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CONTENTS

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HARVEY D. ERICKSON,[2] HENRY SCHMITZ, and
ROSS AIKEN GORTNER

INTRODUCTION

The subject of the permeability of wood, the penetration of liquids and gases into it, and the factors which affect permeability have been studied by a number of workers. Usually, the methods, conditions, and kinds of wood employed by individual workers have been quite different. In some cases, conclusions have been drawn from investigations of such limited scope that they do not appear to be justified. Different workers, and even the same workers, have reported contradictory results concerning the influence of various factors on permeability. In a few cases, certain assumptions have been made that are of doubtful validity and which, if in error, would invalidate the proffered interpretations of the experimental data.

In order to clarify and further establish the status of the permeability of wood, it is necessary that more information be obtained on such subjects as the comparative permeability of various species of wood, for heartwood and sapwood, and for the seasoned and unseasoned conditions. This would give a better indication of the permeability of different species of wood and the influence of seasoning and the duration of flow on permeability. Interesting and important relationships have been indicated by the flow of various organic and inorganic liquids and solutions through wood. However, before broad generalizations can be drawn, it is necessary to verify the experimental data reported and to extend the investigations to a greater variety of woods and experimental conditions.

The relative permeability of springwood and summerwood never has received much experimental consideration. With one or two exceptions, the present views regarding the relative permeability of springwood and summerwood are based on visual observations of the apparent accumulation of liquids in the respective portions of the annual ring. More exact knowledge in this subject may have practical as well as theoretical implications.

Numerous factors probably influence the permeability of wood. Some of them are related to the wood itself, as, for example, pit aspira-

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[1] From the Divisions of Forestry and Agricultural Biochemistry of the University of Minnesota.

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tion, valve action of the tori, the complex structure of wood, the relative volumes occupied by the wood substance and by air, moisture content, and the method of seasoning. Others of those factors are related to the liquid with which the wood is permeated, such as viscosity, surface tension, interfacial tension, and electrokinetic properties. Finally, an interrelation between the characteristics of the wood and the properties of the liquids undoubtedly exists. Obviously, the flow of liquids through wood is an extremely complicated problem, and progress must of necessity be made on a wide front of scientific investigation before actual relationships can be established.

REVIEW OF LITERATURE

It is now quite generally agreed that intercellular movement of liquids in wood occurs mainly through the special structures of the cell wall called pit membranes. Artificially created passageways may also be formed under certain conditions and treatments and may influence the permeability of wood.

Early workers on this problem could find no ready explanation for the permeability of coniferous wood. To all appearances there were no intercellular openings. Tiemann (33) stated that in green wood the cells are enclosed by the continuous and nearly impervious primary wall. To explain penetration of preservative oils, Tiemann suggested that when wood is seasoned below the fiber saturation point narrow microscopical slits develop in the cell walls which provide a means of penetration, and the greater the degree of dryness the more penetrable they become.

Weiss (34) modified this explanation on the basis of his observation that there was greater penetration of creosote in the summerwood than in the springwood of longleaf pine. He concluded that dense summerwood tissue cracked more on drying than did the thinner walls of springwood.

Bailey (1) was the first worker to draw well-founded conclusions that pit membranes play an important rôle in liquid movement. He examined the summerwood of creosoted blocks and found that the secondary walls, in most cases, were unruptured. He also pointed out that air passed very readily through the dry springwood in which checking of walls did not occur and which, according to Tiemann's suggestion, should then be impervious. Even in those cases where the secondary walls had checked, Bailey observed that the primary walls remained unruptured and hence prevented the formation of a passageway to contiguous cells.

Using a carbon suspension, Bailey (2) showed that particles enter the cell through the bordered pits. He concluded that "the pit membranes in the tracheids of living coniferous trees are not entire as has been previously supported, but are perforated by extremely minute openings which are located in the thinner radii of the membranes."

Later investigations on mercury penetration led Scarth (22) to the same general conclusion. Jack pine summerwood, the tracheids of which have very few pits, did not permit the entrance of mercury. In other cases he noticed a marked correlation between lack of penetration and those instances where the torus sealed the pit cavity. Stamm (24) in his studies on the size of the effective openings by electrokinetic methods found that when the length of the interlumener capillaries was assumed to be the thickness of the pit membranes, values were obtained in accord with those obtained by physical methods. Also from the results of the penetration of a mercury sol and India ink into wood he concluded that if openings existed other than those in the pit membranes, they were so small that they had little or no effect on the determination of membrane pore dimensions.

The methods first used by Stamm (24) to determine the effective size of the perforations were electroendosmotic flow, hydrostatic flow, overcoming surface tension in the capillary structure, and permeability to colloidal solutions.

By means of electroendosmosis he was able to determine the total effective capillary cross section of coniferous sections cut in each of the three structural directions. The effective continuous pit capillary cross section was determined from the change in the ratio of the electroendosmotic flow with the change in the thickness of transverse sections.

The hydrostatic flow method is a differential pressure method involving the connection in series with the supply line of a wood section and a standard glass capillary. Two manometers were so connected that the effective pressure acting on each could be determined, and the ratio of the pressures represented the ratio of the flow through the standard glass capillary to the flow through the unknown capillary system of the wood.

Combining electroendosmotic flow data with hydrostatic flow studies, he found the average diameter for two coniferous woods to range from 11 to 23 $m\mu$. The maximum effective diameter of the perforations was found by measuring the pressure necessary to overcome the surface tension of the liquid in the capillaries of the wood and applying the surface tension formula for liquid rise in a capillary tube (Jurin's method). The maximum effective diameters of the pores in the pit membranes were found to range for five species of wood from 67 to 180 $m\mu$ or about four to eight times larger than the average values by hydrostatic flow.

By electrical conductivity Stamm (25) determined the effective capillary dimensions of wood. He found that the concentration of the K Cl salt solution did not affect the results when it was greater than 0.07 mol per liter. Below this concentration surface conductance in the cell wall accounted for an appreciable amount of current and became more effective as the salt concentration was decreased. Bull and Moyer (6) determined the average pore size of cellulose pulp membranes by a combination of electrical conductivity and liquid flow measurements, and by substituting the equation for electrical conductivity into Poiseuille's law, the average pore size can be calculated.

Stamm (25) combined the data of the ratios of the effective capillary length to the effective capillary cross section with the data from studies on hydrostatic flow, thus giving the average effective radius of the capillaries. For the sections tested, the values found were from 186 to 2,190 $m\mu$ for sapwood of slash pine and coast Douglas fir, the slash pine having the larger openings. The maximum sizes as determined by the surface tension method were found to be 184 to 11,600 $m\mu$ in radius. For the heartwood of several species, the average effective radius ranged from 10.3 to 68 $m\mu$ and the maximum effective radius 34 to 113. Maximum effective radii in the same range were obtained in a later experiment (27).

More recently, Stamm (27) has utilized the differential pressure drop method for determining the changes in pore size with a change in moisture content using air of various relative vapor pressures. The square root of the permeability was plotted against the moisture content of the wood in equilibrium with air of various relative vapor pressures and gave essentially a linear relationship from 0 to 20 per cent moisture content, but at higher moisture contents the permeability was considerably less than the linear relationship indicated. He believed this to be due to condensation of moisture in the small capillaries below the equilibrium saturation pressure, or maximum relative vapor pressure, thus blocking the flow of air. He applied Kelvin's equation for the depression of vapor pressure in a capillary and computed the capillary radius at which the water films were formed.

Buckman, Schmitz, and Gortner (5) had previously found that the rate of flow of benzene decreased with increasing moisture content of wood. The same result was obtained when nitrobenzene was used. They attributed this to the decreased size of the effective openings caused by accompanying increase in swelling with higher moisture contents.

They also used the surface tension method to determine the changes in the maximum effective pore size with increasing moisture content. Higher pressures were required to overcome the surface tension of benzene in the larger capillaries in the sections of increasingly higher moisture content below the fiber saturation point. This demonstrated, they believed, the decreasing maximum effective pore size with increasing moisture content, and corresponds to their results obtained on the average effective capillary size.

The situation with regard to changes in size of the cell cavities with varying moisture contents is quite different (27). Transverse sections less than a fiber length in thickness gave practically no change in equilibrium permeability to air of different relative vapor pressures. Stamm (26) again reached this conclusion from volume and dimension changes caused by swelling and shrinking. This did not hold true in wood not dried under stress-free conditions.

The penetration of various liquids into wood has been studied by a number of workers. In the earlier methods of studying permeability, the specimens of wood were subjected to impregnation tests under pressure and elevated temperatures. The two general criteria of penetration used in this impregnation method are the distance of the penetration into the wood in the three directions (radial, tangential, and longitudinal) and the amount of liquid absorbed. The other method for measuring penetration or permeability is the measurement of the rate of flow of the liquid through a section of the wood. This method employs the test section as a membrane and enables more definite data to be obtained concerning permeability and response to given factors.

Teesdale (30) and Teesdale and MacLean (31, 32) have studied the resistance of various woods to treatment with preserving fluids. Teesdale (30) found that resin ducts, and especially the radial ducts, were very effective as passageways for the preservative oils. Sapwood was found to treat more easily than heartwood in species having highly developed resin canal systems. In those species without resin ducts, there was little difference. Teesdale believes that the more insoluble resin in the ducts of heartwoods adds to the difficulty of penetrating them. Scarth (22) also found this difference in penetration between heartwood and sapwood, and gave the same explanation.

The ease of penetration of the sapwoods of pines, spruce, and other species seemed to be a property of the tracheids, which, with the resin ducts, rendered the woods very susceptible to treatment. Based on the color line in the wood, Teesdale (30) observed that some sapwood treated like heartwood and some heartwood treated like sapwood, these conditions being possible in the same cross section of the tree. Scarth (22) found bands or belts of different permeabilities which extended across the grain from sapwood into heartwood, along the growth rings tangentially or merely along one or several rings.

Concerning the impregnation of hardwoods, Teesdale and MacLean (31) found the most important structural factor influencing penetration to be the condition of the vessels in the wood, that is, the extent to which they were plugged by tyloses. Next in importance was the relative permeability of wood cells to the preservative oil. It was found that the treatment of the diffuse-porous group of woods was much less uniform than in the ring-porous group.

Microchemical studies of tyloses (enlarged protruding pit membranes of the parenchyma cells adjoining the vessels of hardwoods) have been made by Isenberg (14) in order to determine their structure and composition. Three general types were found in the species studied. The first type had thin walls composed chiefly of lignin; the second type was composed of an outer layer of lignin and a secondary cellulosic layer; and the third type or the oak type had a lignin primary layer, a secondary layer of cellulose, and a tertiary or innermost layer of lignin.

All the workers on penetration mentioned so far (Bailey, Weiss, Teesdale, and MacLean) found little or no penetration either into the wood ray cells or into other parenchyma cells.

One of the more important developments of the last two decades that concerns penetration is the study of pit aspiration or the closing of pit cavity by the adherence of the torus to one of the secondary walls forming the outer boundaries of the bordered pit. Griffin (10) is credited with the first studies made on pit aspiration and its effect on penetration. Actual counts of aspirated and unaspirated pits made on Douglas fir for both the mountain and lowland types and in the green and seasoned condition revealed that mountain Douglas fir had a considerable number of aspirated summerwood tori in the green wood of both heartwood and sapwood. This was not the situation, however, in the lowland specimens. Air-dry mountain Douglas fir had an increased number of aspirated tori in the springwood and summerwood, whereas for the lowland type the tori of the springwood aspirated, but those of the summerwood did not. Oven-drying caused increased aspiration in both types. When the heartwood of lowland Douglas fir was thoroly soaked in alcohol and oven-dried, aspiration did not occur.

Creosoted specimens indicated an inverse relation between penetration and the number of aspirated pits (10, 11). MacLean (20) also reported a large proportion of displaced tori, the springwood having a larger number of aspirated pits than the summerwood. He believed that these factors were partly responsible for the resistance of refractory conifers to penetration. Scarth's experiments on mercury penetration corroborated this.

Phillips (21) investigated the problem quite extensively and found essentially what has already been accredited to the workers mentioned in this connection. He found, in addition, that during the drying of green wood, the number of aspirated pits increased gradually until the fiber saturation point approached when aspiration occurred in almost all the springwood pits. The change was very abrupt, and indicated that the critical point was associated with the loss of the last traces of free water in the cells. Phillips states that the closure of pits may be caused by evaporation of the last drop of water in the pit cavity causing the torus to be drawn gradually toward the pit aperture by the surface tension of the annular meniscus between the pit aperture and the torus. More closure occurred in springwood than in summerwood during the early stages of drying. He believes this is related to the difference in rigidity of the pit membranes and to the size of the pit apertures.

Scarth and Spier (23) have suggested that natural pit closure may result from the release of resin and other colloidal matter into the tracheids when the living cells of the wood die. Their chief basis for this statement was that non-resinous conifers exhibited incomplete pit closure in their heartwood. It is an interesting fact that they were unable to open the pits by extraction of resins with a number of solvents nor by extraction with mild lignin solvents. Phillips also found that soaking the wood did not relieve pit aspiration. Griffin (10) reported that steaming caused no change in the position of the tori. This indicates the resistant nature of aspirated pits to treatment.

Below the fiber saturation point, Phillips (21) found that the tori were in a stable condition since moisture differences below that point had no effect on aspiration. The proportion of unaspirated pits was found to increase with increasing wall thickness while the diameters of the pits in the summerwood remained nearly the same. Phillips offers two ideas on this topic: One is that the secondary wall in itself offers resistance to the forces causing pit aspiration, and the other is that such wall thickening is indicative of a more rigid and stouter pit membrane. Stamm (25) in his electrical conductivity experiments found that the length of the effective capillaries of the pit membrane increased with density within the same species. This would support the latter of the two theories.

From actual count and calculations, Phillips arrived at average values for unaspirated pits per tracheid which ranged from 0.5 to 6.3 for springwood and from 2 to 11 for summerwood in air-dry wood of the five species examined.

There are several statements in the literature concerning the difference in permeability between springwood and summerwood. Scarth (22) found that summerwood was more permeable than springwood in both heartwood and sapwood of seasoned white spruce. Scarth and Spier (23) after subjecting red spruce to higher pressure (100 pounds per square inch), found that in the sapwood the dye had stained the tracheids of the springwood, but not so many in the summerwood. In the heartwood, the reverse was true. Teesdale (30), after working on creosote penetration into seasoned wood, decided that in most species the summerwood was more penetrable than the springwood. This was not true, however, for redwood, yew, and tamarack. MacLean (17) measured the penetration of zinc chloride solution and found, likewise, a better penetration in the summerwood than in the springwood for some woods, but with others it was difficult to determine. Creosote, with most species, also gave the greater penetration in the summerwood.

Buckman (4) found that in the majority of the rings, in the sapwood of freshly creosoted southern yellow pine, the springwood contained more creosote than the summerwood. This was attributed to the greater available space of the springwood. The higher creosote concentration in the summerwood of some rings was accounted for by a greater penetration. The difference in ease of penetration, however, caused the summerwood to absorb relatively more creosote than the springwood only when the total absorption of the ring was low or when conditions of relative available space differed prior to treatment.

The effects of viscosity on the penetration of preserving oils were first studied by Teesdale and MacLean (32), who found no relationship. The fluidity of the liquids was expressed in Engler numbers or relative viscosity instead of in absolute units of viscosity as is done today. Frosch (7) has studied the change in viscosity of creosotes distilled from a single tar and found that the viscosity of the distillate increased with the distillation range. Teesdale and MacLean, however, had used mixtures of different oils, and found no relation between penetration and relative viscosity.

Bateman (3) recalculated Teesdale and MacLean's data expressing the viscosity in centipoises and concluded that very definite relationships existed between viscosity and penetration of preserving oils, and that they could be expressed by mathematical equations. He believed that the free carbon had no effect other than what would be expected from increasing the viscosity. MacLean (17, 18, 19, 20) performed other experiments in an attempt to determine the effect of viscosity, temperature, time of treating period, and pressure. Greater penetration was evidenced, the temperature rises giving the greater increase in penetration for both zinc chloride solution and creosote mixtures.

In order to determine the effect of temperature alone on the ease of penetration of creosote into wood, MacLean (19) maintained the original viscosity of the creosote by adding the necessary amount of a high viscosity creosote to compensate for the effect of the higher temperature on the original creosote, and by adding definite amounts of viscous petroleum oil, and raising temperature until the standard viscosity was reached following which penetration tests were carried on.

From these experiments he decided temperature was only of minor importance as compared with the absolute viscosity. He thought it probable that besides decreasing viscosity the high temperature effect was due to a more rapid heating of the wood which favored treatment in some way.

However, Sutherland, Johnston, and Maass (15, 29) found that temperature above 70° C. caused a permanent increased effect on penetrability. Scarth and Spier (23) boiled red spruce heartwood in water for 12 hours and found that the permeability or the rate of flow was increased from one cubic centimeter to 20 cubic centimeters for the same period of 20 hours under hydrostatic pressure. They believed the increased permeability to be due to increased porosity of the cell wall since no evidence was obtained that the pits had opened.

The experimental findings of Howald (12) concerning viscosity and penetration are very different from the conclusions arrived at by MacLean. Of two oils of approximately the same absolute viscosity, the oil having the slightly higher viscosity gave an average absorption nine times greater than that of the other oil. Matched specimens were used. Thinking that the low penetration might be due to peptized colloids in in the oil, he continued work on the problem and found experimental evidence in support of the hypothesis (13).

Howald was unable to find a true relationship between the surface tension or the interfacial tension of the oil and its penetration qualities. Recently Frosch (8, 9) attempted to correlate surface tension and interfacial tension with the distillation range of creosote distilled from a single coal tar. His results disclosed no apparent correlation in either case.

Johnston and Maass (15) found that penetration into dry wood was initially rapid but was generally about 25-30 per cent of the equilibrium green wood value. On the other hand, Buckman, Schmitz, and Gortner reported that for several woods which they used, seasoning apparently had no pronounced permanent effect on their permeability to water. Bailey (2) reported a better penetration in the green sapwoods of several conifers than in the seasoned sapwoods.

Several groups of workers (5, 15, 29) have investigated the relation between pressure and rate of flow. With some woods the increase in rate of flow is proportional to the pressure applied, and with other woods a disproportionate increase in flow is obtained per unit change of pressure.

Johnston and Maass (15) believe the disproportionate increase in flow with increase of pressure to be caused by stretching of the pit membranes at higher pressures, thus enlarging their openings and increasing permeability. In a later paper, Stamm (27) contends that this is not the case as his data from permeability changes to air of different relative vapor pressures are just the opposite of what they should be if the membranes stretched appreciably. He explained his deviations by the existence of impact turbulence at high velocities of flow.

The comparative permeability of heartwood and sapwood and the comparative permeability in the structural directions has been found for a very few species (15, 29). Sapwood was from 100 to 200 times as permeable as heartwood. The rate of flow in longitudinal direction for sections of more than one fiber length in thickness was approximately one hundred times as great as in the radial or tangential direction for sections of the same thickness. Sutherland, Johnston, and Maass (29) reported that the "observed apparent penetration" radially and tangentially through heartwood was less than nine per cent of the longtitudinal flow, while in sapwood the value was only two per cent.

APPARATUS AND METHODS

The data on the permeability of seasoned and unseasoned sapwoods and heartwoods for the various species of wood were obtained with the use of an apparatus similar, in its essential features, to that used by Buckman, Schmitz, and Gortner (5) in their studies on the movement of liquids in woods. A few improvements were made on the brass type of apparatus such as increased tank capacity, larger size generally, the use of valves, and better fitted and aligned discs. The most important change was probably the feature of having four sets of discs connected in tandem on the supply line, thus enabling four sections of wood to be run simultaneously. The brass apparatus was used for the determination of the rate of flow of benzene through wood, and, in some cases, for water also.

The apparatus for use with inorganic salt solutions and water was constructed of glass tubing, rubber pressure tubing, and rubber stoppers between two steel plates, the latter connected with bolts which screwed through the lower plate. The openings in the rubber stoppers were matched for each pair and drilled to a uniform size. Between these four pairs of rubber discs the sections were clamped tightly by drawing the plates together with the bolts. Glass tubing and heavy rubber tubing were used to construct the feed lines. A glass container was used as the supply tank in this apparatus.

Pressure was supplied from a tank of compressed air equipped with a reduction valve and a gauge of 50 pounds per square inch maximum capacity. For low pressures, a mercury manometer was employed. The liquid, after penetrating the sections, flowed into a burette. The time necessary for a given volume to flow through the section was timed with a stop watch.

The initial rate of flow represents the flow in cubic centimeters per minute shortly after the pressure was applied. When the liquid penetrated very rapidly, the flow was timed after a lapse of only a few seconds, but when the rate of flow was very slow, more time was required to adjust the system and eliminate certain difficulties. In either case, it was felt that the error from this source was usually negligible.

The area exposed to the path of flow was 1.47 square centimeters for the brass apparatus and approximately the same for the glass-rubber apparatus. A slightly smaller area, however, had no apparent effect on the rate of flow as measurements of the exposed area on the surface of the sections after a determination showed about an equal effective area in both cases.

Two pressures were used in the determinations of the permeability of the woods excluding the springwood and the summerwood experiments. A pressure of 5 centimeters of mercury was used for those woods which were permeated by that pressure and a pressure of 20 pounds per square inch was used for those woods which were resistant to penetration.

In studying the permeability of springwood and summerwood, the section was exposed to the opening in the lower rubber disc as described above, but the area through which flow was actually measured was limited on the upper side to the area of a copper tube, with sharpened edge, four millimeters inside diameter, which was compressed until the sides were parallel. This tube was inserted into a tight-fitting rubber stopper on which the steel plate was drawn down. By careful placement on either the springwood or the summerwood of fast-growth wood, the permeability of the two portions of the annual ring could be measured. Altho there were a number of difficulties encountered which need not be discussed here, it is believed the readings of this experiment possessed a fair degree of accuracy.

No attempt was made to control the temperature at which the observations were made. Fluctuations of several degrees in the temperature of the room occurred, but had no noticeable influence on the results.

The sixteen species of wood used in the work were:

Jack pine	(*Pinus banksiana* Lambert)
Loblolly pine	(*Pinus taeda* Linnaeus)
Longleaf pine	(*Pinus palustris* Miller)
Norway pine	(*Pinus resinosa* Solander)
Shortleaf pine	(*Pinus echinata* Miller)
Slash pine	(*Pinus caribaea* Morelet)
Eastern larch or tamarack	(*Larix laricina* [Du Roi] Kock)
White spruce	(*Picea glauca* [Moench] Voss)
Black spruce	(*Picea mariana* [Miller] Britton, Sterns and Poggenberg)
Eastern hemlock	(*Tsuga canadensis* [Linnaeus] Carriere)
Western hemlock	(*Tsuga heterophylla* [Rafinesque] Sargent)
Coast Douglas fir	(*Pseudotsuga taxifolia* [LaMarck] Britton)
Balsam fir	(*Abies balsamea* [Linnaeus] Miller)
Northern white cedar	(*Thuja occidentalis* Linnaeus)
Paper birch	(*Betula papyrifera* Marshall)
White oak	(*Quercus alba* Linnaeus)

The specific names are those given by Sudworth (28).

All sections were sawed from logs of freshly felled trees whose histories were known. All sections used were transverse sections one centimeter in thickness. Usually several series of sections were cut from the same log, each series generally extending two to three feet along the long axis, from both the heartwood and the sapwood when each was present in sufficient quantity. The sections of only one series, if the number was great enough, were used in the experiments. Alternate sections of each series were divided into two groups. One group received a seasoning treatment, whereas the other group was placed in jars, covered with distilled water, and set in the cold room until ready for use.

With most woods, however, the determinations on unseasoned wood were made almost immediately after the sections were sawed, care being taken to prevent loss of moisture. Those that were kept in distilled water for a day or two did not appear to have altered in permeability according to some test determinations.

Sections to be seasoned were placed in a cabinet equipped with a fan, heating elements, two type C Bahnson humidifiers, wet and dry bulb thermometers, and automatic controls for maintaining constant temperature and humidity. A uniform temperature of 30° C. was used in drying. The relative humidity of the air in the cabinet was lowered gradually as the sections reached equilibrium with the existing conditions.

Unfortunately, all the woods were not seasoned to the same degree of dryness. The moisture content of each kind of wood after seasoning is given in the following tabulation:

Moisture Content, on Dry Weight Basis, of the Sections of the Various Woods after Seasoning

Species of wood	Sapwood	Heartwood
	Per cent moisture	Per cent moisture
Jack pine	12.70	12.07
Loblolly pine	9.48	....
Longleaf pine	9.90	9.60
Norway pine	12.49	11.70
Shortleaf pine	9.87	....
Slash pine	9.56	....
Eastern larch	12.00	12.32
White spruce	6.30	6.02
Black spruce	....	6.41
Eastern hemlock	12.36	12.07
Western hemlock	12.08	11.70
Coast Douglas fir	11.00	11.40
Balsam fir	6.28	5.70
Northern white cedar	11.85	11.43
Paper birch	5.30	5.85
White oak	13.40	11.50

Before the seasoned and unseasoned sections were tested for their permeability, they were evacuated by means of a vacuum desiccator and a water vacuum pump for a total time of 30 minutes, distributed in three periods of approximately 10 minutes each. It was found necessary to pre-humidify the seasoned sections prior to placement in water, otherwise the exterior of the section would swell so rapidly that the dry interior would check or honeycomb.

This process was necessary only when water or a salt solution was to be used. Since benzene causes practically no swelling of wood, the sections could be submerged in that liquid and evacuated. The maximum vacuum drawn over water was about 28.5 inches of mercury; over benzene it was equal to the vapor pressure at the temperature of the liquid.

Three liquids were used in this work: Distilled water, 3 per cent zinc chloride solution (3 grams of chemically pure zinc chloride in 100 cubic centimeters of solution), and commercial benzene. The benzene was obtained from two different sources. One lot was not filtered before using. In the second lot, there evidently were materials in the benzene which decreased the rate of flow with time much more than should be expected. This benzene was filtered through a thick wad of absorbent cotton with the aid of a vacuum. The woods with which the first lot of commercial benzene was used include the sapwoods of loblolly pine, shortleaf pine, slash pine, white spruce, balsam fir, and paper birch, and the heartwoods of longleaf pine, black spruce, white spruce, and balsam fir. The remainder of the woods were tested with the second and filtered lot of benzene.

Since equilibrium is reached only after several hours in most cases, an arbitrary time limit of 2.75 hours was used. After this period of time the flow was definitely nearing the equilibrium state as indicated by the flattening of the rate of flow curves with time, and afforded a means of comparing the various woods. Occasionally a wood was found which was so permeable that the very rapid rate made it impractical to continue the run for the usual time as the supply tank was not of sufficient capacity. In some cases it was found desirable to discontinue one or two of the units after a time and proceed with the units which had shown themselves as being representative or an average of the group. By this selection, it was felt that the results still possessed good reliability. In a few cases, extrapolated values are given. This was done only when conditions enabled one or two additional values to be found by extrapolation which were thought to be fairly accurate. When differences in rate of flow between the preceding time intervals were not small, or when only a few readings were available, extrapolation was not thought to be justifiable.

In the vast majority of the determinations, however, four sections were used and the values reported represent an average of their individual values.

EXPERIMENTAL RESULTS

Effect of Continuous Flow

In the permeability experiments on the heartwood and sapwood of the species studied, a decrease in rate of flow with time was found in practically all cases (Tables 1-6). The effect of continuous flow is most noticeable when water is streamed through the sections. Table 1 gives the rate of flow of water through the more permeable woods, chiefly sapwoods, for which a pressure of five centimeters of mercury was used. In both seasoned and unseasoned woods the decrease in flow was about the same. The values for the pine sapwoods show that the rate of flow decreased only to about one-half after a continuous flow of 2.75 hours. In most woods, however, the drop in flow is much greater, 50 to 90 per cent of the initial values. The effect of continuous flow of water on birch sapwood was more marked than for other sapwoods. For seasoned and unseasoned birch sapwood the final rate of flow was less than 10 per cent of the initial value.

The same situation prevails with the woods for which a pressure of 20 pounds per square inch was used, which includes all the heartwoods and also seasoned white spruce sapwood, except when benzene was used. In this group the decrease in rate of flow with time was usually greater than for sapwoods. For most of the woods, the final rate was considerably less than one-third of the initial rate of flow. Eastern hemlock and balsam fir heartwoods both had final rates of less than 10 per cent of the initial rates for the unseasoned condition and six and five per cent, respectively, when seasoned (Table 2). With a few woods the usual decline in rate of flow of water was preceded, for a short time, by an increased rate. These woods were unseasoned white oak sapwood and seasoned northern white cedar sapwood in Table 1; unseasoned Norway pine heartwood, seasoned white spruce sapwood, and seasoned jack pine heartwood of Table 2.

Table 1. Rate of Longitudinal Flow of Water through Unseasoned and Seasoned Sections of Wood One Centimeter Thick

(Pressure, 5 centimeters mercury)

Kind of wood	Unseasoned wood				Seasoned wood			
	Cubic centimeters per minute after				Cubic centimeters per minute after			
	0 hours	0.5 hours	1.5 hours	2.75 hours	0 hours	0.5 hours	1.5 hours	2.75 hours
Jack pine sapwood	17.4	15.0	12.0	9.51	7.65	3.89	2.39	1.65
Loblolly pine sapwood	3.61	3.32	2.75	2.20	5.82	4.22	2.55	1.76
Longleaf pine sapwood	6.27	4.61	3.46	2.55	11.0	7.04	4.43	3.06
Norway pine sapwood	23.9	22.3	14.9	9.16	6.76	3.50	2.01	1.22
Shortleaf pine sapwood	13.3	8.30	5.98	4.46	7.26	5.89	4.39	3.19
Slash pine sapwood	14.8	11.6	8.80	6.17	19.2	14.7	10.7	8.02
Eastern larch sapwood	16.4	9.84	5.81	4.21	3.60	2.49	1.77	1.30
White spruce sapwood	33.4	22.3	14.7	10.1	0.024	....	....	....
Eastern hemlock sapwood	20.0	6.69	4.50	2.95	4.68	2.16	1.38	0.996
Western hemlock sapwood	43.9	21.6	11.9	7.94	17.6	9.72	5.77	3.76
Western hemlock heartwood	0.353	0.298	0.221	0.17	0.825	0.458	0.292	0.205
Douglas fir sapwood	47.1	24.2	13.3	8.35	44.7	32.3	23.3	17.1
Douglas fir heartwood	0.118	0.067	0.048	0.032	0.078	0.049	0.042	0.033
Balsam fir sapwood	10.4	10.18	5.53	3.15	8.58	5.48	3.82	2.69
N. white cedar sapwood	11.8	7.31	4.10	2.71	0.558	0.710	0.607	0.517
Paper birch sapwood	50.0	8.93	4.91	3.87	56.0	15.41	7.67	5.32
Paper birch heartwood	6.0	2.50	1.44	0.98	8.36	3.93	2.69	2.45
White oak sapwood	0.301	0.708	0.48	0.372	0.662	0.538	0.483	0.300

With 3 per cent zinc chloride solution, the decline in permeability with continued flow was much less. Table 3 shows that two-thirds of the seasoned and unseasoned woods of the low-pressure groups had a final rate of 50 per cent or more of the initial rate of flow. In the high-pressure group, approximately one-half of them maintained such a high percentage of the initial flow (Table 4). As to the peculiar increase in rate of flow prior to the usual decrease, there were more instances of this with the seasoned sections of the low-pressure group (Table 3) than when water was used (Table 1). For the unseasoned sections and for woods of the high-pressure groups, Tables 3 and 4 show that only a very few woods possessed this peculiarity with the salt solution.

Table 2. Rate of Longitudinal Flow of Water through Unseasoned and Seasoned Sections of Wood One Centimeter Thick

(Pressure, 20 pounds per square inch)

Kind of wood	Unseasoned wood				Seasoned wood			
	Cubic centimeters per minute after				Cubic centimeters per minute after			
	0 hours	0.5 hours	1.5 hours	2.75 hours	0 hours	0.5 hours	1.5 hours	2.75 hours
Jack pine heartwood	0.063	0.054	0.048	0.034	0.008	0.009	0.008	0.007†
Longleaf pine heartwood	0.331	0.180	0.118	0.088	0.403	0.320	0.210	0.142
Norway pine heartwood	0.405	0.420	0.303	0.233	0.896	0.678	0.450	0.309
Eastern larch heartwood	0.766	0.469	0.273	0.191	1.62	0.680	0.361	0.244
Black spruce heartwood	0.090	0.056	0.036	0.022	0.190	.085	0.050	0.031
White spruce heartwood	0.814	0.578	0.389	0.261	0.882	0.482	0.258	0.160
White spruce sapwood	....	....	....	....	1.30	1.52	1.54	1.52
Eastern hemlock heartwood	3.76	1.26	0.567	0.324	3.59	0.803	0.360	0.215
Western hemlock heartwood	7.48	3.12	....	0.95	6.09	2.74	1.34	0.932*
Douglas fir heartwood	2.16	1.14	0.782	0.566	1.92	1.12	0.705	0.524
Balsam fir heartwood	4.98	1.88	1.02	0.470	10.5	1.95	0.814	0.477
N. white cedar heartwood	0.706	0.355	0.208	0.140	0.857	0.421	0.253	0.176
White oak heartwood	0.208	0.107	0.061	0.043	0.249	0.132	0.069	0.042

* Extrapolated value.

† In this experiment a pressure of 40 pounds per square inch was used. The initial value for a pressure of 20 pounds per square inch was .007 cubic centimeters per minute.

Table 3. Rate of Longitudinal Flow of Three Per Cent Zinc Chloride Solution through Unseasoned and Seasoned Sections of Wood One Centimeter Thick

(Pressure, 5 centimeters mercury)

Kind of wood	Unseasoned wood				Seasoned wood			
	Cubic centimeters per minute after				Cubic centimeters per minute after			
	0 hours	0.5 hours	1.5 hours	2.75 hours	0 hours	0.5 hours	1.5 hours	2.75 hours
Jack pine sapwood	16.8	12.8	10.4	9.03	5.82	5.43	4.79	4.12
Loblolly pine sapwood	8.63	6.13	4.61	3.98	6.02	3.70	3.06	2.84
Longleaf pine sapwood	9.60	9.50	9.49	9.14	15.2	14.8	12.4	11.5
Norway pine sapwood	25.2	20.5	16.1	13.6	5.37	6.71	6.21	5.59
Shortleaf pine sapwood	9.0	6.23	4.83	4.32	8.52	8.80	7.65	6.22
Slash pine sapwood	13.7	13.16	11.58	10.58	17.70	18.50	17.90	15.40
Eastern larch sapwood	17.62	15.35	12.12	10.54	3.67	3.42	2.99	2.75
White spruce sapwood	49.3	43.1	38.4	27.4*	....	....	....	....
Eastern hemlock sapwood	21.9	14.9	11.1	8.79	4.66	3.55	2.59	2.13
Western hemlock sapwood	28.8	24.6	22.5	18.1	29.4	23.5	19.7	16.0*
Western hemlock heartwood	0.315	0.349	0.411	0.388	1.173	1.178	0.996	0.871
Douglas fir sapwood	34.2	30.9	27.6	23.5	46.5	37.0	24.1	17.6
Douglas fir heartwood	0.115	0.098	0.085	0.077	0.212	0.223	0.201	0.183
Douglas fir sapwood	7.20	6.45	5.95	5.73	7.97	4.21	3.66	3.34
N. white cedar sapwood	15.50	12.8	10.77	9.33	0.708	1.000	1.045	1.025
Paper birch sapwood	49.0	45.7	....	....	62.8	49.5	....	....
Paper birch heartwood	7.13	5.20	4.45	3.34	20.5	16.4	....	....
White oak sapwood	0.097	0.344	0.769	0.697	0.707	0.732	0.739	0.699

* Extrapolated value.

Table 4. Rate of Longitudinal Flow of Three Per Cent Zinc Chloride Solution through Unseasoned and Seasoned Sections of Wood One Centimeter Thick

(Pressure, 20 pounds per square inch)

Kind of wood	Unseasoned wood				Seasoned wood			
	Cubic centimeters per minute after				Cubic centimeters per minute after			
	0 hours	0.5 hours	1.5 hours	2.75 hours	0 hours	0.5 hours	1.5 hours	2.75 hours
Jack pine heartwood	0.012	0.015	0.020	0.019	0.021	0.023	0.021	0.02
Longleaf pine heartwood	0.241	0.185	0.146	0.120	0.459	0.421	0.349	0.280
Norway pine heartwood	0.742	0.722	0.633	0.568	0.871	0.784	0.671	0.587
Eastern larch heartwood	1.08	1.17	0.956	0.793	2.37	1.49	1.108	9.17
Black spruce heartwood	0.362	0.313	0.264	0.232	0.489	0.429	0.386	0.347
White spruce heartwood	1.09	0.858	0.454	0.338	0.846	0.695	0.579	0.537
White spruce sapwood	....	....	....	....	1.066	0.984	0.973	0.948
Eastern hemlock heartwood	6.06	3.45	2.29	1.79	8.53	3.33	2.19	1.60
Western hemlock heartwood	8.20	5.57	4.49	3.51*	18.1	9.60	6.89	4.20*
Douglas fir heartwood	3.03	2.49	1.76	1.45	4.27	2.86	2.12	1.82*
Balsam fir heartwood	10.5	4.47	2.66	1.86	14.55	7.18	5.27	4.12
N. white cedar heartwood	1.16	1.22	0.952	0.785	1.058	1.047	0.847	0.756
White oak heartwood	0.234	0.112	0.089	0.076	0.221	0.123	0.094	0.081

*Extrapolated value.

Benzene, like zinc chloride solution, was reduced in rate of flow to a relatively small extent when it flowed continuously through the seasoned sections of the low-pressure group. Table 5 shows that in almost all of the determinations in the low-pressure group the final rate was equal to or greater than one-half of the initial rate of flow. In many cases the decrease was only 10 or 20 per cent. For the woods of the high-pressure group (Table 6), the decrease in flow from the beginning of the run to the end of the run was somewhat greater than with zinc chloride solution, but was not markedly so. (This does not mean that the actual rate of flow was less, for, as a matter of fact, it was greater. This can be seen at a glance from Tables 5 and 6 where the initial and final rates are compared for the three liquids.) Only about two-thirds of the heartwoods had a final rate of flow which was approximately two-fifths or more of their initial rate. Balsam fir heartwood was affected in this respect more than the others.

Heartwood and Sapwood Permeability

Data on the comparative permeability of heartwood and sapwood were obtained for only western hemlock, coast Douglas fir, and paper birch. Since one does not know the rate of flow-pressure relationship for the sapwood and heartwood of each species, it is not legitimate to make comparisons by computing the number of times one pressure is greater than the other.

It was found that these three heartwoods, however, were appreciably permeable at the low pressure and could thus be compared directly at the same pressure used for the corresponding sapwoods. The heartwoods of the other species were impermeable to water at a pressure of 5 centimeters of mercury (eastern hemlock and balsam fir heartwoods were not tested). If flow occurred, it was so slow over a period of several minutes that it could not be detected by the methods used.

The smallest difference in rate of flow between heartwood and sapwood existed in paper birch. Tables 1 and 3 show that the permeability of the unseasoned sapwood to water was about four times that of the heartwood and to zinc chloride solution about ten times, based on final rates. The seasoned sapwood (Tables 1, 3, and 5) was about twice as permeable as the heartwood to water, seven times as permeable to benzene, and less than three times as permeable to zinc chloride solution as the heartwood. Briefly stated, paper birch sapwood was from two to ten times as permeable as the heartwood, depending on the treatment and the liquid used. This small difference is explained by the partial plugging of the vessels in the heartwood by tyloses and infiltration substances.

Western hemlock was in an intermediate position. In comparing the final rates of flow, Tables 1 and 3 show that the green sapwood was about 46 times more permeable than the heartwood to both water and zinc chloride solution. Tables 1, 3, and 5 show that the seasoned sapwood permitted a rate of flow of benzene 11 times greater than the seasoned heartwood, and 18 times greater with both zinc chloride and water. Coast Douglas fir gave a rather wide range of results. The values with unseasoned sapwood were about 260 and 300 times the values with heartwood for water and zinc chloride solutions, respectively. With the seasoned sapwood the values were 80, 96, and 518 times the heartwood values for benzene, zinc chloride solution, and water, in the order named.

It is not desired to imply that these comparisons represent the true values; they are merely the values of the experiment and undoubtedly would show considerable variation if different samples were used.

Effect of Seasoning on Permeability

The effect of seasoning on wood was studied from the standpoint of its influence on permeability. For purposes of comparison, the final rate of flow, after 2.75 hours of continuous flow of the liquid, is used here as indicating the changes in permeability caused by the seasoning treatment. From the data in Tables 1 to 4, inclusive, there are two possible series of comparisons, one in which water was used on seasoned and unseasoned wood, and the other in which zinc chloride solution was used.

The first observation that is made is that seasoning apparently affected various species to a different extent. In some cases, no change resulted from seasoning, while in others permeability was altered to a considerable extent. The change in permeability with seasoning of the more permeable woods to water is shown in the data for seasoned and unseasoned wood of Table 1. The greatest change was with white spruce sapwood which in the seasoned state was only one one-thousandth as permeable as paired green sections. Seasoned sapwood sections of jack pine, Norway pine, and northern white cedar were less than one-fifth as permeable as matched unseasoned sections. Seasoning of coast Douglas fir sapwood and paper birch heartwood increased their permeability to more than twice that of the unseasoned sections. In the other woods, the change with seasoning, in increasing or decreasing permeability, was either not as great or was negligible.

When a comparison is made of the permeability of seasoned and unseasoned woods in the more permeable group to three per cent zinc chloride solution, the results are somewhat different for several species. Table 3 shows that seasoned northern white cedar sapwood was about one-tenth as permeable as matched unseasoned sections. Some of the approximate fractional values of the permeability of seasoned wood compared with unseasoned material were: eastern hemlock and eastern larch sapwoods, one-fourth; loblolly pine and coast Douglas fir sapwoods, three-fourths; western hemlock sapwood and white oak sapwood remained essentially unchanged. Comparisons of paper birch sapwood and heartwood are not so well based, because the duration of three out of the four determinations was only one hour. However, the heartwood gave indications of maintaining a permeability several times greater than the unseasoned sections, which was also the case when water was used. The sapwood was probably not greatly changed. With zinc chloride solution, as with water, a few woods became more permeable after seasoning. Seasoned shortleaf pine and slash pine sapwoods were one and one-half times as permeable, and coast Douglas fir heartwood was more than twice as permeable as the unseasoned sections.

The permeability of the resistant woods to water was not altered as markedly by seasoning as was the case for some woods in the permeable group. The interesting feature of this group, chiefly heartwoods, (tested at 20 pounds per square inch), is that there were fewer cases of decreased permeability and more instances of a slightly increased final rate of flow with seasoning. Furthermore, the decrease, when it existed, was less than 50 per cent of the value for the unseasoned sections.

The results of the determinations with water are presented in Table 2. Seasoned white spruce and eastern hemlock heartwoods were diminished in permeability to two-thirds of the unseasoned values. Norway pine and black spruce heartwood increased in permeability with seasoning about one and one-third times, and longleaf heartwoods about one and two-thirds times. Other heartwoods were apparently unchanged by seasoning.

When zinc chloride solution was used, the ratio of the permeabilities of seasoned to unseasoned heartwoods was somewhat greater than when water was used. Table 4 shows that eastern hemlock, jack pine, Norway pine, northern white cedar, and white oak heartwoods were practically unaffected in their final rate of flow by seasoning. The other woods when seasoned were more permeable to the salt solution, but to a varying extent. Black spruce and white spruce heartwoods increased in permeability by one-half, while balsam fir and longleaf pine heartwoods became more than twice as permeable with the seasoning treatment. In this regard, the results with white spruce and balsam fir heartwoods do not correspond to those obtained with distilled water.

White spruce sapwood, seasoned and unseasoned, could not be compared because in the green condition this wood was so permeable that it was run in the low-pressure group. Obviously, the effect of seasoning was very profound on this wood.

Effect of Various Liquids

The extent to which different liquids affect the permeability of wood was measured for both the heartwood and sapwood of the species in the seasoned and unseasoned conditions. Obviously the green or unseasoned condition could not be used with benzene to measure the effect of liquids alone since the presence of free water would introduce surface effects peculiar to systems of immiscible liquids. Hence, only seasoned wood was used with commercial benzene.

The initial rate and the rate of flow after 2.75 hours of continuous flow are tabulated in Tables 5 and 6. The former shows that for zinc chloride solution, the initial rate of flow may or may not be greater, for the various sapwoods, than the initial rate of flow of water. The final rate of flow, however, was in all cases greater than the final rate for water, the difference depending upon the kind of wood.

With benzene, the initial rate of flow was several times that of water, differing in this respect from the determinations using zinc chloride solution. The final rate of benzene flow was from 2 to 11 times the final rate of flow of water for the corresponding woods. Coast Douglas fir heartwood permitted benzene to flow 23 times as rapidly as water at the same low pressure. If the final rate of flow of water through white spruce sapwood were available, the ratio of benzene to water permeability would be much greater than the above value.

In the resistant group, an inspection of Table 6 shows that the initial rate of flow of zinc chloride solution through the seasoned sections was less than the initial rate for water in some cases; in others it was about the same, and in the remainder it was from one to three times as great. The latter condition existed in less than one-half of the runs. With benzene the initial rate of flow was 1 to 20 times the initial rate for water for the corresponding woods, or about 1 to 11 times the initial rate for zinc chloride solution. The final rate for zinc chloride solution ranged from less than 1 to 9 times the final value of water, depending upon the kind of wood. With benzene the final values of flow were from 1 to 36 times that of water; all but two, however, were from 1 to 13 times as great. Compared with the values for zinc chloride solution, the final rate of flow of benzene was from two-thirds to 7 times more for the same woods.

Table 5. A Comparison of the Rates of Flow of Water, Zinc Chloride Solution, and Benzene through Seasoned Sections of Wood One Centimeter Thick

(Pressure, 5 centimeters mercury)

Kind of wood	Initial rate of flow in cubic centimeters per minute			Rate of flow after 2.75 hours in cubic centimeters per minute		
	Water	Zinc chloride	Benzene	Water	Zinc chloride	Benzene
Jack pine sapwood	7.65	5.82	19.7	1.65	4.12	16.5
Loblolly pine sapwood	5.82	6.02	18.6	1.76	2.84	9.26
Longleaf pine sapwood	11.0	15.2	37.7	3.06	11.5	30.7
Norway pine sapwood	6.76	5.37	20.2	1.22	5.59	12.2*
Shortleaf pine sapwood	7.26	8.52	24.1	3.19	6.22	16.2
Slash pine sapwood	19.2	17.7	45.5	8.02	15.4	....
Eastern larch sapwood	3.6	3.67	6.87	1.30	2.75	6.17
White spruce sapwood	0.024	....	1.96	....	....	2.73
Eastern hemlock sapwood	4.68	4.66	14.2	0.996	2.13	9.53*
Western hemlock sapwood	17.6	29.4	46.0	3.76	16.0*	24.1*
Western hemlock heartwood	0.825	1.173	4.16	0.205	0.871	2.38
Douglas fir sapwood	44.7	46.5	92.2	17.1	17.6	58.2*
Douglas fir heartwood	0.078	0.212	0.926	0.033	0.183	0.758
Balsam fir sapwood	8.58	7.97	12.75	2.69	3.34	6.00
N. white cedar sapwood	0.558	0.708	1.89	0.517	1.025	1.53
Paper birch sapwood	56.0	62.8	165.0	5.32	....	....
Paper birch heartwood	8.36	20.5	63.4	2.45	....	14.5
White oak sapwood	0.662	0.707	1.78	0.300	0.699	1.09

* Extrapolated value.

For further information on the effect of different liquids, the results of water and zinc chloride solution determinations on unseasoned wood may be compared. Comparing Table 1 with Table 3 it is found that the initial rate of flow of zinc chloride solution was but slightly higher, on the average, than the initial rate of water. The final rate of flow of the salt solution through the permeable unseasoned woods, however, was not as greatly different from that of water as was the case with the seasoned sections.

Altho there were two or three cases in which the difference was small, in the remainder of the determinations the final rate of flow of the salt solution was from 2 to 4 times the final rate of flow for water.

In the group of unseasoned heartwoods, Table 4 when compared with Table 2 shows that the initial rate of flow of zinc chloride solution through the sections was, on the average, from 1 to 2 times the initial rate of water.

The final rate of flow of the salt solution was from 1 to 10 times the final value for water for the matched sections, the average being about 4 times.

Table 6. A Comparison of the Rates of Flow of Water, Zinc Chloride Solution, and Benzene through Seasoned Sections of Wood One Centimeter Thick

(Pressure, 20 pounds per square inch)

Kind of wood	Initial rate of flow in cubic centimeters per minute			Rate of flow after 2.75 hours in cubic centimeters per minute		
	Water	Zinc chloride	Benzene	Water	Zinc chloride	Benzene
Jack pine heartwood	0.008	0.021	0.161	0.007	0.02	0.136
Longleaf pine heartwood	0.403	0.459	1.19	0.142	0.280	1.00
Norway pine heartwood	0.896	0.871	10.9	0.309	0.587	4.24
Eastern larch heartwood	1.62	2.37	5.44	0.244	0.917	2.57
Black spruce heartwood	0.196	0.489	1.12	0.031	0.347	0.419
White spruce heartwood	0.882	0.846	0.657	0.160	0.537	0.417
White spruce sapwood	1.30	1.066	....	1.52	0.948	....
Eastern hemlock heartwood	3.59	8.53	32.4	0.215	1.60	7.91
Western hemlock heartwood	6.09	18.1	55.8	0.932*	4.2*	....
Douglas fir heartwood	1.92	4.27	17.4	0.524	1.82*	5.58*
Balsam fir heartwood	10.5	14.55	21.15	0.477	4.12	2.86*
N. white cedar heartwood	0.857	1.058	0.738	0.176	0.756	0.401
White oak heartwood	0.249	0.221	1.72	0.042	0.081	0.390*

* Extrapolated value.

Briefly stated, the initial flow of zinc chloride solution through sapwood was, on the average, very little more than the initial rate of flow for water. With heartwood, the increased initial rate of flow was generally fairly definite. The final rate of flow of the salt solution was, by and large, considerably in excess of the final rate for water for all the woods, both for the seasoned and unseasoned sections. With benzene, on the other hand, the initial rate was several times that of water, and the difference between the final rates of flow of the two liquids through matched seasoned sections was even greater.

Permeability of the Various Woods

As one would expect, the various woods differed in their permeability to a given liquid. It has already been pointed out that seasoning affected some woods more than others; consequently, the list of the woods in the order of their permeability would differ depending upon whether one is speaking of seasoned or unseasoned wood.

The data for permeability of the unseasoned, less resistant woods to water are presented in Table 1. A classification of the various woods based on their decreasing final rates of flow is as follows: white spruce, jack pine, Norway pine, coast Douglas fir, western hemlock, slash pine, shortleaf pine, eastern larch, paper birch, balsam fir, eastern hemlock, northern white cedar, longleaf pine and loblolly pine sapwoods, paper birch heartwood, white oak sapwood, western hemlock, and coast Douglas fir heartwoods. Expressed in cubic centimeters per minute, the range in permeability was from 10.1 to 0.032 cubic centimeters per minute in the order listed. If one considers only the coniferous sapwood, the extreme final rates of flow were 10.1 and 2.2 cubic centimeters per minute, and represent the flow through white spruce sapwood and loblolly pine sapwood, respectively.

When the same woods are listed in the order of decreasing permeability to zinc chloride solution (taken from the final rates of flow as given in Table 3), it is found that the order is slightly but not seriously different.

The order of permeability of the seasoned, more permeable woods (Tables 1 or 5) is somewhat different from that of unseasoned sapwood. The sapwoods most permeable to water were coast Douglas fir, slash pine, paper birch, western hemlock, shortleaf pine, and longleaf pine; followed by balsam fir, paper birch heartwood, loblolly pine, and jack pine; eastern larch, Norway pine, northern white cedar, white oak sapwoods, western hemlock and Douglas fir heartwoods, and white spruce sapwood. Seasoned white spruce sapwood, because of its great imperviousness, should really be in a class by itself when water or aqueous solutions are used.

With zinc chloride solution, the order was nearly the same except that the members of the intermediate group in particular were in different relative positions (from Table 3).

With commercial benzene, a number of species are shifted when compared to the orders for water and zinc chloride solution. A comparison of the specific permeabilities can be made from the data of Table 5.

It is noted that sapwoods such as those of coast Douglas fir, western hemlock, eastern larch, and white oak retain their same relative position under practically all conditions. This is due to their greater differences from the average permeability in the case of coast Douglas fir and white oak.and to the fact that they normally lie near the average value as with eastern larch.

The unseasoned heartwoods may be grouped, on the basis of their permeability to water at 20 pounds (Table 2), as follows: The most permeable woods were western hemlock, coast Douglas fir, balsam fir, and eastern hemlock; the intermediate group consisted of white spruce, Norway pine, eastern larch, northern white cedar; and the least permeable were longleaf pine, white oak, black spruce, and jack pine. Using zinc chloride (Table 4), the results gave the same grouping but with somewhat different order within each group, which is probably not significant. Paper birch heartwood under all conditions was of the same order of permeability as the sapwoods.

With seasoned heartwoods, the orders were not greatly different (Table 6). With water, the results obtained placed western hemlock, coast Douglas fir, balsam fir, and Norway pine in the most permeable group; eastern larch, eastern hemlock, northern white cedar, white spruce, and longleaf pine were intermediate; and white oak, black spruce, and jack pine were the least permeable. Using zinc chloride solution, the most permeable woods were western hemlock, balsam fir, coast

Douglas fir, and eastern hemlock; those intermediate were eastern larch, northern white cedar, Norway pine, and white spruce; and those least permeable were black spruce, longleaf pine, white oak, and jack pine. With commercial benzene, Group 1 consisted of western hemlock, eastern hemlock, coast Douglas fir, and Norway pine; Group 2, or the intermediate group, consisted of balsam fir, eastern larch, and longleaf pine; and Group 3 included black spruce, white spruce, northern white cedar, white oak, and jack pine.

It is noticed that the order for members of the heartwoods remains essentially the same for the several liquids and for the seasoned and unseasoned conditions.

In the above presentation of the comparative permeability of woods, the kinds of woods are listed in groups and also in the actual order which represents the experimental results. Since the errors of small sampling may be greater in some cases than the difference between the experimental results for woods of nearly the same permeability, it is best to consider these orders as flexible and approximate classifications which do not represent a gradual and fixed gradation of the permeabilities of the species.

Permeability of Springwood and Summerwood

Sections from the sapwood of two species of wood, slash pine and loblolly pine, were subjected to springwood and summerwood permeability tests in the manner previously described. The sample logs were cut from rapid growth stock and contained no heartwood. Four to six sections of each species were used in both the seasoned and unseasoned woods, (the latter had been stored in distilled water in the cold room for four months). Two to seven measurements were made at different places on different annual rings of the section, for both the springwood and the summerwood.

Table 7. Rate of Longitudinal Flow of Water through Springwood and Summerwood of Seasoned and Unseasoned Southern Pine

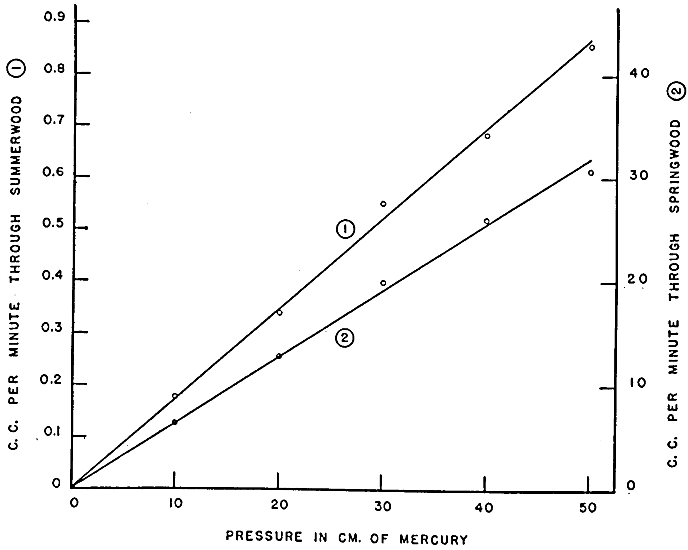
(Pressure, 10 centimeters mercury)

Kind of wood	Initial rate of flow in cubic centimeters per minute			
	Springwood		Summerwood	
	Unseasoned	Seasoned	Unseasoned	Seasoned
Slash pine sapwood	5.37	5.83	0.165	0.204
Loblolly pine sapwood	4.8	2.95	0.584	0.368

In this experiment only readings of the initial rate of flow were taken and are here used as the basis of comparison. Table 7 gives the data on the initial rate of flow of water through the springwood and the summerwood of the seasoned and unseasoned sections of the sapwoods of the two species of wood. The unseasoned springwood of slash pine sapwood was 33 times more permeable than the unseasoned summerwood. In seasoned sections, the springwood was 29 times more permeable to water than the summerwood. A determination made on a portion of seasoned slash pine summerwood free from resin canals gave no significant difference in rate of flow from that of other portions of summerwood possessing resin canals.

Loblolly pine sapwood did not exhibit such a large difference in rate of flow between the springwood and the summerwood. In both the seasoned and unseasoned sections, the springwood was eight times more permeable than the summerwood. This also indicates that seasoning had little effect on the permeability of either the springwood or the summerwood. Observations during these tests indicated that those regions having numerous resin canals were less permeable, on the average, than areas relatively free from resin canals.

FIG. 1. CHANGES IN RATE OF FLOW WITH PRESSURE IN SPRINGWOOD AND SUMMERWOOD OF SEASONED SECTIONS OF SLASH PINE ONE CM. THICK



In order to determine whether the above relationships were true of pressures for other than 10 centimeters of mercury, the relationship of the rate of flow to changes of pressure was found for the two kinds of woods over a range of pressure of 10 to 50 centimeters of mercury. The average values of two determinations on seasoned slash pine are given graphically in Figure 1. It shows that the rate of flow was a linear function of the pressure applied for both the springwood and the summerwood and indicates that the relationship was constant over the range of pressure used by the fact that the lines pass through the origin.

Values for loblolly pine which were obtained in a similar manner are not presented. Altho these determinations were not as satisfactory or the results as uniform as those for slash pine, nevertheless a selection of the best values or the values of the better experiments free from anomolies gave, when plotted, essentially a straight line relationship between the rate of flow and the pressure applied for both springwood and summerwood.

DISCUSSION

It is not surprising that in practically all of the determinations, the rate of flow tended to decrease, with the duration of the run, toward an equilibrium value. This has been observed previously by Sutherland, Johnston, and Maass (29), and by Buckman, Schmitz, and Gortner (5) in their studies on the permeability on wood. Furthermore, this phenomenon has been observed with synthetic membranes.

As one would expect, the extent of the decrease from the initial to the final rate of flow varied widely among the woods examined. A few exhibited only a small decrease in permeability, during the total period of continuous flow, and the rate of flow of a few fell off very markedly. The unseasoned sapwoods of the pines, for example, gave a final rate of flow of water which was about one-half the initial rate. On the other hand, the final rate of flow of water through paper birch sapwood and balsam fir heartwood was about a tenth of initial value. It is evidently characteristic of the green sapwoods that were studied, that continued flow of liquid through the sections causes the rate of flow to become less rapid. Of the unseasoned sapwoods examined, only white oak sapwood showed an appreciable increasing rate of flow which preceded the usual decline.

In those cases in which the rate of flow does not decrease immediately, the time during which flow increases or remains nearly the same may be about an hour, altho it is usually less. Deviations of this kind were most commonly observed with seasoned woods, especially seasoned sapwoods with zinc chloride solution. The reason for this is not known, but evidently new channels and capillaries are opened which are effective in transport of the liquid or else the existing capillaries are enlarged or made more effective. The fact that green sapwood, in general, did not exhibit this peculiarity, except in two woods, indicates that green woods are in a stable state and respond similarly and as ordinary membranes. In the case of a seasoned sapwood such as white spruce, which shows a decided increase in rate of flow with time, the zinc chloride solution apparently has a greater loosening (peptizing) effect on the obstacles blocking the flow through the pit membranes since those woods which are reduced in permeability by seasoning are usually the ones that give an increase in rate of flow with time preceding the usual decrease.

There is also the possibility that trapped air or incomplete evacuation of the air from the blocks may cause sufficient surface tension effects to prevent a capillary from conducting the liquid. Some investigations along this line showed evacuation of the sections increased the rate of flow of aqueous solutions through seasoned sapwood, but had no effect on green sapwood which had not lost appreciable moisture. This is what would be expected because in green or unseasoned sapwood the tracheids (in conifers) are probably filled with water and hence surface tension problems are minimized. The fact that many seasoned woods, after several evacuations, give about the same rates of flow as the unseasoned woods shows that the evacuation is complete for those capillary systems in the section which are the most effective in the flow of the liquid.

Altho many species of wood have heartwood of low moisture content (some have only a few per cent of free water), it was found that several 10-minute evacuations of the green heartwood had no effect on the permeability of such heartwoods as of jack pine, black spruce, white spruce, and longleaf pine. One would not expect to find much difference in this case since the pressure of the experiment exceeds the vacuum applied by almost one-half. Hence, if the pressure applied could not break the surface films in the small capillaries, it is readily conceivable that the lesser force of vacuum would not be able to do so.

It was noticed with some of the resistant woods run at 20 pounds pressure that the liquid which came through during the first few minutes to an hour or more was charged with air, as evidenced by rise of numerous minute bubbles in the liquid above the section. This was probably air from the interior of the section which had been progressively forced out or had dissolved, under pressure, in the liquid. Before the run is begun, the resistant section is opaque to strong light, whereas after the run the region exposed to the path of flow is then translucent. This indicates that the tracheids are now practically filled with water, being more in the nature of a continuous solid-liquid system. In some cases enough air was replaced by water throughout the section to cause the sections to sink in water, which it would not do prior to the usual run.

Whether this loss of air during the first stages of the determination was of great importance for those heartwoods which had been evacuated is not known. But from actual experiments, there is reason to believe that with most of the seasoned heartwoods, the more impermeable ones excepted, failure to evacuate the sections does not cause much difference in the final rate of flow at the pressure used, altho the initial rate may or may not be different.

It is not likely that the diminishing rate of flow with time is caused by gradual closure of the pit apertures by the tori. Birch sapwood and heartwood, white oak heartwood and occasionally sapwood all respond in much the same way as the conifers. Furthermore, it is unlikely that a pressure of 5 centimeters mercury would cause pit closure.

It has been suggested (5) that the degree of polarity of the organic liquid and the specific effects of various salt solutions on the surface electrical properties may contribute to differences in rate of flow of various liquids by changing the effective capillary size and by creating an electrical back pressure. Referring to the great decrease in flow of water with time for paper birch sapwood, it would seem that this can be explained on an electrokinetic basis. The larger vessels of paper birch are of the order of 100 μ in diameter. The scalariform perforation plates situated at the junctions of the vessel segments and the openings between these bar-like plates are easily visible with the microscope. For this reason, the vessels should not be subject to the possibility of blocking or plugging by colloidal particles which might be in the liquid in spite of the use of distilled water and filtered salt solution and commercial benzene. If plugging effects were the predominant factor in slowing down the rate of flow, it would be expected that the conifers, with their smaller openings in the pit membranes, would be affected to a much greater extent than a hardwood whose vessels are free from tyloses and relatively open. This, however, was not the situation.

The tendency of zinc chloride solution to maintain the initial rate is what might be expected from a knowledge of the usual effects of salt solutions on permeability. It is observed that usually the initial rate of flow is not significantly different for water than for zinc chloride solution. Evidently the effective pore size of the capillaries is not changed to any extent at the initial stage, except in some resistant woods. If the concentration and kind of salt solution are of importance, which is probably true tho the minimum effective concentration is not known, then it is reasonable to suppose that the washing or leaching of the wood with water during the course of the runs might alter the rate of flow by reducing the ions present in the wood substances and in its surfaces. In any event, the results indicate that the salt solution inhibits or prevents to a considerable extent the factors which retard flow.

That the effect of an increased, sustained rate of flow of zinc chloride solution is probably not caused by an appreciable increase in the actual size of the capillary openings, but rather is a result of the chemical character of the salt solution itself, is illustrated by a series of experiments in which distilled water and zinc chloride solution were successively streamed, without release of pressure, through longitudinal sections of unseasoned balsam fir heartwood. The following tabulation presents the data which are the averages of four sections for each of the two series.

Liquid	Time of flow in minutes		Rate of flow in c.c. per min.	
	(A)	(B)	(A)	(B)
Water	0	0	5.88	3.15
	60	60	1.68	1.45
	120	120	1.11	1.10
	150	......	0.96	....
$ZnCl_2$* solution	5	1	1.25	1.56
	30	30	1.29	1.40
	60	60	1.29	1.35
	90	......	1.26	....
Water	5	5	1.04	1.37
	30	15	0.90	1.28
	60	45	0.77	1.06
$ZnCl_2$* solution	......	1	....	1.26
	......	15	....	1.17
	......	45	....	1.12

* 0.1 N solution with series A, and 3 per cent solution with series B.

The sequence of figures shows definite breaks in the rate of flow trends whenever one liquid is substituted for the other. The change is usually abrupt, the one exception being the replacement of 3 per cent zinc chloride solution with distilled water in series B. Nevertheless, the rapid decrease in rate of flow of water following the first few minutes also renders these results tantamount to the other changes. In addition, there is the possibility that the one-hour period of flow of 3 per cent zinc chloride (approximately 4.5 times as concentrated as 0.1 N) caused considerable salt to be dissolved in the wood and non-active capillaries, which, with the change to water, gave up sufficient amounts of the ions during the first few minutes to affect the rate of flow and prevent an abrupt change. It is also noticed that the flow decreases in the zinc chloride phases are less than in the water phase and that the second change to zinc chloride is not as effective as the first; the latter may or may not be of significance, demanding further investigation.

Results similar to those given above were obtained from two series of experiments with 0.1 N cupric chloride solution.

The values reported by other workers (15, 29) give sapwood a permeability of 100 to 200 times that of the heartwood in conifers. It is obvious, therefore, that these values are not the limits by any means, because in the present series of experiments western hemlock was considerably lower than the above minimum and coast Douglas fir on several occasions was several times the reported maximum. It is also conceivable that much greater differences in permeability would be found in woods that have very resistant heartwood but very permeable sapwood; for example, unseasoned jack pine and longleaf pine. The heartwoods of these species show no permeability at low pressure, and are very impervious even at a pressure of 20 pounds per square inch. The more variable results obtained with coast Douglas fir are probably largely due to biological variation, which seems to be more pronounced in the woods of very low permeability, in this case the heartwood run at low pressure.

The effect of seasoning on the permeability of wood has been presented elsewhere in some detail. The data of Tables 1 to 4, inclusive, show that seasoning did not have the same effect on all of the woods. As a matter of fact, only a few sapwoods, those of jack pine, Norway pine, northern white cedar, and white spruce, showed what might be regarded as a marked reduction in longitudinal permeability. White spruce sapwood was the only wood whose permeability was greatly changed by a seasoning treatment. The permeability of unseasoned white spruce sapwood, as reported by Buchman, Schmitz, and Gortner (5), was about the same as that found for the heartwood, both very resistant. The values found in this work for seasoned white spruce sapwood are in the same approximate range, but the permeability of the green sapwood as reported here is very much greater than they report, and is of the same order or magnitude as the permeability of other unseasoned sapwoods. Concerning the other two woods which they found did not change in permeability to any great extent with seasoning, Norway pine sapwood was reduced in permeability to water in the present investigations to about one-seventh of the value for unseasoned sapwood. With zinc chloride solution the difference was not as great, being a little less than one-half. The results obtained for the effect of seasoning on balsam fir heartwood are in agreement with the results obtained by them, namely, that seasoning causes no appreciable change in permeability to water.

There is little generalization value in the statement by Johnston and Maass (15) that penetration into dry wood is initially rapid but generally 25 to 30 per cent of the equilibrium green wood value. The results of this study show that in general the initial rate of flow of water through seasoned sapwood is less than that for the unseasoned wood. The equilibrium values of the flow through seasoned sections as compared with unseasoned sections varies with the species and cannot be limited to even an approximate figure when speaking of a number of species. It is interesting to note that Bailey (2) in an early work reported, in a qualitative way, the effects of seasoning in a number of sapwoods. He obtained a better penetration of India ink particles in the green sapwoods of white pine, pitch pine, spruce, hemlock, larch, and cedar than in the seasoned materials. Altho white pine and pitch pine were not used in this study, the results with the other species show that Bailey's observations were correct.

From the reports in the literature concerning pit aspiration, one would expect that seasoned sapwood would be practically impervious. If, as Griffin (10), Phillips (21), and others report, aspiration is so complete as to leave only a very few unaspirated pits per tracheid, especially in the springwood, than one would expect a pronounced drop in permeability with seasoning to a relatively dry condition. Since a pronounced reduction in permeability was not found for the majority of cases, it indicates that if pit aspiration occurs, it does not have the marked influence on permeability which has been attributed to it. At least, this is true for the woods worked with under the conditions of this study.

According to the data of Phillips (21) on the sapwoods of five species of conifers, there are only 0.5 to 6.3 unaspirated pits per tracheid in the springwood and from 2 to 11 unaspirated pits per tracheid in the summerwood, depending on the species. This would mean that some tracheids would have no inlet and outlet since two openings obviously is the minimum, while in other tracheids only a very few more openings than the required minimum would be present. This is a vastly different situation from the green sapwood where the average number of unaspirated pits varies, for the same species, from 40 to 92 for the springwood, and from 8 to 25 for the summerwood tracheids. If Phillips' results can be considered to be representative for other pines, spruces, larches, and Douglas fir, and if Griffin's (10) correlation of lack of penetration with the degree of pit aspiration is true, then one would expect a very large decrease in permeability with seasoning. As a matter of fact, only one or two per cent of the pits in the springwood would be functioning, and only a small fraction of those in the summerwood tracheids.

It is shown from Tables 1 and 3 that these expected tremendous changes are not the rule but rather the exceptions for the species used in this study. White spruce sapwood is the only one which decreased in permeability to the same extent that Phillips found pit aspiration to change in the species which he studied. Besides white spruce sapwood, northern white cedar was one of the woods most affected by seasoning, but to a much lesser extent. In such a case, aspiration of all but 10 or 15 per cent of the tori would be expected to give the rate of flow obtained on the basis of the green unaspirated condition. With woods such as longleaf pine, slash pine, and coast Douglas fir sapwoods, there evidently is little or no pit aspiration with seasoning because the rate of flow of water remains practically the same as with unseasoned sections (assuming that pit aspiration causes the decreased flow). Between these extremes of seasoning effects are the majority of the sapwoods which show a gradation in their change of permeability with seasoning. The kind of wood is undoubtedly a determining factor, for altho the results are slightly different when zinc chloride solution is used, those differences which are probably not due to biological variation are still present in almost the same magnitude.

The results of the determination on seasoned and unseasoned heartwood indicate that, in general, seasoning has no appreciable effect on their longitudinal permeability. Table 2 shows that the final rates of flow of water through seasoned heartwoods are slightly greater in some woods, about the same in others, and in the rest are slightly less than the corresponding unseasoned heartwoods. With zinc chloride solution (Table 4) the difference in flow for the various heartwoods favors an increased rate in the case of the seasoned materials. For both liquids it is noticed that where the final rate of flow for seasoned heartwood is more than that for the unseasoned heartwood, the initial rate is also greater, and vice versa. Because the differences are relatively small and not very consistent, especially with water, one is probably not justified in ascribing these minor changes to seasoning effects on aspiration. On the contrary, it indicates that the process of pit aspiration usually associated with seasoning does not take place in these heartwoods or, if it does, it is certainly balanced by some other factor that is not evident. The more reasonable conclusion is that pit aspiration does not occur with seasoning beyond what already exists in the unseasoned heartwood.

Benzene had a higher initial as well as final rate of flow for a given wood than either water or zinc chloride solution. This is undoubtedly due, in part, to such factors as the lesser viscosity of benzene, its non-polar nature, and the increased effective size of the capillaries of the pit membranes in the seasoned woods. The rôle of each is difficult to evaluate except in the case of viscosity. Similar to the effect of the zinc chloride solution, the final rate of flow of benzene was from 1 to 20 times that of water. The high rate of flow of benzene is not explained on the basis of a lower viscosity, for water has not even twice the viscosity of benzene. It is not likely that resin is dissolved out of the resin ducts causing them to be effective transport channels for the liquid because with those woods without resin ducts the effect of benzene is about as great, both initially and finally, as with woods which possess a resin duct system. Seasoned white spruce sapwood, however, was profoundly increased in permeability when benzene was used; at a pressure of 5 centimeters of mercury, it gave a rate of flow greater than that obtained with zinc chloride solution at a pressure of 20 pounds per square inch. It would seem that in such a case the benzene must have a solvent action either on the resin in the ducts, causing them to become effective in conducting liquid, or on the aspirated pits, assuming them to be so, causing the tori to be released sufficiently for the passage of benzene through the pit membrane.

There is some doubt whether the results of the determinations using commercial benzene are the true values for two reasons. Firstly, one lot of benzene used on a few woods was unfiltered; and, secondly, even tho filtered commercial benzene of the second lot (which in the unfiltered condition decreased in rate of flow more than would be expected from other determinations) gave the same results as chemically pure benzene on eastern hemlock sapwood and Norway pine sapwood, this may not necessarily have held true for all other woods. Consequently it is probable that the decrease in rate of flow with time is greater in some instances than would be true if chemically pure benzene were used. For example, balsam fir heartwood (Table 6), which represents the extreme in decrease from the initial to the final rate of flow, has been previously reported (4) to cause only a slight decrease in rate of flow with chemically pure benzene.

Returning to the discussion of the various results in the rate of flow with the three liquids used in this study, it is desirable to discuss their effects of permeability from the standpoint of the properties of the liquid and the conditions of the experiment. It has been pointed out that the greater final rate of flow of zinc chloride and benzene over that of water is not correlated with viscosity, tho in the case of benzene it very likely has some effect. Several reports in the literature attempt to establish that the viscosity of a liquid is the chief factor which determines its penetration into wood. This topic of viscosity effects on penetration deserves further discussion in the light of more recent knowledge.

By constructing from MacLean's data (18), using Table II and Figures 2 and 4, a hypothetical experiment analogous to the actual determinations, the results show that altho viscosity is held constant, penetration and absorption may increase markedly with temperature. Assuming MacLean's statement that the temperature effect in itself is only as it affects viscosity, which he believes to be the determining factor of penetration, it is found from Figure 4 of his paper (18) that a given penetration demands a different viscosity for each of the creosote mixtures. Thus a measurement of the viscosity of the unknown mixture would not indicate its penetrability. Furthermore, the viscosity curves of the creosote and creosote mixtures have different slopes at the same viscosity, the lower range included, which means that the viscosity-penetration relationship varies with the creosote mixtures. This is illustrated by the different constants necessary for the equations of the curves. These differences must be due to the nature of the systems, temperature effects, or both.

From MacLean's (18) data in Table III plus the use of the viscosities given in Table II, for purposes of comparison, the figures show that while penetration in general may follow viscosity changes, a measurement of the viscosities of the systems will not predict their order in penetration. The figures also indicate that altho the mixtures decrease more rapidly in viscosity with increasing temperature than creosote does, the penetrations and absorptions are inversely related to the decrease in the difference between the slopes of the curves of penetration plotted against viscosity. This means that there are factors present which do not respond to or follow viscosity changes, and which become more prominent or apparent even tho the viscosities of the mixtures decrease more rapidly than does the viscosity of the creosote.

From Table I of the same paper the use of different oils with one creosote, all at the same temperature, also indicates that viscosity is not the only important factor affecting penetration. If more than one creosote had been used, it is likely that greater differences would have occurred for it would give a wider number of variables, just as differences between the several oils used show that the magnitude of penetration need not be determined solely by viscosity when two or more systems are compared.

Howald's results (12, 13) on the blocking effects of an oil peptized colloid, and the unrelated penetration of preservative fluids and viscosity serve to illustrate this to some degree.

Bateman's (3) and MacLean's (18, 19) statement that temperature has no other effect than that of changing the viscosity is not supported by Scarth and Spier (23) and by Sutherland, Johnston, and Maass (29). The former found pronounced and permanent penetration changes with a temperature of 100° C., and the latter group of workers found permanent changes at a temperature of 70° C. Johnston and Maass (15) also found that at elevated temperatures the rate of flow of water was greater than the accompanying changes in viscosity.

Adding a high viscosity creosote or petroleum oil to fluid to keep viscosity constant (19) at increasing temperatures is of doubtful validity because it involves the introduction of other variables into the system by the addition of an oil or creosote of unknown properties. Bringing it into a system in which heat and dilution lower its viscosity does not necessarily imply that the inhibitive factors of penetration have been correspondingly destroyed.

The importance of the chemical composition of a liquid on the resulting rate of flow has also been illustrated by the recent experiments of Bull[3] in which the lower members of the homologous series of normal primary alcohols were forced through a membrane of cellulose pulp. Velocity of flow times viscosity, which should remain constant if all factors other than viscosity are constant, was plotted against the number of carbon atoms in the molecule. However, the velocity of flow of the alcohols increased with increasing carbon number of the molecule even when viscosities had been taken into consideration. Using a carbon membrane, the reverse order was found to be true.

These results are similar to those obtained with water and benzene which represent extremes in polarity and hence different affinities for the wood substance. The polar groups of water are probably oriented toward the polar groups of the capillary walls and held there with considerable firmness for some distance into the liquid of the capillary, thus reducing the effective size of the capillary. Benzene, being a nonpolar compound, has little or no affinity for the polar wood substance, which may be a cellulose-pectin complex (16) since the flow is through the pit membranes, and hence is more free to flow through the capillaries. The effects of zinc chloride and benzene on permeability and of other organic liquids and inorganic salt solutions (5, 29) also demonstrate that factors other than those that are directly measurable exert a powerful influence on permeability, the effect varying with the species.

Recognizing the fact that in the flow of liquids through wood, as in any capillary system, viscosity must be an important factor, nevertheless evidence indicates that there are other factors which we know little

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[3] Bull, H. B., and Wronski, J. P. Streaming of liquids through small capillaries. Jour. Phys. Chem., 41:463-468. 1937.

about which may greatly affect the permeability of a given wood to a given liquid.

An arrangement of the woods of each pressure group in the order of their permeability has been given in the section embodying the experimental results. It must be emphasized that these orders or classifications do not necessarily represent the true relationship of one wood to another in so far as permeability is concerned. It means, simply, that *these are the orders for the experimental results of these investigations for the conditions of the experiments and for the samples used.* The difference in permeability between some of the woods is not of sufficient magnitude to constitute a real or true difference for such limited sampling. Wood is a material which varies considerably in certain physical properties, and permeability is one of them. A different sampling might place these woods in a somewhat different order. This is suggested by the fact that permeability values for the sections used in each determination, the average of which is the figure reported in the tables, may vary considerably among themselves.

The maximum difference in the rate of flow between any two of the four sections was sometimes 100 per cent or more, altho this was not the general rule. The sapwood sections of a given wood usually were more uniform in permeability than were the heartwood sections. This is probably due to the variation of the intensity of the action of such factors that caused the change from sapwood to heartwood at the time that the transition took place. This would include the infiltration of chemical substances, pit aspiration, the hardening of resinous materials, and other influences which actually cause heartwood formation. These instances of wide divergence are apparently not anomalies.

In order to obtain some idea of the relative permeabilities at a higher pressure, the pressure at the end of the runs with water on unseasoned heartwoods was increased to 50 pounds per square inch and to 20 centimeters mercury on the unseasoned sapwoods. The initial rate of flow was recorded. On this basis the results showed the heartwoods had essentially the same order, based on permeability, as that obtained from the equilibrium rates of flow of water at a pressure of 20 pounds per square inch on the same unseasoned sections; general but not exact agreement was obtained with the order of the sapwoods on the final rate of flow basis at a pressure of 5 centimeters of mercury.

Sections of western hemlock sapwoods from near the heartwood and near the edge of the log were tested with the purpose of determining whether or not the inner sapwood differed in permeability from the outer portion of the sapwood. The sapwood was found to be equally permeable throughout its width (about 2.5 inches) and circumference. A similar experiment was conducted on the heartwood of coast Douglas fir. Only the normal variation was observed, showing that the permeability did not vary with the distance from the pith. This is in accordance with Phillips' observation (21) that the structure, size, and degree of aspiration of the pits are about the same from near the pith to the outer heartwood.

White oak sapwood has two distinct regions which are very different in permeability. The reported values are for the region inside the last two or three annual rings. It is noted from Tables 1 and 3 that flow is very slow when compared to the flow through coniferous sapwoods and paper birch sapwood. But when the section was placed so that part of the last annual ring was included in the circular openings in the discs, the rate of flow was increased tremendously by even that small area of the last annual ring or two actually within the circular opening. This supports the concept that only the last annual ring or two is very effective in the translocation of water in the sapwood of white oak and in some other species of hardwoods. Evidently, the vessels in the remainder of the annual rings of the sapwood are filled with tyloses to such an extent that the flow of liquid is practically inhibited at the same pressure which causes rapid flow in most sapwoods.

Sutherland, Johnston, and Maass report that unseasoned sapwoods show increased penetration to water in the order: hemlock, balsam, red pine, and white spruce. This agrees fairly well with the results obtained in this study. However, the difference in permeability between balsam fir sapwood and eastern hemlock is of doubtful significance, but a considerable difference in permeability exists between the first two woods and last two.

The permeability of the unseasoned sapwood sections of the southern pine species may be somewhat lower than the true values because of the exudation of resin after sawing the sections and during the storage period (the southern pine group was not tested immediately after the sections were sawed). It may be that the close contact of the sections with each other caused the resin to be smeared over the same or the adjacent section to some extent and probably filled the open end of the tracheids thus rendering them incapable of conducting liquid. With the seasoned sections this error is probably not as large because the sections were kept apart and seasoned immediately after sawing.

An interesting feature of the comparative permeabilities of the various unseasoned sapwoods is that the average final rate of flow values are not greatly different for the majority of the species. With the unseasoned coniferous sapwoods, the maximum final rate of flow of water was less than five times the minimum. The permeabilities of these coniferous sapwoods give a distribution approaching the normal curve whose extreme values are probably not much different from those obtained in these experiments considering unseasoned coniferous sapwoods as a whole. From the biological standpoint, it seems reasonable to suppose that the differences in permeability between sapwoods of various species should not be very great, otherwise translocation of liquids would be greatly affected. There must be a minimum permeability in order to meet the transpirational needs of the tree altho that minimum may be dependent to some extent upon the character and environment of the tree. It would be interesting to extend this study to many samples of the same species grown in a variety of ecological environments.

When the coniferous sapwoods are seasoned, the extreme and average values of permeability are much different from those of the seasoned sapwoods. Due to the effect of seasoning, the average rate of flow was considerably less than that with unseasoned sapwoods.

The heartwoods of various species show considerable differences in permeability. Table 2 shows that unseasoned jack pine had the slowest rate of flow, about 0.007 cubic centimeters of water per minute, and that unseasoned western hemlock, which gave a flow of 0.95 cubic centimeters per minute, was the most permeable. Of the total of 12 heartwoods, only 5 had a final rate of flow between 0.191 cubic centimeters and 0.47 cubic centimeters per minute. With zinc chloride solution, the range in permeability of the same unseasoned heartwoods was 0.019 cubic centimeters to 3.51 cubic centimeters per minute. Six of them had a final rate of flow of from 0.568 cubic centimeters to 1.86 cubic centimeters per minute. The remainder of the heartwoods are more widely scattered either above or below these values.

In contrast to statements reported in the literature that in seasoned wood the summerwood is more permeable than the springwood, it was found that the springwood was more permeable than the summerwood in the sapwoods of two species of southern pine, and that the permeabilities were practically the same for the seasoned condition as for the unseasoned condition.

The difference between the magnitude of the ratios for the two species can be explained in part by the fact that the summerwood of the slash pine was of greater apparent density than the summerwood of the loblolly pine, the latter showing almost a transitional stage through a considerable part of the summerwood. The hardness of the two species was also much different. The lesser permeability of the summerwood is probably caused by fewer and smaller pits and by thicker pit membranes assumed to be coincident with increasing density of the wood.

These ratios of permeability are constant over a range of pressure of from 10 centimeters to 50 centimeters of mercury, as shown in Figure 1 by the straight lines which pass through the origin.

Measurements of rate of flow of water on an area of seasoned slash pine summerwood and on an area of seasoned loblolly pine springwood, both free from resin ducts, yielded about the same values as were obtained in other regions. On the other hand, an area in loblolly pine springwood containing numerous resin ducts was somewhat less permeable than the nearby regions of the same annual ring. This indicates that the resin ducts in these woods were of minor importance at these pressures in so far as flow of water was concerned. The slightly lower values obtained when resin ducts were numerous were probably due to the plugging of the tracheids surrounding the ducts by exudation of resin before the dry state was reached in seasoning, since white powdery deposits around the ducts were distinctly visible.

Altho a discrepancy seemingly exists between the data of Teesdale (30) and Buckman (4) and the conclusions reported in this bulletin concerning the relative permeability of springwood and summerwood for the same species of wood, too much emphasis should not be placed on a comparison of this kind. In creosoting a pole, the penetration is largely in the radial direction; hence, penetration may be limited to some extent by the least permeable layer of wood and may be affected by such factors as the presence of air and moisture in the cell cavities, the distance from the surface, the degree of seasoning, springwood and summerwood, the higher temperatures, the presence of resin canals and the properties of the resin, and the character of the preservative fluid.

In this investigation, however, the longitudinal permeability was measured instead of the radial penetration into the large piece of wood. This permits the springwood to function independently of the summerwood and has few complicating features in either portion, since the absence of air in the tracheids and the separate measurements of flow enable the determination of permeability values at nearly normal conditions.

CONCLUSIONS

1. The longitudinal permeability of a number of species has been determined on both the heartwood and the sapwood in the seasoned and unseasoned conditions. The effect on permeability of duration of continuous flow, seasoning, and various liquids has been studied. The comparative permeability of heartwood and sapwood and of springwood and summerwood was found for several species.

2. In general, the rate of flow of a liquid through wood decreased with continued flow and approached equilibrium after about three hours, depending upon the kind of wood. The decrease in flow with time was generally considerably greater with water than with zinc chloride solution or commercial benzene.

3. The ratio of the sapwood to heartwood permeability varied for each of the three species tested. The ratios for a given species differed, usually depending on the liquid used and to some extent on the seasoning treatment. On the basis of increasing ratio of sapwood to heartwood permeability, the order was: paper birch, western hemlock, and coast Douglas fir. The comparative permeability of sapwood to heartwood is probably very different for the various species.

4. The change in the permeability of sapwoods caused by seasoning varied with the kind of wood. With a few exceptions, no great change occurred with seasoning. Seasoned heartwoods were generally about as permeable as the unseasoned. Either pit aspiration does not occur as

extensively and intensively as reported in the literature, or else it does not greatly influence longitudinal permeability.

5. The kind of liquid used very definitely affected the equilibrium rate of flow in practically all the woods. The order of increased flow was: water <zinc chloride solution <benzene. The initial rates of flow of the liquids also differed under certain conditions and with various woods.

6. The character of a liquid may so affect the permeability that the viscosity factor may be completely obscured. There is evidence that electrokinetic effects and polarity of the liquid affect the flow of liquids through wood. Successive changes of water and zinc chloride solutions forced through one kind of wood were accompanied by definite differences in the trend of the rate of flow. Apparently the pore size of the wood membrane was not permanently affected by the salt.

7. Woods differ in their permeability to a given liquid both in the magnitude of flow and in the extent of the decrease in the rate of flow with time.

8. Springwood was considerably more permeable longitudinally to water than the summerwood in the seasoned and unseasoned sapwoods of two southern pines. Under the conditions of the experiment, resin ducts apparently did not assist the flow of water through the sections.

9. The unseasoned sapwoods of the species studied have a limited range of permeability; the majority fall within a spread of about a hundred per cent. The unseasoned heartwoods exhibited a wider range of permeability and less uniformity, as a group and individually, than did the sapwoods.

10. The orders of arrangement of the woods based on final rates of flow are given. With unseasoned sapwoods the orders are about the same for both water and zinc chloride solution. The orders of arrangement of seasoned sapwoods are shifted somewhat from that of the unseasoned sapwoods, but are not greatly different for the three liquids. The orders of arrangement of the heartwoods are essentially alike for the three liquids used and for the seasoned and unseasoned sections.

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