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Title SOME ANATOMICAL FEATURES OF DOUGLAS-FIR WOOD RATED PERMEABLE AND REFRACTORY

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The variation in treatability between wood species and even within a species is known to exist. Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) heartwood samples collected from mills throughout the state by the Oregon Forest Research Center were treated with creosote, and a distinct difference in degree of permeability was noted. The objective of this paper was to examine some of these samples for anatomical variation which may exist between the permeable and refractory woods.

The anatomical characteristics selected for study were fiber length, springwood lumen size, and the diameter of the bordered pit structures in the springwood. Four refractory and three permeable samples of Douglas-fir heartwood were used to investigate lumen and pit sizes, and 24 samples were macerated for fiber length measurements. A statistical analysis was made on all measurements considered.

The average fiber length for the permeable samples ranged from 5.06 mm to 6.16 mm, and the group average was 5.59 mm. The refractory samples ranged from 3.19 mm to 4.09 mm, and the group average was 3.68 mm.

The lumen cross-sectional area of the springwood fibers was largest in the permeable woods.

The bordered pit structures (annulus, torus and aperture) in the springwood were not significantly different in size between the permeable and refractory woods.

SOME ANATOMICAL FEATURES OF DOUGLAS-FIR WOOD RATED PERMEABLE AND REFRACTORY

by

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SOME ANATOMICAL FEATURES OF DOUGLAS-FIR WOOD RATED PERMEABLE AND REFRACTORY

INTRODUCTION

The penetration of liquids into wood is very important in both the pulp and paper industry and the wood preserving industry. Wood chips for paper must be completely penetrated with cooking liquors to insure a uniform separation of wood fibers. Without proper penetration the outside fibers of the chip become overcooked, while the chip center remains undercooked or chars (7, p. 86). The primary objective in wood preservation is to increase the service life of wood through the penetration and retention of a toxic preservative. The ultimate cost of wood structures is decreased because the need of frequent replacements in permanent and semi-permanent construction is avoided (12, p. 4).

The impregnation of wood with any liquid is a complicated chemical, physical and anatomical problem. Douglas-fir (_Pseudotsuga menziesii_ (Mirb.) Franco) heartwood is no exception, and the problem is further complicated because the resistance to penetration varies within this species.

Douglas-fir heartwood samples collected by the Oregon Forest Research Center from sawmills throughout

Oregon were treated with creosote. A distinct difference in degree of permeability was noted in this material. This paper concerns basic research into the anatomical characteristics which may be related to permeable and refractory behavior of Douglas-fir heartwood to liquid penetration.

OBJECTIVES

The objective of this study was to investigate some anatomical features of permeable and refractory Douglas-fir heartwood. The procedure followed to achieve this objective was:

1. Make a preliminary investigation of fiber lengths, lumen sizes and pit diameters on several wood samples from each permeability group.
2. To expand the research on the anatomical feature that appeared most significant in the preliminary analysis.

THE STRUCTURE OF DOUGLAS-FIR (4, 13, 28)

Wood of all species is composed primarily of the same chemical substances. These substances are arranged in the form of cells of different kinds and shapes, but mostly consisting of a spindle shaped space completely surrounded by a wall. The great variety of shapes and arrangements of these cells mainly account for the physical differences in the various kinds of wood.

Douglas-fir is composed of those cell types or elements found in conifers. Wood is an anisotropic material and these elements are divided into those whose long axes are parallel to the longitudinal axis of the tree, and those which are elongated radially (Figure 1).

The longitudinal elements of Douglas-fir are primarily wood tracheids. They constitute over 90% of the volume of most softwoods. Burr and Stamm (6, p. 240) describe these cells as hollow, cellulosic tubes, tapered and closed at both ends, and somewhat rectangular or elliptical in cross section. The tracheids are from three to six millimeters long and overlap longitudinally about one fourth to one third of their length in the tree.

Two distinct zones, namely springwood and summerwood, exist within each growth ring. These are the result of rapid growth at the beginning of each growing season, which later slows down as the season advances. During the period of fast growth when conduction of water and raw food materials to the crown is important, thin-walled tracheids with large lumens are formed. As growth slows down in the latter part of the growing season, thick-walled tracheids are formed. These add strength to the stem of the tree and do not aid in conduction to the same extent as the springwood tracheids.

Although the tracheids are not continuous tubes, liquids are able to pass from the lumen of one tracheid to another through minute openings in the cell wall called pits. The pits are located on the radial walls of the springwood tracheids and are concentrated towards the ends. They are normally in a single vertical row on the wall, but occasionally form double rows. The pits in the summerwood are smaller, less numerous, and in the last formed row they also may be located on the tangential wall.

The bordered pit is the nature of pitting between wood tracheids. A pit cavity is developed when the cell wall forms a domed structure with a small aperture. Two such adjacent structures constitute a bordered pit-pair. A dividing membrane is stretched between the two adjacent pit cavities with a thickened area (torus) occupying the center portion.

Softwoods also may possess longitudinal parenchyma cells. In Douglas-fir these cells are quite sparce and scattered throughout the growth ring. Parenchyma cells store reserve food and extractives in the living tree. They can usually be identified by their flat, blunt ends and "simple pits" on the cell wall. These simple pit-pairs are merely round holes in the contiguous cell walls with a dividing membrane between them. Pit cavities and tori, as found in the bordered pit-pairs, are lacking.

Specialized, resin secreting cells, called epithelial parenchyma, line the vertical resin ducts in Douglas-fir and Larix, Picea and Pinus species. Since the resin ducts are postcambial in formation and occur only as intercellular spaces, they are not listed as a specific cell type.

Wood elements oriented in the transverse or radial direction are found entirely in wood rays. Wood rays are of two types, uniseriate and fusiform. The uniseriate rays generally are one cell in width and from one to many cells in height. In Douglas-fir, ray tracheids form the marginal cells of the ray, and the other ray cells are parenchymatous. The fusiform ray consists of the same elements as the uniseriate and epithelial cells that surround a transverse resin duct. As a result these rays are many cells wide in the middle and taper to one cell in width at the margins. The primary functions of wood rays are food storage and translocation from the inner bark (phloem) to the living cells in the tree stem.

Within the stem of a tree, a heartwood and sapwood zone is found. All cells in the heartwood are dead and this portion of the stem provides mechanical support for the tree. In sapwood the tracheids die shortly after they are formed, but still function as conducting elements. The parenchyma cells remain alive as long as they are in the sapwood.

Douglas-fir heartwood and sapwood do not differ in basic structure, although there are certain changes that occur when sapwood becomes heartwood. Numerous aspirated pits are associated with heartwood tracheids. A bordered pit becomes aspirated when the torus moves to one side of the pit cavity and closes the pit aperture. Resins and other extractives in the heartwood usually become hard and remain deposited within the resin ducts and cell lumens.

Even though Douglas-fir wood appears to be composed of many channels for liquid movement, its permeability varies greatly within the species. Therefore, all factors related to permeability of wood must be considered before any one factor or combination of factors can be successfully correlated with permeability.

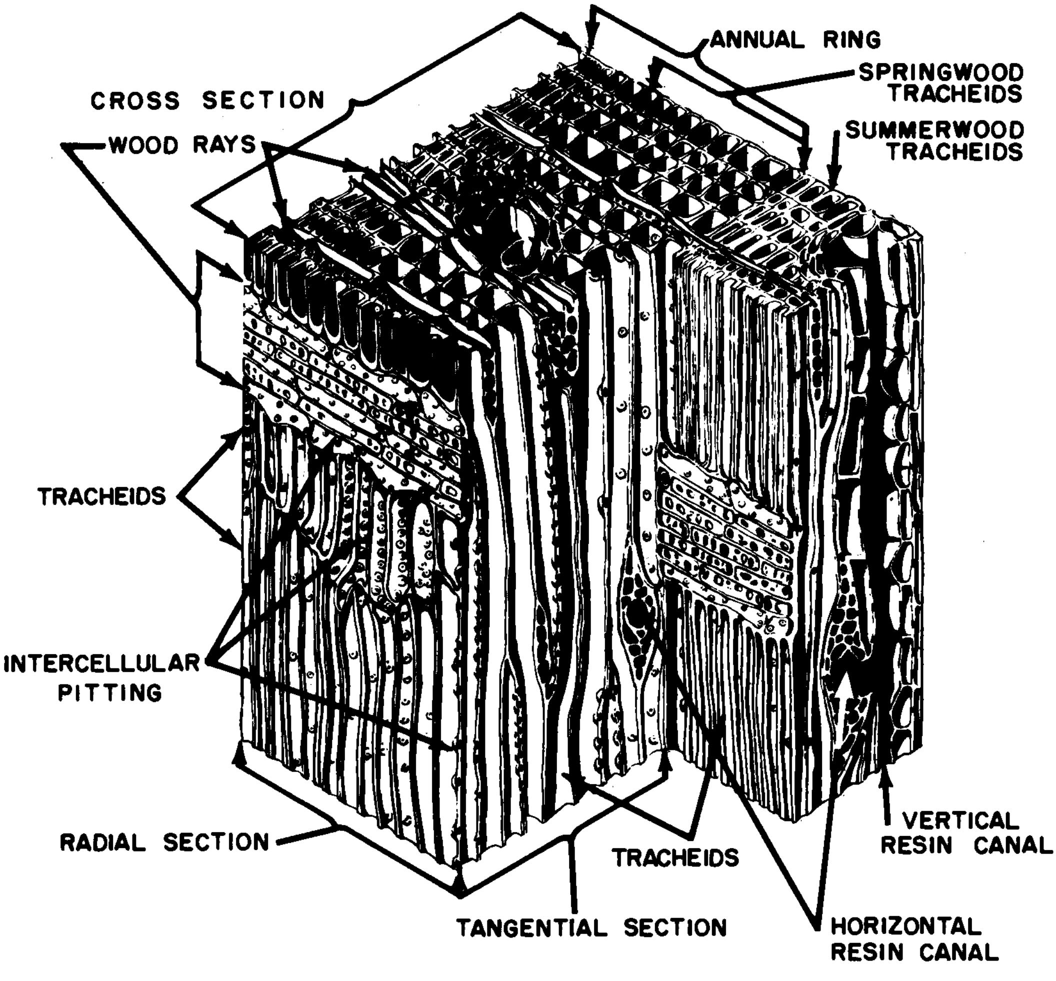

Figure 1
DRAWING OF A SMALL CUBE OF SOFTWOOD
(Courtesy of Oregon Forest Research Center)

LITERATURE REVIEW

Penetrability in coniferous heartwood is related to the structure of the elements composing it. Penetration in the longitudinal direction is many times faster than in the radial or tangential directions (15, p. 171).

In Douglas-fir the major passageways for liquid flow in the longitudinal direction are through the tracheids and resin ducts. Because resin ducts are larger and longer than the individual tracheids, they would seem to appear responsible for a large part of the flow of liquids in wood.

Work by Wagg (19, p. 174) indicated there may be a relationship between treatability and number of resin ducts. In the more permeable Coast type Douglas-fir resin ducts were found to outnumber seven to one those in the refractory Rocky Mountain form in both number per ring and number per unit area. His results also showed more longitudinal resin ducts in the wider growth rings. The possibility of refractoriness was therefore associated with rate of growth.

Resin ducts may not be responsible for complete penetration since they are not always free to conduct liquids. If liquid distribution through the surrounding cells is not sufficient, resin ducts would not account for springwood penetration because they are located primarily in the summerwood zone of the growth rings in Douglas-fir.

Further evidence of flow through tracheids has been illustrated where rate of penetration or flow increased with pressure to a greater extent than expected (3, p. 37). If only resin ducts were responsible for penetration, there would not be a wide departure from proportionality to pressure.

I. W. Bailey (2, p. 135) observed the flow of carbon particles from tracheid to tracheid and concluded that the particles traveled through the bordered pits. Since this observation, the relationship of pits to permeability has been carefully studied.

Initial work on the flow of liquids under pressure through the tracheids were designed to determine which structures or conditions offered the greatest resistance to penetration. Stamm (25, p. 42) conducted experiments which showed the major resistance of flow in the longitudinal direction was in the bordered pit openings in the cell wall. He first checked the flow through wood cross sections less than a tracheid length along the grain and obtained a percentage value for the effective capillary area of the cross section for cell lumens. As the thickness of the wood sections was increased, more and more tracheids terminated and the flow was forced through the pits. The effective capillary cross section dropped rapidly, which indicated greater resistance in the pits. When a thickness corresponding to the maximum tracheid length was reached, a value representing resin duct and pit communication cross section was found.

Laws which govern the flow of liquids through capillary tubes of constant diameters apparently can not be readily applied. Hawley (11, p. 19-21) set up a relationship which stated:

> "If only orifices (pits) determined the rate of penetration, then it will take only one unit of time to fill the first set of cavities through one set of orifices, two units of time to fill the second set of cavities through two orifices, and so forth."

From this assumption the following formula was derived:

$$x = ay\left(\frac{y + b}{2b^2}\right)$$

where x = time required to penetrate y.
y = depth of penetration.
a = time required to fill the first cell cavity.
b = length of a cell cavity in direction of flow.

When comparing two woods of different degrees of permeability, the size of the cell cavity and the effective open pit area appear to be the variables in the equation.

Fleischer (9, p. 154) found the lumen cross sectional area to be larger in permeable Douglas-fir. Since a correlation between tracheid length and lumen area has been observed (10, p. 37), it might also be expected that the tracheids were longer in the permeable sample.

Since pits offered the greatest resistance to flow of liquids through the wood, research on pits and pit structure has been quite extensive. Microscopic techniques have improved with the development of better equipment and sometimes supported new and contradictory conclusions.

All liquids which flow from the lumen of one tracheid to another must pass through the membrane supporting the impermeable torus in the bordered pit-pair. In photographs taken by West (29, p. 22) at high magnifications under a light microscope, this dividing membrane appears to be composed of many strands radiating from the torus to the outer edges of the pit cavity. Marts (17, p. 382) illustrates the membrane in Douglas-fir by phase contrast as "a radial network of ribbon-like strands and what appear to be radial openings, variable in size." Photomicrographs by Côtè (8, p. 299-300) using an electron microscope show these strands as microfibrils which form a membrane porous to relatively large particles. In the heartwood pits of certain species this porosity appears reduced by the presence of nodules on the microfibril strands.

In a review of literature on pit studies, Stone (26, p. 14) found that percentagewise aspirated pits were more abundant in refractory woods. This should appear very significant in penetration, since in this condition the torus is forced against the pit aperture, thereby acting as a valve which would seem to obstruct flow through the pit (Figure 2).

Stone analyzed photomicrographs of aspirated pits at high magnifications and found a space between the torus and the edge of the pit aperture. He concluded that the surface of the torus was too rough to completely seal the aperture to flow of most liquids.

Most observations on pit aspiration and other wood structures have been made from wood sections cut on a microtome for microscopic study. The chance of disrupting the wood structure during sectioning and slide preparation for microscopic study should not be overlooked as a possible source for misrepresenting actual conditions.

Summerwood generally is more permeable than springwood in the heartwood region of Douglas-fir (20, p. 174). Several reasons may account for this difference. As previously mentioned the resin ducts are localized in the summerwood area of the growth ring. The pits in the summerwood tracheids are smaller and fewer in number than found in the springwood tracheids, but they often occur as pit canals with the thickened portion (torus) in the dividing membrane apparently lacking (4, p. 136). The summerwood lumens are also smaller, and capillary action of the preservative may account for greater penetration.

Because the samples used in the research for this paper were rated almost entirely on the amount of longitudinal penetration, the anatomical features which affected penetration in this direction have been emphasized. Some gross characteristics of these wood samples showed that the permeable and refractory group included woods which had from 10 to 30 rings per inch. The specific gravity, based on ovendry weight and unseasoned volume, was 0.49 for the permeable group and 0.48 for the refractory group (18).

One author (5, p. 77) suggests that for passage of liquids in one anatomical direction, permeability must also be good in the other directions. Liquids may bypass local impermeable spots in the wood, which may otherwise have prevented further penetration.

Flow in the tangential direction is dependent entirely upon liquid passage across the tracheid lumens and through the bordered pits. Here again, the pits would be offering the greatest resistance to flow.

In the radial direction penetration of the preservative requires good flow through the rays. In the fusiform ray, the transverse resin duct may aid penetration if it is free of occlusions. Fleischer (9, p. 154) found more rays, both uniseriate and fusiform, per unit area on the tangential surface of the permeable Douglas-fir wood.

Although no previous literature on the effect of tracheid length on penetration was found, there has been much work on tracheid length as related to position in the tree. Spurr and Hyvärinen (24, p. 571) have made an excellent review of research on this subject prior to 1954. They concluded that tracheid length increases rapidly in most species from the pith until after 20 to 50 years of growth. At this time the tracheids have reached a maximum length, and in subsequent years the average remained rather constant, although the individual variation from the mean length may be considerable. Variation of tracheid length within a growth ring also existed. Latewood tracheids were found to be slightly longer than earlywood tracheids.

In Douglas-fir, Anderson (1, p. 41) found that tracheid length increased with distance from the pith. This relationship was independent of height, provided the cross section was taken from any height somewhat above the ground level. Within a distance of 20 to 200 millimeters from the pith of two trees, the average tracheid length ranged from about two to five millimeters.

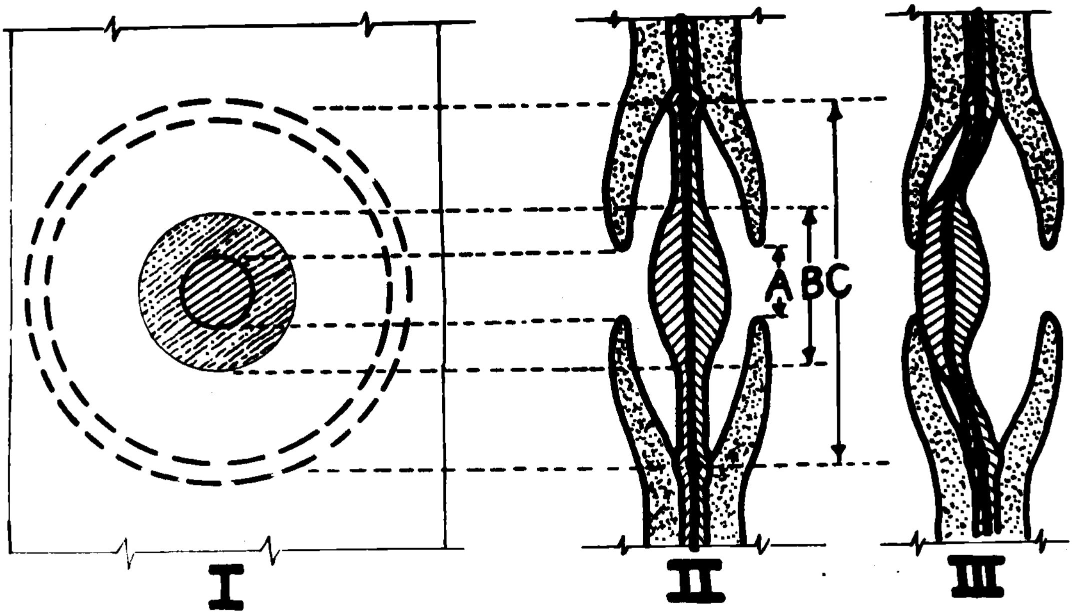

Figure 2. Bordered pit diagram

I. Bordered pit as seen on a radial section.

II. Bordered pit-pair as seen on either a tangential or cross section.

A. Aperture
B. Torus
C. Annulus

III. Bordered pit in an aspirated condition.

SAMPLE COLLECTION

Rough, green two-by-fours of Douglas-fir heartwood were collected from sawmills throughout Oregon by R. D. Graham and D. J. Miller for penetration studies at the Oregon Forest Research Center, Corvallis, Oregon. The towns in which mills were located were the only identification noted for the source of the samples.

Specimens about 1.2 by 1.2 by 6-inches were prepared and treated with creosote by Graham and Miller. The degree of penetration was determined by a visual estimate of the percent of area treated on a split radial face of the treated block. Ratings from one (almost no penetration) to six (complete penetration) were assigned each sample. Samples with semipermeable ratings showed mainly summerwood penetration. In a comparison of side penetration and longitudinal penetration, the latter was found responsible for almost all penetration into the blocks.

The variation in penetrability with geographic location in Oregon was quite striking as shown in Figure 3. Douglas-fir heartwood from mills in eastern Oregon was almost completely refractory to creosote penetration, while heartwood from mills along the coastal area was quite permeable.

Matched, untreated samples of material which had been given permeability ratings were obtained from the Oregon Forest Research Center for anatomical studies. Only heartwood which was very permeable or very refractory was studied.

Preliminary investigations were made on seven samples of Douglas-fir heartwood. Three samples were rated permeable, and four refractory. One of the refractory samples was from northwestern Oregon, and the other three were from eastern Oregon. The permeable samples were all from western Oregon.

The fiber [1/] length analysis on these samples indicated that more specimens in each group should be used. For this portion of the study, 17 additional samples were obtained, making a total of 12 permeable and 12 refractory samples.

Table 1 shows the location by town of the samples used for anatomical studies.

1/ The common term for tracheids is "fibers", and it will be used throughout the rest of the paper.

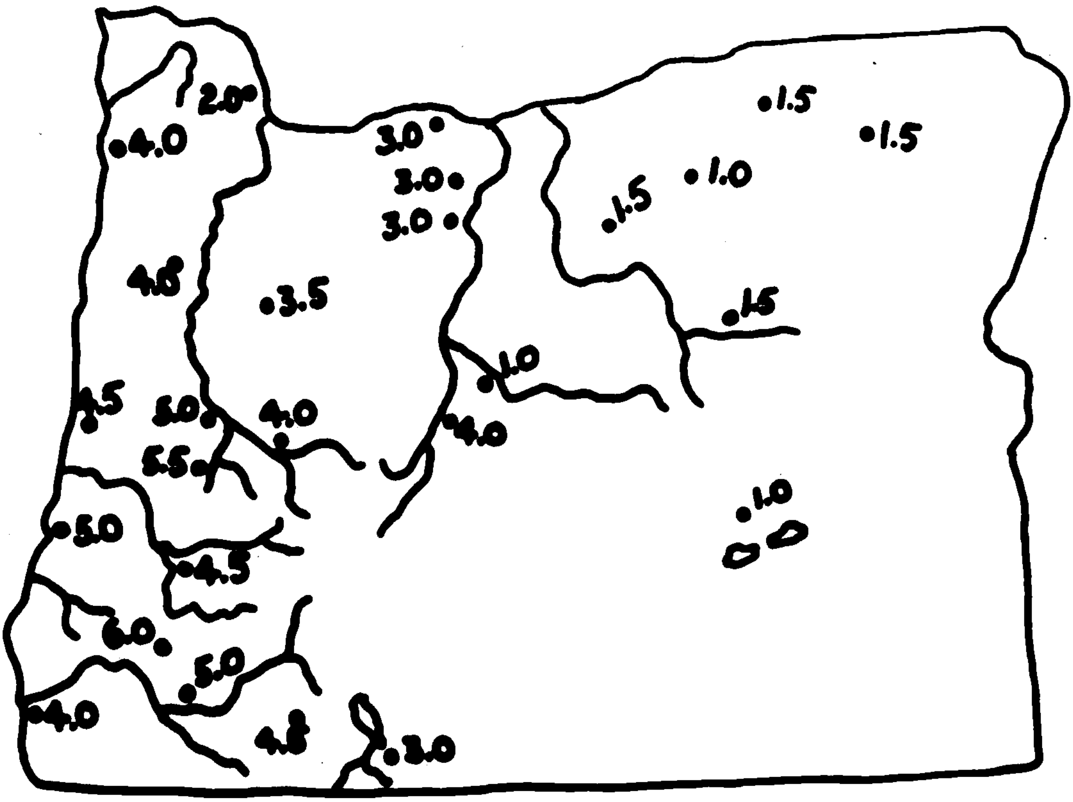

Figure 3. Map of Oregon showing variation in permeability with geographic location.

(Information obtained from Oregon Forest Research Center)

TABLE 1

SUMMARY OF RESULTS

Sample No.	Location	Ave. Fiber Length (mm)	Ave. Lumen Size Radial (microns)	Ave. Lumen Size Tangential (microns)
		PERMEABLE WOODS		
89	Cottage Grove	6.16		
28	Eugene	6.07		
38	West Fir	5.99		
94	Dallas	5.84		
90	Cottage Grove	5.72		
42	Tillamook	5.57		
19	Glendale	5.47		
*20	Glendale	5.45	39.96	36.66
14	Medford	5.34		
*88	Cottage Grove	5.24	40.22	34.50
*30	Eugene	5.17	40.79	35.67
10	Coos Bay	5.06		
	AVERAGE	5.59	40.32	35.61
		REFRACTORY WOODS		
*33	Heppner	4.09	25.06	27.39
32	Heppner	4.03		
51	La Grande	4.00		
57	Prineville	3.90		
*65	St. Helens	3.84	27.82	23.95
56	Prineville	3.81		
36	Hines	3.69		
*50	La Grande	3.54	31.92	27.77
*34	Hines	3.48	27.05	27.64
4	Mt. Vernon	3.36		
35	Hines	3.22		
101	Kinzua	3.19		
	AVERAGE	3.68	27.96	26.69

* Samples used in preliminary studies.

TECHNIQUES

Preparation of Material for Anatomical Study

Seven samples of Douglas-fir heartwood were prepared for sectioning, and 24 samples were macerated for fiber length measurements. The microtome sections were used for pit and lumen measurements.

Sectioning. Small wood blocks were soaked in cold water under a vacuum until completely saturated. The saturated blocks were then trimmed with a razor blade to provide a radial, tangential, and cross section from each sample. The sectioning was done with an American Optical sliding microtome (Figure 4) and a Spencer microtome knife sharpened carefully with a levigated alumina solution on a Berkley knife sharpener (Figure 5).

Cross sections were cut 12 microns in thickness, and the tangential and radial sections were 24 microns. The sections were stained with a Safranin O stain (14, p. 62) and mounted in Karo syrup on glass slides. Only sections of the same thickness were mounted together on one slide.

Maceration. A macerating technique using acetic acid and sodium chlorite as outlined by Spearin and Isenberg (23, p. 214) was used on small segments from each block of wood. These "matchstick" size segments were selected in such a manner to include the full range of growth rings represented on a heartwood sample. This was to insure that any variability in fiber length with age of tree was taken into consideration when an average for the sample or the group was calculated.

After the wood had been treated with the macerating solution, the small segments were carefully washed and gently teased apart (Figure 6). The fibers were stained with dilute Safranin O and stored in water with alcohol added as a preservative.

Methods Used for Measurements

Fiber length. Many techniques have been devised for fiber length measurements. Wilson (30, p. 84-88) has given an excellent review of the techniques developed prior to 1954. These methods were based on either direct measurement under a microscope with a calibrated eyepiece or projection of the fiber image on a calibrated screen. For this study all fiber length measurements were made with a microscope and a calibrated eyepiece.

A small number of fibers were placed on a glass slide with an eyedropper. A predetermined pattern of scanning the slide was employed to prevent measuring any fiber more than once, and generally one slide was sufficient to obtain 10 observations. Both springwood and summerwood fibers were measured, and no attempt was made to separate them during measuring or recording.

A total of 180 fibers from the permeable woods and 200 fibers from the refractory woods were measured. Graff and Miller (10, p. 35) found that a sample of 150 fibers gave a 0.08 mm error, and a sample of 200 fibers gave a 0.05 mm error. On this basis the average fiber length for the permeable and refractory groups should be accurate enough to indicate any differences.

Lumen measurements. Fiber lumens were measured from the cross sections of seven samples. Three photographs were taken of each sample; each picture represented one growth ring. The pictures from each sample were taken from areas representing different radial groups of fibers. A 35 mm Exacta camera mounted on a Spencer microscope was used to take the photographs (Figure 7).

Enlargements were made from each photograph, and lumen measurements were taken directly from the enlargements. All photographs and enlargements were at the same magnification in order that a statistical analysis could be made on the data.

Only springwood lumens were measured because the summerwood cells were generally out of focus on the photographs. Springwood appeared to be the limiting factor for good treatability since creosote concentration was in the summerwood of the semipermeable woods.

Both the radial and tangential diameters of the fiber lumens were measured. Distortions occurred on the edges of the enlargements, thus only the middle 20 to 25 radial rows of fibers were suitable for study.

Since the radial dimensions of the lumens appeared relatively constant from row to row of cells within a given growth ring, one row was selected from the photograph of each ring by a random numbers table. Each growth ring consisted of as many observations as there were springwood cells. Springwood and summerwood were separated by Mork's Principle (22, p. 3), which states:

> "All tracheids in which the common wall between two cell wall cavities multiplied by two is equal to or greater than the width of the lumen are considered as summerwood; those in which the value is less than the width of a lumen are considered as springwood (all measurements being made in the radial direction)."

Two sets of tangential dimensions were taken from each growth ring; one from the early springwood region and one from the late springwood region.

The fibers of Douglas-fir are square to hexagonal in cross section with the tangential walls generally parallel to each other. Radial dimensions therefore are easy to record, but tangential dimensions must be estimated to an extent since the radial walls are not always parallel.

Pit measurements. Several pit measurements were taken from the radial wood sections previously prepared for microscopic study. These included the diameters of the pit annulus, torus, and aperture.

Measurements were taken directly from the sections with a microscope. Since a complete cell wall of any one fiber was not present, areas where pits were present had to be chosen for study. Fifteen pits were measured from the springwood zone of each sample.

Figure 4. American Optical microtome for wood sectioning.

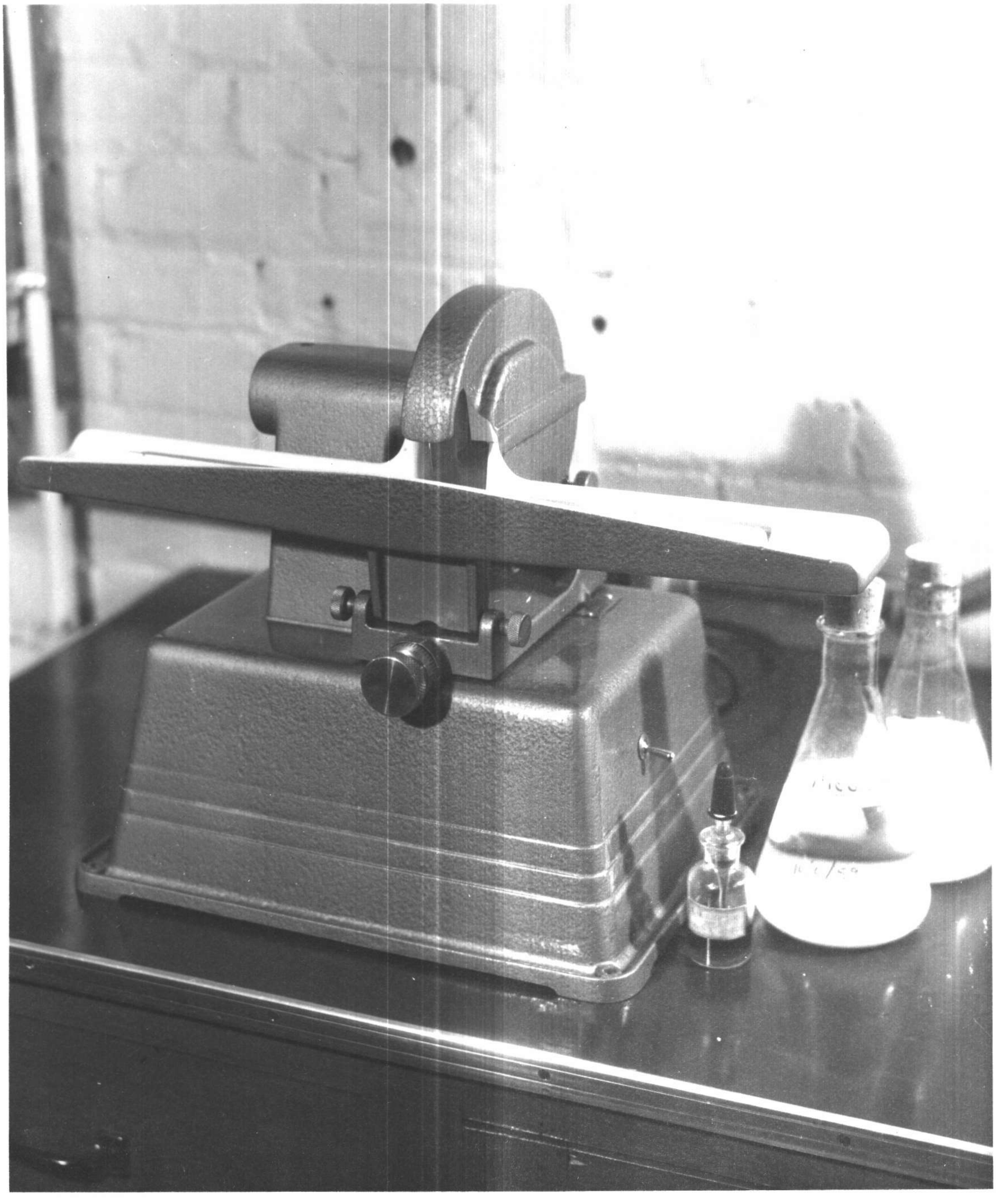

Figure 5. Berkley microtome knife sharpener.

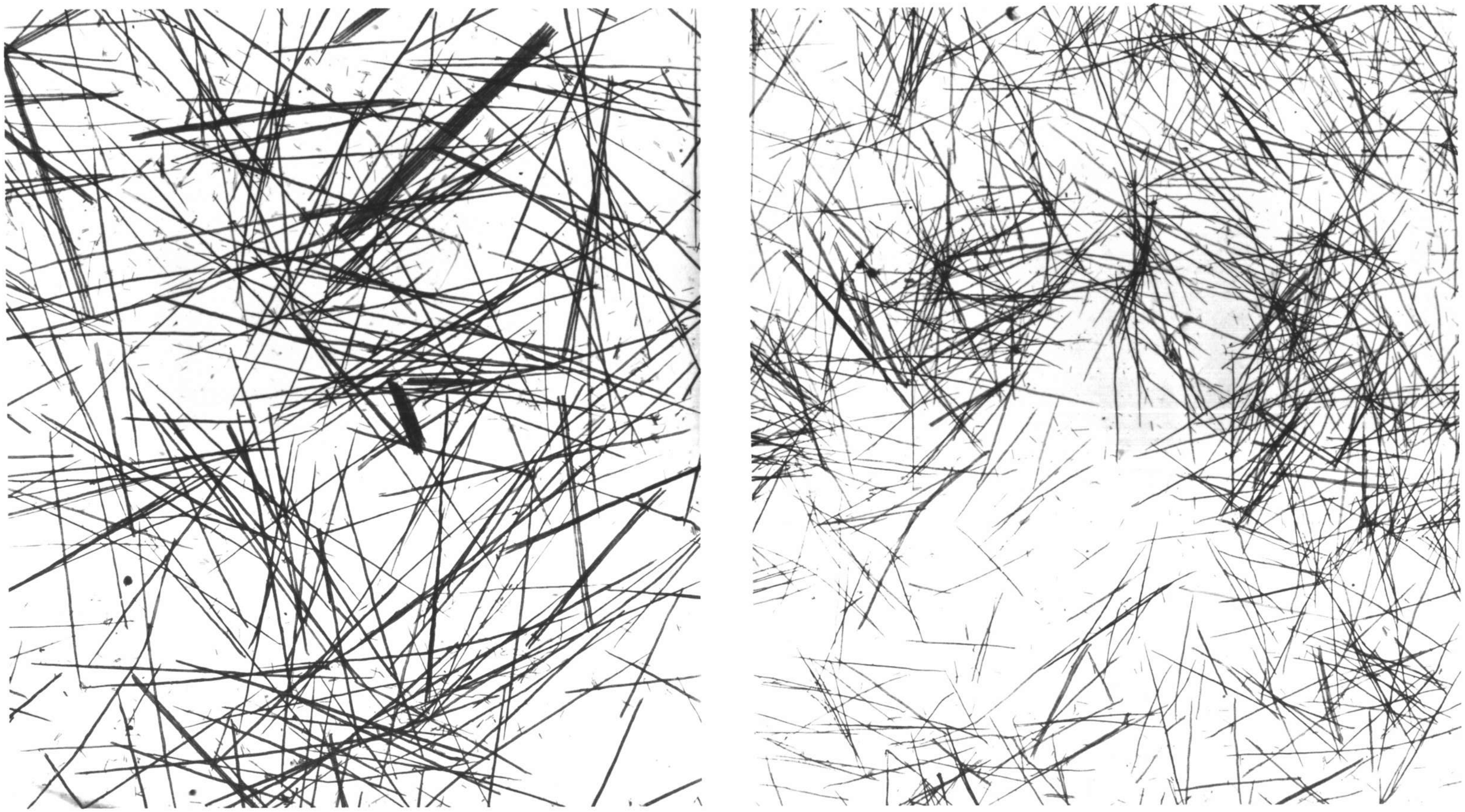

Figure 6. Macerated fibers from a permeable sample (left) and a refractory sample (right) of Douglas-fir heartwood. (Magnification: 7X)

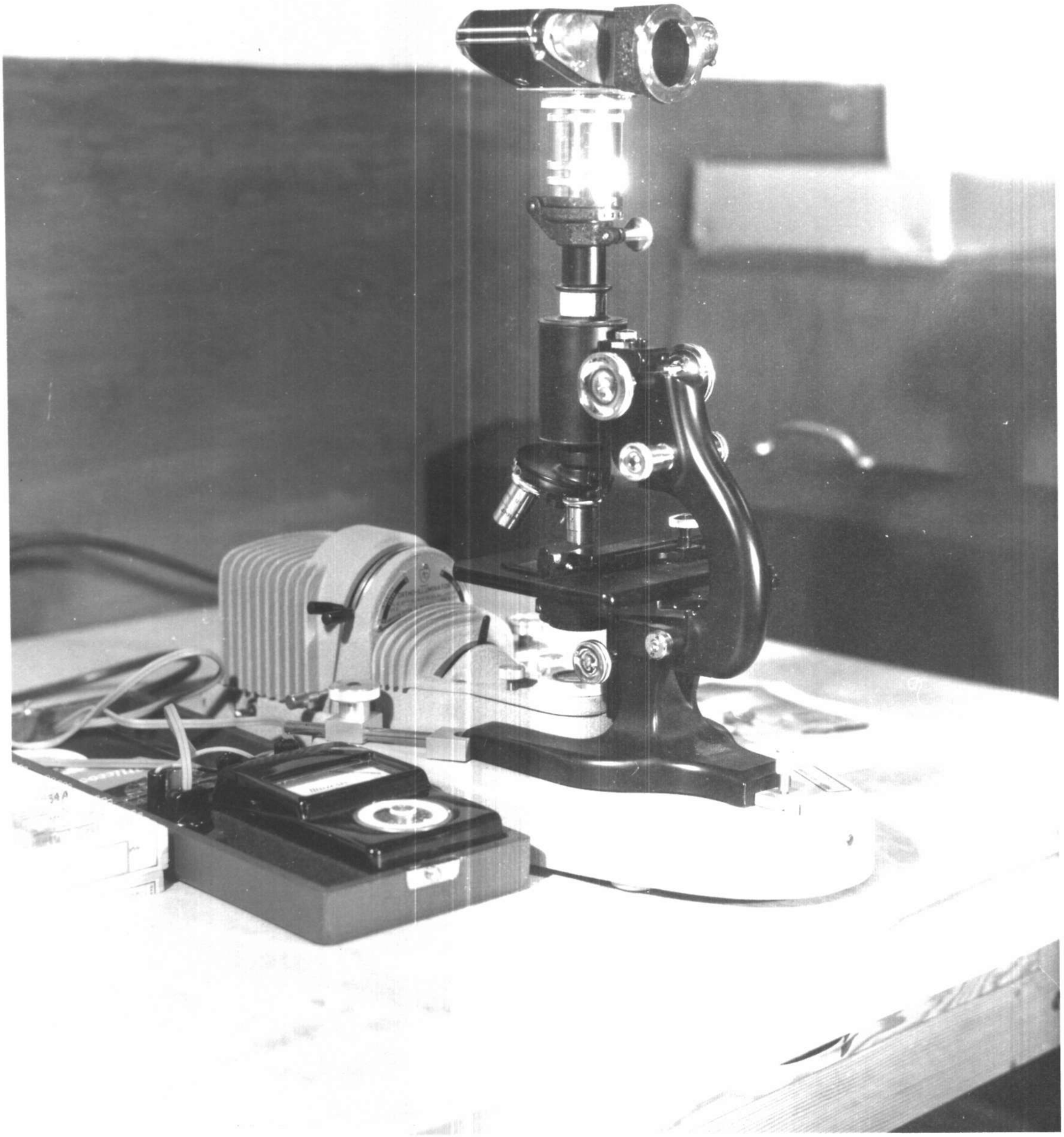

Figure 7. Exacta camera mounted on a Spencer microscope for photographing wood sections.

STATISTICAL ANALYSES

A statistical analysis was made on all anatomical measurements considered. The experimental design was based on a hierarchical classification (16, p. 326). Under this classification the refractory and permeable woods were considered as two independent groups. These groups were further broken down into various levels or subgroups, depending on the observations taken and the method of recording. The acceptance or rejection of a hypothesis was determined by the magnitude of the F-value in the analysis of variance. Critical regions were based on a significance level of one percent.

RESULTS

Fiber Length

In the preliminary investigations on the seven samples of Douglas-fir heartwood, the average fiber length differed greatly between the permeable and refractory groups. Thirty fibers from each sample were measured, and a statistical analysis was made. The significant difference in fiber lengths was evident in the size of the F-value obtained in the analysis of variance (Table 2).

Since the variation of fiber lengths within a sample was small in comparison to the variation among samples in a group, a larger number of wood samples was obtained, and ten fibers from each sample were measured.

In the new results (Table 2) the significance difference still existed among samples in a group, but the F-value for "Between Groups" became very large and further supported the findings that the fiber lengths differed greatly between the permeable and refractory groups.

Although individual fiber length measurements overlapped between the two groups, none of the samples rated permeable had an average fiber length which fell into the refractory group, or vice versa. The average fiber lengths for the permeable samples ranged from 5.06 to 6.16 mm, and the group average was 5.59 mm. The refractory samples ranged from 3.19 to 4.09 mm, and the group average was 3.68 mm.

The average fiber length for each wood sample is given in Table 1. These are ranked in order of decreasing length to show the range within a group, and the order does not necessarily indicate degree of permeability within a group.

Lumen Size

Since the radial and tangential dimensions of the springwood cell lumens were measured and recorded individually, a separate analysis of variance was made on each, rather than combining them as a lumen area (Table 2).

The "Between Groups" F-value for both the tangential and radial dimensions was significant. For all samples measured, the permeable woods had the largest lumens (Table 1).

In the analysis of variance for tangential lumen size, the F-value for "Samples in Group" was also significant, which indicated that the variation in size among samples was greater than either the variation within a growth ring or the variation between the early springwood zone and the late springwood zone. These results indicated that for further work in this area more wood samples should be included, and measurements could be taken from only one zone in the springwood.

For the analysis on the radial lumen dimension, "Rings in Sample" was significant. This indicated that the variation in size was greater among growth rings within a wood sample than the variation within a ring. In this case more growth rings, either within a sample or from more individual wood samples, should be included in future studies.

Pit Sizes and Distribution

The analysis of variance for the bordered pit measurements in the springwood showed no relationship to permeability of Douglas-fir heartwood (Table 2).

Although any variation in pit size was insignificant between the two groups of wood, there appeared to be a higher frequency of fibers with double rows of pits on the radial wall in the permeable samples. This observation was evident on both the radial and cross sections.

In the permeable samples the fiber cross sections show a greater tendency toward having more than four sides. Since the texture in the radial direction is also quite coarse, the radial wall of these fibers is generally wide enough to support more than one vertical row of bordered pit-pairs. Often one of the rows of pits appear to lead to one adjacent fiber lumen and the second row of pits to another adjacent lumen (Figure 8). The fibers of the refractory woods seem more square in cross section and are finer textured. They tend to have a radial wall that will support only one vertical row of pits, and thus offer communication with only one row of cells (Figure 9).

TABLE 2

ANALYSIS OF VARIANCE: EFFECT ON PERMEABILITY

Source of Variation	D.F.	Sum of Squares	Mean Square	F
		FIBER LENGTH (7 Samples)		
Between Groups	1	4,289.80	4,289.80	73.15*
Samples in Group	5	293.20	58.64	5.12*
Error	203	2,327.07	11.46	
Total	209	6,910.07		
		FIBER LENGTH (24 Samples)		
Between Groups	1	10,469.067	10,469.067	189.58*
Samples in Group	22	1,214.921	55.224	4.77*
Error	356	4,118.152	11.568	
Total	379	15,802.140		
		TANGENTIAL LUMEN SIZE (7 Samples)		
Between Groups	1	1,959.2719	1,959.2719	48.42*
Samples in Group	5	202.3399	40.4680	7.11*
Zone in Ring	7	39.8558	5.6937	0.61
Error	852	7,956.9874	9.3392	
Total	865	10,158.4550		
		RADIAL LUMEN SIZE (7 Samples)		
Between Groups	1	1,866.4543	1,866.4543	52.40*
Samples in Group	5	178.0912	35.6182	1.18
Rings in Sample	14	423.6639	30.2617	3.74*
Error	441	3,564.3274	8.0824	
Total	461	6,032.5368		
		PIT ANNULUS SIZE (7 Samples)		
Between Groups	1	0.5571	0.5571	12.87
Samples in Group	5	0.2165	0.0433	3.55
Rings in Sample	14	0.1710	0.0122	1.03
Error	84	1.0010	0.0199	
Total	104	1.9456		
		PIT APERTURE SIZE (7 Samples)		
Between Groups	1	0.0580	0.0580	5.09
Samples in Group	5	0.0568	0.0114	4.22
Rings in Sample	14	0.0373	0.0027	1.00
Error	84	0.2270	0.0027	
Total	104	0.3791		
		PIT TORUS SIZE (7 Samples)		
Between Groups	1	0.0909	0.0909	8.82
Samples in Group	5	0.0513	0.0103	4.12
Rings in Sample	14	0.0343	0.0025	0.66
Error	84	0.3160	0.0038	
Total	104	0.4925		

* Significant at 1% level.

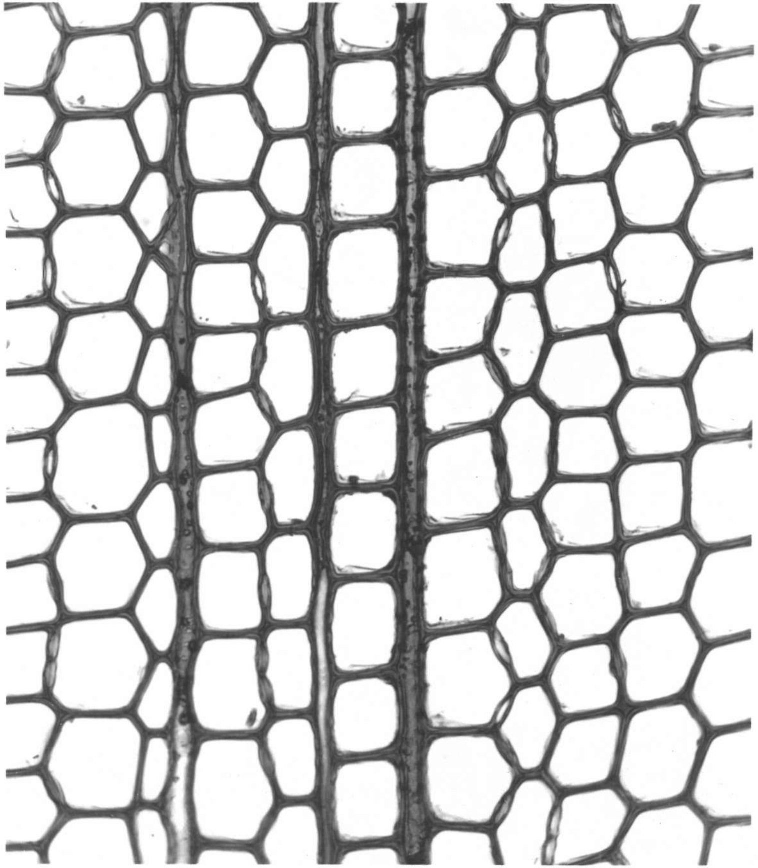

Figure 8. Cross section of a permeable Douglas-fir heartwood sample. (Magnification: 190X)

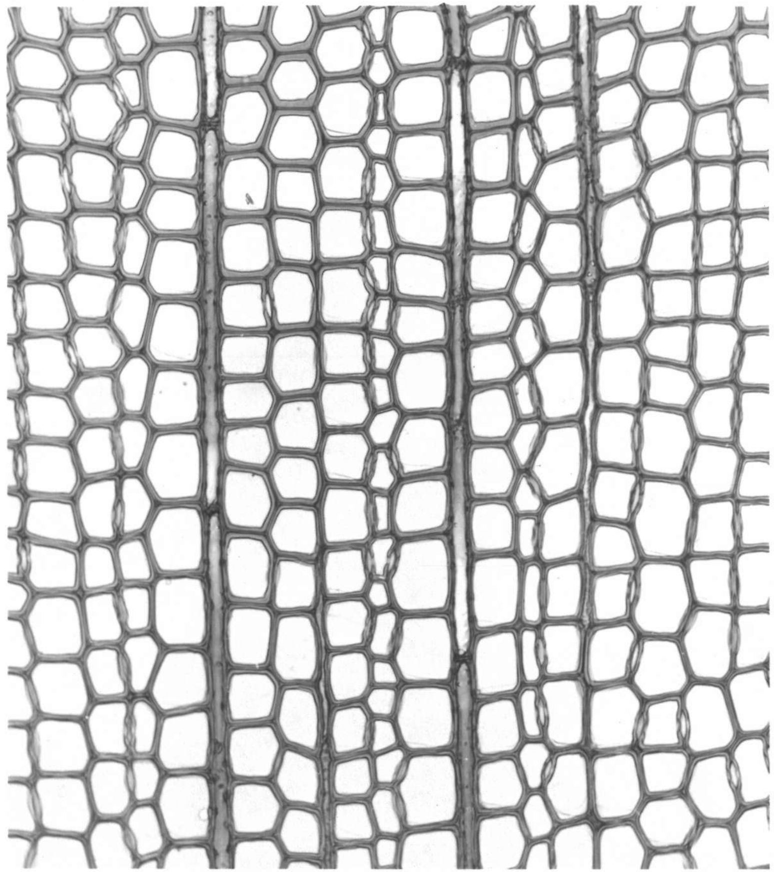

Figure 9. Cross section of a refractory Douglas-fir heartwood sample. (Magnification: 190X)

CONCLUSIONS

The results of this study on anatomical differences between permeable and refractory Douglas-fir heartwood offer the following conclusions:

1. The average fiber length of the permeable woods is considerably longer than the average of the refractory woods.
2. The springwood fiber lumens are largest both radially and tangentially in the permeable woods.
3. The permeable and refractory woods have the same size bordered pit structures (annulus, torus and aperture).
4. The fibers in the permeable woods exhibit a greater tendency to be hexagonal in cross section with a radial wall capable of supporting a double row of bordered pits, while in the refractory woods the fibers appear more square with one row of bordered pits on each radial wall.

RECOMMENDATIONS

The correlation between anatomical features and penetrability of Douglas-fir heartwood cannot be fully understood until all factors have been thoroughly investigated; therefore, the following recommendations are made for those interested in continuing this phase of the study:

1. If possible, permeable and refractory wood from the same geographical area should be studied to eliminate the location variable.
2. In fiber length studies a faster fiber-measuring system based on a projection method could be used. At this same time woods in a "semi-permeable" group could also be included in the study.
3. A simple, efficient method of determining the frequency, or number, of pits on the radial walls of the fibers should be investigated.
4. The possibility of nodules on the microfibril strands of the pit membrane in refractory woods may be significant in reducing flow of liquids into wood. This could only be studied properly with the electron microscope.

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