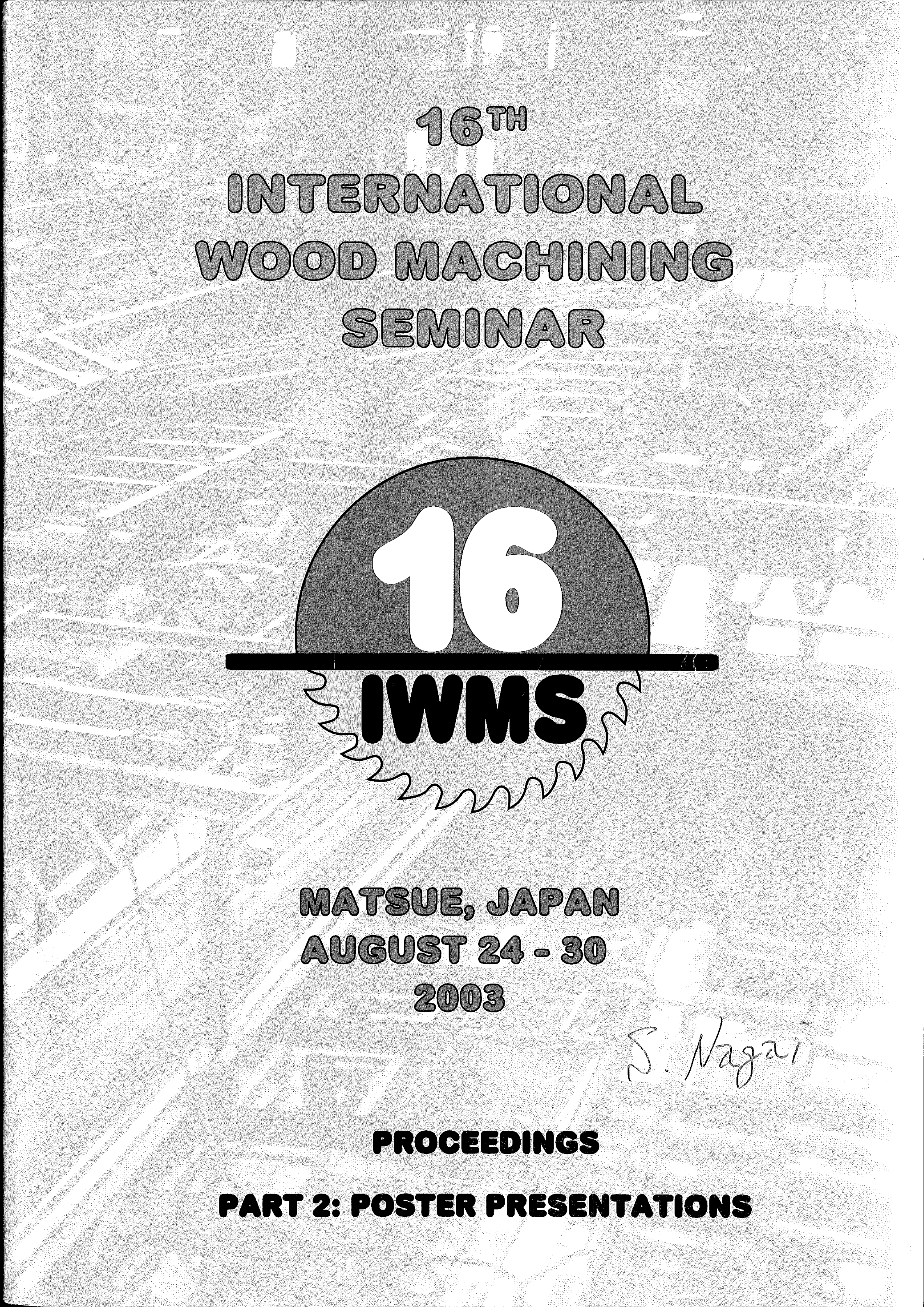

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PROCEEDINGS

PART 2: POSTER PRESENTATIONS

THREE-DIMENSIONAL GAS PERMEABILITY IN LOGS OF *CRYPTOMERIA JAPONICA* D. DON

Nagai Satoshi[1], **Taniguchi Yoshiaki**[2], **Nakai Takahisa**[3], and **Abe Hisashi**[4]

[1] Forestry Technology Institute,
Hyogo Prefectural Technology Center for Agriculture, Forestry and Fisheries,
Shiso-Gun, Hyogo 671-2515, Japan
E-mail: satoshi_nagai@pref.hyogo.jp

[2] Department of Technology Education, Nara University of Education, Nara 630-8528, Japan
E-mail: yoshiaki@nara-edu.ac.jp

[3] Department of Natural Resources Process Engineering,
Shimane University, Matsue 690-8504, Japan
E-mail: jaja@riko.shimane-u.ac.jp

[4] Japan International Research Center for Agricultural Sciences, Tsukuba 305-8686, Japan
E-mail: abeq@affrc.go.jp

ABSTRACT

The permeabilities of heartwood, intermediate wood, and sapwood were investigated in green logs of *Cryptomeria japonica* D. Don using glass tubes connected to manometers, which were inserted into the logs from the transverse surface. Pressure changes inside the logs were monitored as the atmospheric pressure outside the logs was changed in a vacuum chamber. The exposed log surfaces were changed by coating them with epoxy resin or by removing the bark. In some logs, slits were made from the outside to the center.

In the heartwood, gas permeation was scarcely detectable in any of the three directions, longitudinal, tangential, or radial. In contrast, the permeability in the intermediate wood was remarkably high in both the longitudinal and tangential directions. In the sapwood, the tangential permeability was high, and the longitudinal and radial permeabilities were low.

In logs with only the tangential surfaces exposed to the outer atmosphere, a decrease in pressure was first detected in the intermediate wood. This phenomenon demonstrated the presence of radial passages through which gas flowed from the ambient atmosphere to the intermediate wood. The pressure variations in the sapwood consistently followed the pressure changes in the intermediate wood, rather than the pressure changes outside the logs.

INTRODUCTION

The intermediate wood of *Cryptomeria japonica* D. Don is designated “white rings” (Kurotori[1]) or “white zone” (Nobuchi and Harada[2]). It appears whitish and is clearly distinguishable from heartwood and sapwood in transverse sections (Sano and Nakada[3]).

Nobuchi and Harada[2] reported that the moisture content decreased going from the sapwood-white zone boundary into the white-zone wood; in addition, the percentage of aspirated pit pairs suddenly increased in the sapwood-white zone boundary. On the other hand, water distribution in the heartwood varied with the type of tree and the position within the tree (Nakada *et al.*[4]; Nakada *et al.*[5]); the heartwood moisture content ranged from 46% to 254% (Nakada *et al.*[6]).

It is difficult to evenly dry wood from trees with such an uneven distribution of water. It is commonly accepted that the permeability of heartwood is low and that the white-zone wood prevents radial water movement from the heartwood toward the outer layer during drying. Studies of the gas permeability of *Cryptomeria japonica* have been conducted using small clear specimens (Matsumura *et al.*[7]; Matsumura *et al.*[8]; Fujii *et al.*[9]) and medium-size clear specimens (Amemiya[10]; Kawabe and Mori[11]) in which the moisture contents were conditioned under the fiber saturation point. However, there has been only one report of a study on wood permeability using green wood specimens of a realistic size (Amemiya and Inoue[12]); Amemiya and Inoue[12] studied gas permeability in relation to wood preservation and did not report on the permeability of white-zone wood. The behavior of life-size specimens of green wood reflects the actual behavior of wood during the drying process. In this study, the three-dimensional gas permeability of logs was investigated with respect to the heartwood, the white-zone wood, and the sapwood of green logs (Nagai and Taniguchi[13]; Nagai and Taniguchi[14]).

MATERIALS AND METHODS

Materials

Sample trees were 30-year-old *Cryptomeria japonica* grown in the experimental forest of the Forestry Technology Institute of the Hyogo Prefectural Technology Center for Agriculture, Forestry, and Fisheries (Yamasaki, Hyogo Prefecture, Japan). Two trees were felled and six logs, one meter in length, were obtained from above breast height.

Two disks were cut from each end of the logs.. A strip, which was 3 cm in width and 2 cm in thickness and included the pith, was cut from one of the disks from each end. A chisel was used to separate it into heartwood, white-zone wood, and sapwood. The moisture content of each separate wood block was determined. The mean moisture content in the log was determined using the remaining disk from each end. Moisture content was calculated using the following equation:

$$Mc = [(Wg - Wd) / Wd] \times 100,$$

where Mc (%) is the moisture content, Wg (g) is the weight of the green block/disk, and Wd (g) is the weight of the block/disk dried at 105°C.

Logs were then finished in 850-mm lengths for the pressure measurements. The outlines of the log specimens used are shown in Table 1.

Table 1. Outlines of log specimens.[13, 14]

No. of specimen	Length (mm)	Mean diameter (mm)	Density (g/cm^3)	*Mc* in heartwood (%)	*Mc* in white-zone wood (%)	*Mc* in sapwood (%)	Mean *Mc* in log specimen (%)
1	850	170	0.85	98	66	223	160
2	850	165	0.84	96	66	219	154
3	850	179	0.82	64	61	227	150
4	850	173	0.80	63	59	221	145
5	850	168	0.79	57	60	208	141
6	850	185	0.82	70	69	244	152

Note: Nos. 1, 2 and Nos. 3-6 were obtained from the same trees respectively. *Mc*: Moisture content.

Pressure measurements

A glass tube was positioned in the middle of each wood layer of a transverse section, at a 50 mm tangential distance from a line that represented the site of a potential slit from the outside to the center of each log (Fig. 1c). To insert the glass tubes, first one hole with a 10 mm diameter and 50 mm depth was drilled longitudinally into each wood layer (*i.e.*, the heartwood, the white-zone wood, and the sapwood) of a transverse section. The transverse surface was sealed and the three holes were filled with epoxy resin (Fig. 1a). After the resin cured, another hole, 6 mm in diameter and 100 mm in depth, was drilled to extend beyond the bottom of each epoxy-filled hole. Glass tubes 6 mm in diameter were inserted into the holes, and the gaps between the glass tubes and the transverse surface were sealed with epoxy resin (Fig. 1b). The log was then placed in a vacuum chamber, and each glass tube was connected separately with a nylon tube to a mercury manometer set outside the chamber (Fig. 2).

To confirm the accuracy of this system, three nylon tubes were connected to manometers and inserted into the vacuum chamber before each experiment. The manometers detected exactly the changes under vacuum, confirming that there was no leakage from the system. After each experiment, the log remained connected to the manometers and was cut into 15 cm lengths; all the surfaces were sealed with epoxy resin. No changes were then detected by the manometers under vacuum, confirming that there had been no leakage from the system during the experiment. Furthermore, when the three nylon tubes were removed from the glass tubes and kept in the chamber, pressure changes were accurately detected under vacuum, confirming again that there had been no leakage from the system during the experiment.

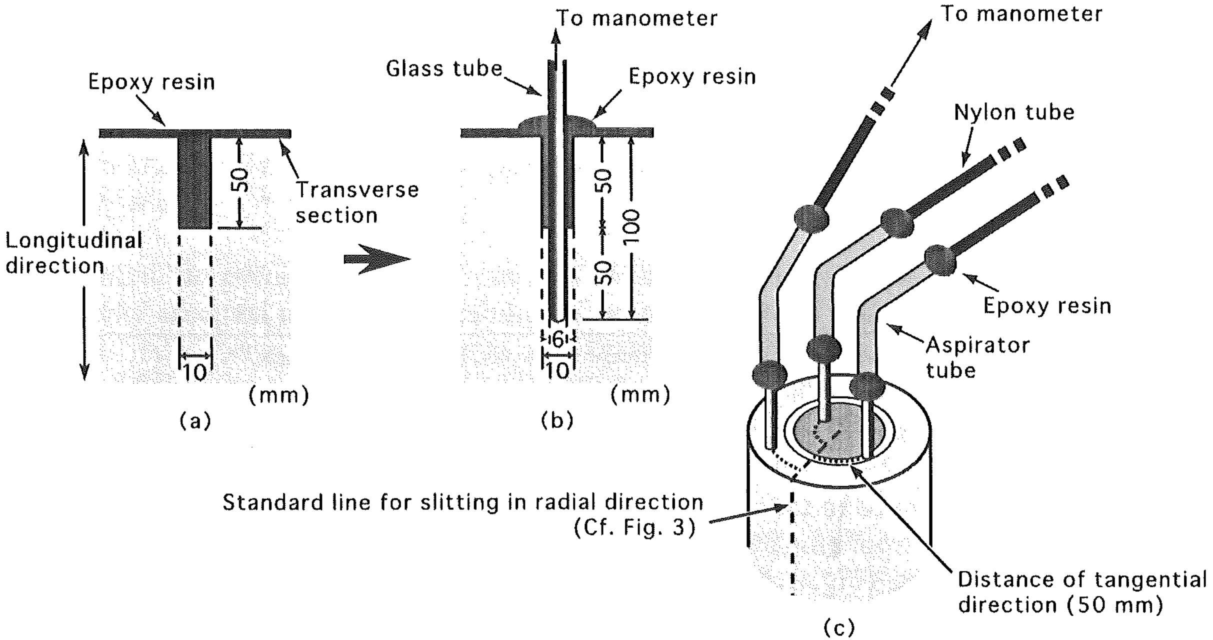

Fig. 1. Methods for measuring pressures in log specimens.[13]

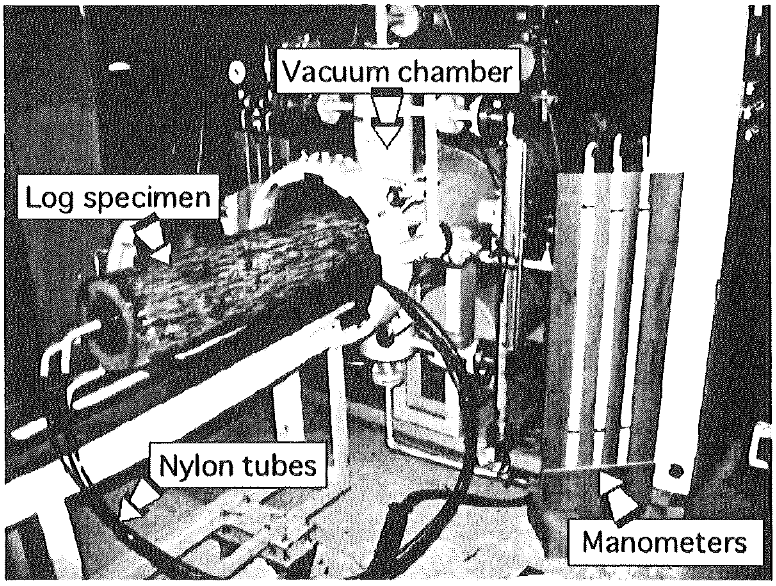

Fig. 2. Apparatus used for the experiments.[13]

Log conditions

Figure 3 shows the experimental conditions for five of the logs studied. The exposed log surfaces of Nos. 1-5 were changed during the experiments by altering the conditions of the surfaces (Fig. 3). For log No. 6 (Fig. 4), the exposure of the white-zone wood in the end section was varied, and conditions were alternated between the vacuum and the atmospheric pressure states in the vacuum chamber.

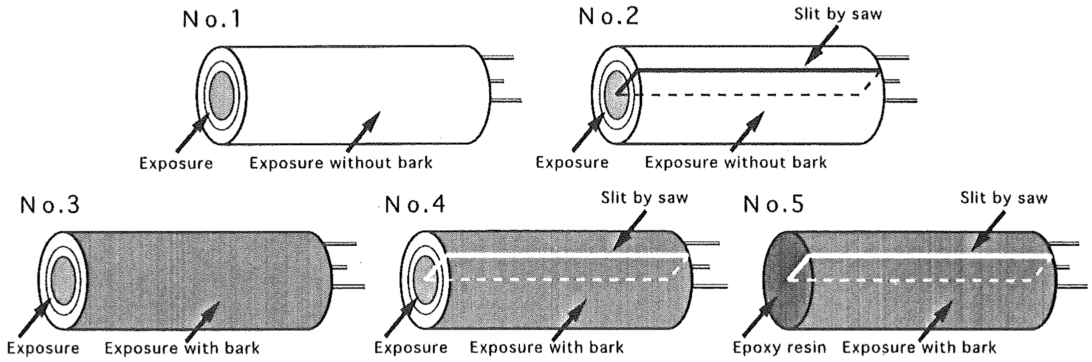

Fig. 3. Details of log specimens (Nos. 1-5).[13]

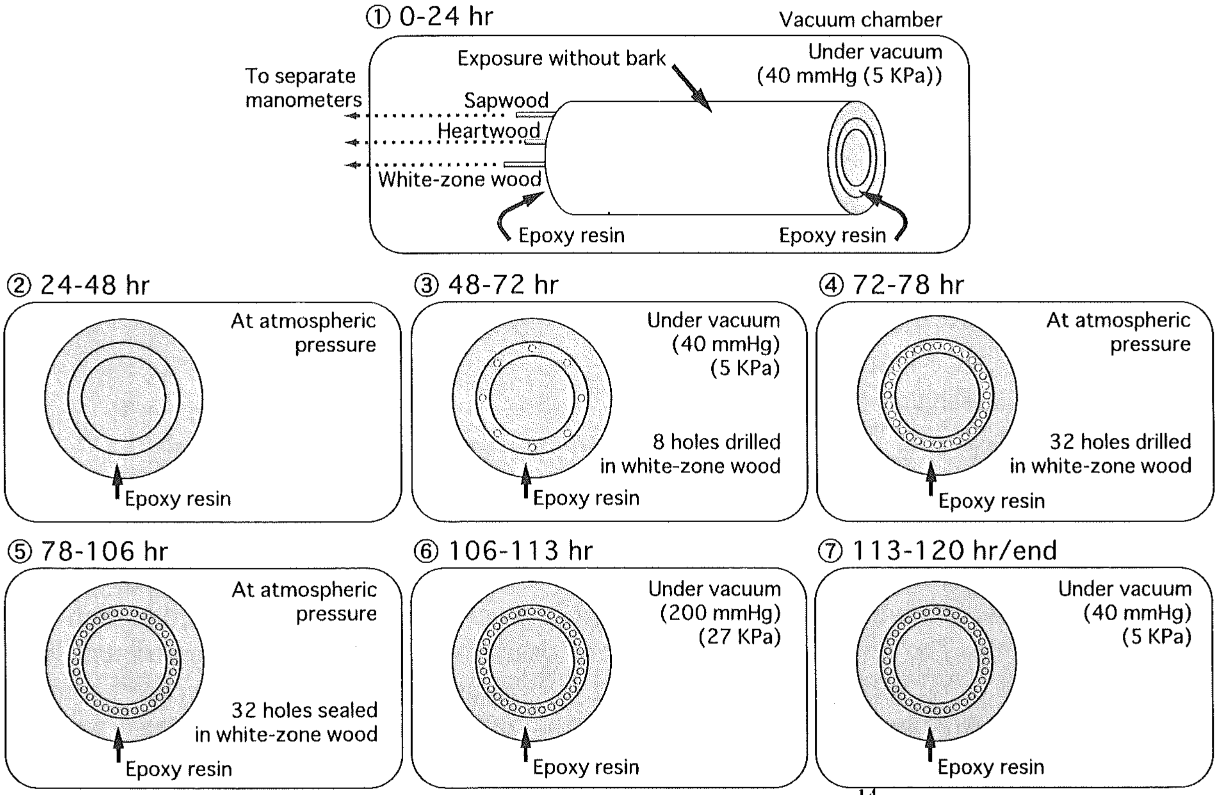

Fig. 4. Details of log specimen (No. 6).[14]

RESULTS AND DISCUSSION

Basic gas permeability

The results of the experiments with Nos. 1 and 2 are shown in Figure 5. In log No. 1, the pressure decrease in the heartwood was scarcely detectable under vacuum. In contrast, the pressure in the white-zone wood decreased immediately under vacuum. This result confirmed that the permeability of the white-zone wood was remarkably high. On the other hand, the pressure in the sapwood did not begin to decrease until the log had been under vacuum for five hours. Only the transverse surface of the white-zone wood of log No. 1 was exposed to the outer atmosphere (Fig. 3); thus, the decrease in pressure resulted from permeation in the longitudinal direction. The transverse surface of the heartwood was exposed to the outer atmosphere, and the outermost layer of the heartwood was surrounded by white-zone wood in which the pressure was decreasing at the same rate as the atmospheric pressure. Therefore, the white-zone wood did not prevent the radial movement of water/vapor from the heartwood toward the outer layer, and the permeability of the heartwood was very low, regardless of the presence or absence of white-zone wood.

The pressure in the sapwood decreased much earlier in log No. 2 (Fig. 5), which had additional exposure of the radial section (Fig. 3), than it did in log No.1. This suggests that the permeability of sapwood is high in the tangential direction. The pressure in the heartwood scarcely decreased despite the additional exposure of the radial section. The pressure in the white-zone wood of No. 2 decreased immediately under vacuum as it did in No. 1.

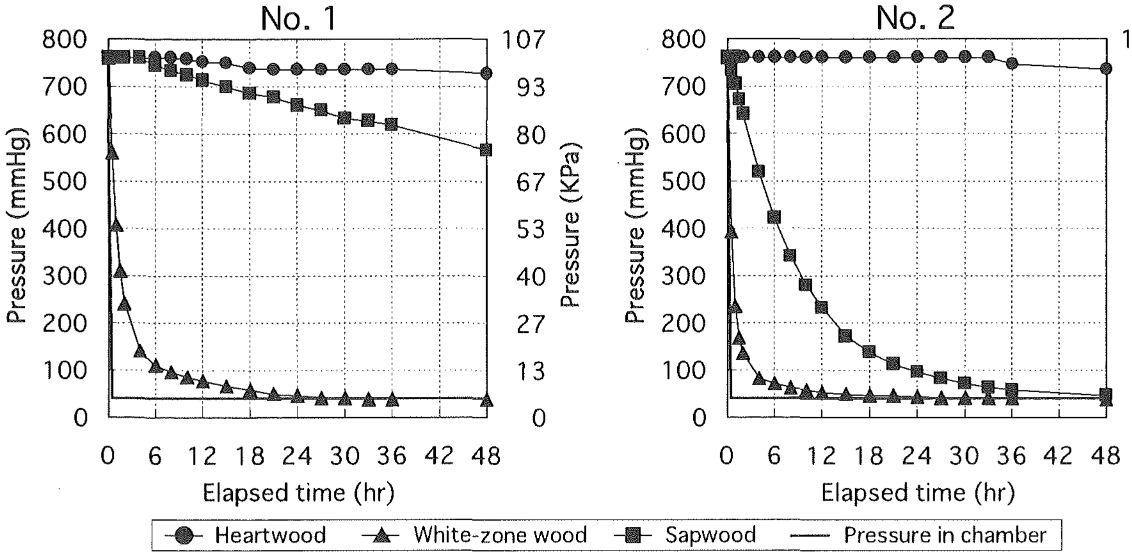

Fig. 5. Changes in pressures in Nos. 1 and 2 during the stages under vacuum.[13]

The results of Nos. 3-5 are shown in Figure 6. Although the moisture content of the heartwood of Nos. 3-5 was obviously lower than in Nos. 1 and 2 (Table 1), permeation was scarcely detectable. The results obtained from the heartwood of Nos. 1-5 are consistent with reports of studies using small and mid-size clear specimens (Matsumura *et al.*[7]; Matsumura *et al.*[8]; Fujii *et al.*[9]; Amemiya[10]; Kawabe and Mori[11]). In addition, the results suggest that the permeability of heartwood is remarkably low regardless of the moisture content.

The rate of pressure decrease in the white-zone wood of log No. 5 was not as rapid as in Nos. 3 and 4 (Fig. 6). Because the transverse surfaces of Nos. 3 and 4, but not of No. 5, were exposed, it was concluded that the longitudinal permeability of the white-zone wood was remarkably higher than the tangential permeability. Nakada *et al.*[4] reported that intermediate wood, which contains less free water in the lumina of most tracheids in the earlywood, was observed in all sections examined from various heights along the stem, though water remained in the outermost terminal part of the growth ring, including the latewood. Sano and Nakada[3] reported that the extent of deposition of incrusting materials varied among individual bordered pit membranes in the intermediate wood. Furthermore, the pressure decreased at a faster rate in the white-zone wood with wider growth rings (Nagai and Taniguchi[15]). These previous reports suggest that gas can flow longitudinally and tangentially through the dehydrated lumina of tracheids and through the partially incrusted bordered pit membranes in the earlywood of the white-zone wood.

The pressure in the sapwood decreased faster in log No. 5, which had a sealed transverse surface, than it did in No. 4, which had an exposed transverse surface (Fig. 6). In other words, sealing the transverse surface did not reduce the rate of pressure change in the sapwood, suggesting that the longitudinal permeability is low in the sapwood of green logs. In addition, the pressure in the sapwood of Nos. 2 (Fig. 5), 4, and 5 (Fig. 6) decreased faster than in Nos. 1 (Fig. 5) and 3 (Fig. 6), although the tangential distance (between the slit and the glass tube in the sapwood; 50 mm; Fig. 1c) was longer than the radial distance (between the log surface and the glass tube) in Nos. 2, 4, and 5. The results suggest that the sapwood is more permeable in tangential directions than in radial directions. Nakada *et al.*[6] reported that sapwood in trees was almost saturated with water. Amemiya and Inoue[12] reported that the gas flow from the surfaces of green logs toward the sapwood in the radial direction was scarcely detectable. In the sapwood of green wood, the percentage of aspirated pit pairs is very low (Nobuchi and Harada[2]; Fujii *et al.*[9]), however, it is probable that the water prevents the longitudinal and radial gas flows from the outer atmosphere toward the sapwood. Possible reasons for the gas flow in tangential directions in sapwood will be discussed later.

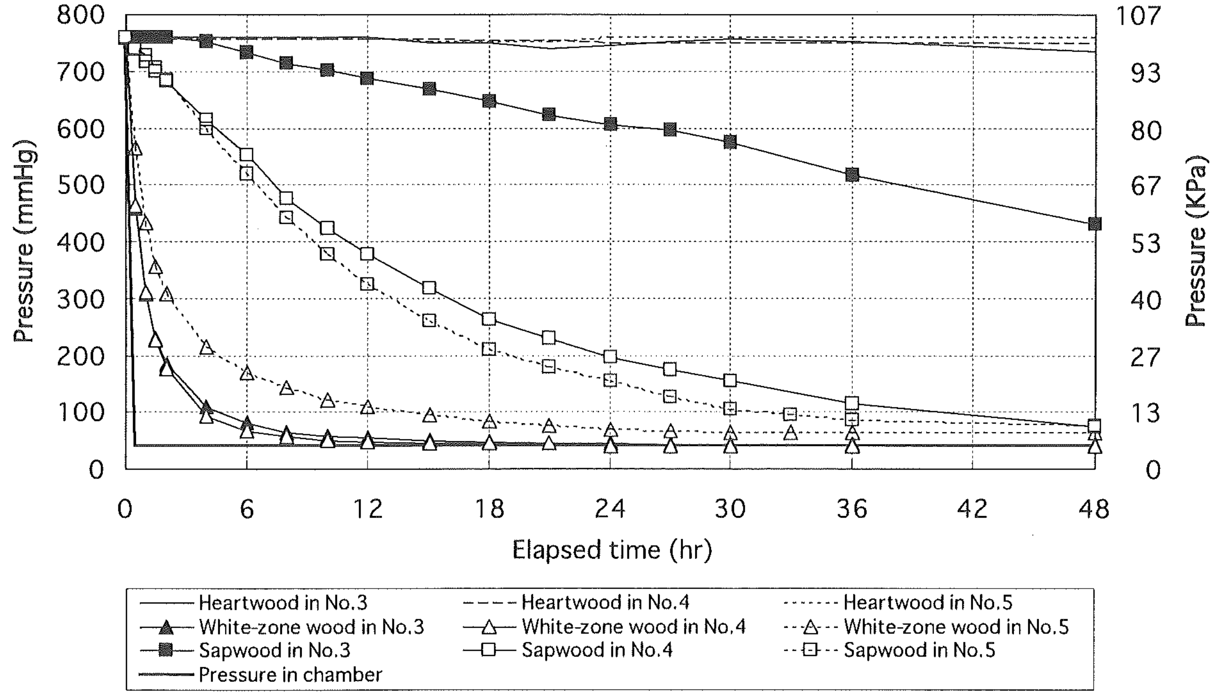

Fig. 6. Changes in pressures in Nos. 3-5 during the stages under vacuum.[13]

Gas flow in the radial direction

The pressure in the sapwood began to decrease after several hours under vacuum (No. 1 in Fig. 5 and No. 3 in Fig. 6); the passages through which gas flows are still controversial. In addition, remarkable permeability of the white-zone wood was revealed in the longitudinal and tangential directions. Next, gas flow in the radial direction from the white-zone wood, through the sapwood, and to the ambient atmosphere was investigated in green logs (Nagai and Taniguchi[14]).

The results from log No. 6 are shown in Figure 7. Although only the log's surface (*i.e.*, the outermost layer of sapwood) was exposed in the chamber, the decrease in pressure was first detected in the white-zone wood. On the other hand, the pressure in the sapwood did not begin to decrease until four hours under vacuum, much the same as in Nos. 1 (Fig. 5) and 3 (Fig. 6). It seemed that the pressure decreases in the sapwood were affected by the gas flow from the white-zone wood. In order to investigate the passages, the pressure in the chamber was alternated between the vacuum state and the atmospheric pressure state, and the exposure of the end section of the white-zone wood was varied (Fig. 4). The results shown in Figure 7 can be summarized as follows:

1) When the chamber was at atmospheric pressure, the pressure in the sapwood continued to decrease (Fig. 7, arrow 2).
2) When the chamber was at atmospheric pressure, the pressure in the white-zone wood increased slowly (Fig. 7, arrow 3), and the pressure in the sapwood also increased slowly (Fig. 7, arrow 4). When the pressure in the white-zone wood increased rapidly (Fig. 7, arrow 7), the pressure in the sapwood also increased rapidly (Fig. 7, arrow 8).
3) Pressure changes in the sapwood consistently followed pressure changes in the white-zone wood (Fig. 7, arrows 4, 6, 8, and 14).

In other words, pressure variation in the sapwood was consistently affected by the gas flow from the white-zone wood, rather than from the log's surface. The results obtained from the experiments with Nos. 1 (Fig. 5), 3 (Fig. 6), and 6 (Fig. 7) suggest that the passages between the white-zone wood and the glass tube inserted into the sapwood developed over several hours after commencing the vacuum. This means that the inner layer of the sapwood is more permeable than the outer layer.

The tangential permeability of the sapwood was high (No. 2 in Fig. 5; Nos. 4 and 5 in Fig. 6), with the inner layer of sapwood being more permeable than the outer layer. In addition, Nagai and Taniguchi[15] revealed an inverse relationship between the percentage of the air volume in the sapwood and the elapsed time until the pressure in the sapwood decreased to the middle-pressure state (*i.e.*, 400 mmHg; 53 KPa) after commencing the vacuum in the chamber. These two results suggest that the percentage of the air volume may be larger in the inner layer than in the outer layer of sapwood (Nagai and Taniguchi[14]). It is possible that gas flowed in tangential (from the slit) and radial (from the white-zone wood) directions in the inner layer of the sapwood of Nos. 2, 4, and 5.

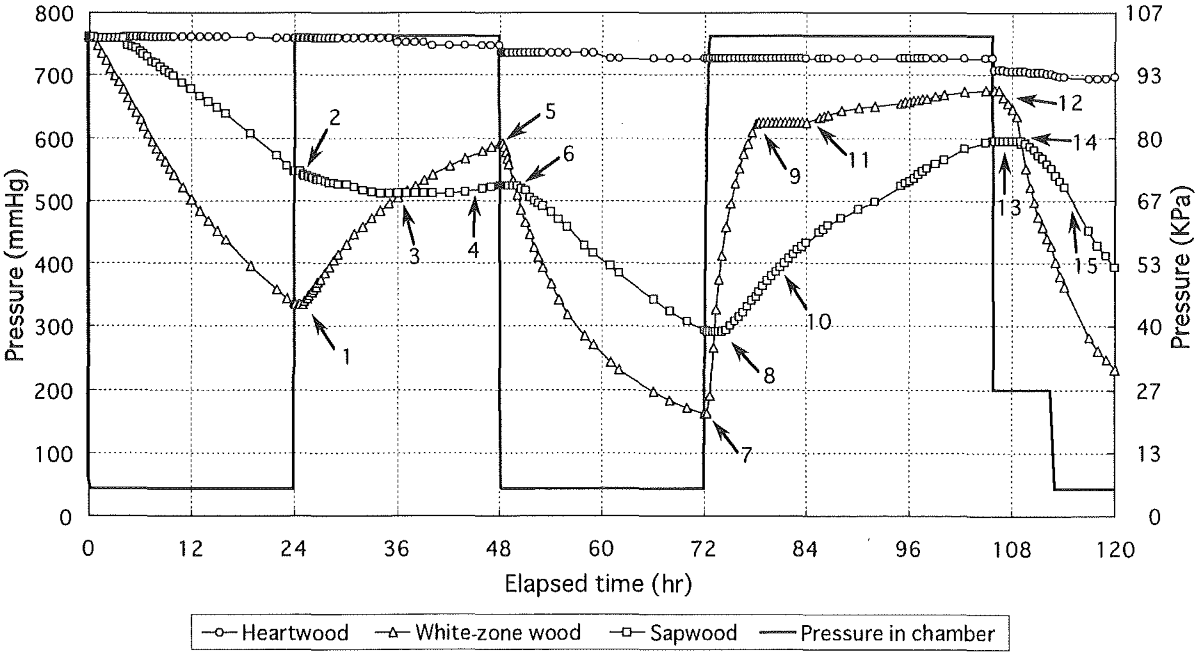

Fig. 7. Changes in pressure in No. 6 under alternating vacuum and atmospheric pressure.[14]

Passages of gas flow to intermediate wood

Higuchi[16] made several important observations regarding heartwood formations, which are induced by intermediate wood, dehydration, and air permeation. Back[17] suggested that the intercellular spaces along the ray parenchyma act as gas canal systems in living wood. Mio and Matsumoto[18] observed rays in many dicotyledonous and coniferous woods, including *Cryptomeria japonica*, and found that intercellular spaces commonly existed along the ray parenchyma. They also suggested that the spaces act as gas canal systems for the ray parenchyma cells in trees.

To investigate the passages, four different logs, 20 cm in length and containing bark on which no branch or knot was observed, were prepared. The experiments were carried out with only the surface of the log's bark exposed to the outer atmosphere under vacuum and atmospheric pressure (Nagai and Taniguchi[14]). The pressures in all four logs changed in the same manner as that seen during the first 48 hours of Figure 7. This phenomenon demonstrated that there are radial passages through which gas flows between the white-zone wood (*i.e.*, the intermediate wood) and the ambient atmosphere, passing through the sapwood and the log's bark. We suggest that these passages are the intercellular spaces along the ray parenchyma.

Moreover, the high permeability of the intermediate wood of green logs suggests that the intermediate wood in standing trees may also be permeable and may have radial gas canals through to the ambient atmosphere.

CONCLUSION

The three-dimensional gas permeability of green *Cryptomeria japonica* D. Don logs was investigated with respect to the heartwood, the intermediate wood, and the sapwood. The results are summarized as follows:

1) The gas permeability of the intermediate, or white-zone, wood was remarkably high as compared with that of the heartwood and sapwood.
2) In the heartwood, gas permeation was scarcely detectable in any of the three directions regardless of the moisture content.
3) In the intermediate wood, gas permeability was high in both the longitudinal and tangential directions, and longitudinal permeability was clearly greater than tangential permeability.
4) In the sapwood, tangential permeability was clearly greater than radial permeability.
5) The gas permeability of the heartwood, intermediate wood, and sapwood was graded on the basis of radial exposure, as a result of a slit that was made from the outside to the center of the logs: intermediate wood (exposed to the radial section with slit) ≥ intermediate wood (without slit) > sapwood (exposed to the radial section with slit) >> sapwood (without slit) >> heartwood (both).
6) There were radial passages through which gas flowed between the intermediate wood and the ambient atmosphere, passing through the sapwood and the log's bark.
7) Gas permeation in the radial direction toward the sapwood progressed from the intermediate wood, rather than from the ambient atmosphere.

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Prof. Chiaki Tanaka, 16th IWMS Organizing Committee,
Faculty of Science and Engineering, Shimane University, 690-8504 Matsue, Japan
Tel: (+81) 852-32-6562 Fax: (+81) 852-32-6123
iwms-16@riko.shimane-u.ac.jp http://www.jwrs.org/cnf/iwms16/

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