CYCLIC FREEZING EFFECTS ON TRACHEID BORDERED PITS[1]

Harvey D. Erickson and *Yang-Hsien Chen*
College of Forest Resources, University of Washington, Seattle, WA 98195

(Received 24 December 1973)

ABSTRACT

Repeated freezing and thawing of wet wood of western hemlock (*Tsuga heterophylla* (Raf) Sarg.) caused changes in some tracheid bordered pits ranging from partial pit aspiration to tori loose and moved out of the pit cavities. Influencing factors were: lower temperatures, position in the specimen, number of freeze cycles, water content of the wood, and manner of preparation. The most damaging effects by cyclic freezing occurred near the end-grain surface of the blocks. At 1 cm from the end, very little change occurred. Lowering the freezing temperature and increasing the number of freeze cycles increased the number of pits affected but not in direct ratio. Pit damage near the block ends was slightly greater in green wood that was water-saturated before cyclic freezing. Storing sapwood blocks for 8 months before cycling tended to decrease the number of unaspirated pits. In fresh sapwood, 96% of the bordered pits were unaspirated; in heartwood only 7%. In green heartwood, cyclic freezing deaspirated some of the pits near the block ends. Relationships of the results to natural phenomena are discussed.

Additional keywords: Tsuga heterophylla, sapwood, heartwood, freezing, thawing, bordered pits, pit damage, pit aspiration, microtome-cryostat.

INTRODUCTION

Although freezing and thawing of wood are common in trees and the use of wood products, the subject has received only a small amount of study by wood scientists. Graf and Egner (1940) studied the effect of repeated freezing on bending strength, compressive strength, and resistance to impact of pine, spruce, and ash. The samples showed no change in these strength properties after 10 cycles of freezing at –15 C in a water-saturated condition. Thunell (1940) reported that the modulus of elasticity in bending and impact resistance of water-saturated pine timber (*Pinus sylvestris*) remained unchanged after 15 cycles of freezing at –15 C and thawing.

The effects of only a single cycle (prefreezing) before drying upon shrinkage and drying characteristics have been reported in several papers. Representative of these are the reports of Cooper et al. (1970, 1972), who noted some decrease in shrinkage and collapse during drying of black walnut and other species, and the report of R. W. Erickson et al. (1972), who obtained less creep in small redwood beams during drying if the wood was prefrozen.

It seemed possible that even though mechanical strength does not change with limited cycling of freezing, the delicate structure of bordered pits might be affected by the cycling of phase change of water and the resulting volume change and crystallization effects of the freezing of water in the tracheids. This is the subject of our report.

MATERIALS AND PROCEDURES

The wood was fresh western hemlock (*Tsuga heterophylla* (Raf) Sarg.), which was 30 years old and 11 inches dbh and was cut on 25 June 1971. The log sections were wrapped to prevent drying during transporting and were stored at 2 C. Blocks, 1 cm × 1 cm × 2 cm along the grain, were cut from sapwood and heartwood, free from compression wood, with a smooth-cutting circular saw. Three blocks were assigned to each test and were randomly chosen. Three consecutive microtome sections cut from

[1] The research described was part of a project funded by the U.S. Forest Service as Grant No. 3 and administered by the Institute of Forest Products, College of Forest Resources, University of Washington, Seattle, WA.

each block provided 9 samples in each test for statistical analysis.

A microtome-cryostat, model CTD, with a Minot custom rotary microtome made by International Equipment Company was used to cut the frozen-wood sections that constituted most of the sections used in this study. Nonfrozen sections were cut on a standard sliding AO microtome. In our previous study (Erickson and Chen 1973), we described in detail the use of this equipment for microtomy of woody tissue to obtain high-quality sections 2 to 12 μm in thickness. Transverse sections, 10 μm thick, were used for examination because they provided adequate perspective of detail and were easy to handle. The specimen blocks were thoroughly saturated with water before microtoming as this had been proved to be very important to provide maximum support, during cutting, by ice in the lumens.

In our first experiment, some test specimens were solvent-seasoned, embedded in Spurr media[2], and cut with a sliding microtome for comparison with results obtained from the rotary microtome-cryostat method. The solvent-seasoning involved immersing the 3-mm blocks for 8 hr in each of the following solutions: 50% ethanol, 100% ethanol, 1 to 2 ethanol-benzene, and 100% benzene. After evaporation of benzene by air-drying, the wood was vacuum impregnated with the resin mix, transferred to a gelatin capsule that was then filled with resin, capped, and heated to 40–45 C for curing. Unpublished work in this laboratory on epoxy resins as embedding media established that the Spurr media—which are combinations of cycloaliphatic diepoxide, flexibilizer resin, and hardner—have low viscosity (60 cps) and better embedding properties than several other epoxy resins tested, including Araldite 502 and Epon 812. We increased the proportion of flexibilizer D.E.R. 736 to 9 parts in the standard medium "C" (company data) to decrease the hardness of the cured resin, to reduce damage to the knife edge, and to minimize resin-cracking in the section.

The resin solution for embedding was colored with Sudan Black B to give positive location of the resin in the wood structure. Before sectioning, the resin was trimmed back to the end grain; then the assembly was soaked in water for 3 hr before sections were cut on the sliding microtome.

The frozen sections were placed on glass slides, thawed, and double-stained on the slide. Safranin and haematoxylin were used for practically all sections and the mounting medium was Karo syrup.

In the first phase of the study, we determined the percentage of unaspirated pits in fresh western hemlock sapwood and heartwood and compared the results of two cutting techniques on the condition of bordered pits, (1) microtome-cryostat and, (2) solvent-seasoning following by embedding with Spurr media.

In the second phase, the first group of tests involved separate sets of sapwood specimens that were frozen and thawed for 25 cycles and 50 cycles at –20 C and 25 C, –36.5 C and 25 C, and for 10, 25, and 50 cycles at –100 C and 25 C. First, however, the blocks were evacuated in water at 20 inches of mercury for 20 min and kept submerged for not less than 20 min after the vacuum was broken. This was done before the cycling test and after every five cycles during the test to minimize partial drying. The average moisture content of these sapwood blocks was then about 210%. The second test group involved heartwood and only one freezing temperature and one number of freeze cycles. With the third test group no evacuation was used before or during freeze-cycling of fresh sapwood (170% MC) and heartwood (36% MC). The blocks were frozen and thawed for 25 cycles at –20 C and +25 C and at –36.5 C and +25 C, respectively. The fourth test group related to the influence of storage at 2 C of sapwood blocks in 3 layers of polyethylene, 0.001 inch thick, before freeze cycling the wood. Other details of the above tests are given in the tables and text that follow.

[2] Sold by Polysciences, Inc., Warrington, Pennsylvania 18976.

The blocks for each of the cycling tests were wrapped in two small polyethylene bags (0.001 inch thick) to minimize the moisture loss. The bags of blocks were hung in the air in the specified low-temperature cabinet for the cycling tests to prevent the rapid conductive heat loss from one surface that would occur if laid directly on the metal. The blocks were in the cabinet for at least 8 hr and at 25 C for 5 hr.

Following cycling, the portions of the blocks to be sectioned were prepared by sawing, with a jeweler's saw, pieces not over 3 mm along the fiber axis to provide small blocks of one growth ring that could be firmly frozen to the mounting disc. About 70–90 μm of wood was cut off with the microtome to remove surface roughness. The block was then thawed and evacuated in water to obtain near-saturation. After remounting on the disc, up to 40 μm may have been cut in places until the block could be positioned so as to obtain a complete section with full thickness.

The bordered pits were examined mainly in the earlywood zone because of the greater sensitivity to treatment due to larger and less rigid pit membranes. The photographs of the anatomical features of wood are 1050×.

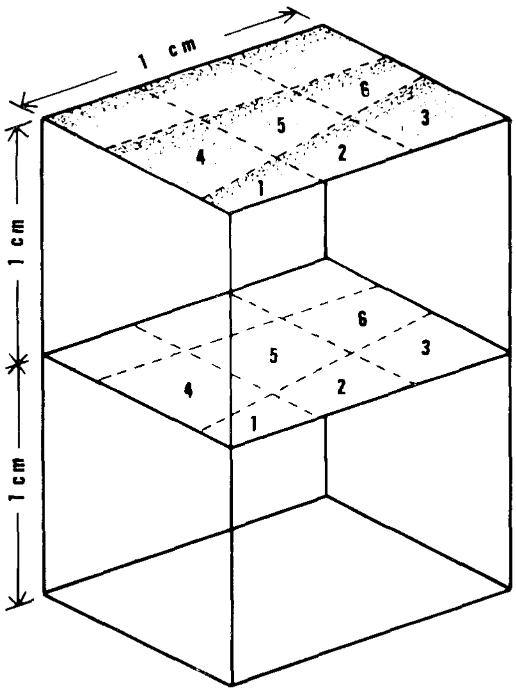

FIG. 1. Pattern of the block levels, zones, and rings used for specimens for cutting microtome sections. Shown are middle and edge rings, and zones 1–6 for both the end and midlength level at 1 cm.

RESULTS AND DISCUSSION

Microtomy and sapwood-heartwood comparisons

The pattern of block levels and the zones of specimen sampling are shown in Fig. 1. The first experiment evaluated the effect of 25 cycles between –20 C and +25 C upon tracheid bordered pits and compared the results of two cutting conditions: microtome-cryostat and solvent seasoned-resin embedded. The results are given in Table 1. In the wood near the end of the blocks, there were fewer normal, unaspirated pits in the rings at the edges than in the middle ring by a substantial figure for both types of microtomy. There were no significant differences, at the 5% level, between percents of unaffected pits among the zones within the annual rings based on pooled data for all treatments and levels in the block. However, Duncan's multiple-range test showed a small but significant difference between zones 1 and 3 in the outer ring of microtome-cryostat sections but only at the end of the block. This indicated greater variation in pit damage within the outer ring than in the middle ring. For this reason, the middle rings were chosen for most of the subsequent studies on microscopic effects even though response to cyclic freezing was not maximum in these rings.

In addition to differences between middle and edge rings at the block ends, the data for the cryostat technique show that there was much less damage by cyclic freezing at midlength of the block than at the end, regardless of whether the ring was in the middle or at an edge. The average of nearly 93% unaffected pits in the middle of the block proves that cyclic freezing

TABLE 1. *Comparison of percent unaspirated bordered pits of sapwood after 25 cycles between –25 C and +25 C as measured by two cutting conditions*

	Zones	Microtome-cryostat[a]		Solvent seasoned–resin embedded
		Middle of block	End of block	End of block
		%	%	%
Outer	1	92[b] (255)[c]	35[b] (250)[c]	70[b] (1180)[c]
Ring	2	93 (229)	33 (260)	71 (227)
	3	92 (203)	28 (142)	72 (172)
Middle	4	93 (134)	46 (347)	91 (969)
Ring	5	94 (263)	45 (360)	92 (479)
	6	92 (252)	48 (357)	90 (108)

[a]Blocks were cycled at original M.C. and were water saturated just before cryostat sectioning.

[b]Each percentage is the average of three consecutive sections.

[c]Total number of pits in each group in brackets.

effects there were minor because about 96% or more of the pits were unaspirated in twice-frozen wood prior to cyclic freezing; and those effects were small compared to the effects on pits near the end of the block (only 28–48% unaffected pits).

A multiple-range test revealed that the two sectioning techniques gave different results for the wood at the end of the block. The sections from wood solvent-seasoned and embedded in Spurr medium showed slightly higher proportions of unaffected pits in the end of the block than the sections cut using the microtome-cryostat system. These results may be due to weakened margos, caused by cyclic freezing, having been better protected by the surrounding resin in the resin-embedded sections (Fig. 2). Also the margos of microtome-cryostat sections may more readily show, during handling and staining, any previous damage (Fig. 3) because of loss of support after the ice is melted. Less difference between the two methods would be expected in the middle of the block because of the uniform and high percentage of undamaged pits in that position. The microtome-cryostat method was considered to be less time-consuming and more sensitive to the weakened pit membranes than the resin-embedding method and was used as the major sectioning method in our study.

For detailed studies of the effects of cyclic freezing and thawing, the conditions of the bordered pit pairs were classified as follows: 1) unaspirated or unaffected, 2) partly aspirated, 3) aspirated, and 4) damaged. The torus of the partly aspirated pit is displaced to one side though not actually touching the pit border (Fig. 3-b), whereas the torus of the aspirated pit appears to be against the border (Fig. 3-a). The damaged pits are those in which the margos are ruptured to some extent, and the tori may be partly outside the pit (Fig. 3-c, Fig. 4-a) and, in some cases, a torus has broken loose and migrated outside the pit chamber as in Fig. 4-b. This condition is not believed to be due to damage during handling and mounting of the section. If it were, the

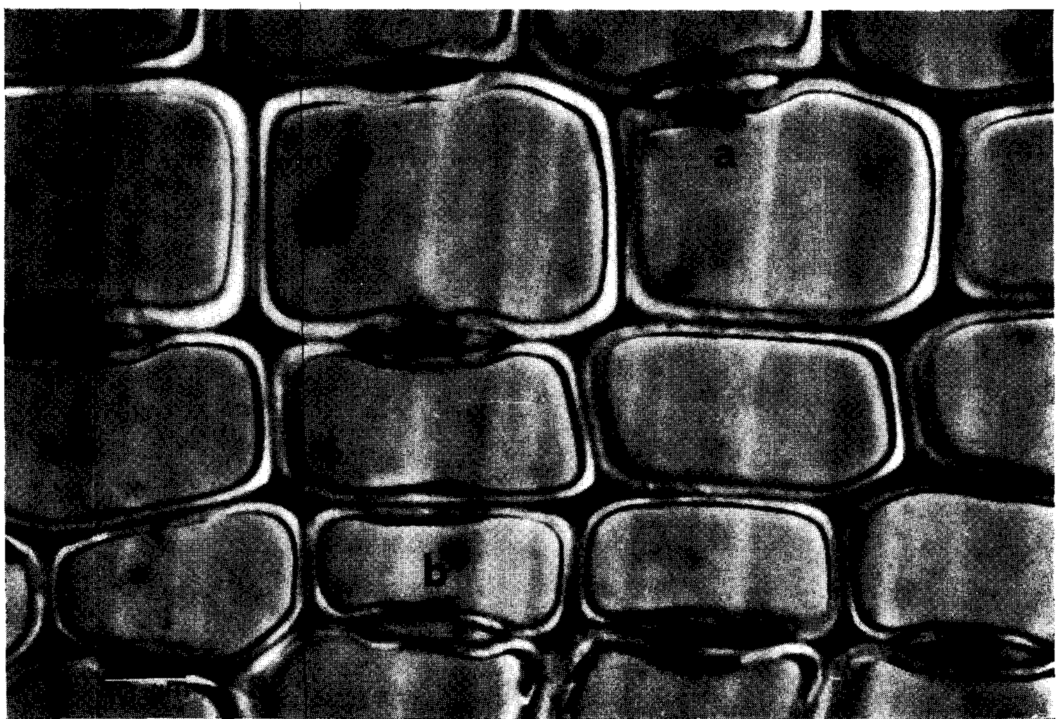

FIG. 2. Sapwood freeze cycled 25 times, –25 to +25 C, solvent-seasoned and embedded in Spurr medium still in place. The section, cut near end of block, shows two dislodged tori at a and b.

condition would appear regularly in all experiments. In Fig. 2 and Fig. 4 the tori of damaged pits are displaced in different directions, which indicates that knife direction (tangential) was not the cause of the damage.

Almost all, 96%, of the earlywood pits of fresh, untreated outer sapwood were unaspirated. The other 4% were mainly only partly aspirated. The percent of unaspirated pits decreased to 26% in the transition zone and to 7% in the heartwood (Table 2). The percent within each part is quite consistent. Torus positions in heartwood were not studied in detail, but they appeared to be mainly fully aspirated. Although the table shows that cutting wood by both cryostat and solvent seasoned-resin embedded systems yielded essentially the same results in percentage of unaspirated pits, it is probable that the percent of pits with the torus in the median position should be even higher than 96% by the cryostat system if two freezings had not been used, because the later work showed that the effect of freezing cycling near the end of a block apparently begins with the initial cycle. The percentage of unaspirated pits in fresh hemlock reported above is substantially higher than the percentage reported by Lin et al. (1973) for the same species. They found, in the sapwood, that only 62.5% were unaspirated and 23% were completely aspirated. In the heartwood, 3% were unaspirated and 84% were aspirated.

Effects of freeze cycling and temperature

Twelve freezing-and-thawing tests on western hemlock sapwood are shown in Table 3. The variables are number of cycles, freezing temperature, and position in the block. Each table entry is the mean of the total number of pits of nine sections.

Bordered pits close to the ends of the blocks were much more affected than those in the middle of the block for all freezing

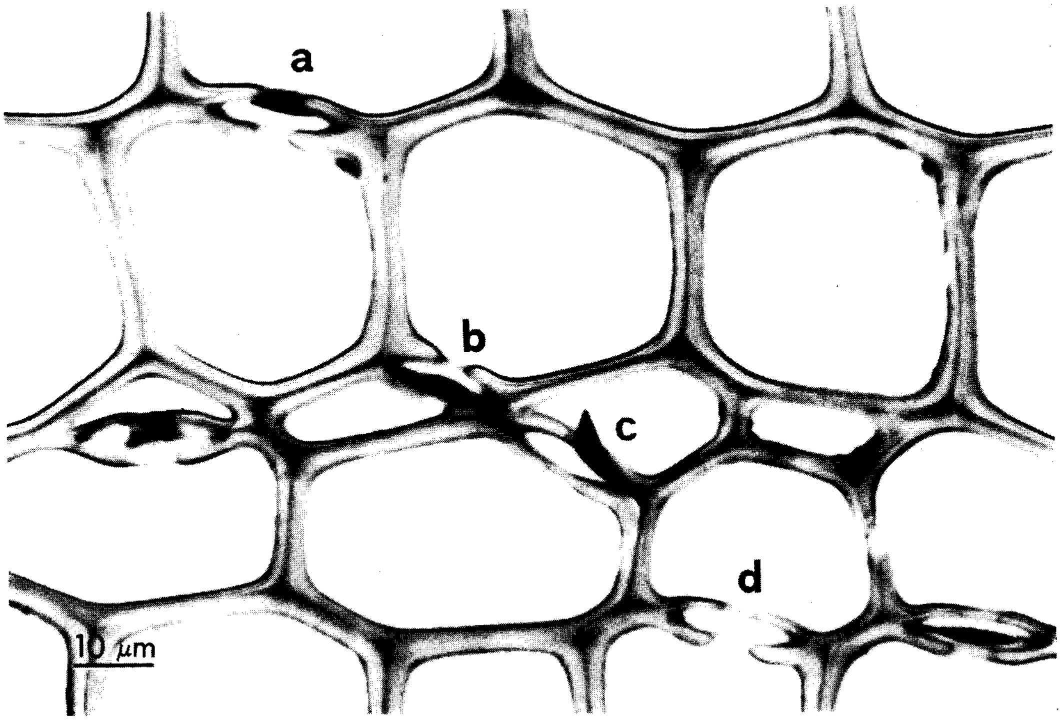

FIG. 3. Microtome-cryostat section of sapwood cycled 25 times, −25 to +25 C; a) aspirated pit, b) partly aspirated pits, c) torus torn loose on one side, d) pit cavity with no torus, and to the right, an unaspirated pit.

temperatures and number of cycles. The rate of heat transfer longitudinally in wood is greater than the rate across the grain, which will result in different freezing rates in the end and the middle of the blocks. The injury to pit membranes from freezing and thawing tests is probably a matter of unbalanced mechanical forces. During freezing of the blocks, ice formation and crystal growth are accompanied by expansion. Possibly, the margo strands act as nucleation sites for crystal growth. Any difference in rate or location of freezing in the lumens and pit cavities could cause a displacement of the torus and stretching of the membrane. Near the end of the block, freezing is quicker and expansion forces can occur most easily along the lumen toward the surface whereas, transversely, the tubular cell wall acts as a limiting boundary, except in the region of the pits where crystal growth may be unbalanced and may cause additional interaction. The repeated crushing and lateral pressure on the membranes and tori in the pit cavities probably result in weakened and ruptured pit membranes and dislodged tori (Fig. 3-c and 4-a and b). Near the middle of the length of the block, the longitudinal forces are more balanced, and relatively little damage is done.

The freezing temperature and number of freezing cycles employed were also associated with the percent of normal pits after cycling (column 4) but mainly at the block ends. Both lower freezing temperature and increased number of freezing cycles increased the percent of aspirated pits. The first-order interactions of position and temperature, and position and cycles were significant at the 1% level. The interaction between freezing temperatures and cycles was not significant, but the second-order interaction of the three variables was significant.

The pits that were affected by cyclic

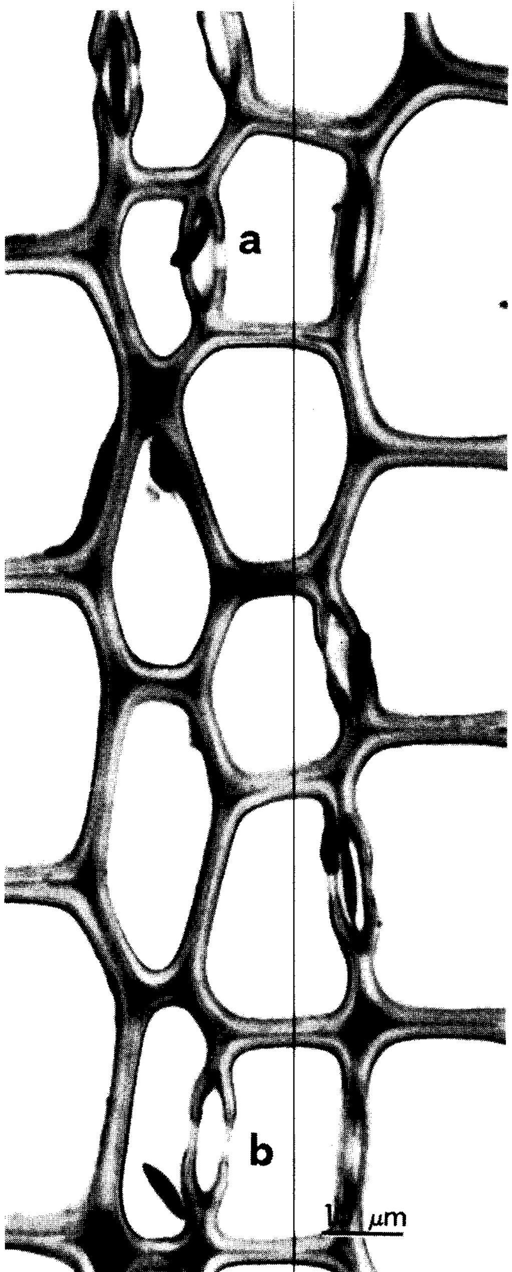

FIG. 4. Section cut by microtome-cryostat from near the end of blocks that were freeze-cycled 50 times, −100 to +25 C. a) one of two tori that are partly outside the pit chamber and, b) an empty pit cavity and a torus outside the cavity. Sections from uncycled wood showed normal unaspirated pits.

TABLE 2. *Percents of unaspirated pits in fresh samples of sapwood and heartwood using cryostat and resin-embedding systems*

		Cutting Method	
	Growth Ring	Microtome-cryostat. % unaspirated	Solvent-seasoned, resin-embedded. % unaspirated
Sapwood	Ring 2	94	96
	Ring 15	96	96
	Ring 18	96	96
Transition	Ring 21	26	
Heartwood	Ring 24	7	
	Ring 27	7	
	Ring 30	7	

freezing are listed by type in columns 5, 6, and 7. For all test conditions the number of damaged pits near the block ends was usually more than 10 times the number of partly aspirated pits and 2 to 8 times (average of 5 times) the number of aspirated pits. Not only were the ratios high, but there were actually far more damaged pits (59%) in the most extreme treatment conditions, −100 C and 50 cycles, than there were unaspirated pits (29%). The percent of damaged pits was more nearly equal to that of normal pits for the mildest condition of freeze-cycling, −20 C and 25 cycles.

In the midlength position, however, the number of pits actually damaged averaged only 3.4% for all the tests, and only 5.8% were aspirated, which was about the same as the percent of partially aspirated pits.

Table 4 shows that sapwood specimens that had high moisture contents at the start and were evacuated in water initially and every 5 cycles during 25 cycles at −20 C and +25 C had 4% more of the pits near the end changed from the normal condition than those specimens that had somewhat lower moisture contents and were not evacuated and soaked during cyclic treatment. Filling the voids of the block, especially at the ends, causes more expansion in the lumens and inside the pit cavities during ice formation, thus creating additional stresses on more pit membranes near the

TABLE 3. *Proportions of normal bordered pits and pits changed in some way during cyclic freezing at different temperatures*

Position in block 1	Temperature °C 2	No. of freeze cycles 3	Unaspirated pits[a] % 4	Partly aspirated pits % 5	Aspirated pits % 6	Damaged pits % 7
End	-20, +25	25	41.7	4.0	17.0	37.3
		50	34.6	3.6	12.6	49.2
of	-36.5, +25	25	34.7	2.1	10.0	53.2
		50	30.3	5.8	15.8	48.1
block	-100, +25	25	32.4	3.9	6.8	56.9
		50	29.2	4.8	7.2	58.8
Middle	-20, +25	25	91.6	2.2	4.0	2.2
		50	88.9	3.7	4.8	2.6
of	-36.5, +25	25	87.6	2.9	5.8	3.7
		50	85.4	2.0	7.6	5.0
Block	-100, +25	25	89.3	3.7	4.2	2.8
		50	85.0	2.7	8.3	4.0

Analysis-of-variance factors and confidence levels for columns 4 through 7.

Source of variation	4	5	6	7
Position in block	0.01	0.01	0.01	0.01
Temperature	0.01	NS	0.05	0.01
Cycles	0.01	NS	NS	NS
Position - Temp.	0.01	NS	0.01	0.01
Position - Cycles	0.01	NS	NS	NS
Temp. - cycles	NS	NS	NS	0.05
Position - temp. - cycles	0.01	0.01	NS	0.01

[a] In fresh wood, the % of unaspirated pits was 96 or more.

ends than if less water is present. Table 4 also indicates that storage may increase slightly the effect of freezing and thawing on the displacement of tori. The blocks stored for 8 months before freeze cycling 25 times at −20 C had 38% unaspirated pits after cyclic treatment as compared to 42% for saturated, fresh, unstored wood and 46% for unsaturated, fresh wood also freeze-cycled 25 times. It is possible that a partial drying occurred during storage and caused some pit aspiration although the blocks had been thoroughly wrapped with polyethylene film and stored at 2 C. The three sets of blocks were significantly different at the 1% level.

From the results presented, it was clear that 25 cycles of freezing at −20, −36.5, or −100 C caused substantial change in the pits near the end of a block but the effect of 50 cycles was far less than double that of 25 cycles. Therefore, a 10-cycle test was added to a replication of 25 and 50 cycles on matched blocks, which were evacuated before cycling and after every 5 cycles, using the most extreme temperature combination: −100 and +25 C. The results are shown in Fig. 5. The percent of normal pits decreased rapidly during the first 10 cycles, then tapered off with increasing cycles. If a curve had been determined for wood away from the end, it should show much less decrease, judging by the data in Table 3.

The effect of cyclic freezing on heartwood was tested but using only sections cut near the end of the blocks. The first set of blocks was cycled at its original moisture content of 36% with no evacuation at any time, and a second set was first evacuated

TABLE 4. *The effect of storage and moisture content of sapwood on bordered pit membranes after 25 cycles of −20 C to +25 C; sections cut near the end surface*

	Fresh Wood		Stored Wood
	170% initial MC. No evacuation during cycling	210% MC after evacuation. Evacuated every 5 cycles	at 2 C for 8 mo before cycling and evacuations
Unaspirated pits Av. of 9 Sections	46%	42%	38%
MC at the end of test	170%	210%	210%

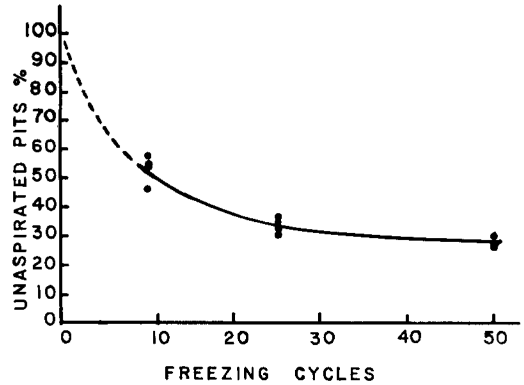

FIG. 5. The effect of number of freeze-cycles between −100 and +25 C on the percent of unaspirated pits near the ends of the block.

and soaked to an MC of 170% and evacuated and soaked every 5 cycles thereafter. Both sets were subjected to 25 cycles at −36.5 C and 25 C. The set with 170% MC had almost twice as many unaspirated pits (19%) as the set with 36% MC (11%), and both sets had higher values than the 7% for fresh, uncycled heartwood (except for one quick freeze for end-trimming reported in Table 2). The deaspiration probably is the result of repeated ice formation and expansion in the lumens and in the pit apertures that force the tori of some aspirated pits away from the pit borders. The effect on wood deeper in the block along the grain was not determined, but it probably would be less than near the end.

General comments

Considering the results reported above on the effects of freeze-cycling on bordered pits in green wood, it is understandable why a tree may experience many freezes throughout its life and still not have its structure and permeability affected to a major degree. The 10–15% decrease in normal pit condition 1 cm from the block end in 50 freeze-cycles is significant but rather small and some of that was only partly aspirated pits. The drastic effects on pits near the block ends by cyclic freezing probably does not apply to living trees; otherwise there should be a much lower percent of unaspirated, normal pits in sapwood than observation indicates for trees subjected to cold winters. The tree has no end-grain exposure in its xylem. However, we do not know of enough detailed studies on the quality of bordered pits in a variety of species, and especially from trees located in climates with cold winters where the sap is definitely frozen once or more each year, to say that the pits in sapwood or heartwood are not affected to some extent by cyclic freezing. Is there a relationship between cyclic freezing of a species such as white spruce, normally grown in a cold temperate zone, and its characteristically impermeable sapwood after air-drying, which may be due to weakened margos from cyclic freezing, therefore making the pits more susceptible to aspiration then they otherwise would be? Or, is this phenomenon due only to an inherent sensitivity of the pit membranes to forces causing aspiration upon drying?

There was slightly less pit change in wood not completely water-saturated as contrasted to completely saturated wood. Assuming that this result applies also to zones away from end grain, then it would seem plausible that a relatively low degree of pit aspiration in native sapwood of some species grown in regions with freezing winters could be due, in part, to moisture content somewhat less than complete saturation. Perhaps a small volume of air is desirable or even necessary to prevent freezing damage, and some of the expansion volume of water into ice is accommodated by small air spaces in the wood. Progressive crystallization in lumens may force unfrozen water into the air spaces, compressing the air and also causing dissolving of air into the water. Cooper et al. (1970) found no expansion of black walnut at 60% MC when it was frozen. Temperature decrease would also cause some decrease in gas volume due to Charles' law and a decrease in vapor pressure of water. As freezing progresses inwardly in a tree, it is possible that volume changes by annual rings for example, could also be accommodated by forcing some sap toward and even into the heartwood as freezing advances.

Radial distribution of water in sapwood may vary and most fresh sapwood probably is not saturated. For example, ring no. 2 in this study had 178% MC and saturation MC calculation was 190%. Some blocks initially at 170% were 200 to 210% after two evacuations and soakings. Choong et al. (1970) found that the degree of water saturation in the sapwood of loblolly pine was 67 to 74%.

Our results may have some relationship to those reported by workers on the effect of prefreezing on shrinkage, drying rate, and collapse, for example, Cooper et al. (1970), and Erickson et al. (1972). It is possible that only a small effect on opening up pits due to freezing would be an important improvement in very impermeable heartwood. In this sense, the damage to pits and deaspiration in heartwood reported in this paper would augment their explanation of free water relationships to the chemical components of wood. However, it seems unlikely that a single freezing could have much effect since pit changes even at the ends of the blocks were mainly after a number of cycles.

The cyclic freezing at −100 C produced a physical effect on the test blocks that did not occur at −36.5 or −20 C. After about 9 cycles, most blocks end-checked several mm deep into 2 or 3 parts. Because of the manner of wrapping the blocks with plastic film (and with extra water) cyclic soaking, evacuations, weight checks, and visual inspections, we do not think these checks were caused by drying. It is thought that the end-checking was due to the rapid freezing at the ends and a subsequent substantial tangential contraction in the frozen portion, due to the exposure to the very low temperature while freezing and expansion were taking place farther back. This is not the same as the "coldness shrinkage" described by Kubler (1962), which was maximum with wood at 40% MC. He reported no change or even expansion in wood of high MC such as used here.

The comparative effect on wood by freezing at greatly different rates and the effect of many cycles of freezing and thawing on drying characteristics of wood should be explored.

CONCLUSIONS

Repeated freezing and thawing of small blocks of western hemlock sapwood caused changes in the earlywood tracheid bordered pit pairs, which ranged from partial aspiration to rupture of the strands in the membrane and dislodged tori. The effect was greatest near the end-grain surface and pits in the growth rings near the edges were affected more than those in the middle rings. However, the middle rings of the blocks were chosen for most of the microscopic examinations because of their more uniform data. The microtome-cryostat technique was used for most of the study. It is less time-consuming and more sensitive to physical effects on pit membranes caused by cyclic freezing than the Spurr media-embedding method on solvent-seasoned wood which, however, gave about the same results on fresh, uncycled wood.

The injury to pit membranes was probably caused by repeated localized strains resulting from ice formation in cell lumens and pit cavities. Lowering the freezing temperature and increasing the cycles caused more pits to be altered. In wood near the end surface, the greatest single effect was damage to the margos (37 to

59%), and the second-ranked effect was apparent pit aspiration. In the midlength of the block, 85–95% of the tori were still in the median position after 25 to 50 cycles and less than 5% showed permanent damage.

Pits near the end of blocks with very high water contents were more affected than pits in blocks well below saturation. Sapwood blocks stored for 8 months at 2 C before cyclic freezing had slightly fewer unaspirated pits than did fresh wood after similar cycling, but some undetected end-drying may have occurred.

In fresh sapwood, 96% of the earlywood tori were in the normal, median position but in fresh heartwood only 7% were unaspirated. These are higher values than reported by Lin et al. (1973). Cyclic freezing caused some deaspiration of heartwood pits near the block ends, and increasing the water content of the heartwood before cyclic freezing caused even more deaspiration of pits.

When saturated sapwood was freeze-cycled at –100 C and +25 C, the decrease in normal pits was curvilinear with number of cycles with nearly no change at 50 cycles. Blocks cycled at a low of –100 C end-checked after about 9 cycles.

There may be a slight relationship between our results and those reported by others on the beneficial effects of prefreezing heartwood before drying. Relationships of the results to trees in temperate climates are discussed.

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