# CHANGES IN TRANSVERSE WOOD PERMEABILITY DURING THE DRYING OF *DACRYDIUM CUPRESSINUM* AND *PINUS RADIATA* *

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## ABSTRACT

When softwoods are dried and subsequently impregnated with waterborne preservatives two problems frequently occur—preservative screening of multi-salt preservatives and difficult re-drying. To study the causes, the permeability of *Dacrydium cupressinum* Lamb. (rimu) and *Pinus radiata* D. Don wood was measured along the three principal directions. These two softwood species are anatomically very similar, but differ in that rimu has no resin canals. The radial and tangential permeabilities of the green sapwood of the two species were similar and of the order of $10^{-16}$ m$^2$. The transverse permeability of the green rimu intermediate wood was lower and of the order of $10^{-17}$ m$^2$. After drying and resaturation the radial and tangential permeability of the rimu intermediate wood were practically unchanged, while the transverse permeability of the sapwood dropped to that of the intermediate wood. For *P. radiata* sapwood the tangential permeability decreased to $10^{-18}$ m$^2$. In contrast, after drying and resaturation the radial permeability of *P. radiata* sapwood was of the order of $10^{-14}$ m$^2$, two orders of magnitude greater than for the green wood. This increase in radial permeability was caused by an interplay of flow along the radial and axial resin canals.

It is believed that the absence of preservative screening in *P. radiata* sapwood during impregnation is due to rapid dispersal of preservative solution along the resin canals, followed by movement into the tracheids where the preservative fixes to the cell walls. This mechanism cannot operate in rimu wood as it does not have resin canals, and so preservative screening occurs.

**Keywords:** preservative screening; axial permeability; radial permeability; tangential permeability; intermediate wood; sapwood; resin canals; *Pinus radiata*; *Dacrydium cupressinum*.

## INTRODUCTION

One of the problems in the timber preservation industry is preservative screening, which makes it impossible to treat a large number of species satisfactorily with multi-salt

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preservatives (Wilkinson 1979). For instance, during the preservative treatment of dry *Dacrycarpus dacrydioides* (A. Rich.) de Laub. (kahikatea) sapwood with copper-chrome-arsenate (CCA) solution, the CCA components are preferentially absorbed from the solution as it enters the board surfaces. Hence, the advancing liquid front is depleted in active ingredients, particularly copper. This leads to very low or zero preservative loadings in the centre of the boards of refractory species such as kahikatea and rimu. On the other hand, screening is not a problem for such species as *P. radiata.*

Re-drying of treated timber presents another problem to the timber industry. The redrying rate of treated *P. radiata* is much slower than for green wood, even if the initial moisture content is the same (Kininmonth 1965). It is not clear whether this slow drying is associated with the presence of the preservative, or whether it is caused by the anatomical changes that occur in the wood during drying.

Consequently, it was decided to study the changes in transverse permeability that occur when green wood is dried and resaturated with either water or CCA solution. *Pinus radiata*, New Zealand's most important commercial species, was chosen as a typical non-refractory species, and rimu as a refractory species with a similar anatomical structure.

## MATERIALS AND METHODS

### Identification Numbers

In Table 1 are listed details of the trees or series of boards for which the permeability was measured. Each identification number refers to a separate source of materials and series of measurements. For example, No. 32 refers to a *P. radiata* tree which had 28 annual rings at a height of 2.9 m above the ground. This tree had a slight lean which resulted in somewhat different permeabilities in the compression and tension sides of the tree.

### Cutting of Boards and Permeability Specimens

Boards were cut into two end-matched sections. The first was used for cutting into green permeability specimens, and the second was dried as indicated in Table 1. The high temperature (HT) drying schedule used was 120°C dry bulb / 70°C wet bulb.

Longitudinal specimens were cut from the first board section to dimensions 25 x 25 mm wide and 23 mm along the grain. Transverse specimens were always sawn slightly oversize. They were then split to ensure the permeation direction was truly radial or tangential and not affected by spiral grain. They were finally chiselled with a specially sharpened chisel on all six sides to 20.0 x 20.0 mm by 6 mm thick in the appropriate direction of permeation. The chiselling had the same effect as microtoming and removed surface resistance to flow (Booker 1977) and prevented sleeve leakage (*see below*).

### Permeability Measurement

The longitudinal permeability was measured using techniques described previously (Booker & Kininmonth 1978). The transverse permeability is only 0.01% of the longitudinal permeability; hence, to measure transverse permeability it is essential to prevent leakage

TABLE 1–Description of materials used

| Identification No. | Species | Description | Use | dbh (mm) | Drying method |
|---|---|---|---|---|---|
| 32 | *P. radiata* | Log section with 28 growth rings at 2.9 m height | Green permeability | 300 | – |
| 38 | *P. radiata* | Six boards from trees of similar age, from sawmill | Permeability of green, and dried-and-resaturated wood | – | Forced-air dryer |
| 48 | Rimu | Two separate baulks A and B from sawmill | Permeability of green, and dried-and-resaturated wood | – | Air-dried in laboratory |
| 49 | *P. radiata* | Six dry boards | Permeability of dried-and-resaturated wood | – | Air-, kiln-, and HT-dried |
| 50 | Rimu | Log section cut 5.2–6.2 m above ground | Permeability of green, and dried-and-resaturated wood | 370 | Forced-air dryer, 14–26°C |
| 51 | Rimu | Log sections cut at 1.6–2.7 m, 5.7–6.7 m, and 8.8–9.8 m above ground | Permeability of green, and dried-and-resaturated wood | 322 | Forced-air dryer, 14–26°C |
| 72 | *P. radiata* | One sapwood and one heartwood board from a sawmill | Gas permeability of dry wood | – | Air-, kiln-, and HT-dried |

from the cut tracheids. This was achieved by enclosing the specimens on all four sides by a 0.5-mm-thick pressurised rubber sleeve. The apparatus used was based on a design by Choong & Kimbler (1971) to which several improvements have been made. The water permeant was deaerated ultrasonically (Booker 1977) and the specimens were deaerated before use to prevent embolism (Booker & Kininmonth 1978).

### Impregnation

From the dried board sections, strips about 30 mm along the grain were cut and impregnated with distilled water using the vacuum/pressure method with a vacuum stage of 1.3 Pa ($10^{-2}$ mm Hg). Similar strips of dry wood were cut from the boards of No. 38 and 48 and impregnated with a 0.80% solution of CCA salts. From the resaturated strips permeability specimens were sawn, split, and chiselled as already described, and the permeability was measured.

## RESULTS AND DISCUSSION

### Permeability of Green Sapwood

The permeability values for green wood are listed in Table 2. The axial permeability is recorded in units of $10^{-15}$ m$^2$ and the transverse permeability in units of $10^{-18}$ m$^2$. The green longitudinal permeability values of *P. radiata* and rimu sapwood were very similar. This

TABLE 2–Permeability of green wood in three directions

| Species | Identification number | Type of wood | Comment | Axial permeability ($10^{-15}$ $m^2$) | | | Radial permeability ($10^{-18}$ $m^2$) | | | Tangential permeability ($10^{-18}$ $m^2$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Value* | N† | Range | Value | N | Range | Value | N | Range |
| *P. radiata* | 32 | Sapwood | | 3600 ± 900 | 5 | 2700–4900 | 85 ± 50 | 18 | 30–168 | 263 ± 33 | 17 | 189–326 |
| | 38 | Sapwood | | 4100 ± 1900 | 6 | 2500–6900 | 65 ± 33 | 18 | 18–144 | 410 ± 200 | 17 | 169–774 |
| *P. radiata* | – | Intermediate | | *Impossible to determine permeability values* | | | | | | | | |
| Rimu | 48A | Sapwood | | 2300 ± 500 | 5 | 1900–3100 | 140 ± 41 | 20 | 77–220 | 430 ± 80 | 13 | 371–620 |
| | 48B | Sapwood | | 1700 ± 300 | 5 | 1300–2000 | 90 ± 36 | 5 | 47–129 | 270 ± 10 | 3 | 260–271 |
| | 48 | Sapwood | A & B averaged | 2000 ± 500 | 10 | 1300–3100 | 129 ± 44 | 25 | 47–220 | 400 ± 100 | 16 | 260–620 |
| | 50 | Sapwood | | 4800 ± 600 | 2 | 4400 & 5300 | 500 ± 80 | 3 | 428–583 | 550 ± 20 | 4 | 522–563 |
| | 51 | Sapwood | | 3800 ± 700 | 7 | 3200–5100 | 370 ± 130 | 9 | 111–530 | 390 ± 60 | 10 | 306–470 |
| | 50 & 51 | Sapwood | 50 & 51 averaged | 4000 ± 800 | 9 | 3200–5300 | 400 ± 130 | 12 | 111–583 | 432 ± 92 | 14 | 306–563 |
| Rimu | 48A | Intermediate | | 60 ± 2 | 2 | 57 & 62 | 3.2 ± 2.3 | 8 | 1.0–8.3 | 1.4 ± 0.4 | 3 | 1.1–1.8 |
| | 50 | Intermediate | | 490 ± 90 | 3 | 390–580 | 24 ± 10 | 3 | 14–33 | 80 ± 6 | 3 | 74–85 |
| | 51 | Intermediate | | 730 ± 180 | 6 | 550–1000 | 30 ± 14 | 7 | 19–59 | 51 ± 14 | 6 | 36–71 |
| | 50 & 51 | Intermediate | 50 & 51 averaged | 640 ± 180 | 10 | 390–1000 | 29 ± 12 | 12 | 14–59 | 60 ± 18 | 9 | 36–85 |

* Values are shown as mean ± standard deviation
† Number of specimens

is a physiological requirement for efficient flow of sap in the trees along the trunk. The radial and tangential permeabilities of green rimu and *P. radiata* were also very similar.

## Permeability of Intermediate Wood

Intermediate wood is the region between sapwood and heartwood. It differs from heartwood in that its ray parenchyma cells are alive and it is not impregnated with polyphenols, and it differs from sapwood in its lower moisture content and permeability. For both *P. radiata* and rimu the intermediate wood cannot be distinguished chemically or visually from sapwood after the wood is dried. In green wood the difference in moisture content between sapwood and intermediate wood causes a slight but clearly detectable difference in colour. This allows a distinction to be made between sapwood and intermediate wood for *P. radiata* and rimu as well as other species such as *Pinus contorta* Loudon, *Cryptomeria japonica* (L. f.) D. Don (Japanese cedar), and *Populus* (poplar). Dye penetration along the grain direction for a green rimu specimen, using the techniques described by Booker (1984), is shown in Fig. 1 which is equivalent to a graph of longitudinal permeability

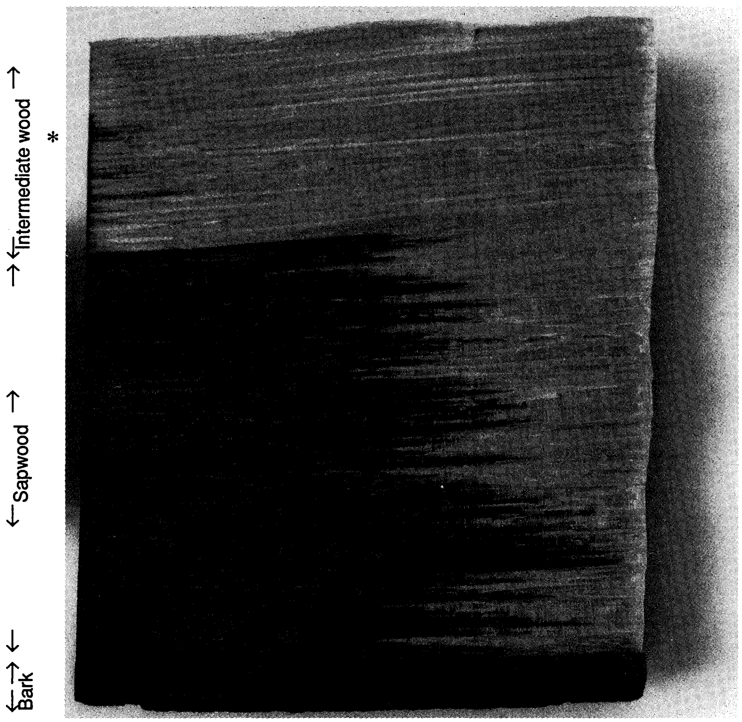


FIG. 1–Dye-flow through a green rimu specimen cut from baulk 48A 100 mm along the grain direction. The direction of flow is from left to right. The penetration of the intermediate wood is very small compared to that of the sapwood. The boundary between sapwood and intermediate wood was recorded before the dye penetration experiment.
* = position of the end of dye- inflow gasket.

as a function of radial position. The boundary between sapwood and intermediate wood was recorded before dye infusion. At the boundary the permeability drops abruptly, as does the moisture content. In a *P. radiata* specimen where the boundary passed through the middle of the earlywood of an annual ring, the sapwood part of the annual ring's earlywood was 95% saturated, while the intermediate wood part of the earlywood was only 49% saturated. For seven other specimens from other trees with the transition boundary passing through the middle of the earlywood of an annual ring similar results were obtained. For rimu (No. 48A) the saturation dropped from 98.6% in the inner sapwood to 34.2% in the outer intermediate wood.

In *P. radiata* the intermediate wood is usually only one ring wide, which is too narrow to be able to cut permeability specimens. In the rimu trees the intermediate wood was very wide; in fact, in trees No. 50 and 51 there was no heartwood. The low permeability values of the intermediate wood (Table 2) are reflected in the shallow depth of dye penetration in the intermediate wood in Fig. 1.

## Permeability Values of Dry and Green Rimu

It should be stressed that the permeability values listed in Table 3 were obtained on specimens that were cut from dried boards. If the green specimens are dried and resaturated their permeability is considerably higher than that of the bulk dried material, and hence unrepresentative (unpubl. data).

The permeability of rimu sapwood in all three directions decreased sharply when intermediate wood formed (Table 2). Similarly, the permeability of the sapwood decreased sharply when the wood was dried (Tables 2 and 3). In Table 4 can be seen more clearly the relative drop in sapwood permeability that occurred during the formation of intermediate wood in the tree, and during drying.

For each rimu tree, the decreases in sapwood permeability during intermediate wood formation and during drying were substantial and of similar magnitude. For example, for tree No. 48A the tangential permeability decreased by a factor of 307 on intermediate wood formation and by 370 on drying, while the equivalent factors for radial permeability were 44 and 60. In contrast, the permeability of intermediate wood changed very little during drying (Tables 2, 3, and 4). These results indicate that it is highly probable that the same anatomical changes occur in the sapwood of rimu during intermediate wood formation and during drying. The main structural change during drying of softwoods is the aspiration of the double-bordered tracheid to tracheid pits (Phillips 1933). In some species collapse of parenchymatous tissue also occurs (Bamber 1972b).

While the decrease in permeability of tree No. 48 during intermediate wood formation and during drying was very similar (Table 4), these decreases were much greater than for trees No. 50 and 51. These two trees were of the same age and grew in close proximity. The above differences may be due to more complete pit aspiration in the wood of tree No. 48 which was considerably older than the other two.

## Permeability of Green and Dry *Pinus radiata*

The decrease in tangential permeability of *P. radiata* sapwood during drying by a factor of 205 was similar to that for rimu sapwood where the decrease ranged from 6- to 370-fold

TABLE 3–Permeability of dry wood in three directions

| Species | Identification number | Type of wood | Comment | Axial permeability ($10^{-15}$ $m^2$) | | | Radial permeability ($10^{-18}$ $m^2$) | | | Tangential permeability ($10^{-18}$ $m^2$) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Value* | N† | Range | Value | N | Range | Value | N | Range |
| Rimu | 48B | Sapwood | Water resaturated | 7.1 ± 1.9 | 3 | 6.1–9.3 | 1.5 ± 0.6 | 5 | 1.2–2.5 | 0.73 ± 0.21 | 9 | 0.52–1.25 |
| | 50 | Sapwood | Water resaturated | 722 | 2 | 722 & 722 | 23 ± 7 | 3 | 16–33 | 56 ± 5 | 4 | 49–62 |
| | 51 | Sapwood | Water resaturated | 1190 ± 270 | 7 | 940–1750 | 56 ± 41 | 13 | 16–122 | 60 ± 35 | 10 | 19–120 |
| | 50 & 51 | Sapwood | Averaged | 1090 ± 310 | 9 | 720–1750 | 50 ± 39 | 16 | 16–122 | 59 ± 30 | 14 | 19–120 |
| Rimu | 50 | Intermediate | Water resaturated | 1120 ± 150 | 4 | 980–1260 | 11 ± 1 | 3 | 11–13 | 70 ± 32 | 6 | 14–116 |
| | 51 | Intermediate | Water resaturated | 1750 ± 760 | 7 | 1140–3270 | 15 ± 7 | 8 | 5.7–27 | 99 ± 36 | 9 | 14–143 |
| | 50 & 51 | Intermediate | Averaged | 1520 ± 670 | 11 | 980–3270 | 14 ± 6 | 11 | 5.7–27 | 88 ± 37 | 15 | 14–143 |
| *P. radiata* | 38 | Sapwood | Water resaturated | 45 ± 25 | 11 | 19–68 | 1400 ± 1200 | 31 | 540–4820 | 2 ± 2 | 28 | 0.3–9.0 |
| | 49 | Sapwood | Water resaturated | – | – | – | 25 000 ± 14 000 | 11 | 8000–46 000 | 5 ± 4 | 11 | 0.4–10 |
| | 72 | Sapwood | Air permeability | – | – | – | 83 000 ± 28 000 | 18 | 32 000–138 000 | – | – | – |
| | 72 | Heartwood | Air permeability | – | – | – | 26 000 ± 21 000 | 13 | 8800–78 600 | – | – | – |
| Rimu | 48B | Sapwood | CCA resaturated | 15.1 ± 6.7 | 6 | 10–28 | 1.3 ± 0.2 | 5 | 1.1–1.5 | 0.60 ± 0.10 | 8 | 0.43–0.71 |
| *P. radiata* | 38 | Sapwood | CCA resaturated | 58 ± 31 | 10 | 27–89 | 4900 ± 4000 | 38 | 180–5400 | 13 ± 9 | 25 | 4.1–22.3 |

* Values are shown as mean ± standard deviation
† Number of specimens

TABLE 4–Permeability decrease factor during intermediate wood formation and drying

| Description | Species | Identification number | Axial | Radial | Tangential |
|---|---|---|---|---|---|
| Sapwood to intermediate wood conversion | Rimu | 48A | 38 | 44 | 307 |
| | | 50 | 9.8 | 21 | 6.9 |
| | | 51 | 5.2 | 12 | 7.6 |
| Intermediate wood drying | Rimu | 50 | 0.44 | 2.2 | 1.1 |
| | | 51 | 0.42 | 2.0 | 0.52 |
| | | 50 & 51 | 0.42 | 2.1 | 0.68 |
| Sapwood drying | Rimu | 48B | 239 | 60 | 370 |
| | | 50 | 6.6 | 22 | 9.8 |
| | | 51 | 3.2 | 6.6 | 6.5 |
| | | 50 & 51 | 3.7 | 8.0 | 7.3 |
| Sapwood drying | *P. radiata* | 38 | 91 * | 1/21.5 † | 205 |

* The axial permeability of dried *P.radiata* sapwood is governed mainly by flow along a few of the axial resin canals, and to a lesser extent by flow along latewood tracheids. By contrast, axial flow in green sapwood occurs almost entirely along earlywood tracheids.

† This indicates an increase in radial permeability by a factor of 22.

(Table 4). This decrease is caused by pit aspiration. In contrast, while the radial permeability of rimu decreased by a factor of 6 to 60, the radial permeability of *P. radiata* sapwood actually increased; in the No. 38 sapwood boards it increased by a factor of 22. In two other sets of *P. radiata* boards (No. 49 and 72) the radial permeability after drying was very high (of the order of $10^{-14}$ $m^{2)}$ and quite variable. The reason for these high radial permeability values was investigated by passing toluidine blue dye solution through the specimens, splitting them, and examining the flow paths. The dye solution entered the tangential-longitudinal (TL) surface via a large number of radial resin canals. It followed these to the vertical resin canals, where the flow was redistributed axially to other radial resin canals. Dye was not observed in rays that did not contain a radial resin canal.

## Photographic Evidence of Radial Flow along Resin Canals

Flow along resin canals is shown in Fig. 2–7. Dye solution penetrated the specimen shown in Fig. 2 from the bottom. Radial conduction occurred along the radial resin canals, one of which intersects a heavily stained axial resin canal (top of photograph). An enlargement of the junction is shown in Fig. 3. The dye spread from the radial resin canals into the ray parenchyma cells and from there into adjacent tracheids. A thick transverse section with heavily stained radial and axial resin canals that obviously interconnect is shown in Fig. 4 and the intersection of such canals in transverse section in Fig. 5. In Fig. 6 can be seen a tangential-longitudinal section with a stained cross-cut radial resin canal, marked "A". Whether the second conducting ray system ("B") included a resin canal is not clear as the cells have collapsed.

In Fig. 7 it can be seen that the conducting resin canals are continuous through both earlywood and latewood, and that the dye spread more readily from the resin canals into the tracheids of the latewood than the earlywood. This is demonstrated even more clearly in Fig. 2 in which a layer of unstained tracheids can be seen above the inflow surface, with

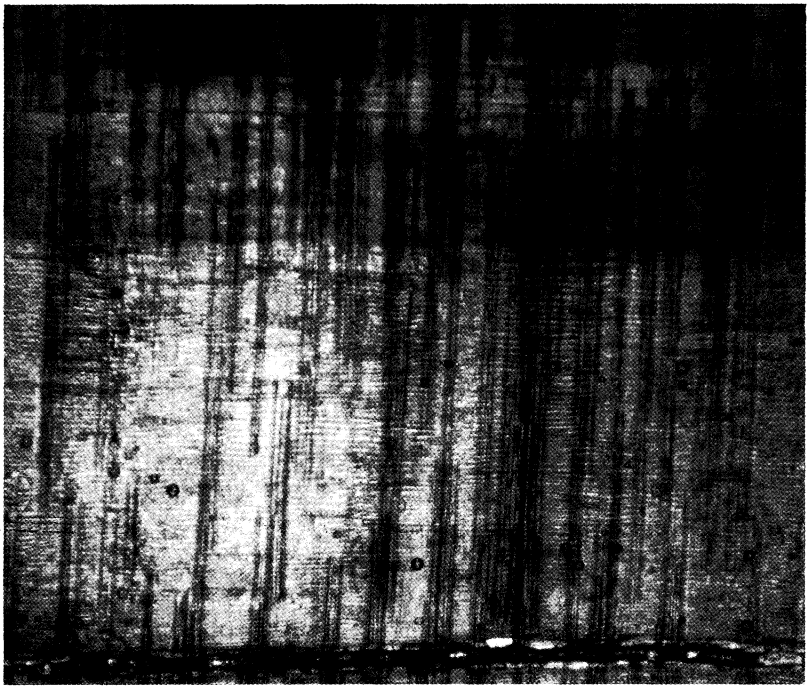

FIG. 2–Movement of dye solution in the radial direction of dried-and-resaturated *P. radiata* sapwood. The inflow surface is at the bottom of the photograph. The main radial resin canal interconnects with the axial resin canal at the top of the photo staining it heavily.

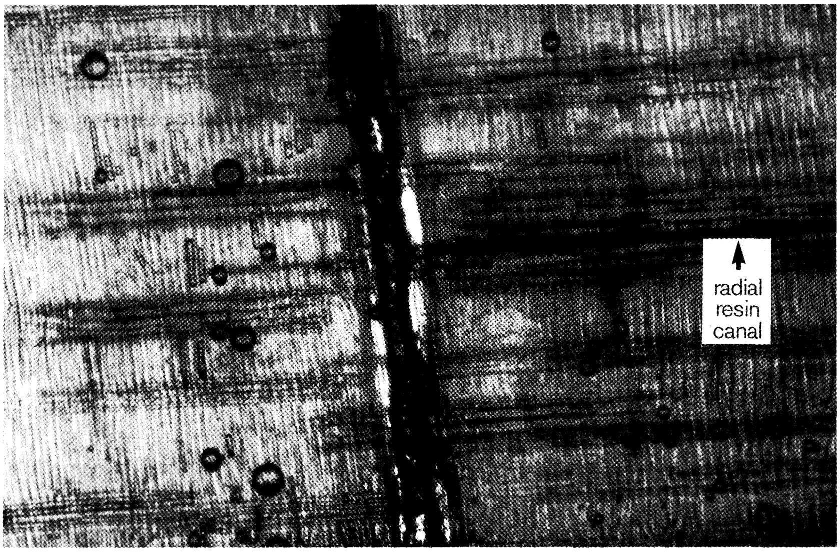


FIG. 3–Enlargement of the intersection of the radial and axial resin canals in Fig. 2

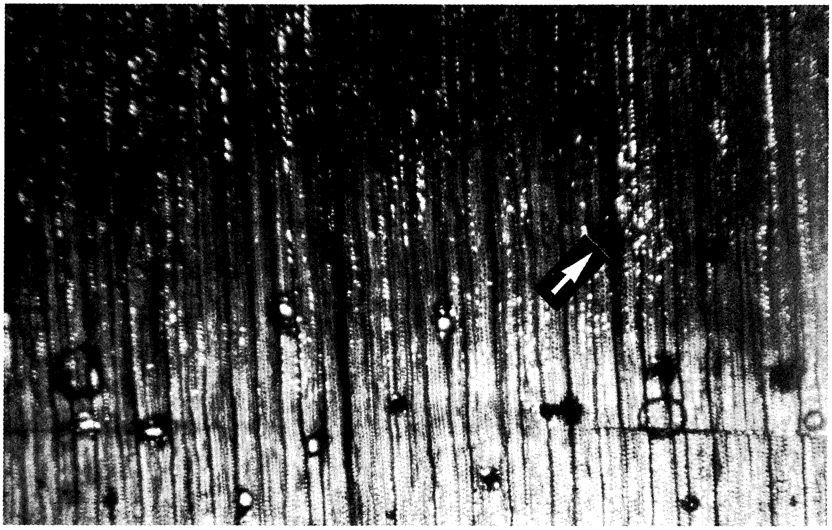

FIG. 4–Transverse section showing stained radial and axial resin canals. An intersection of a radial and an axial resin canal is arrowed

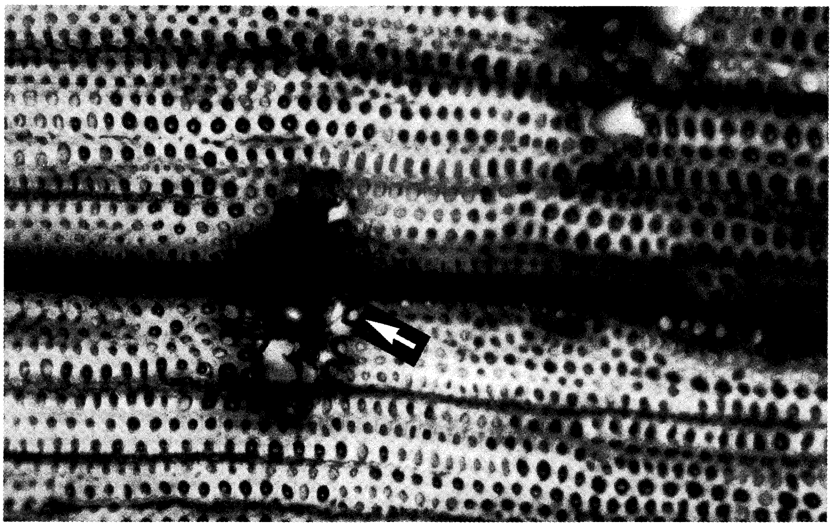

FIG. 5–Intersection of a radial and an axial resin canal in transverse section

above it a layer of latewood tracheids stained with dye solution from the radial resin canals. This agrees with the observation that, in sapwood, the latewood is easier to impregnate than the earlywood.

## Previous Studies of Pathways of Preservative Impregnation

According to McQuire (1970), during preservative impregnation the high-pressure preservative solution penetrates the ray parenchyma and ruptures the ray-to-tracheid-pit membranes, thus allowing the tracheids to become filled with preservative. Bamber &

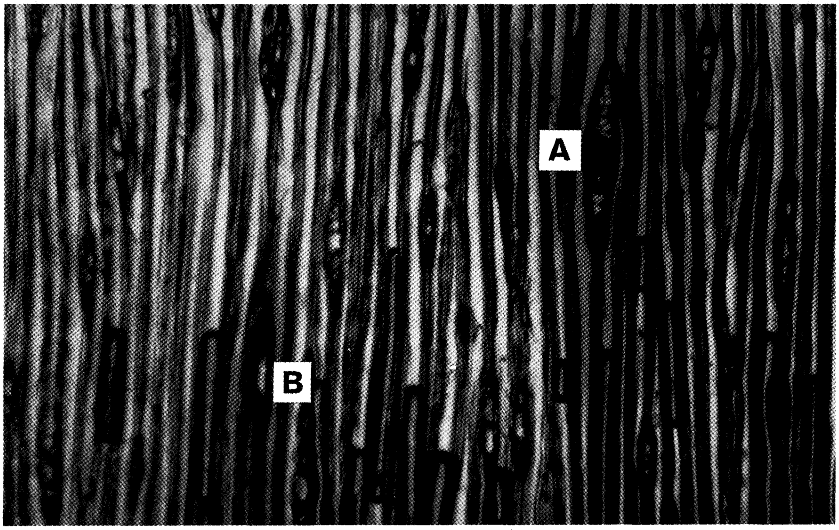


FIG. 6–Radial dyeflow seen in tangential-longitudinal section

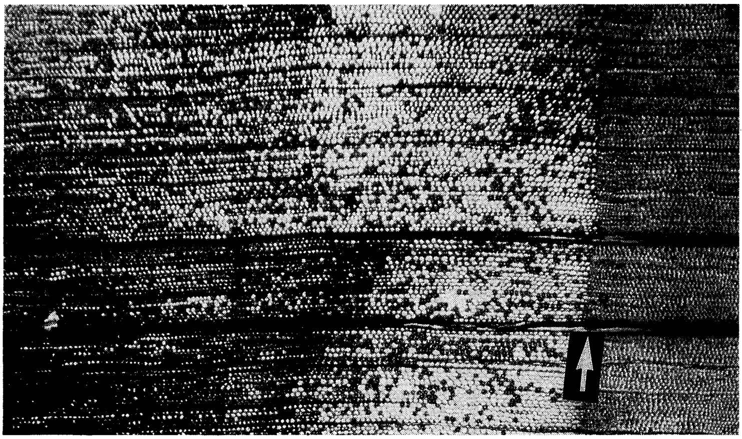

FIG. 7–Two conducting radial resin canals passing through both earlywood and latewood. A stained axial resin canal (arrowed) is visible near the earlywood to latewood boundary

Burley (1983) claimed that drying by itself is sufficient to cause collapse of the horizontal and vertical parenchyma cells.

Bamber & Burley (1983) proposed a model in which radial flow in dry *P. radiata* sapwood occurs along interstitial spaces created by the collapse of the walls of the thin ray parenchyma cells. However, they also stated that the collapse of parenchyma cells creates both radial and longitudinal interstitial spaces along rays and resin canals along which relatively free movement of liquids can take place (Bamber 1972b), thus increasing the radial permeability of dry pine wood. Bamber & Burley (1983) suggested a further flow mechanism: "The bordered pits of latewood and ray tracheids are rarely closed. However, although aspiration obviously restricts flow across the pit, it does not prevent it and liquid movement still takes place through these structures (Kishima 1965)". However, the extremely low tangential permeability values in Table 3 for rimu (No. 48B) and *P. radiata* sapwood (No. 38 and 49) show that flow through a series of aspirated pits is practically non-existent. In addition, even if ray tracheid pits do not aspirate, the fact that the radial permeability increases sharply on drying means that ray tracheid conduction can at best make only a very small contribution to the total dry wood permeability.

Olsen (1987) observed for dry *P. radiata* specimens that had been soaked: "It is noticeable that the stained rays are often in contact with a resin canal. The collapse of the parenchymatous cells described by Bamber and Burley could be the explanation for this phenomenon." Although Olsen (1987) did not say so, it can be seen in Fig. 3 in her thesis that vertical resin canals were frequently stained in advance of the main dye front. Clearly, the radial and vertical resin canals were also major pathways for penetration in Olsen's specimens.

## Model for Preservative Impregnation of *Pinus radiata* Wood

The following model for preservative impregnation of dry *P. radiata* wood is based upon the dye flow and permeability results shown in Fig. 2–7 and Table 3, as well as the observations of the above investigators. During preservative impregnation, the main flow into *P. radiata* sapwood occurs along the radial resin canals while practically no flow occurs along rays that do not contain a resin canal. When one of the conducting radial resin canals connects with an axial resin canal, axial flows occurs along the latter. From the axial resin canal this flow is then redistributed into other radial resin canals in direct communication with it. The interstitial spaces created by the collapse of ray parenchyma and epithelial cells form secondary flow paths. From the radial resin canals the preservative solution enters the interstitial spaces created by the collapse of epithelial cells and ray parenchyma. From the interstitial spaces it then enters the tracheids via the ray-to-tracheid pits. In the latewood the preservative can flow readily between adjacent tracheids via open pits, so that impregnation of the latewood is relatively simple. In the earlywood, however, tracheid-to-tracheid flow is extremely difficult and requires a high pressure, as the earlywood pits are generally aspirated. While it is possible to fill the earlywood tracheids with preservative solution under high pressure, the aspirated pits make subsequent redrying very difficult. A schematic representation of the model is shown in Table 5.

TABLE 5–*Pinus radiata* sapwood impregnation model

Solution enters the radial resin canals
Flows along a succession of radial and axial resin canals
Flows from radial resin canals into interstitial spaces created by drying-induced collapse of ray parenchma (Bamber 1972)

↓

Through the ray to tracheid pits (damaged by drying and possibly high pressure)

↓

Into the tracheids

↓

Adjacent latewood tracheids filled via the interconnecting non-aspirated pits

Soaking, low pressure → Pits between earlywood tracheids are aspirated. No flow into adjacent earlywood tracheids.

High pressure → Solution forced through the aspirated pits. Redrying of the wood is very difficult.

It should be stressed that by no means all radial and vertical resin canals are able to take part in conduction. Their ability to do so depends mainly upon the amount of resin blocking the canals. This is affected by a large number of factors such as the response of the tree to wounding, whether the tree was suffering water stress at the time of felling, the length of time between felling, sawing, and drying, as well as the drying schedule used. In addition, the number of resin canals per square metre is highly variable between trees. All these factors are responsible for the large differences in the resaturated sapwood permeabilities of *P. radiata* in the radial direction shown in Table 3, as well as the variations in treatability normally encountered in the preservation industry.

In *P. radiata* heartwood the parenchymatous tissue and the resin canal tissue are lignified (Bamber 1972a). Presumably, this results in reduced collapse of the ray parenchyma and epithelial cells during drying. In the sapwood the resistance to flow from the radial resin canals into the interstitial spaces and from there into the damaged ray-to-tracheid pits should be relatively low. If in the heartwood few intercellular spaces are created by cell collapse, preservative solution can flow from the radial resin canals into the tracheids only by first passing through the resin canal wall into the ray parenchyma cells and then penetrating the undamaged ray-to-tracheid pits that in the heartwood are heavily encrusted with extractives (Krahmer & Côté 1963). Once within the tracheid system the solution would have to pass from tracheid to tracheid via pits that are aspirated and heavily encrusted with extractives (Krahmer & Côté 1963). This model explains the apparent paradox that *P. radiata* heartwood has both a high radial permeability of $2.6 \times 10^{-14}$ $m^2$ (Table 3) and low treatability. Radial flow along the radial/axial resin canal system in heartwood experiences little resistance, but flow from the radial resin canals into the tracheids has such a high resistance that it is almost non-existent.

## Preservative Screening

In rimu and other softwoods that do not have resin canals, impregnation can occur only by liquid movement along the ray parenchyma and along tracheids whose pits are nearly all aspirated. These pits are very impermeable, as is shown by the very low tangential permeability values for dried-and-resaturated sapwood in Table 3. During the impregnation of rimu the rate of penetration is very slow, because the permeabilities are very low. This means that the solution is in intimate contact with the cell walls of the exterior of a board for a relatively long time. During this time the active ingredients of the multi-salt solution are depleted by fixation in the cell walls. Fixation occurs at different rates for the different components of the solution. As the solution advances into the wood and the concentration of active components decreases, the amount of chemical available for fixation in the cell walls decreases. This results in a concentration of salts in the wood that decreases towards the core and that is different for the individual components of the multi-salt solution. This is known as preservative screening. If the permeability is very low, a wet core with little or no preservative loading may result.

## Permeability of Wood after CCA Treatment

Softwoods are difficult to redry after impregnation with CCA solution. For both rimu and *P. radiata* water-resaturated and CCA-resaturated specimens had almost identical permeabilities (Table 3). It follows that the redrying problems of treated wood are associated with the anatomical changes caused by drying, and not with the chemical reaction between the preservative and the cell wall.

## CONCLUSIONS

During drying of rimu sapwood both the radial and tangential permeabilities decreased very sharply. For *P. radiata* sapwood the tangential permeability also decreased sharply, but the radial permeability increased. Drying caused flow paths for liquid movement to open up along the radial and axial resin canals. Preservative solution movement along these resin canals allows rapid impregnation with minimal screening in *P. radiata* sapwood.

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