LONGITUDINAL AND TRANSVERSE PERMEABILITY OF BALSAM FIR WETWOOD AND NORMAL HEARTWOOD

Torsten Lihra[1]
M.Sc. Candidate

Alain Cloutier†
Assistant Professor
Département des sciences du bois et de la forêt
Faculté de foresterie et de geomatique
Université Laval
Sainte-Foy, QC
Canada G1K 7P4

and

Shu-Yin Zhang†
Research Scientist and Group Leader
Resource Assessment and Utilization
Forintek Canada Corp.
Sainte-Foy, QC
Canada G1P 4R4

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ABSTRACT

The occurrence of wetwood in balsam fir is a problem in the drying of sawn lumber: drying time increases and moisture content of dried lumber is heterogeneous. Permeability may be used as an indicator of drying rates. Longitudinal, radial, and tangential intrinsic permeability of balsam fir wetwood and normal heartwood was measured in this study. The longitudinal intrinsic permeability was about 2,000 times and 9,000 times higher than the tangential and the radial intrinsic permeability, respectively. Wetwood had a higher longitudinal permeability than normal heartwood, but no significant difference was found between the radial and tangential directions. Sampling height in the tree, basic density, and growth ring width had no effect on the intrinsic permeability. An increase of latewood percentage in the growth rings resulted in an increase in longitudinal intrinsic permeability and a decrease in tangential intrinsic permeability. Radial flow seemed to be controlled by ray blockage in wetwood and normal heartwood, which may result in radial impermeability of wood. A poorly drained stand seemed to favor wetwood formation.

Keywords: Intrinsic permeability, *Abies balsamea* L. Mill., wetwood, wood drying, wood anatomy, SEM.

INTRODUCTION

Balsam fir (*Abies balsamea* L. Mill.) is among the most important commercial softwoods in eastern Canada and northeastern United States. The occurrence of wetwood in balsam fir creates a problem for the drying of lumber: the drying time increases; the moisture content of the dried lumber is heterogeneous; warp and checking increase; and discoloration frequently develops on wetwood surfaces (Ward and Pong 1980). The result is a high percentage of degraded sawn lumber and value loss. Garrahan et al. (1994) compared the moisture content distribution in green lumber from the SPF (spruce, pine, fir) group. They concluded that normal heartwood

[1] Present address: Forintek Canada Corp., 319 rue Franquet Sainte-Foy, QC, Canada G1K 7P4.
† Member of SWST.

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of jack pine (*Pinus banksiana* Lamb.) and balsam fir had a lower moisture content than black spruce (*Picea mariana* Mill.). However, balsam fir had a large range of moisture content within and between boards, and their local moisture content values were three times as high as those in jack pine and black spruce heartwood. The drying time for balsam fir boards was about twice as long as for black spruce and seven times longer than for jack pine. Furthermore, the distribution of moisture content after drying was still heterogeneous for the balsam fir boards. Dokken and Lefebvre (1973) reported a longer drying time and an uneven distribution of moisture in dried balsam fir veneer made out of wetwood.

Other species heavily affected by wetwood include true firs (*Abies* spp.), poplars (*Populus* spp.), and hemlocks (*Tsuga* spp.). For species such as eastern white pine (*Pinus strobus* L.), red oak (*Quercus rubra* L.), and maple (*Acer* spp.), wetwood is found in many trees of one region and may be completely lacking in trees of another region (Ward and Pong 1980).

Mechanical injury and bacterial infection are the most frequent explanations proposed for wetwood formation, but it is not clearly proven whether they are the cause or the result of wetwood formation. Etheridge and Morin (1962) reported that dead branch stubs conduct water directly to the heartwood of living balsam fir trees. Schink et al. (1981) reported that wetwood samples from standing trees of eastern cottonwood (*Populus deltoides* Bartr.), black poplar (*Populus nigra* L.), and American elm (*Ulmus americana* L.) contained a high number of anaerobic pectin-degrading bacteria of the genus *Clostridium.* Shaw et al. (1995) found mechanical injury to be the initiating factor for wetwood formation in western hemlock. Schroeder and Kozlik (1972) believed that wetwood was due to the response to injury by the tree. They considered that the bacterial population found in wetwood was the result of the high moisture content, which favors bacterial growth. Verkasalo et al. (1993) found red oak wetwood to be prone to internal checks during conventional drying. According to Schink et al. (1981), the inclination of wetwood to develop internal checks during drying is due to the activity of anaerobic pectin-degrading bacteria, which weakens the middle lamella between softwood tracheids or hardwood fibers.

Since wetwood areas in green wood are usually associated with high moisture content areas in kiln-dried lumber, it is reasonable to study the permeability of wetwood as compared to normal heartwood or sapwood. Permeability is a measure of ease with which fluids flow through a porous solid under the influence of a pressure gradient (Siau 1995). Since drying involves the movement of fluids in wood, permeability is often used as an indicator of drying rates. Ward (1986) measured the longitudinal gas permeability and drying rates of sapwood, heartwood, and wetwood of white fir (*Abies concolor* Lindl.) and of two poplar species (*Populus tremuloides* Michx. and *Populus grandidentata* Michx.). Wetwood was found to be more permeable than normal heartwood but less than sapwood. The drying time, however, was longer for wetwood than for normal heartwood due to the higher initial moisture content of wetwood. Schneider and Zhou (1989) reported similar results for gas and water permeability of balsam fir sapwood, normal heartwood, and wetwood. They explained that deposits on wetwood-bordered pit membranes prevented complete aspiration and therefore facilitated greater flow through wetwood than heartwood.

The use of liquids, especially water, as permeating fluid complicates the permeability measurements. Entrapped air in wood may block pit openings, and high pressures are necessary to pass the liquid-air menisci through these openings (Kelso et al. 1963). Small particles and air bubbles in the water may be filtered by wood, resulting in a gradually decreasing number of pathways (Flynn 1994). Water permeability measurement requires full saturation of specimens. Even under vacuum-pressure cycles, the full saturation of balsam fir is difficult to obtain due to pit membrane aspiration. For these reasons, gas is more often preferred to liquid for wood permeability determinations.

The objective of this study was to measure the intrinsic permeability of balsam fir wetwood and normal heartwood in the longitudinal, radial, and tangential directions and to relate it to the following wood characteristics: sampling height in the tree, basic density, growth rings width, and latewood percentage in the growth rings.

BACKGROUND

Darcy's law applied to gas flow through wood may be written as follows (Siau 1995; Perré 1987):

$$k_g^* = \frac{QL}{A\Delta P}\frac{P}{\bar{P}} \tag{1}$$

where k_g^* is the apparent or "superficial" gas permeability with slip flow ($m_{gas}^3\ m_{wood}^{-1}\ s^{-1}\ Pa^{-1}$), Q is the volumetric gas flow rate ($m_{gas}^3\ s^{-1}$), L is the length in the flow direction (m_{wood}), A is the cross-sectional area of the specimen (m_{wood}^2), ΔP is the pressure differential across the specimen (Pa), P is the pressure at which Q is measured (Pa), and $\bar{P}$ is the average pressure across the specimen (Pa).

When a gas flows through a capillary whose diameter is in the same order of magnitude as the average free path between the gas molecules, Knudsen diffusion, also called slip flow, becomes significant and must be considered in the permeability measurement. Slip flow occurs in softwood pit openings and increases with the reciprocal average pressure. The gas permeability corrected for slip flow may be obtained from the Klinkenberg equation (Siau 1995):

$$k_g^* = k_g\left(1 + \left(\frac{b}{\bar{P}}\right)\right) \tag{2}$$

with

$$b = 3.8\lambda\left(\frac{\bar{P}}{r}\right) \tag{3}$$

and

$$\lambda = \frac{2\mu}{\bar{P}}\sqrt{\frac{RT}{M}} \tag{4}$$

where k_g is gas permeability corrected for slip flow ($m_{gas}^3\ m_{wood}^{-1}\ s^{-1}\ Pa^{-1}$), b is the Klinkenberg factor (Pa), λ is the average free path between gas molecules (m), μ is the viscosity of the fluid used to determine k_g (Pa s), R is the universal gas constant (8.31 J $mol^{-1}\ K^{-1}$), T is the absolute temperature (K), and M is the molecular weight of the gas (kg mol^{-1}).

Equation (2) shows that the apparent gas permeability, k_g^*, is a linear function of the reciprocal average pressure. Actually, the gas permeability k_g represents the "true" gas permeability corrected for slip flow and can be determined graphically from the intercept of a plot of k_g^* against $1/\bar{P}$. The gas permeability k_g is by definition the permeability of the solid to the permeating gas. By introducing the viscosity of the gas, the intrinsic (or "specific") permeability of the solid can be obtained as follows:

$$K = k_g\mu \tag{5}$$

where K is the intrinsic permeability ($m_{gas}^3\ m_{wood}^{-1}$), and μ is the viscosity of the fluid used to determine k_g (Pa s). K is independent of the permeating gas used and is only a function of the porous structure of the body.

MATERIAL AND METHODS

Material

Ten balsam fir trees at ages of 43 to 121 years with a diameter at breast height (1.4 m) of 17 to 27 cm were felled in July 1997 at Université Laval's Forêt Montmorency experimental station, 40 km north of Québec City. Five of these trees had grown on a well-drained stand, the remaining five on a poorly drained stand. Three one-meter-long logs were cut from each tree: the butt log, the middle log, and the top log. One disc about 20 mm thick was cut at each end of the logs and packed in a polyethylene bag for the determination of cambial age and green moisture

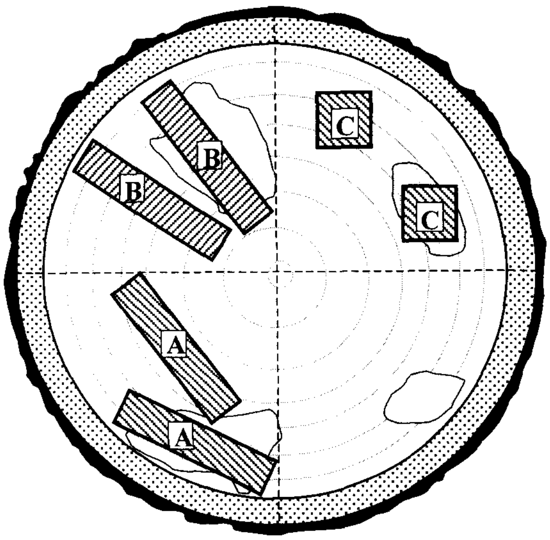

FIG. 1. Cross section of the cutting diagram for matched permeability specimens. A: specimens for radial flow (25 mm × 80 mm × 140 mm); B: specimens for tangential flow (80 mm × 25 mm × 140 mm); C: specimens for longitudinal flow (35 mm × 35 mm × 150 mm). The dotted area represents sapwood, and gray areas represent wetwood.

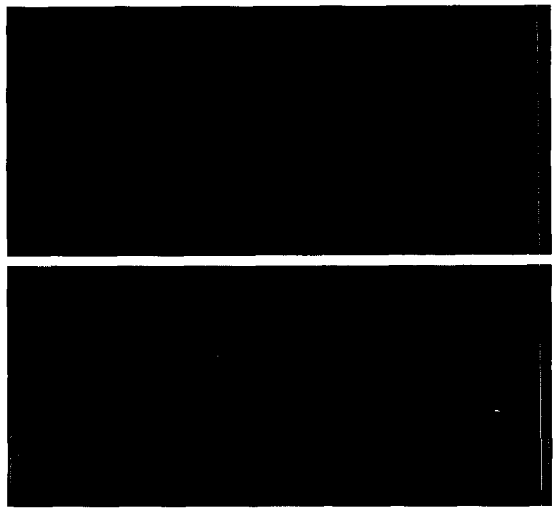

FIG. 2. Cross section of balsam fir 2 × 4's showing typical internal checks in wetwood after oven-drying. The wetwood was delineated before drying.

content. The logs and discs were shipped immediately to the laboratory of the Département des sciences du bois et de la forêt at Université Laval in Québec City. The logs were sawn through a longitudinal-radial plane in two half-cylinders to expose the wetwood, a procedure used by Etheridge and Morin (1962). The wetwood visible on the flat surface of each half-cylinder was delineated with an indelible pencil to show clearly the pattern of wetwood distribution on the flat surface. The flat surface of each half-cylinder was then photographed to measure the proportion of the surface occupied by wetwood using the WinCAM™ image analysis software.

Matched 35-mm × 35-mm × 150-mm (*R, T, L*) specimens for longitudinal flow, 25-mm × 80-mm × 140-mm (*R, T, L*) specimens for radial flow, and 80-mm × 25-mm × 140-mm (*R, T, L*) specimens for tangential flow measurements were cut in the middle and butt logs (Fig. 1). One of the matched specimens was located in wetwood and the other one in normal heartwood. Drying tests were previously performed with wetwood specimens obtained from sawmills to find an adequate drying method. Conventional drying, freeze-drying, and microwave drying resulted in internal checking of the wetwood, as shown in Fig. 2. To prevent changes in the minute structure and extractive content of wood, solvent exchange drying was not used. Mild air-drying at 25°C and 90 to 70% relative humidity at an air velocity of 1 m/s prevented the development of internal checks in the wetwood. As mentioned by Ward (1986), the aspiration of tori in sapwood due to air-drying results in severe reduction of permeability. However, it is known that heartwood permeability is not affected by air-drying (Arganbright and Wilcox 1969; Markstrom and Hann 1972). The specimens were air-dried from green to about 12% moisture content within 30 days, and then cut to the final dimensions. A schematic representation of the specimens used for permeability measurements is given in Fig. 3. For longitudinal permeability measurements, cylindrical specimens of 24 mm in diameter and 123 mm in length were used. For radial and tangential permeability measurements, discs of 50 mm in diameter and 8 mm in thickness were used. The final cut of the end

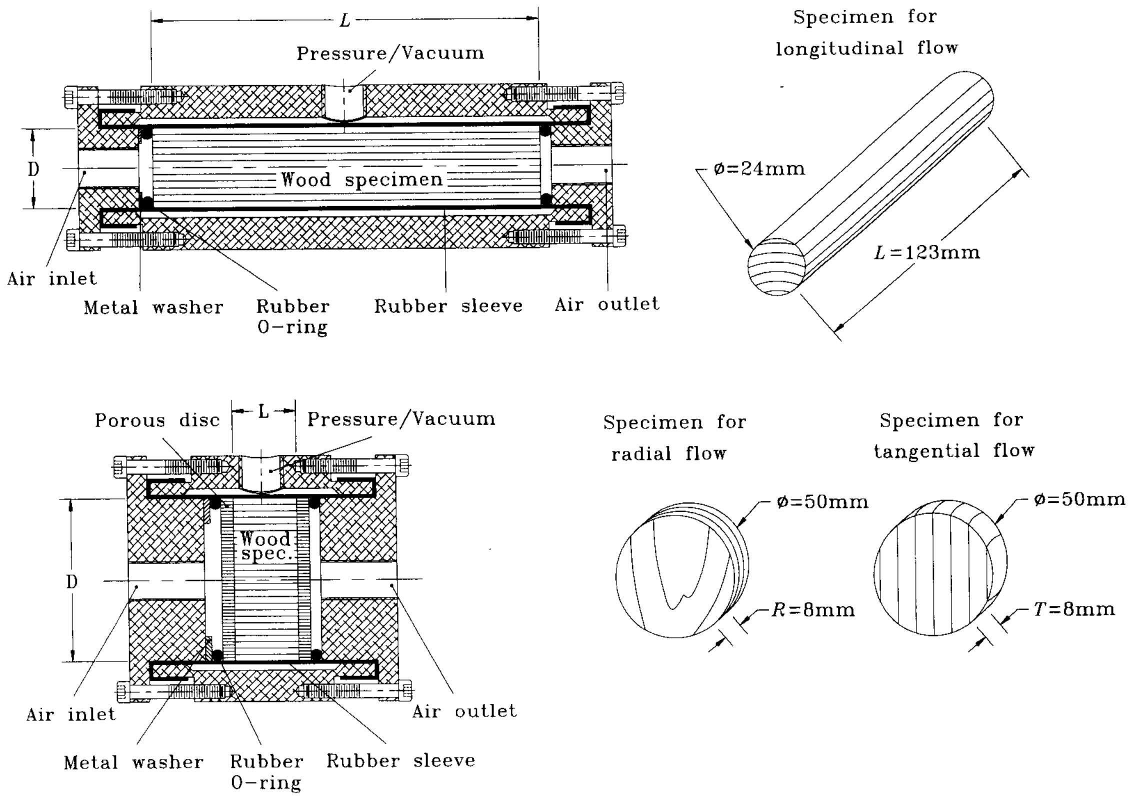

FIG. 3. Specimen holder for longitudinal (top left) and transverse (bottom left) flow measurements, and schematic representations of the specimens used for longitudinal flow (top right), radial flow (bottom left), and tangential flow (bottom right).

surfaces was made with a microtome to obtain the highest permeability values possible as proposed by Perng (1980).

Gas permeability measurements

The gas permeability measurements were made with medical air and an apparatus derived from those used by Tesoro et al. (1974) and Perré (1987) (Fig. 4). A compressed medical air cylinder supplied the gas. A set of pressure gauges indicated pressure differences over 50 kPa, and a mercury manometer was used to indicate pressure differences under 50 kPa. Three flowmeters indicated the flow rate over a total range of 0.05 to 14,000 ml/min. Figure 3 shows the specimen holders used for longitudinal and transverse permeability measurements. A pressure of 600 kPa was applied to the rubber sleeve surrounding the specimen to prevent air leaks by the specimen edge. Vacuum could also be applied around the rubber sleeve through the vacuum pump shown in Fig. 3 to facilitate the introduction of the specimen in the specimen holder. Silicon seal was applied on the edge of the specimen to provide a tight seal with the rubber sleeve. A 7-mm-thick basswood disc was placed on the inlet and outlet side of the specimens for transverse permeability measurements to distribute the air flow over the cross-section and prevent end-effects. Silicon seal was also applied to the edge of these disks. To prevent turbulent flow, pressure differences from 100 to 400 kPa for transverse flow and 2 to 40 kPa for longitudinal flow were used resulting in a flow rate not exceeding 10 ml/min. The apparent gas permeability $k_g{}^*$ was

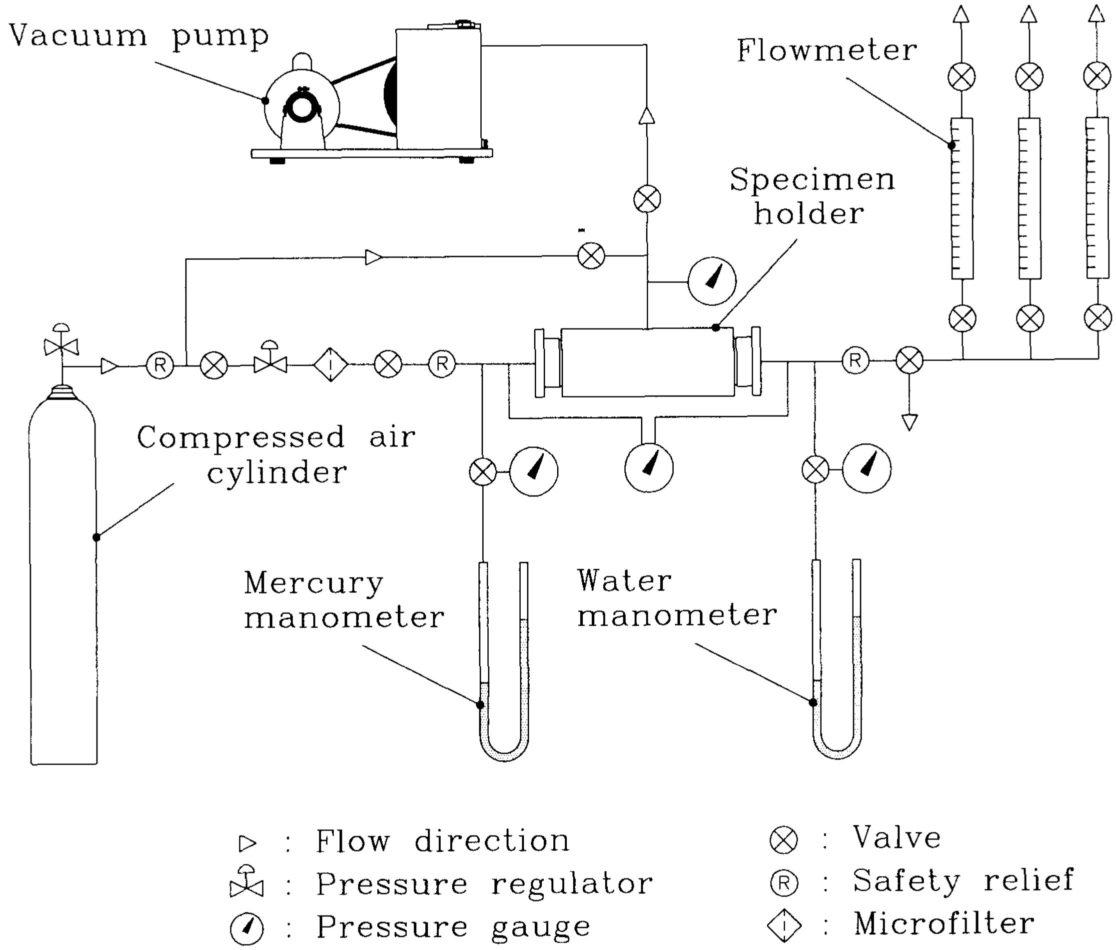

FIG. 4. Schematic diagram of the apparatus used to measure gas permeability.

measured at three pressure levels. A plot of k_g* against $1/\bar{P}$ made it possible to determine k_g, the gas permeability corrected for slip flow. Equation (5) was then used to calculate the intrinsic permeability K.

Determination of wood characteristics

The following wood characteristics were determined for each specimen used for gas permeability measurement: wetwood presence or absence, sampling height in the tree, basic density, average width of the growth rings, and average latewood percentage in the growth rings. The test specimens were free of compression wood. A Kolmogorov-Smirnov test for normality was performed for the data collected for each characteristic. Non-parametric tests (Kruscal-Wallis) were performed with the SPSS™ software to determine the influence of wood characteristics on the intrinsic permeability with significance given to 95% probability level. Small 5-mm³ cubes were cut from wetwood specimens for scanning electron microscope (SEM) analysis to determine the presence or absence of bacterial activity.

RESULTS AND DISCUSSION

Basic tree characteristics

Basic characteristics of the trees sampled for this study are presented in Table 1. The

TABLE 1. *Basic characteristics of the trees used in this study.*

Stand	Tree	Age (years)	DBH (m)	Height (m)	Average annual ring width (mm)	Average basic density (three samples per tree) (kg/m^3)
Well-drained	1	43	0.21	14.9	2.4	299
	2	46	0.27	18.6	3.1	285
	3	51	0.18	13.9	2.2	276
	4	48	0.23	17.1	2.5	282
	5	47	0.19	16.5	2.6	299
Poorly drained	1	121	0.22	16.5	0.9	336
	2	99	0.20	14.1	1.2	360
	3	117	0.27	18.2	1.2	292
	4	58	0.17	13.7	2.1	272
	5	113	0.21	14.2	1.0	350

TABLE 2. *Distribution of moisture content within trees.*

Stand	Tree	Log	Moisture content (%)		
			Heartwood	Sapwood	Wetwood
Well-drained	1	butt	83	197	199
		middle	45	195	205
		top	76	183	188
	2	butt	52	194	212
		middle	59	178	191
		top	48	161	178
	3	butt	90	195	198
		middle	65	165	181
		top	86	180	130
	4	butt	63	152	—
		middle	98	195	237
		top	82	183	195
	5	butt	65	225	—
		middle	58	175	233
		top	99	165	—
Poorly drained	1	butt	41	121	172
		middle	53	153	173
		top	71	154	176
	2	butt	63	176	215
		middle	79	176	211
		top	53	161	199
	3	butt	57	177	234
		middle	61	170	223
		top	51	138	188
	4	butt	53	231	249
		middle	89	200	182
		top	95	205	197
	5	butt	69	163	248
		middle	77	140	232
		top	65	130	122

trees from the wet stand were older and had a slower growth rate than those from the dry stand, resulting in a higher basic density and narrower annual rings. The distribution of moisture content within trees is presented in Table 2. Wetwood moisture content is comparable to that in sapwood, but it is up to four times higher than the overall moisture content in the normal heartwood. The sapwood had a slightly higher moisture content in the butt log. The moisture content of normal heartwood in the butt, middle, and top logs did not show a clear pattern. The wetwood moisture content was generally higher in the butt log.

Wetwood configuration and proportion

Typical configurations of wetwood as seen from the flat surface of the half-cylinder produced from the butt logs and the middle logs are shown in Fig. 5. Wetwood was most often confined to the medullar region of the stems with frequent streaks in the outer heartwood. The configuration of wetwood in the top logs was similar to the midheight logs, but the proportion was lower. In most cases, wetwood present around branches was connected to medullar wetwood. The more frequent occurrence of wetwood in the medullar region in the butt logs and around dead branches in the middle logs suggested that the point of entry of wetwood in the stem is in the roots and around branches. This wetwood configuration is essentially identical to that reported by Etheridge and Morin (1962).

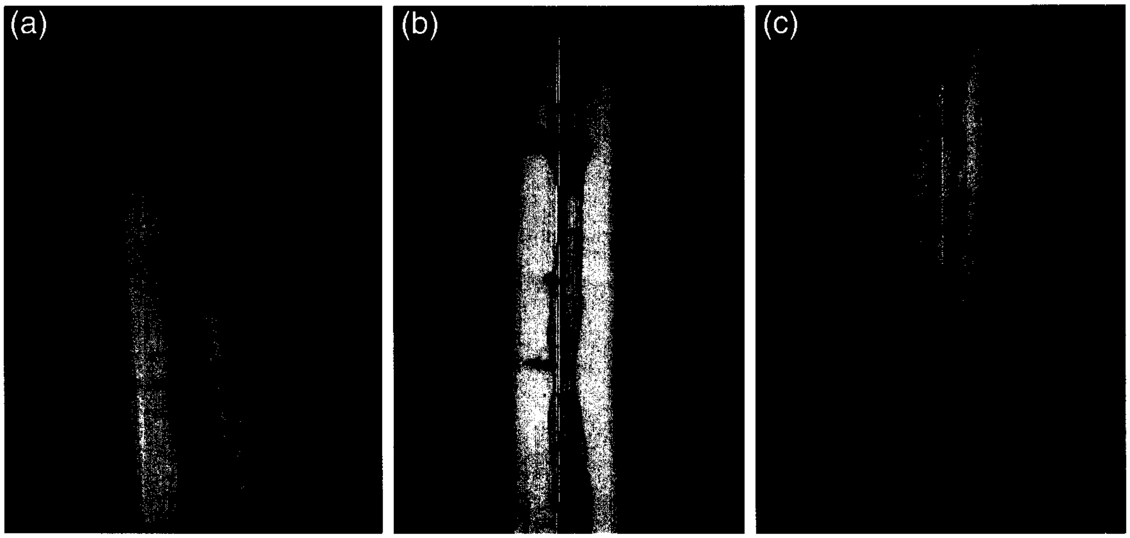

FIG. 5. Photograph of wetwood patterns. a) medullar wetwood in the butt log; b) and c) medullar and streaks of wetwood in contact with branch stubs in midheight logs.

The WinCam™ color analysis software was used to determine the proportion of the radial plane of the logs occupied by wetwood. The results are presented in Table 3. The radial plane of the logs obtained from the poorly drained stand contained an average of 12.9% wetwood compared to 9.7% for the well-drained stand logs. The higher proportion of wetwood in the logs obtained from the poorly drained stand is due to the higher proportion of wetwood in the butt logs, which is twice as high as for the well-drained stand. It is worth mentioning that the proportion of wetwood measured in the middle and top logs for both sites is similar. Our results demonstrate that poor site drainage favors the occurrence of wetwood, mainly in the lower medullar region of the stem.

Permeability measurements

Apparent gas permeability measurements were performed at different average pressures to correct the results for slip flow. Typical plots of the apparent gas permeability, k_g*, against the reciprocal average pressure, $1/\bar{P}$, obtained for longitudinal, radial, and tangential flows are presented in Fig. 6. The plots obtained for longitudinal flow showed a clearly linear relationship and, therefore, the occurrence of slip flow. However, the slope of the relationship obtained for radial and tan-

TABLE 3. *Percentage of the radial plane of the logs occupied by wetwood.*

	Well-drained stand			Poorly drained stand		
Tree	Butt log (%)	Middle log (%)	Top log (%)	Butt log (%)	Middle log (%)	Top log (%)
1	19.8	6.2	17.0	7.7	8.3	2.3
2	7.0	15.9	0.9	17.4	2.8	2.1
3	16.1	25.8	7.8	30.3	15.0	10.5
4	0.0	14.8	15.7	17.8	26.5	22.1
5	0.0	6.5	0.0	6.4	10.5	4.5
Average by log	7.6	13.3	8.3	15.9	14.6	8.3
Average by site		9.7			12.9	

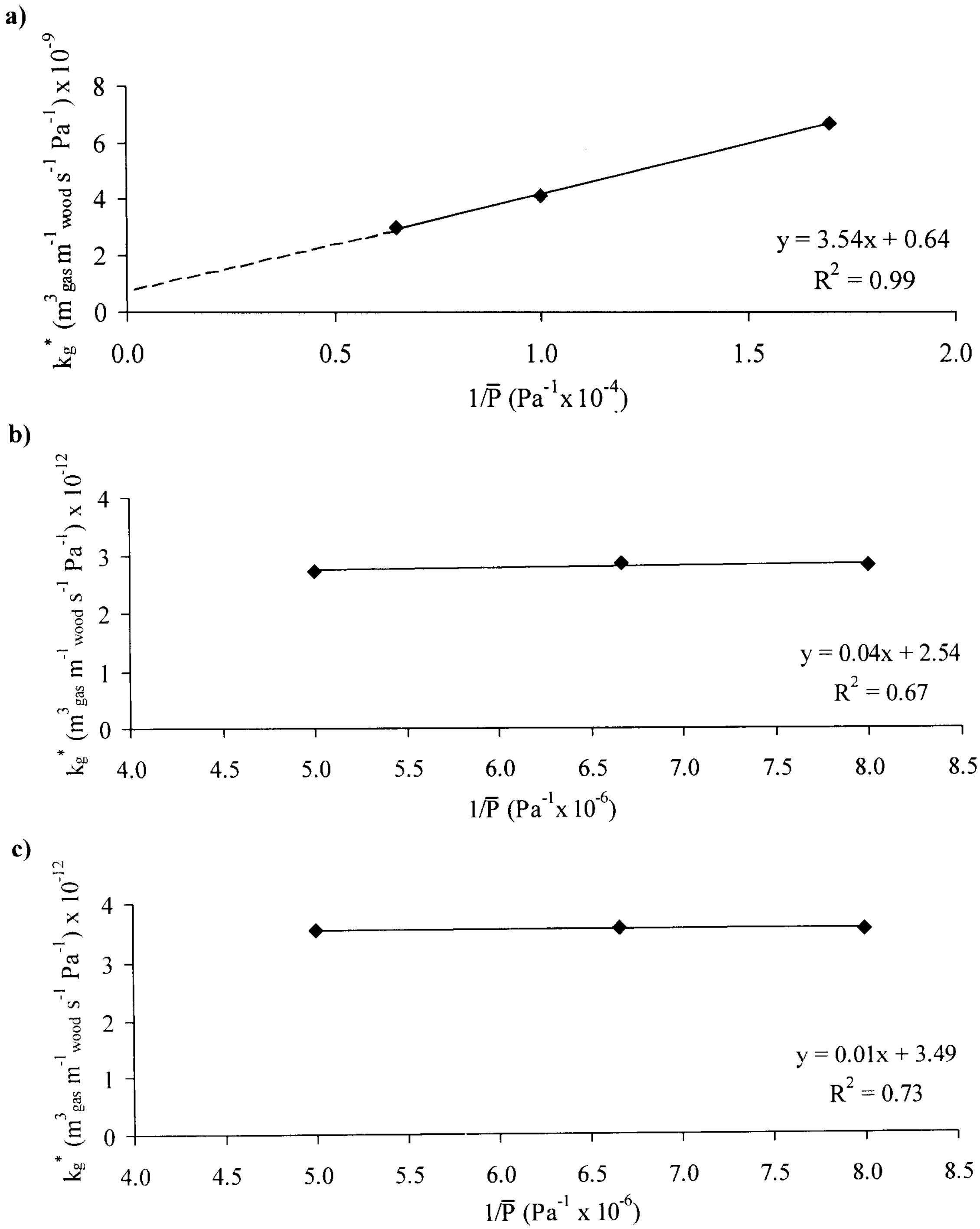

FIG. 6. Typical plot of the apparent permeability against the reciprocal average pressure for a) longitudinal flow, b) radial flow, and c) tangential flow.

TABLE 4. *Overall intrinsic permeability of balsam fir.*

Flow direction	n	Intrinsic permeability K ($m^3_{gas}\ m^{-1}_{wood}$) Average	Std. deviation	Minimum	Maximum
Longitudinal	40	1.2×10^{-13}	1.2×10^{-13}	3.2×10^{-15}	4.1×10^{-13}
Radial	19	1.3×10^{-17}	2.0×10^{-17}	0	6.2×10^{-17}
Tangential	13	5.5×10^{-17}	3.7×10^{-17}	1.0×10^{-17}	12.8×10^{-17}

gential flows was found to be equal to zero, indicating the absence of slip flow in those directions. The average pressure used for the radial and tangential flow measurements (125 to 200 kPa) may explain this result. At a temperature of 23°C and a pressure over 100 kPa, the average free path of the air molecules is about 0.05 μm (Eq. 4). It is therefore smaller than the diameter of the openings between the pit membrane strands. In these conditions, no slip flow takes place. The average of the apparent gas permeability taken at the three average pressures considered was then used for further analysis in the case of the radial and tangential directions.

Outliers were detected using a box plot graph and removed from the data set. From this procedure, two data points out of 42 were removed from the longitudinal intrinsic permeability data set and two data points out of 21 were removed from the radial intrinsic permeability data set. No data point was removed from the tangential permeability data set. A Kolmogorov-Smirnov test for goodness of fit was then applied to each data set. It revealed that the longitudinal and radial intrinsic permeability data were not normally distributed. Rice and D'Onofrio (1996) also found non-normally distributed longitudinal permeability data for white pine, red spruce, and balsam fir. The overall intrinsic permeability results are presented in Table 4. The overall average longitudinal intrinsic permeability was 1.2×10^{-13} $m_{gas}{}^3\ m_{wood}{}^{-1}$ compared to 1.3×10^{-17} $m_{gas}{}^3\ m_{wood}{}^{-1}$ in the radial direction and 5.5×10^{-17} $m_{gas}{}^3\ m_{wood}{}^{-1}$ in the tangential direction. The longitudinal intrinsic permeability was about 2,000 times higher than the tangential intrinsic permeability and about 9,000 times higher than the radial intrinsic permeability. A comparison of the intrinsic permeability obtained for wetwood and normal heartwood is presented in Table 5. The results show that wetwood had on average a higher intrinsic permeability in the three directions, but the difference was statistically significant for the longitudinal direction only due to the high standard deviations. In fact, the standard deviation of most of the average intrinsic longitudinal and radial permeability values presented in Tables 4 and 5 exceeded the average values due to the non-normality of the distributions.

The average intrinsic permeability values obtained in this study for normal heartwood and wetwood are in the same order of magnitude as other results reported for fir wood. Osnach (1961) obtained longitudinal, tangential, and radial gas permeability values of 4.4×10^{-14}, 0.17×10^{-17}, and 1.5×10^{-17} $m_{gas}{}^3\ m_{wood}{}^{-1}$ (0.045, 0.017×10^{-4}, and 0.153×10^{-4} darcys), respectively for fir heartwood. Ward (1986) reports a longitudinal intrinsic gas permeability not corrected for slip flow of 190×10^{-14} and 59×10^{-14} $m_{gas}{}^3\ m_{wood}{}^{-1}$ (1.93 and 0.6 darcys) for white fir (*Abies concolor*) wetwood and normal heartwood, respectively. Schneider and Zhou (1989) reported a ratio of wetwood to normal heartwood longitudinal permeability of 9:1 for balsam fir. Our results show a higher longitudinal intrinsic permeability in wetwood than in normal heartwood but in a ratio of 2:1. However, the large variation associated with our data does not permit drawing strong conclusions about that point. In a recent study, Rice and D'Onofrio (1996) reported a longitudinal intrinsic gas permeability not corrected for slip flow of 3×10^{-14} $m_{gas}{}^3\ m_{wood}{}^{-1}$ for balsam fir heartwood. This is lower than the average longitudinal perme-

TABLE 5. *Average intrinsic permeability values for the wood characteristics considered in this study.*

	Average intrinsic permeability K (m^3_{gas} m^{-1}_{wood})								
	$K_L \times 10^{-14}$			$K_R \times 10^{-17}$			$K_T \times 10^{-17}$		
	n	Average	Std. dev.	n	Average	Std. dev.	n	Average	Std. dev.
Type of wood									
Wetwood	18	17.1	12.4	8	12.9	33.1	5	6.5	5.1
Normal heartwood	22	8.2	9.5	11	1.3	1.8	8	4.7	2.0
Sampling height									
Butt log	15	14.3	9.4	10	1.6	2.0	13	5.5	3.7
Middle log	25	11.0	12.9	9	1.0	2.0	—	—	—
Basic density									
<300 kg/m³	16	10.1	12.2	8	1.5	2.1	8	6.3	2.7
≥300 kg/m³	24	13.7	11.4	11	1.2	1.9	5	4.1	5.0
Growth ring width									
<1.9 mm	26	11.8	11.2	15	1.0	1.7	5	4.8	4.4
≥1.9 mm	14	13.0	12.9	4	2.6	2.6	8	5.9	3.5
Latewood percentage									
<20%	14	6.0	8.7	8	0.8	1.8	7	7.5	3.7
≥20%	26	15.6	11.9	11	1.7	2.4	6	3.1	2.1

ability obtained in our study for normal heartwood (8.2×10^{-14} m_{gas}^3 m_{wood}^{-1}) but still in the same order of magnitude.

Effect of wood characteristics on permeability

About 50% of the specimens used for radial permeability measurement showed a zero, or at least unmeasurable flow at pressures allowable with our apparatus (up to 400 kPa). This explains the zero value presented as the minimum radial intrinsic permeability in Table 4. These apparently airtight specimens were present in both wetwood and normal heartwood of trees from the dry and wet stands. A higher intrinsic permeability was expected in the radial direction due to the presence of ray parenchyma cells, which should provide substantial flow paths. It was the case for wetwood but not for normal heartwood as shown in Table 5. A close examination of the ray parenchyma of the airtight specimens with optical and scanning electron microscopes (SEM) revealed that almost all ray cells were blocked with an extractive substance as shown in Fig. 7. These specimens became permeable after extraction with alcohol-benzene and yielded radial intrinsic permeability values in the same range of magnitude as the specimens that did not show this type of blockage. That confirmed the hypothesis that radial flow was controlled by localized ray blockage. Therefore, this may explain part of the problems encountered when drying balsam fir in general: heterogeneous drying rates between and within boards resulting in heterogeneous final moisture contents. These findings emphasize the advantages of a drying technology inducing a major flow of water in the longitudinal direction of wood, such as vacuum-drying.

Scanning electron microscope analyses of normal heartwood and wetwood showed differences in the pit structure, which confirms the results of Schneider and Zhou (1989). Nearly all of the earlywood pits, and approximately 60% of the latewood pits, were aspirated. Figure 8 shows normal heartwood pit structure with the torus in unaspirated position (a). Pit structures in wetwood (b and c) often contained amorphous deposits on the torus and membrane. These deposits, not found in normal heartwood, may prevent complete aspiration of the pit and increase permeability as suggested by Schneider and Zhou (1989). The nature of the deposits was not determined, but they do not have the same appearance as those found by Schneider and Zhou (1989). Eriksson et al. (1990) showed SEM images of sim-

FIG. 7. Micrographs of balsam fir ray parenchyma cells blocked by extractives. a) tangential plane (400 ×); b) radial plane (400 ×) (Micrographs: André Béliveau); c) tangential plane (SEM, 600 ×).

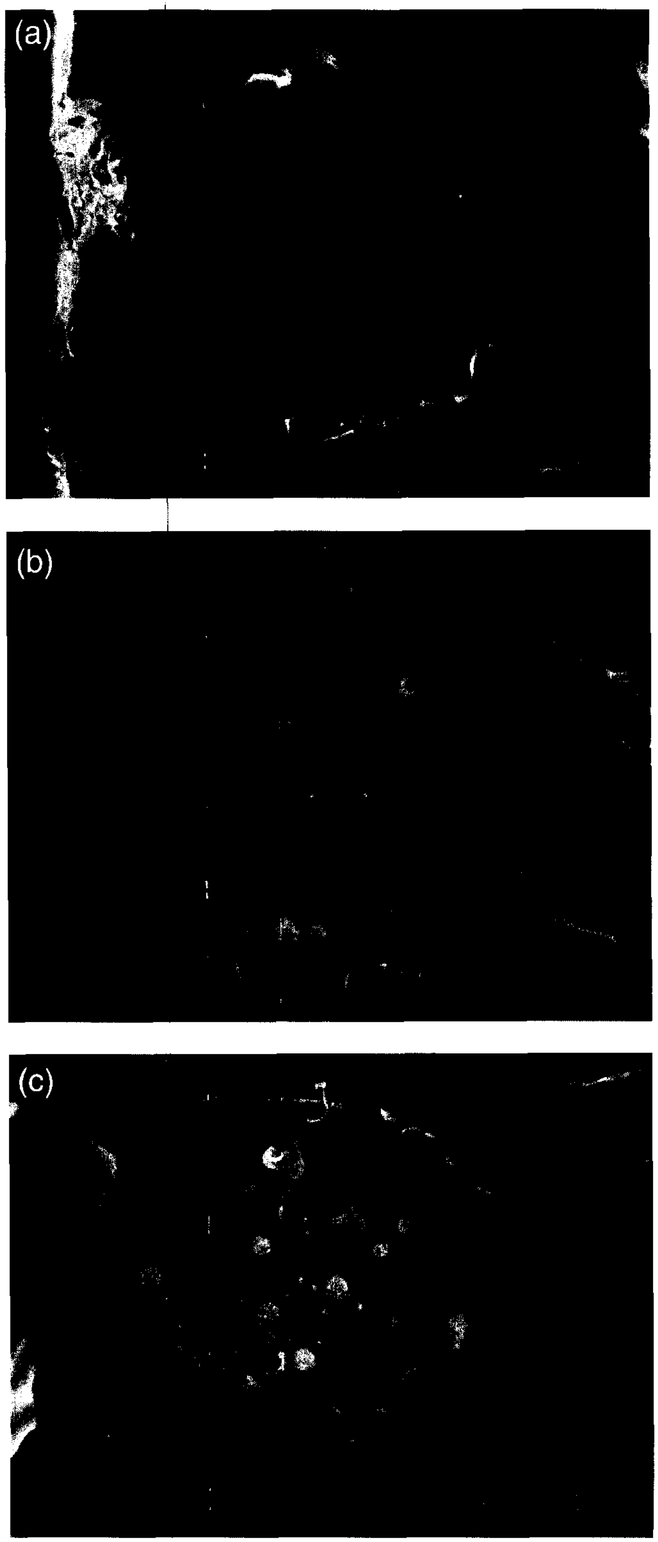

FIG. 8. Scanning electron micrographs of balsam fir bordered pits. a) pit in normal heartwood (7000 ×); b) deposits on the pit torus and membrane in wetwood (7000 ×); c) deposits on the pit torus and membrane in wetwood (7000 ×).

TABLE 6. *Results of the Kruscall-Wallis test on the effect of wood characteristics on the intrinsic permeability.*

Characteristic	Flow direction Longitudinal	 Radial	 Tangential
	Calculated χ^2 (H-statistic)		
Wetwood presence	6.955*	1.047	1.053
Sampling height	2.626	1.396	—
Basic density	1.983	0.008	2.600
Growth ring width	0.029	2.429	1.375
Latewood percentage	9.011*	0.414	6.630*

* Significant at α = 0.05.

ilar deposits on softwood pits, which they identified as bacteria.

To determine the influence of the chosen wood characteristics on permeability, non-parametric analysis was used to analyze the data. The data set of each characteristic was divided in groups permitting the performance of Kruscal-Wallis tests on the permeability data with the SPSS™ software. The average intrinsic permeability values for each group in longitudinal, radial, and tangential directions are presented in Table 5. The results of the Kruscal-Wallis tests are shown in Table 6. A significantly higher permeability for longitudinal flow was found between wetwood and normal heartwood. The sampling height in the tree (for tangential measurements, only the butt log specimens were used), growth ring width, and basic density had no significant influence on the intrinsic permeability. The latewood percentage was found to be significant for longitudinal and tangential flow. The longitudinal intrinsic permeability increased, and the tangential intrinsic permeability decreased with an increasing latewood percentage. The lower proportion of aspirated pits in latewood compared to earlywood can explain the higher longitudinal permeability obtained with an increasing latewood percentage. It is more difficult to explain why an increasing latewood percentage had a significant negative impact on tangential flow. One can speculate that the smaller diameter of the latewood pit openings can result in a higher resistance to fluid flow in the tangential direction. We must stress that 40 samples were used for longitudinal intrinsic permeability measurements compared to only 13 for tangential intrinsic permeability. It would therefore be appropriate to increase the number of tangential permeability measurements to confirm this observation.

CONCLUSIONS

The main objective of this study was to measure the intrinsic permeability of balsam fir normal heartwood and wetwood. Specific objectives were to determine the impact of some wood characteristics on intrinsic permeability and to evaluate the influence of soil drainage on wetwood formation. The results showed that the longitudinal intrinsic permeability of balsam fir wetwood was significantly higher than for normal heartwood. The longitudinal intrinsic permeability was generally from 2,000 to 9,000 times higher than those in the transverse directions. The radial flow seemed to be controlled by ray blockage, which may result in radial impermeability of the wood. An increasing latewood percentage in the growth rings resulted in an increasing longitudinal and decreasing tangential intrinsic permeability. The trees grown on a poorly drained stand had 33% more wetwood than those grown on a dry stand, the lower medullar region of the stem being mostly affected.

These findings may indicate that the main factor explaining difficulties in drying balsam fir wood by forced-air convection drying is not the lower permeability of wetwood but rather the lower radial permeability of localized areas in wetwood and normal heartwood. As a practical implication of this, one may speculate that a drying technology involving an important longitudinal flow of water in wood, such as vacuum-drying, would lead to a faster and more homogeneous drying than forced-air convection drying at atmospheric pressure, which involves transverse flow of water in wood, mainly in the radial direction for flat-sawn lumber. It should be noted that this work was based on a relatively small number of samples. Large-scale studies are necessary to confirm the local or general character of ray blockage in balsam fir and to examine the permeability of wetwood in greater details.

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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. *Cited in* J. C. Ward, 1986. The effect of wetwood on lumber drying times and rates: An exploratory evaluation with longitudinal gas permeability. Wood Fiber Sci. 18(2): 288–307.

DOKKEN, M., AND R. LEFEBVRE. 1973. Drying veneer peeled from seven New Brunswick balsam fir logs. Can. Dep. Environ. Inf. Rep. OP-X-60. 20 pp.

ERIKSSON, K. E. L., R. A. BLANCHETTE, AND P. ANDER. 1990. Microbial and enzymatic degradation of wood and wood components. Springer Verlag, New York, NY. 407 pp.

ETHERIDGE, D. E., AND L. A. MORIN. 1962. Wetwood formation in balsam fir. Can. J. Bot. 40(10):1335–1345.

FLYNN, K. A. 1994. A review of the permeability, fluid flow, and anatomy of spruce (*Picea* spp.). Wood Fiber Sci. 27(3):278–284.

GARRAHAN, P. A., M. SAVARD, AND D. A. CANE. 1994. Sorting and drying eastern SPF on the basis of initial moisture content. Forintek Canada Corp. Rep., project no. 3743K441. 118 pp.

KELSO, W. C., R. O. GERTJEJANSEN, AND R. L. HOSSFELD. 1963. The effect of air blockage upon the permeability of wood to liquids. Univ. of Minnesota Agric. Exp. Sta. Tech. Bull. 242. 40 pp.

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. Sta., Fort Collins, CO. 7 pp. *Cited in* J. C. Ward, 1986. The effect of wetwood on lumber drying times and rates: An exploratory evaluation with longitudinal gas permeability. Wood Fiber Sci. 18(2):288–307.

OSNACH, N. A. 1961. The permeability of wood. Derev. Prom. 10(3):11–13. *Cited in* G. L. Comstock, 1970. Directional permeability of wood. Wood Fiber 1:283–289.

PERNG, W. R. 1980. Studies on flow in wood II. Mokuzai Gakkaishi 26(4):219–226.

PERRÉ, P. 1987. Le séchage convectif de bois résineux: choix, validation et utilisation d'un modèle. Thèse de doctorat, Université Paris VII. 251 pp.

RICE, R. W., AND M. D'ONOFRIO. 1996. Longitudinal gas permeability measurements from eastern white pine, red spruce, and balsam fir. Wood Fiber Sci. 28(3):301–308.

SCHINK, B., J. C. WARD, AND J. G. ZEIKUS. 1981. Microbiology of wetwood: Importance of pectin degradation and clostridium species in living trees. Appl. Environ. Microbiol. 42(3):526–532.

SCHNEIDER, M. H., AND L. ZHOU. 1989. Characterization of wetwood from four balsam fir trees. Wood Fiber Sci. 21(1):1–16.

SCHROEDER, H. A., AND C. J. KOZLIK. 1972. The characterization of wetwood in western hemlock. Wood Sci. Technol. 6(2):85–94.

SHAW, D. C., R. L. EDMONDS, W. R. LITTKE, J. E. BROWNING, AND K. W. RUSSEL. 1995. Incidence of wetwood and decay in precommercially thinned western hemlock stands. Can. J. For. Res. 25:1269–1277.

SIAU, J. F. 1995. Wood: Influence of moisture on physical properties. Virginia Polytechnic Institute and State University Press, Blacksburg, VA. 227 pp.

SPSS® 7.0. 1996. SPSS Inc., Chicago, IL.

TESORO, F. O., E. T. CHOONG, AND O. K. KIMBLER. 1974. Relative permeability and the gross pore structure of wood. Wood Fiber Sci. 6(3):226–236.

VERKASALO, E., R. J. ROSS, A. TENWOLDE, AND R. L. YOUNGS. 1993. Properties related to drying defects in red oak wetwood. For. Prod. Lab. Res. Pap. FPL-RP-516, USDA, Forest Serv. Forest Prod. Lab. Madison, WI. 10 pp.

WARD, J. C. 1986. The effect of wetwood on lumber drying times and rates: An exploratory evaluation with longitudinal gas permeability. Wood Fiber Sci. 18(2):288–307.

———, 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. Sta. Portland, OR. 56 pp.

WINCAM®. 1998. Instruments Regent Inc., Québec, Canada.