VARIATION IN LONGITUDINAL PERMEABILITY OF GREEN RADIATA PINE WOOD

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ABSTRACT

The longitudinal permeability of four 27-year-old trees of radiata pine (**Pinus radiata** D.Don) was measured by passing deaerated water through de-gassed green wood specimens 20 mm long. Significant permeability differences were found between trees, and there was a negative correlation between longitudinal permeability and density. The longitudinal permeability of sapwood increased significantly with height in the stem from the butt to just below the crown. No consistent pattern of variation was observed with radial position over a cross-section. This is attributed to the relatively large fraction of the permeation area in the outer sapwood that is occupied by latewood, and to the presence of compression wood. An abrupt decline in permeability occurred at the boundary between the wet sapwood and dry wood zones. Results were in general agreement with those of comparable studies on other species.

INTRODUCTION

Knowledge of the permeability of green wood is helpful to an understanding of moisture movement during drying and of sap flow in the standing tree. This article gives details of the longitudinal or axial permeability to water of green radiata pine wood, and compares the results with similar studies on other species.

Booker (1977) has shown that a water flow rate that is practically constant with time can be achieved through the fresh xylem wood of radiata pine, provided both the water and the wood are thoroughly de-gassed before use. This procedure prevents the occurrence of air-embolism in the wood. In the same article it was also shown that to obtain true bulk-permeability values free from surface effects it is essential to cut the inflow and outflow end-surfaces cleanly with a sharp blade to remove the damage caused by the sawing process. The water was deaerated by ultrasonic cavitation under vacuum.

A number of authors have investigated the variation of longitudinal permeability with height and cross-sectional position in the tree for several species, using either gas-permeability or water-permeability methods. Unfortunately the variation with height and cross-sectional position of respectively the longitudinal gas-permeability of seasoned sapwood and the longitudinal water-permeability of green xylem are unrelated (Booker, 1977). This occurs because the magnitude of the large change in longitudinal permeability that takes place on seasoning depends on the position the wood occupied in the tree, presumably because of differences in wood structure. Consequently such gas-permeability data cannot be compared with the results of this study.

Other authors have determined the variation of water-permeability with height and/or cross-sectional position in the tree. Prior to the publication of Kelso, Gertjejansen and Hossfeld (1963) it was not realised that it is essential to deaerate the water permeant. As a result all permeability values reported prior to 1963 are too low, with one exception (Erickson and Crawford, 1959). Even after 1963 many authors published data badly affected by air-embolism (Booker, 1977). As a result there are only four articles known to the authors with which the data in this article can be compared, and it will be shown that there is excellent agreement with these (Erickson and Crawford, 1959; Comstock, 1965; Kininmonth, 1970; Markstrom and Hann, 1972).

MATERIALS AND METHODS

Three internodal discs were obtained from each of four 27-year-old radiata pine trees at three height levels: just below the lowest branch of the crown (the "C" level); from a height of 0.6 m above the ground (the "A" level); and approximately halfway between these two levels (the "B" level). From each disc two sectors were chosen from opposite sides (for convenience called "North" and "South"), and from each sector four specimens were cut from the outer-, middle-, and inner sapwood, and the heartwood. These specimens are S1, S2, S3, and H respectively. Moisture content specimens were also cut from each sector and the green weight, green volume, and dry weight of each specimen were measured. This allowed the determination of density, moisture content, and percentage moisture saturation.

The permeability specimens were sawn to a width of 25 mm and a length of 21 mm along the grain. This length was chosen after a preliminary experiment that showed that for specimens less than 20 mm long (less than five tracheid lengths) the permeability is abnormally high while for longer specimens the alignment of inflow and outflow becomes a problem due to spiral grain. In order to measure the bulk permeability, free from end effects, both end-surfaces of all permeability specimens were microtomed to expose an undamaged surface. All specimens were stored submerged in beakers of water in a coolstore at 6°C. Before the permeability measurements were made a beaker was placed in a desiccator and evacuated to de-gas the specimens. The vacuum was released after some hours and the wood allowed to soak for 20 minutes. After a few more vacuum cycles the specimens were left overnight under vacuum, ready for use in the morning. To ensure that the wood was always fresh the permeability work on a series of specimens from the same tree was always completed within 2 weeks from felling.

Apparatus

Each permeability specimen is sealed between the flanges of a glass inflow and outflow apparatus by two neoprene O-rings each 14.5 mm in diameter, and the whole assembly is clamped together (Fig. 1). The O-rings on opposite sides of the specimen must be perfectly aligned with respect to the grain, as otherwise some of the potential flow paths are blocked off. Double distilled deaerated water that has been passed through a 100-nm filter is supplied to a funnel from a 2-litre reservoir. A constant level is maintained in the funnel by a needle valve controlled by a float. The funnel is connected by flexible transparent tubing to the glass apparatus holding the specimen.

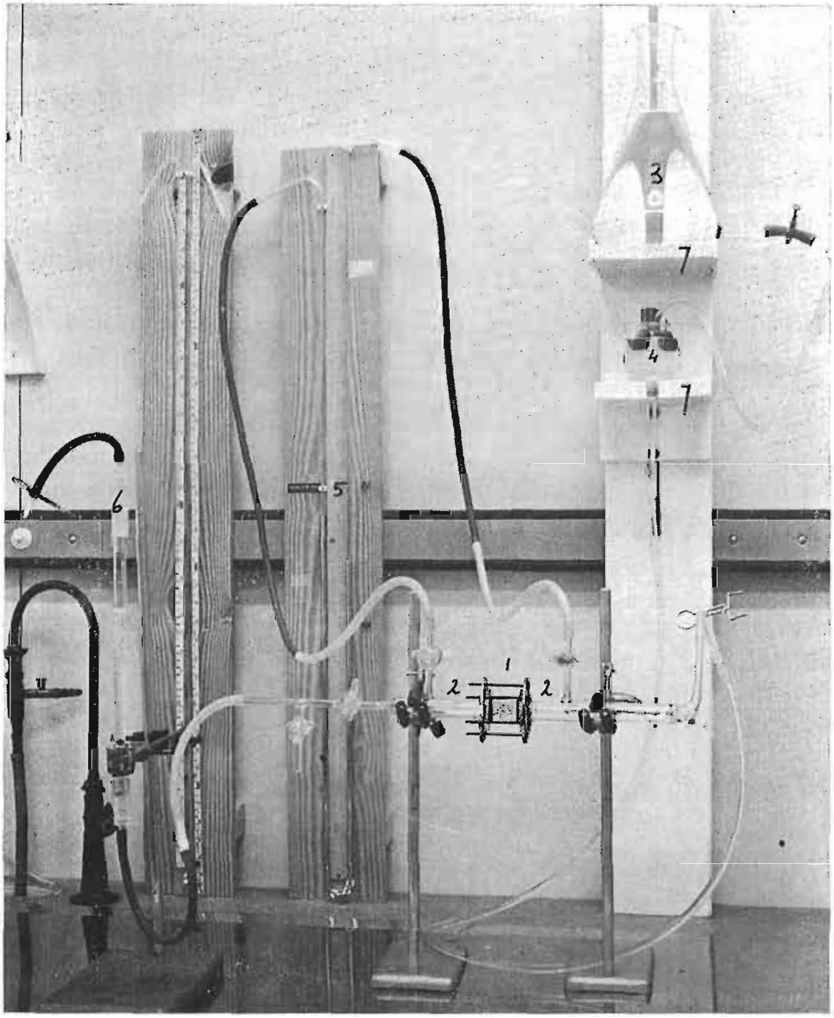

FIG. 1—The permeability apparatus and associated equipment. (1) Permeability specimen, (2) permeability apparatus, (3) 2-litre reservoir of double-distilled deaerated water, (4) needle valve and float, (5) manometer, (6) flow meter, (7) adjustable stands, normally in a higher position.

Usually a hydrostatic pressure equivalent to 94 mm Hg was used. The flow rate through the specimen was measured with a "Tri-Flat" flow meter consisting of a sapphire ball in a tapered tube. It takes 10 seconds for this instrument to give a reliable reading after a steady flow is established.

De-gassing of a specimen can never be absolute. It was found that the maximum flow rate could be slightly increased by starting and stopping the flow a few times. This procedure, similar to that of Chen and Hossfeld (1964), was followed for all specimens to determine the maximum flow rates, from which the permeability was subsequently calculated.

RESULTS AND DISCUSSION

Variation of Permeability with Position in the Tree

The longitudinal permeabilities at different levels and radial positions are presented in Table 1 (The darcy unit of permeability was defined in a previous article; Booker, 1977). The most conspicuous result is that the permeability of the heartwood is negligible compared with that of the sapwood, i.e., less than $1X10^{-4}$ darcy. In a few cases a higher reading was obtained. When the specimens concerned had dye passed through them this showed that either some true sapwood had inadvertently been included in the permeation area (3C,N,H and 3C,S,H), or that one or more resin canals were open to flow. The specimens are so short that the de-gassing procedure can occasionally unblock some resin canals; this has never been observed for longer specimens.

TABLE 1—Permeability values at different tree levels and radial positions

Tree no. and level		Height of tree level (m)	No. of sapwood rings	No. of heartwood rings	Total no. of annual rings	Apparent permeability (darcy)							
						North				South			
						S1	S2	S3	H	S1	S2	S3	H
1	A	0.60	15	>7	>22	6.35	4.18	4.94	0.000				
	B	9.90	12	6	18	8.42	7.94	7.80	0.000				
	C	19.50	10	4	14	9.03	7.29	8.05	0.000				
2	A	0.60	17	>3	>20	3.08	2.00	1.71	$1.0x10^{-3}$	3.37	2.59	2.67	0.000
	B	5.90	14	7	21	4.75	4.74	4.87	0.000	4.93	6.61	3.85	0.000
	C	17.40	12	2	14	6.05	6.33	5.30	0.000	6.01	5.63	5.55	0.000
3	A	0.60	18†	4†	23	3.82	4.28	6.13	$4.2x10^{-4}$	4.04	3.98	5.04	$7.1x10^{-3}$
	B	—	16	≥5	≥21	4.48	7.13	6.84	0.000	4.50	5.26	6.96	0.000
	C	—	13†	4†	18	7.16	9.56	8.00	$3.8x10^{-1}$	6.43	8.59	7.76	$7.9x10^{-2}$
4	A	0.50-1.08	19†	6†	26	2.27	3.64	2.98	—	2.89	3.54	2.74	—
	B	10.51-11.38	14†	6†	21	4.73	6.15	4.08	—	6.12	5.53	3.81	—
	C	19.48-20.23	11†	3†	15	4.65	6.17	4.81	—	6.95	7.32	5.61	—

† Indicates presence of an additional annual ring which contained both heartwood and sapwood. The drywood zone was treated as part of the heartwood. Heartwood, drywood and (wet) sapwood were distinguished visually by their natural colour differences.

Table 1 shows that for all trees the permeability increases from the butt to just below the crown. An analysis of variance in Table 2 shows that this increase is significant at the 99.9% level. It further shows that the variation in permeability between trees is significant at the 99.9% level and that the permeability at a particular level is independent of aspect. Nearly all the variation in longitudinal permeability is accounted for by the variability with height and between trees.

TABLE 2—Analysis of variance, sapwood permeability values of Trees 2 to 4, Table 1

Source of variation	Degrees of freedom	Sum of squares	Mean square	F	Significance level (%)
Trees (T)	2	29.35	14.68	27.2	99.9
Levels (L)	2	92.81	46.40	85.9	99.9
Radial position (P)	2	5.00	2.50	4.6	95*
Sector (S)	1	0.10	0.10	0.2	Not significant
P X T	4	12.70	3.18	5.9	99
Pooled residual	42	22.50	0.54		
Total	53				

* A "t" test of matched pairs of outer-sapwood and inner-sapwood specimens showed no significant difference ($t = 0.39$). On the other hand, dye flow patterns like those of Fig. 2 show a gradual decrease of sapwood permeability from the cambium to the sapwood/drywood boundary. This apparent contradiction is caused by the growth pattern of the trees and the presence of compression wood (see text).

Table 2 shows, rather unexpectedly, that the permeability shows relatively little dependence on radial position. The variation of permeability with radial position can be indicated in another way. The ratio of maximum to minimum permeability for every tree sector (Table 3, column 6) has an average for all sectors of 1.39, ranging from 1.80 to 1.03. Columns 3 and 5 show clearly that both the maximum and minimum permeability in the sapwood can occur in any radial position. It will be shown in a subsequent section that the conclusions in this paragraph need to be qualified, although they are basically correct.

The average permeability at each level has been calculated by averaging the permeabilities of the outer-, middle-, and inner sapwood at each level. The values are tabulated in Table 3, column 7. Column 8 shows the ratio of the average permeability at each level to that at its corresponding "A" level. When this ratio for the "C" levels of the four trees is averaged, it shows that the average permeability at the "C" level is 1.89 times that at the "A" level.

The width of the sapwood is different for the "A" and "C" levels and the inner and middle sapwood specimens consequently occupy different annual ring positions. For instance, specimen 2A, N,S3 comprised the earlywood of ring 15, while 2C, N,S3 was cut from rings 10 to 12. In contrast, the outer sapwood specimens at all levels contain wood of the same annual rings, and it is of interest to determine how the permeability of the *same* sapwood rings varies on ascending from level "A" to "C". The last column of Table 3 shows that the permeability increase of the same growth rings of the *outer* sapwood at the "C" level with respect to the "A" level (82%) is similar to the increase of the *average* permeability (89%).

TABLE 3—Variation of permeability with height, and the ratio of maximum to minimum permeability over a cross-section

Column: 1 Tree number and level		2 Maximum (darcy)	3 permeability (position)	4 Minimum (darcy)	5 permeability (position)	6 Ratio of max. perm. min. perm.	7 Average perm.	8 Ratio of perm. w.r.t. "A" level	9 Perm of S1 (darcy)	10 Av. perm. of S1 at each level	11 Ratio of perm. of S1 at different levels
1	A	6.35	S1	4.18	S2	1.52	5.16	1.00	6.35	—	1.00
	B	8.42	S1	7.80	S3	1.08	8.05	1.56	8.42	—	1.33
	C	9.03	S1	7.29	S2	1.24	8.12	1.57	9.03	—	1.42
2	A,N	3.08	S1	1.71	S3	1.80	2.57	1.00	3.08	3.23	1.00
	,S	3.37	S1	2.59	S2	1.30			3.37		
	B,N	4.87	S3	4.74	S2	1.03	4.96	1.93	4.75	4.84	1.50
	,S	6.61	S2	3.85	S3	1.72			4.93		
	C,N	6.33	S2	5.30	S3	1.19	5.81	2.26	6.05	6.03	1.87
	,S	6.01	S1	5.55	S3	1.08			6.01		
3	A,N	6.13	S3	3.82	S1	1.60	4.55	1.00	3.82	3.93	1.00
	,S	5.04	S3	3.98	S2	1.27			4.04		
	B,N	7.13	S2	4.48	S1	1.59	5.86	1.29	4.48	4.49	1.14
	,S	6.96	S3	4.50	S1	1.55			4.50		
	C,N	9.56	S2	7.16	S1	1.34	7.92	1.74	7.16	6.80	1.73
	,S	8.59	S2	6.43	S1	1.34			6.43		
4	A,N	3.64	S2	2.27	S1	1.60	3.01	1.00	2.27	2.58	1.00
	,S	3.54	S2	2.74	S3	1.29			2.89		
	B,N	6.15	S2	4.08	S3	1.51	5.07	1.68	4.73	5.43	2.10
	,S	6.12	S1	3.81	S3	1.61			6.12		
	C,N	6.17	S2	4.65	S1	1.33	5.92	1.97	4.65	5.80	2.25
	S,	7.32	S2	5.61	S3	1.30			6.95		
Frequency			S1,7x S2,10x S3,4x		S1,7x S2,5x S3,9x	Av. = 1.39		Av. C/A ratio = 1.89			Av. C/A ratio = 1.82

Correlation of Permeability with Density and Moisture Content

A graph has been plotted of permeability versus density for the 33 specimens for which both quantities are accurately known (Fig. 2). The line of best fit obeys the relation:

$$K = 20.74 - 0.03329\ p$$

where K is the permeability in darcy and p is the density in kg/m^3. The coefficient of determination (r^2) is 0.637. The same data points were used to investigate whether a correlation existed between permeability and moisture content as well as permeability and the percentage moisture saturation of wood before it was water saturated. A significant correlation ($r^2 = 0.553$) was found between permeability and moisture content, but no significant correlation exists between permeability and saturation ($r^2 = 0.1179$).

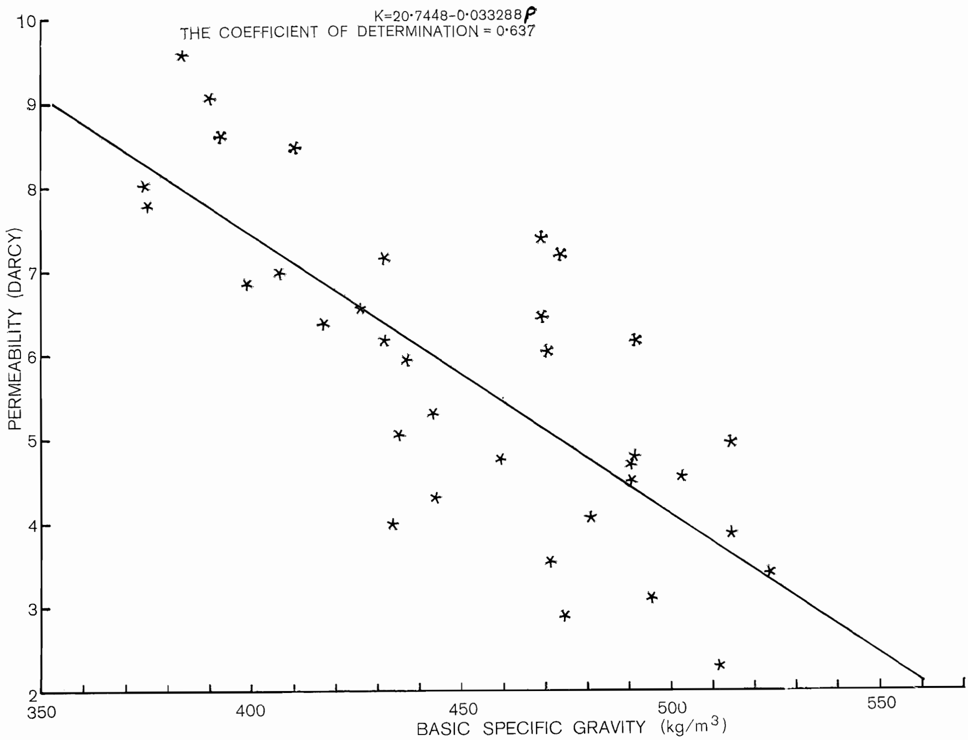

FIG. 2—Relationship between permeability and density.

Effect of the Relative Amount of Latewood on Permeability

The permeability of tree 4 has also been determined with a dye-flow method (Booker, unpubl.). The distance of dye penetration into a given dye-specimen at any point is directly proportional to the permeability at that point. This relationship holds provided the ratio of lumen cross-sectional area to total tracheid cross-sectional area is relatively constant; this ratio is unlikely to vary between earlywood rings (and the latewood does not conduct, see later). A typical dye pattern for one side of a sector of tree 4 is shown in Fig. 3. The photograph confirms that the permeability of the heartwood and the drywood zone is negligible. It also shows that the undifferentiated wood below the bark, as well as the latewood, has negligible permeability compared with the sapwood-earlywood. This raises the question as to how the 14.5-mm diameter O-rings that define the permeation area should be positioned on the permeability specimens. In the case of the outer and intermediate sapwood the annual rings are relatively close together so that each O-ring covers several annual rings. A small change in O-ring position causes little or no change in the amount of latewood under the O-ring, and hence little change in apparent permeability. On the inner sapwood specimens an O-ring covers only one or two annual rings. If the O-ring was centered on an earlywood band, the apparent permeability could be much higher than if it were centred on a latewood band. For the sake of consistency the inner sapwood specimens have been centred on an earlywood band whenever possible.

All previous permeability values have been calculated with the assumption that the complete area enclosed by the O-rings was permeable. It is clear from the above discussion that this gives a very good approximation to the average sapwood permeability, particularly for the outer and middle sapwood. In fact, the permeability across an annual

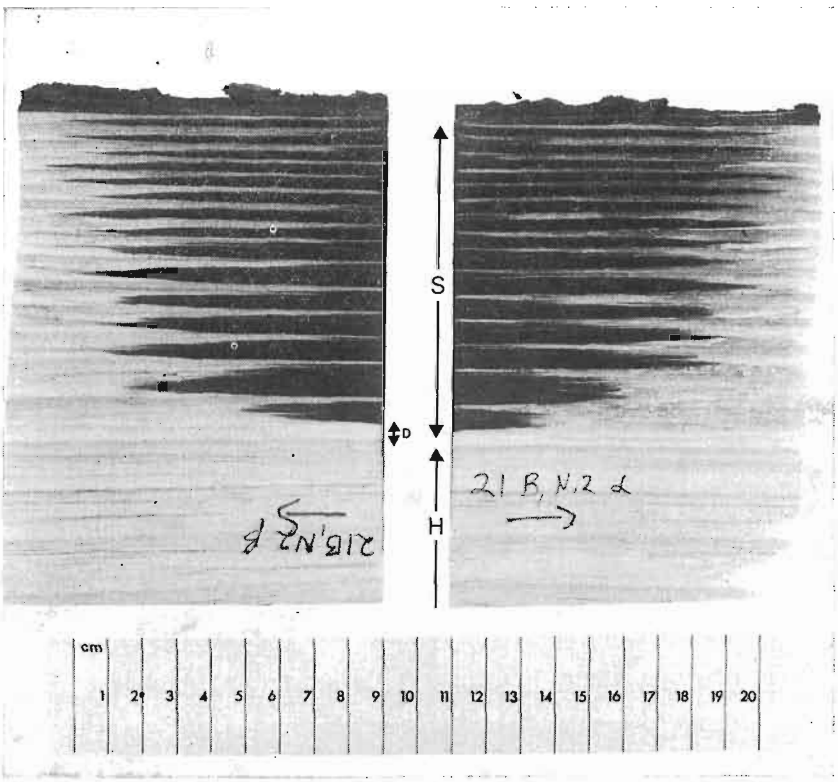

FIG. 3—Dye-flow pattern; north sector, Tree 4, "B" level. Flow cut off abruptly at the drywood boundary. Full travel (103 mm) occurred in ring 5 after 52.8 s using a pressure of 109 mm Hg. S, sapwood; D, drywood zone, H, heartwood.

ring is not constant but continuously variable from effectively zero at the latewood to a maximum somewhere in the central third of the earlywood (Fig. 3). For any given specimen there are three quantities that are of interest—the average permeability, the average permeability of the earlywood, and the maximum permeability in each earlywood ring. Only the first two quantities can be determined for permeability specimens. To avoid confusion the average permeability across a specimen's permeation area will be referred to as the "apparent permeability" and the average earlywood permeability as the "earlywood permeability" in the remainder of this article.

Table 4 shows the earlywood-permeability and apparent-permeability of all specimens of tree 4. More than the usual three sapwood specimens were cut from each sector and to avoid confusion the specimens have been called S_I, S_{II}, etc. counting from the cambium. Equivalence between the specimens of Tables 1 and 3 and those of Table 4 is shown in brackets. The conduction area of each specimen was stained by passing dye through it, after which the area was measured with a dot grid of 82.8 dots/cm^2.

The outer specimens S_I at the "A" and "B" levels of tree 4 are very rich in latewood compared with the S_{II} and S_{III} specimens. The apparent-permeabilities of specimens 4A,N,S_I, 4A,S,S_I, and 4B,N,S_I are very low compared with those of the adjacent S_{II} specimens. The earlywood-permeabilities of the S_I and S_{II} specimens are very similar however. This is confirmed by the dye photograph of Fig. 3. Hence the anomalously low apparent permeabilities of these three S_I specimens at the "A" and "B" levels are caused by the large fraction of latewood in these specimens. Specimens 4B,S,S_I also posses a much larger latewood fraction than its S_{II} neighbour. The apparent permeability of 4B,S,S_I nevertheless exceeds that of its S_{II} neighbour because the earlywood permeability of S_I greatly exceeds that of S_{II}. This is confirmed by the dye-flow pattern for sector 4B,South (not shown).

Table 4 shows that the fraction of a permeability specimen occupied by earlywood increases on ascending a tree, e.g., from 58.1% to 64.8% from 4A,North to 4B,North. This accounts for some of the increase in apparent permeability with height. In addition to this the earlywood permeability also increases with height. Of the 95% increase in apparent permeability from the "A" to the "C" level of tree 4, three-quarters is attributable to the increase in earlywood permeability, and one quarter to the increase in the earlywood fraction.

Comparison of the permeability data with those of other investigators

Data of only four other authors are relevant to the present study (see Introduction). Their data and those of this project appear in Tables 5 and 6. The permeability values by Markstrom and Hann (1972) are included because they show that for the species listed the outer sapwood is somewhat more permeable than the inner sapwood. However, their value for Douglas fir (*Pseudotsuga menziesii* (Mirb.)Franco) is only one quarter of that obtained by Erickson and Crawford (1959) for the same species. Either the wood is less permeable because Markstrom and Hann worked with slow-growing mountain Douglas fir from Colorado and Erickson used coastal Douglas fir, or the specimens and/or water were poorly deaerated.

Comstock (1965) and Markstrom and Hann (1972) find a considerable difference in permeability between the outer and inner sapwood of Eastern hemlock (*Tsuga canadensis* (L.) Carr), Douglas fir, lodgepole pine (*Pinus contorta* Dougl.) and Engelmann

TABLE 4 — Apparent-permeability and earlywood-permeability of tree 4

Specimen	Ring † No	NORTH Apparent Perm. (darcy)	Earlywood Perm. (darcy)	Early-Wood (%)	Specimen	Ring † No	SOUTH Apparent Perm. (darcy)	Earlywood Perm. (darcy)	Early-wood (%)
4 A,N,S_{I} (S1)*	1,2	2.27	5.64	40.2	4 A,S,S_{I} (S1)	1 to 5	2.89	6.48	44.6
S_{II}	4,5,6	3.58	6.27	57.1	S_{II} (S2)	9 to 11	3.54	5.84	60.0
S_{III} (S2)	10,11,12	3.64	5.65	64.0	S_{III}	13,14	3.14	5.97	52.7
S_{IV}	15	2.60	4.74	54.9	S_{IV}	16	2.24	5.03	44.6
S_{V}	17	2.93	4.21	69.5	S_{V}(S3)	18,19	2.74	4.87	56.3
S_{VI} (S3)	18,19,20	2.98	4.74	62.9					
Average		3.00	5.21	58.1			2.91	5.64	51.6
4 B,N,S_{I} (S1)	1,2,3,4	4.73	8.99	52.7	4 B,S,S_{I} (S1)	1 to 6	6.12	10.93	56.3
S_{II} (S2)	7,8,9	6.15	8.58	71.7	S_{II} (S2)	9 to 11	5.53	7.56	72.1
S_{III}	11,12	5.03	7.58	66.6	S_{III} (S3)	14	3.81	5.43	70.2
S_{IV} (S3)	14,15	4.08	5.93	68.0					
Average		5.00	7.77	64.8			5.15	7.97	66.2
4 C,N,S_{I} (S1)	1,2,3	4.65	7.65	60.7	4 C,S,S_{I} (S1)	1 to 4	6.95	10.12	68.8
S_{II} (S2)	5,6	6.17	9.92	62.2	S_{II} (S2)	6 to 8	7.32	10.76	68.0
S_{III}	8,9	5.56	7.76	71.7	S_{III}	8,9	5.12	8.04	63.6
S_{IV} (S3)	11	4.81	6.75	71.3	S_{IV} (S3)	10 to 11	5.61	8.61	65.1
Average		5.30	8.02	66.5			6.25	9.38	66.4

*See text for equivalence of S-symbols.
† Annual rings taking part in conduction, numbered from the bark.

TABLE 5: Comparison of the permeability data with those of other investigators

Author	Year	Species	Water deaerated	Specimens deaerated	Specimen Cut with	Level (m)	Permeability Tree 1	Tree 2	Tree 3	Tree 4	Level av.	(darcy) Species av.	Std dev.	Range	Inter-Tree Variation	Outer/Inner sapwood permeability ratios	Average Outer/Inner Sapwood ratio
Erickson and Crawford	1959	Douglas fir	Partially	Fully	Microtome	3.6	10.70	12.4	8.9	8.2	10.0	10.0			Signif.		
		Western hemlock	Partially	Fully	Microtome	3.6	5.0	6.3	6.0	4.1	5.4	5.4			Signif.		
Comstock [5]	1965	Eastern hemlock	Partially	Fully	Hollow ground saw	0.60	2.5[1]	4.2[1]	6.3[1]	—	4.3[1]	[5] 5.5		1 to 10	Signif. 99.9% level	[1][2]	2.1
						11.6	4.7[1]	7.8[1]	7.6[1]	—	6.7[1]						2.1
Kininmonth	1970	Radiata pine	Partially	Fully	Hollow ground saw	First log	—	—	—	—	—	6.9			—	1.14/0.94/0.80	0.96 (av. 3 ratios)
Booker and Kininmonth	1977	Radiata pine	Fully	Fully	Microtome	0.6	5.2	2.6	4.6	3.0	3.8	5.6		1 to 10	Signif. 99.9% level	[3]	1.06 (av. 21 ratios)
						~9 m [4]	8.1	5.0	5.9	5.1	6.0						
							8.1	5.8	7.9	5.9	6.9						
Markstrom and Hann [5]	1972	Douglas fir +	The same method as Comstock (no details given)			0.9 to 1.5					2.80	[5] 2.41	0.20	—	—		1.38
		Douglas fir*									2.03		0.18	—	—		
		Pinus contorta +									3.03	2.66	0.15	—	—	—	1.32
		Pinus contorta*									2.29		0.13	—	—	—	
		Engelmann spruce +									3.57	2.81	0.29	—	—	—	1.75
		Engelmann spruce +									2.04		0.25				

(1) Values read from a graph
(2) The 12 ratios are: 2.1, 4.6, 1.5, 1.9, 1.2, 1.5, 3.4, 1.4, 2.4, 2.5, 1.8, 1.4
(3) The 21 ratios are: 1.29, 1.08, 1.12, 1.80, 1.26, 0.98, 1.25, 1.14, 1.08, 0.62, 0.80, 0.66, 0.65, 0.89, 0.83, 0.76, 1.06, 1.16, 1.61, 0.97, 1.24
(4) Refer to Table 1
\+ Outer Sapwood
* Inner sapwood
(5) These authors used a short specimen length of 9 mm, tending to increase all permeability values; but by the same factor. Hence the correlations are still real.

TABLE 6: The correlation of permeability with a number of variables

Author	Year	Species	Levels (m)	Perm. ratio of higher to lower level 1	2	3	4	Av.	Correlation of permeability with: Height	Radial Position	Quadrants	M.C.	Density	% Sat.	Growth rate
Erickson and Crawford	1959	Douglas fir	3.6	← Not investigated →					—	—	—	—	r=-0.80	—	—
		Western hemlock	3.6							—	—	—	r=-0.92	—	—
Comstock	1965	Eastern hemlock	0.6 & 11.6	1.84	1.87	1.20	—	1.64	†	†	n.s.	* r=0.636	n.s. r=0.337	—	n.s. r=.061
Kininmonth	1970	Radiata pine	First log	← Not investigated →					—	n.s.	—	—	* F=14.05	—	—
Booker and Kininmonth	1977	Radiata pine	0.6 & 9 m‡	1.56 ←	1.93 cf.	1.29 Table	1.68 3 →	1.62	†	n.s. (qualified)	n.s.	r=0.744	r=-0.80	n.s.	§

* Significant at the 99% level

† Significant at the 99.9% level

‡ The actual height of the "B" level of each tree may be found in Table 1

§ Not investigated. However apparent permeability depends on the fraction of latewood in the permeation area, and hence on growth rate.

spruce (*Picea engelmanni* (Parry)Engelm. (Table 5). Kininmonth (1970) and the present study showed no significant difference in apparent permeability between outer and inner sapwood, yet dye flow patterns like those of Fig. 3 and the data of Table 4 show that the earlywood permeability does tend to decrease towards the sapwood/heartwood boundary. This apparent contradiction can be explained by the general growth pattern of plantation-grown radiata pine, and the presence of compression wood. Usually a reduction in ring width occurs towards the outside of the tree; the percentage of relatively impermeable latewood therefore increases and the apparent permeability decreases. Hence the pattern of maximum permeability, which corresponds to the maximum depth of penetration in each earlywood ring of the dye-flow photograph, is at variance with the apparent permeability pattern, which corresponds to the average depth of penetration over an area including both earlywood and latewood. A further complicating factor is the presence of compression wood, which is a normal feature in plantation-grown radiata pine, and which occurred in all four trees. Severe compression wood causes a sharp reduction in apparent permeability. In tree 3 the outer sapwood consisted of very narrow rings, while severe compression wood occurred in the middle sapwood. Consequently the apparent permeability of the inner sapwood was never less than that of the outer and middle sapwood (Table 3, columns 3 and 5), the reverse of the usual trend.

Table 5 shows that for a given species significant permeability variations occur from tree to tree. No correlation has been found between permeability and quadrant, or percentage saturation of the wood (Table 6). As already discussed the apparent permeability depends strongly on growth rate, which contradicts Comstock's (1965) result.

All authors have found a negative correlation between apparent permeability and density. Latewood has usually a much higher density than earlywood, and its permeability is very much lower (though for reasons of wood structure that are probably not intrinsically related to density). A specimen with a large percentage of latewood will normally have a relatively high density and a low apparent permeability. It is believed that most of the negative correlation between permeability and density is caused by this effect. The positive correlation between permeability and moisture content is explained by the strong correlation between the moisture content and the earlywood fraction of green sapwood.

The two most important results are that the permeability values for all the conifer species listed lie in the range 2 to 10 darcy (2×10^{-12} to 10^{-11} m^2), and that permeability increases significantly with height. In a subsequent paper it will be shown that this increase with height is of considerable physiological significance.

CONCLUSIONS

It has been shown that:

(1) Both the apparent-permeability and earlywood-permeability increase significantly with height in a tree stem.

(2) The increase is greater for the apparent-permeability than for the earlywood-permeability, because the proportion of latewood near the butt of a tree is greater than it is higher in the stem.

(3) No statistically significant variation with radial position in the sapwood exists for the apparent permeability, because the latter is strongly affected by the growth rate of the tree and the presence and severity of compression wood.

(4) Sap conduction paths in a radiata pine consist of concentric earlywood sheaths separated by relatively impermeable latewood sheaths. The heartwood, drywood, undifferentiated wood, and latewood have negligible longitudinal permeability compared with the xylem-earlywood.

(5) A negative correlation exists between apparent permeability and density.

(6) Although a positive correlation exists between apparent permeability and moisture content, no significant correlation exists between permeability and the degree of saturation of the wood.

(7) The experimental results agree well with those of several studies on similar conifer species.

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