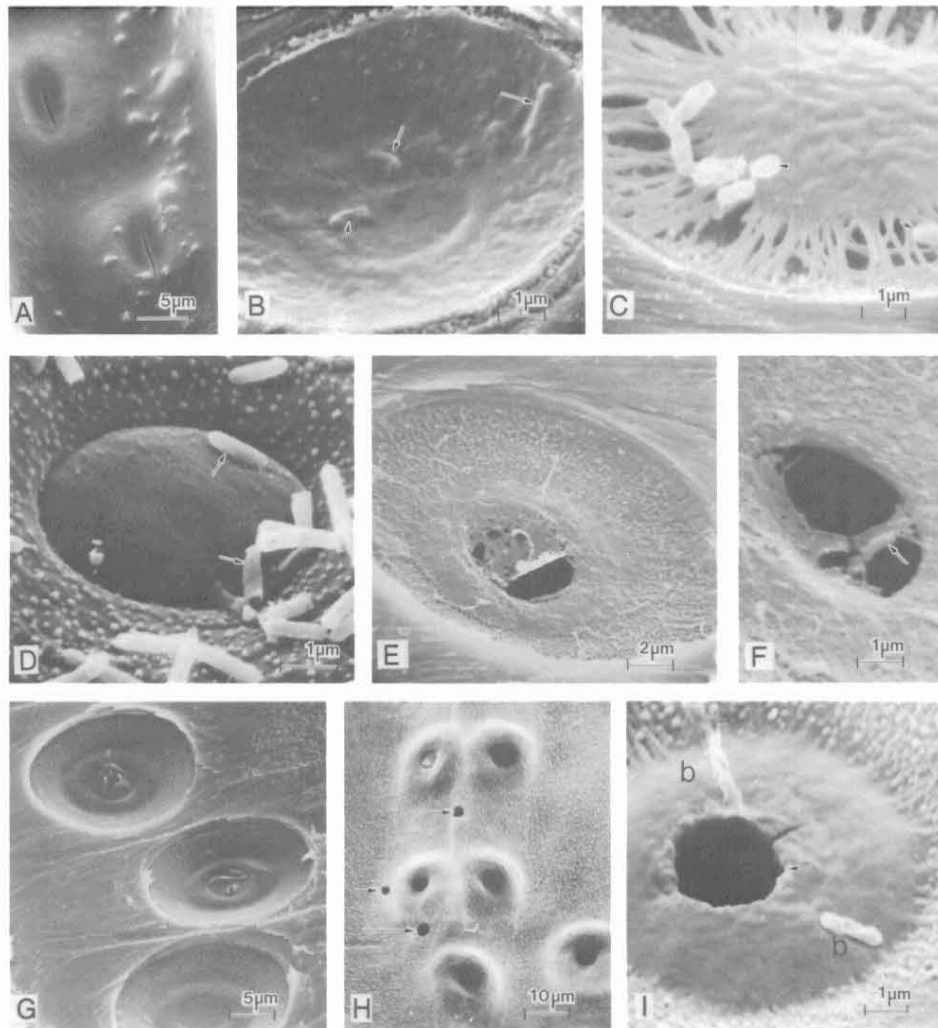


FIG. 7. Scanning electron micrographs of tracheids and bordered pits in wetwood of white fir taken from permeability test specimens. All specimens were ethanol-dried except (G) which was oven-dried. (A) Lumen of earlywood tracheid coated with extraneous material and bacteria (note: cracks developed in extraneous material coating bordered pits during exposure to SEM beam). In wetwood, tori can be either aspirated and coated with extraneous material (B) or unspirated (C), but bacteria (arrows) are present in both types. (D) Bacteria (arrows) attached to aspirated tori will eventually erode and destroy the matrices (E, F). (G) Oven-dried wetheart with ruptures in aspirated tori. (H, I) Holes (arrows) caused by decay fungi are occasionally found in wetheart along with bacteria (b).

had pulsed-current resistances that were significantly lower than the resistances of sapwood and heartwood. Low electrical resistances in wetwood have been attributed by Ward (1984) to increased concentrations of organic ash and charge-carrying ions resulting from bacterial tree infections. Wetwood samples used in this study had encrustations of bacteria and other extraneous material in cell lumens of white fir tracheids (Fig. 7A-F) and aspen vessels (Fig. 8D-F). These encrustations were not observed in normal wood of white fir (Fig. 6) or aspen (Fig. 8A).

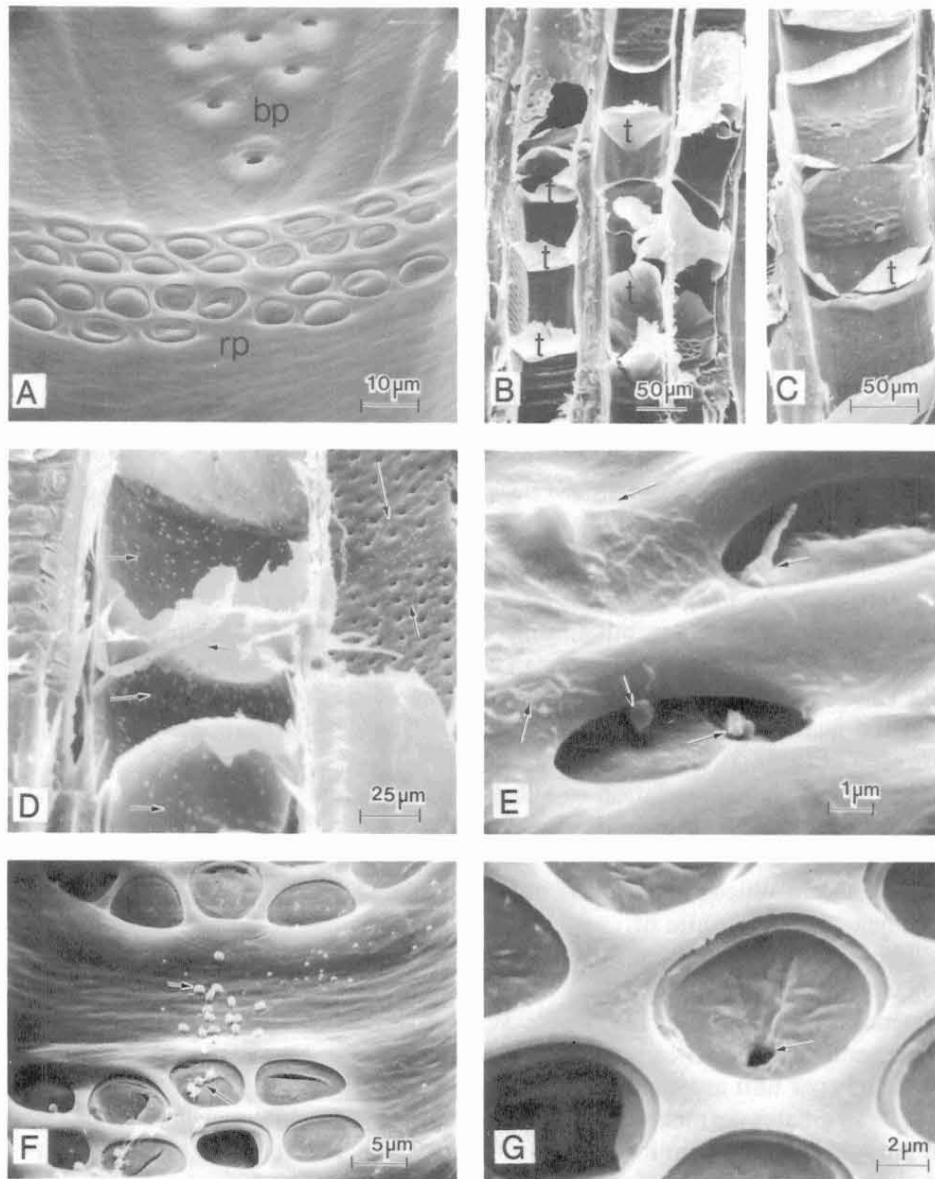


FIG. 8. Scanning electron micrographs of vessels in aspen sapwood (A), heartwood (B, C), and wetwood (D–G) taken from permeability test specimens. (A) Noninfected bigtooth aspen vessel with ray pitting (rp) and bordered pits (bp). Tyloses (t) occluding heartwood vessels in quaking (B) and bigtooth (C) aspen. (D) Scattered masses of bacteria (arrows) throughout vessels of bigtooth aspen wetwood that contains tyloses. (E) Bacteria and extraneous material (arrows) on vessel walls and ray pit membranes of quaking aspen wetwood. (F) Bacteria (arrows) in vessel of bigtooth aspen wetwood with sparse tyloses development. (G) Bigtooth aspen wetwood with a fungal bore hole (arrow) in a ray pit membrane.

Excess extraneous material in wetwood may serve to increase absorptive capacity for moisture as well as lowering resistances to a pulsed-electric current. The possibility that higher absorptivity and water holding capacity decrease the rate of moisture loss in wood needs to be investigated in future wetwood studies.

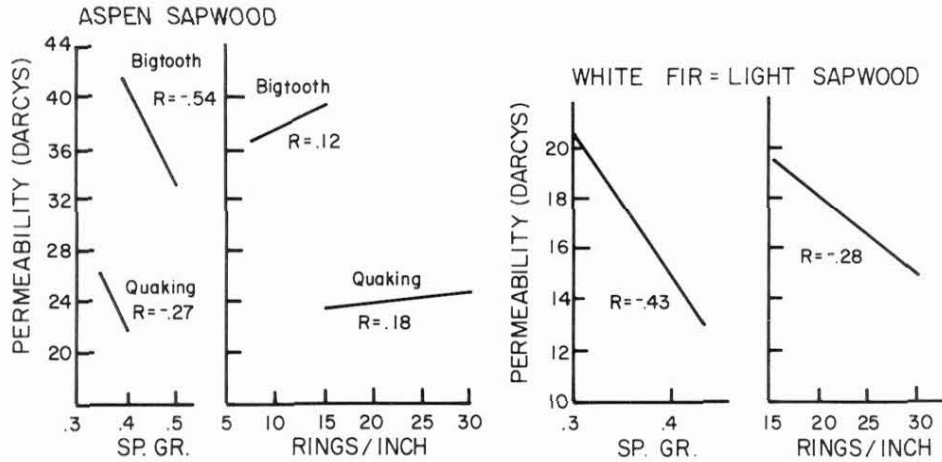


FIG. 9. Relation of specific gravity and growth rate (rings per inch) to LGP of ethanol-dried test cores from sapwood of aspen and white fir.

Specific gravity and growth rate.—Overall, the average specific gravities of aspen and white fir were similar, but among the three wood types of white fir there were wide differences that did not occur in aspen. White fir heartwood had the lowest SG values and white fir wetwood the highest. In this study white fir heartwood had the fastest growth rates with greater amounts of earlywood, which tend to lower SG (Table 3).

There is a weak correlation of SG with longitudinal gas permeability, but the effects are limited to sapwood. Blockage of gas flow by tyloses and aspirated pits tends to obscure SG influences on permeability in heartwood and wetwood. Arganbright and Wilcox (1969) were unable to relate SG to permeability of wetwood and heartwood in white fir.

The correlation between SG of sapwood and permeability is an indirect one. Figure 9 shows that permeability decreases with an increase in SG, which in turn depends on growth rate. For aspen, SG increases with a decrease in number of rings per inch, which means an increase in growth rate. There are a greater number of vessels per unit area in the narrow growth rings of slow-growing aspen, which results in greater permeability. The reverse is true for white fir where an increase in growth rate results in lower SG and increased permeability. The narrow rings in slow-growing white fir usually have a greater volume of dense latewood, which tends to increase SG and reduce permeability. In fast-grown white fir there is a greater volume of less dense earlywood with larger numbers of bordered pits to allow longitudinal gas flow.

SUMMARY AND CONCLUSIONS

Results from this study demonstrate that differences in LGP among sapwood, heartwood, and wetwood cannot always be used to predict differences in their respective drying times and drying rates. Sapwood of both aspen and white fir has the highest permeability values and the fastest drying rates, but not always the shortest drying times. Heartwood has the lowest permeability values, but heartwood lumber with low green MC will dry to final MC in a shorter time than

sapwood lumber with high green MC. Wetwood has the slowest drying rates and longest drying times, but not always the lowest permeability values.

The low longitudinal gas permeability of wetwood and heartwood in relation to the higher permeability of sapwood can be attributed to aspiration of bordered pits in white fir tracheids, and to tyloses formation in aspen vessels. Bacterial infections may explain why wetwood dries at a slower rate than heartwood yet tends to have higher permeability values. Encrustation of bacteria and extraneous material in wetwood could increase its capacity to absorb and hold moisture so that it dries more slowly than heartwood that is free of bacteria. On the other hand, wetwood may be more permeable to fluid flow than heartwood because some wetwood bacteria can destroy aspirated tori in bordered pits of conifers, and abort tyloses development in hardwood vessels.

Additional research is needed to isolate factors contributing to the slow drying of wetwood. Particular attention should be given to absorption-desorption properties of wetwood and the influence of soluble extractives on board moisture gradients during drying. Permeability tests can be a valuable part of future investigations, but they must be designed to measure transverse as well as longitudinal gas permeability. Transverse permeability should be measured during the initial, middle, and final stages of drying to account for the possible migration and blocking action of wetwood extractives, which appear to be more soluble than extractives in normal wood.

The combined effect of drying schedules and migration of extractives on the formation of board moisture gradients during drying must also be considered. Matched board sections should be dried under accelerated and mild schedules and periodically analyzed for concentration of extractives and variations in moisture gradients. It may be profitable to consider steaming of wetwood before and during drying when studying the influence of extractives on drying rates and permeability.

ACKNOWLEDGMENTS

The author is grateful to Theodore Mianowski for sample preparation and measurements of permeability, to Thomas A. Kuster for assistance with scanning electron microscopy, and to John L. Tschernitz for consultation on permeability measurements.

REFERENCES

- ARGANBRIGHT, D. G., AND W. W. WILCOX. 1969. Comparison of parameters for predicting permeability of white fir. *Proc. Am. Wood-Preserv. Assoc.* 65:57-62.
- BANKS, W. B. 1971. Structure of the bordered pit membrane in certain softwoods as seen by scanning electron microscopy. *J. Inst. Wood Sci.* No. 28 (Vol. 5, No. 4).
- BAUCH, J., W. HOLL, AND R. ENDEWARD. 1975. Some aspects of wetwood formation in fir. *Holzforchung* 29(6):198-205.
- , P. KLEIN, A. FRÜHWALD, AND H. BRILL. 1979. Alterations of wood characteristics in *Abies alba* Mill. due to "fir-drying" and considerations concerning its origin. *Eur. J. For. Pathol.* 9(6): 321-331 (73).
- , G. SEEHAN, AND R. ENDEWARD. 1982. Characterization of sapwood and brown heart in *Terminalia superba* Engl. et Diels. *Holzforchung* 36(5):257-263.
- BOOKER, R. E. 1977. Problems in the measurement of longitudinal sapwood permeability and hydraulic conductivity. *N.Z. J. For. Sci.* 7(3):297-306.

- BRAMHALL, G., AND J. W. WILSON. 1971. Axial gas permeability of Douglas fir microsections dried by various techniques. *Wood Sci.* 3(4):223-230.
- BRILL, H., E. BOCH, AND J. BAUCH. 1981. Über die bedeutung von mikroorganismen im holz von *Abies alba* Mill. für das tannensterben. [On the occurrence of microorganisms in the wood of *Abies alba* Mill. and their influence on the fir dieback.] *Forstwiss. Centralbl.* 100(3-4):195-206.
- COMSTOCK, G. L. 1965. Longitudinal permeability of green eastern hemlock. *For. Prod. J.* 15(10):441-449.
- . 1967. Longitudinal permeability of wood to gases and nonswelling liquids. *For. Prod. J.* 17(10):41-46.
- . 1968. Relationship between permeability of green and dry eastern hemlock. *For. Prod. J.* 18(8):20-23.
- , AND W. A. CÔTE, JR. 1968. Factors affecting permeability and pit aspiration in coniferous sapwood. *Wood Sci. Technol.* 2(1968):279-291.
- FRÜHWALD, VON A., P. KLEIN, AND J. BAUCH. 1981. Über die Holzeigenschaften der vom Tannensterben betroffenen Baume (*Abies alba* Mill.). [Wood properties of fir trees (*Abies alba* Mill.) affected by fir dieback.] *Forstwiss. Centralbl.* 100(3-4):207-217.
- HARTLEY, C., R. W. DAVIDSON, AND B. S. CRANDALL. 1961. Wetwood, bacteria, and increased pH in trees. USDA For. Prod. Lab. Rep. 2215, Madison, WI. 35 pp.
- KEMP, A. K. 1957. Study of factors associated with the development of collapse during kiln drying of aspen lumber. Ph.D. thesis, Univ. Minn., St. Paul. 151 pp.
- KININMONTH, J. A. 1973. Permeability and fine structure of certain hardwoods and effects on drying—III. Problems in drying of heartwood. *Holsforschung* 27(1):26-31.
- KNUTSON, D. M. 1968. Wetwood in trembling aspen (*Populus tremuloides* Michx.). Ph.D. thesis, Univ. Minn., St. Paul. 152 pp.
- KOZLIK, C. J., AND J. C. WARD. 1981. Properties of kiln-drying characteristics of young-growth western hemlock dimension lumber. *For. Prod. J.* 31(6):45-53.
- , R. L. KRAHMER, AND R. T. LIN. 1972. Drying and other related properties of western hemlock sinker heartwood. *Wood Fiber* 4(2):99-111.
- LAGERBERG, T. 1935. Barrtgrädens Vattved. [Wetwood in conifers.] *Sven. Skogsvardsforeningens Tidskr.* 33(3):177-264.
- LIESE, W., AND J. BAUCH. 1967. On the closure of bordered pits in conifers. *Wood Sci. Technol.* 1:1-13.
- , AND ———. 1977. Untersuchungen über die wegsamkeit saftfrischen splintholzes von fichte und sitkafichte. [On the permeability of green sapwood of Norway spruce and sitka spruce.] *Holz Roh- Werkst.* 35(7):267-271.
- LIN, R. T., AND C. J. KOZLIK. 1971. Permeability and drying behavior of western hemlock. Proc. 22nd Annual Meeting Western Dry Kiln Club, pp. 44-50. Oregon State Univ., Corvallis, OR.
- , AND E. P. LANCASTER. 1973. Longitudinal water permeability for western hemlock. II. Unsteady-state permeability. *Wood Fiber* 4(4):290-297.
- , ———, AND R. L. KRAHMER. 1973. Longitudinal water permeability of western hemlock. I. Steady-state permeability. *Wood Fiber* 4(4):278-289.
- MACKAY, J. F. G. 1971. Some factors influencing water vapor diffusion in hardwood species. *Wood Sci.* 4(1):62-64.
- . 1974. Reduce drying times and meet moisture-content requirements with aspen dimension lumber. Proc. West. Dry Kiln Club 25th Annu. Meet. May 9-10, Oregon State Univ., Corvallis, OR.
- MARKSTROM, D. C., AND R. A. HANN. 1972. Seasonal variation in wood permeability and stem moisture content of three Rocky Mountain softwoods. USDA For. Serv. Res. Note RM-212, Rocky Mountain For. Range Exp. Stn., Fort Collins, CO. 7 pp.
- PETRIC, B. 1971. Utjecaj strukture na permeabilnost drva cetinjaca. [Influence of wood structure on the permeability of the wood of conifers.] *Sumarski List* 95(5-6):125-140.
- . 1972. Utjecaj strukture na permeabilnost drva listaca. [Influence of wood structure on the permeability of hardwoods.] *Sumarski List* 96(9-10):364-373.
- PETTY, J. A., AND G. S. PURITCH. 1970. The effects of drying on the structure and permeability of wood of *Abies grandis*. *Wood Sci. Tech.* 4:140-154.
- PONG, W. Y., AND W. W. WILCOX. 1974. Spatial distribution of lumber degrade in white fir trees. USDA For. Serv. Res. Pap. PNW-184, Pac. Northwest For. Range Exp. Stn., Portland, OR. 18 pp.

- RESCH, H., AND B. A. ECKLUND. 1964. Permeability of wood . . . Exemplified by measurements on redwood. *For. Prod. J.* 14(5):199–206.
- SACHS, I. B., AND R. E. KINNEY. 1974. Bordered pit margo—Improved method for specimen preparation. *Wood Sci.* 1(1):200–205.
- SCHINK, B. J., J. C. WARD, AND J. G. ZEIKUS. 1981a. Microbiology of wetwood: Role of anaerobic bacterial populations in living trees. *J. Gen. Microbiol.* (123):313–322.
- , ———, AND ———. 1981b. Microbiology of wetwood: Importance of pectin degradation and *Clostridium* species in living trees. *Appl. Environ. Microbiol.* 42(3):526–532.
- SCHROEDER, H. A., AND C. J. KOZLIK. 1972. The characterization of wetwood in western hemlock. *Wood Sci. Technol.* 6(2):85–94.
- SIAU, J. F. 1971. *Flow in wood*. Syracuse University Press, Syracuse, NY. 131 pp.
- SIMPSON, W. T. 1975. Effect of steaming on the drying rate of several species of wood. *Wood Sci.* 7(3):247–255.
- SMITH, H. H., AND J. R. DITTMAN. 1960. Moisture content in kiln-dried lumber. *For. Prod. J.* 10(7):353–357.
- TAKIZAWA, T., N. KAWAGUCHI, M. TAKAHASHI, AND H. YAMAMOTO. 1976. [The observation of the wetwood of Todomatsu (*Abies sachalinensis* Mast.)]. *J. Hokkaido For. Prod. Res. Inst.*, 294(July):6–11. (In Japanese.)
- WARD, J. C. 1984. Influence of wetwood on pulsed-current resistances in lumber before and during kiln drying. *Wood Fiber Sci.* 16(4):598–617.
- , AND C. J. KOZLIK. 1975. Kiln drying sinker heartwood from young-growth western hemlock. *Preliminary evaluation*. Proc. West. Dry Kiln Club 26th Annu. Meet. May 1–2, Oreg. State Univ., Corvallis, OR.
- , AND W. Y. PONG. 1980. Wetwood in trees: A timber resource problem. USDA For. Serv. Gen. Tech. Rep. PNW 112, Pacific Northwest For. Range Exp. Stn., Portland, OR. 56 pp.
- , AND D. SHEDD. 1981. Characteristics for presorting white fir lumber with wetwood. Proc. of West. Dry Kiln Club 32nd Annu. Meet. May 6–8, Oreg. State Univ., Corvallis, OR.
- , AND J. G. ZEIKUS. 1980. Bacteriological, chemical, and physical properties of wetwood in living trees. Pp. 133–166, in J. Bauch, ed. *Natural variations of wood properties*. Mitt. Bundesforschungsanst. Forst-Holzwirtschaft., Hamburg, Nr. 131, Hamburg: Max Wiedehusen.
- WILCOX, W. W., AND C. G. R. SCHLINK. 1971. Absorptivity and pit structure as related to wetwood in white fir. *Wood Fiber* 2(4):373–379.
- WORRALL, J. J., AND J. R. PARMETER, JR. 1982. Formation and properties of wetwood in white fir. *Phytopathology* 72(9):1209–1212.