Technical Bulletin 242 March 1963

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A POROUS MATERIAL is permeated by fluids in response to a pressure gradient. Wood is such a material. Permeability is the property of a porous material which characterizes the ease with which a fluid flows through the material by an applied pressure gradient, i.e., it is the "fluid conductivity" of the porous material. Many of the variables controlling the permeability of porous materials, such as beds of granular substances, should also apply to wood. However, wood is different from such materials in that it has a biological origin. Thus, it was only natural that many early investigators studied the permeability of wood from the viewpoint of the biologist; so wood soon inherited a monotypic classification in this respect, being recognized as a biological porous substance.

Although this *de facto* separation of wood from other porous materials had certain merits, the biological association often impeded advancement because any anomaly in its reaction to permeation by fluids was often attributed to variation inherent in its biological origin.

More recent investigators have approached the subject from the physical scientist's viewpoint but have retained many of the biological concepts to explain the behavior of wood as a porous material.

In the present study wood is assumed to obey the same fundamental laws which are applicable to a wide variety of rigid porous materials.

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Review of Literature

Investigators commonly encountered a decreasing rate of flow, at constant pressure, of the liquid through the wood (Anderson, et al., 1941; Buckman, et al., 1935; Erickson, et al., 1937; Sutherland, et al., 1934). This decrease occurred with all liquids reported, including freshly distilled water. It was rapid at the start of flow but leveled off after 30 to 120 minutes and approached zero flow asymptotically. Thus, to evaluate the effect of different variables, these investigators referred to the latter portion of the flow curve as an "equilibrium" condition and used its value as the basis for comparison.

Several theories were proposed to account for this phenomenon: (1) gradual swelling of wood, (2) pit aspiration, and (3) pivoting of structural units in the wood so as to offer maximum resistance to flow. However, these proposals have not been completely satisfactory. They are not entirely consistent with hydrodynamical principles which were the basis for similar studies of other porous materials (Muskat, 1946).

Another phenomenon encountered by early investigators of wood was a disproportionate increase in rate of flow when pressure was increased, provided a decrease in flow with time preceded increase in pressure (Anderson, et al., 1941; Buckman, et al., 1935; Sutherland, et al., 1934). For softwoods this phenomenon was attributed to a bulging of pit membranes (Sutherland, et al., 1934), thereby increasing the size of the capillaries through which liquid flows. Anderson et al. (1941), however, showed by use of Poiseuille's equation that the degree of stretching required to account for increased flow is a physical improbability. They proposed that fibrous units in pit membranes move laterally with increased pressure so larger capillaries are increased in size at the expense of smaller ones.

King (1899) observed the same phenomenon in quarried sandstone. Ruth (1935) analyzed King's data and concluded that the disproportionality resulted from failure to completely evacuate air from the test material prior to flow studies.

Krier (1951) recently obtained a true equilibrium rate of flow through red maple. He used freshly distilled water and filtered it through a fritted glass filter immediately prior to use. Although this equilibrium rate was maintained for several hours, it represented only about one-fifth to one-eighth of the sample's maximum rate.

By shaving the inflow surface of other samples after the flow rate decreased to a low level, Krier obtained a resurgence of flow. This indicated that the zone of occlusion was largely localized at or near the inflow surface. Photomicrographs of sections taken from this same area showed extraneous materials in cells. Thus, he concluded that the basic cause of the decrease in rate of flow of liquids through wood was a physical occlusion of conducting elements by particles of an unknown complex associated either with the wood or the liquid.

Constant flow rates (without any previous decrease) of distilled water through green and seasoned sapwoods of western hemlock and Douglas fir were recently reported by Erickson and Crawford (1959). This uniformity of flow was obtained at a pressure of 5 cm. Hg. The water was filtered through a fritted glass filter of "fine" porosity immediately before passage through wood.

"Nearly constant rates of flow" were reported by Erickson (1960) in a later study of the same species using similar filtration techniques. However, Erickson and Estep (1962) have been unable to establish constant rates of flow at higher pressures in either green or seasoned Douglas fir heartwood.

Prior filtration of distilled water, especially if aged before use, has been reported to facilitate its flow through other porous materials. Krier (1951) reported that freshly distilled water passed

through a coarse fritted glass filter (40 microns maximum pore size) at a relatively constant rate but that aged distilled water rapidly blocked the same filter. Prefiltration of aged water through a filter of smaller pore size allowed it to pass through the coarse filter at a constant rate.

Further work led Krier to believe that prefiltration removed micro-organisms and extraneous materials from the aged water which would have blocked coarse filter pores.

Prefiltration also improved the passage of distilled water through granular beds consisting of sand and other minerals. Prefiltration eliminated the air evolution from the water as it underwent an increasing pressure drop in passing through the bed. The following quote from page 90 of Muskat (1946) exemplifies the importance of this type of blockage:

> One very common cause of the plugging of a porous medium upon continuous flow of a liquid, as water, through it, is the evolution of air or gas dissolved in the liquid. This gas becomes trapped in the pores of the medium in the form of small bubbles and may decrease the resultant permeability for the liquid to a small fraction of its original value. An effective means for eliminating this difficulty is that of using distilled water and, in addition, prefiltering it before its entry into the sample to be tested.

Workers studying wood were also aware that air could be a factor in wood's resistance to the passage of liquids and took precautions to properly evacuate the test material prior to flow studies. Some exerted special efforts to deaerate the liquid either by boiling or prolonged evacuation prior to its flow through the wood. However, Dean (1944) demonstrated that neither procedure is completely effective. And Pease and Blinks (1947) showed that deaeration of water by evacuation is successful only if the liquid is simultaneously subjected to intense mechanical shock. In all such experiments a decided decrease in rate of flow with time was still observed. Thus, each investigator believed that air evolution from the liquid as it passed through the wood did not account for the decrease—at least under the test conditions.

Gas blockage in wood was demonstrated by de Montigny and Maass (1935) through use of a saturated aqueous solution of carbon dioxide. The solution was forced longitudinally through unseasoned heartwood of jack pine at pressure gradients of from 2 to 6 atm. When the gross pressure differential was such that the net pressure on the liquid fell below the saturation pressure for the gas at a point within the specimen, the permeability decreased to a low level. This was attributed to evolution of the gas from liquid within the wood.

Similar studies with saturated aqueous solutions of carbon dioxide were reported by Wyckoff and Botset (1936) for sands having a wide range of porosities. In commenting on their results, they state:

> At these very low gas-liquid ratios, gas gradually accumulates in the pores until the pressure gradient has built up sufficiently high to flush some of the bubbles out of the pores, a steady state condition finally being obtained in which the bubbles are flushed out as rapidly as they are formed. Since this steady state is a definite characteristic of a given sand and fluid system, it has been called "equilibrium permeability", . . .

Thus, theories advanced to account for decreasing permeability differ depending upon whether the material under investigation was wood or some other porous substance. No logical reason appears for these discrepancies; and assuming that the same variables controlling flow of a liquid through sand also apply to wood, it should be possible to demonstrate that air blockage has an effect upon permeability of wood similar to that described for sand.

Harvey et al. (Part I, 1944) showed that particulate matter in water contains hydrophobic surfaces which function as nuclei for the release of dissolved gas. This evidence suggests that particulate matter

in freshly distilled water could alter the permeability of wood either by (1) physically occluding conducting elements, as proposed by Krier (1951), or (2) functioning as nuclei for evolution of air from liquid as it passes through wood.

Wardrop and Davies (1958) obtained experimental evidence that hydrophobic surfaces probably exist in wood. Such areas also could function as nuclei for evolution of air from liquid as it passes through wood.

Theory of Gas Blockage in Wood

When passing through wood a liquid traverses a complex series-parallel arrangement of fine capillaries. These capillaries vary in size and contain numerous constrictions. If such capillaries are filled with liquid, and a gas bubble is caused to flow through them, the bubble would not pass through the constriction unless a certain critical force is exerted on it. Distortion of the bubble to drive it through would involve increased surface energy at the interface between the gas and liquid at the small end of the bubble. Thus the bubble would transmit less energy than it received.

This incomplete transferal of energy by a gas bubble in a liquid-filled capillary is known as the Jamin effect. The surface tension forces of such a bubble are not in equilibrium, the resultant stress tending to drive the bubble back and out of the constriction. Application of a slight external pressure would drive the bubble partially into the constriction to a position where the distortional surface tension forces would be in equilibrium with the externally applied pressure. Such a system evidently behaves as if the capillary contains an obstruction with little or no flow possible until the bubble is expelled. In a porous material containing capillaries and bubbles of many sizes, each increment of increase in driving pressure would therefore open additional capillaries to liquid flow. The net effect would be a disproportionately greater increase in flow rate with applied pressure. Such behavior is a necessary characteristic of the Jamin effect and has fundamental relationship to the pressure-rate phenomenon of fluid flow in wood.

The Jamin effect might be manifested in two ways in permeability studies on wood. Residual gas bubbles in the wood at the start of flow could move into constrictions and reduce permeability by physically obstructing liquid flow. One would expect such a system to exhibit elastic qualities in relation to applied pressure. So if flow is started through a freshly evacuated sample at a low pressure, any subsequent pressure increase should cause flow to increase disproportionately to applied pressures. However, if flow is started at a sufficiently high pressure to expel the bubbles, and the driving pressure is then reduced to a low level and subsequently increased progressively, one would expect flow to be directly proportional to the pressure.

When a liquid is forced through a pipe of uniform bore a uniform pressure gradient develops along the pipe because of frictional resistance. If, under conditions of constant mass flow, a constriction is placed in the pipe the linear velocity must increase at the point of constriction. According to Bernoulli's principle, when the linear velocity of a fluid in a conductor is thus increased the pressure is decreased accordingly.

Since wood is composed of a complex series-parallel arrangement of such constricted "pipes," the size and distribution of constrictions in the path of flow should considerably influence the linear velocity and pressure distribution. It is reasonable that if a liquid containing a dissolved gas is forced through such a system, containing nuclei, dissolved gas may evolve from the liquid at a constriction where the pressure is below the original saturation pressure for the gas. The resulting bubbles could then be trapped at the next downstream constriction and progressively reduce the wood's permeability

until a state of dynamical equilibrium prevailed. The applicability of such a mechanism to porous granular beds has been amply demonstrated (Muskat, 1946; Ruth, 1935; Wyckoff and Botset, 1936).

Therefore, resolution of the problem of understanding the nature of factors which control permeability of wood would benefit from an experimental demonstration of the applicability of this blocking mechanism. The objective of research presented in this report was to evaluate this applicability and, if possible, demonstrate air blockage as a factor controlling permeability of woods to water.

Experimental Equipment and Materials

To accomplish the stated objective, a first requirement was the development of an experimental equipment system which would permit: (1) versatility of manipulation of fluid flow conditions, and (2) measurement of fluid flow with a high level of confidence.

A schematic diagram of such an apparatus is shown in figure 1. The liquid supply tanks were double-tough Pyrex glass pipe. The apparatus was designed for a maximum working pressure of 50 psi. All lines were constructed of ¼-inch Saran tubing. Valves were brass and other fittings were either of brass or of Saran.

Filtered air was used to force freshly distilled water from the supply tanks through the filter(s) and the wood. The liquid passed from the wood into a flow measurement cell which automatically emptied after accumulation of a predetermined quantity of liquid. The time required for the cell to fill was recorded on a time-function recorder. Pressures up to 20 psi were measured with mercury manometers—electrical contacts in the manometers allowing control of pressure within 1 mm. Hg.

Pressures above 20 psi were manually controlled and were measured with precision test gauges (Spec. No. 44056, Fig. No. 1404, American Machine and Metals, Inc., Sellersville, Pa.). The gauges were dead-weight tested before use and were graduated in ½-psi increments. The manometers and gauges were placed in the system so that pressure could be controlled either upstream or downstream of the filters.

One of the two fluid filters was a bench-mounted Millipore unit (Cat. No. YY22 142 00, Millipore Filter Corporation, Bedford, Mass.) containing type WH Microweb filter medium having an average pore size of 0.45 microns with a maximum variation of 0.02 microns from the average. With this filter, effective filtration was possible without deaeration of the water as a result of measurable pressure drop.

A special cell was designed to hold the cotton filter (figure 2). Except for gaskets and fittings, the cell was constructed entirely of Plexiglas. The cotton filter was confined to a constant length of 1½ inch in a ½-inch outside diameter tube. The pressure drop across this filter was regulated by varying the amount of densely packed surgical cotton placed in the filter holder. A chamber was provided downstream of the filter for collection of any air bubbles accumulating and passing through the filter. The valve in the upstream block of the cell in figure 2 corresponds to valve No. 1, figure 1. When this valve was closed liquid passed through both filters, subjecting it to the pressure gradient across the cotton filter. Opening the valve allowed the liquid to bypass the cotton filter.

The method of electronically measuring liquid flow is based on the change in screen grid current introduced into a crystal-controlled oscillator circuit by stray capacitance from the liquid. Details of the oscillator system are given in figure 3 and table 1. Two electrodes are positioned at different levels in the flow measurement cell. They connect

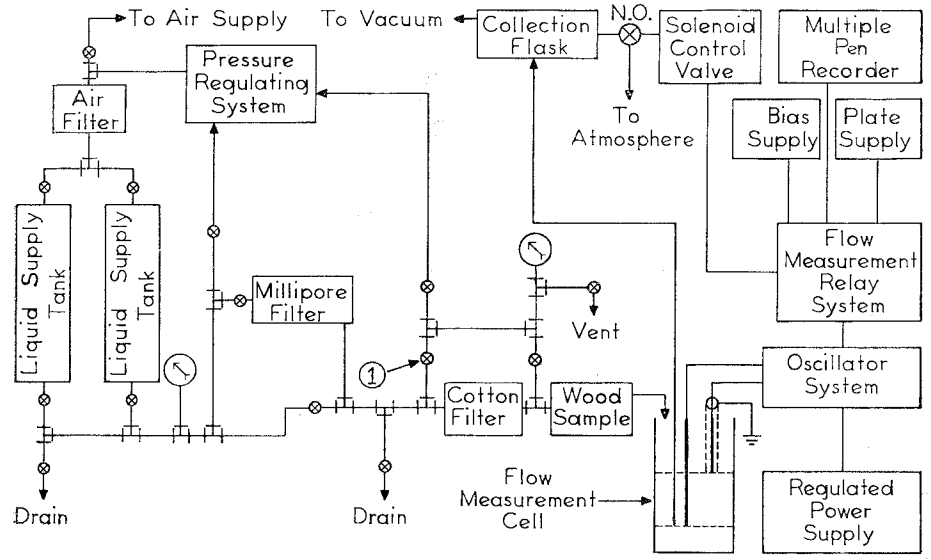

Fig. 1. Schematic diagram of permeability apparatus.

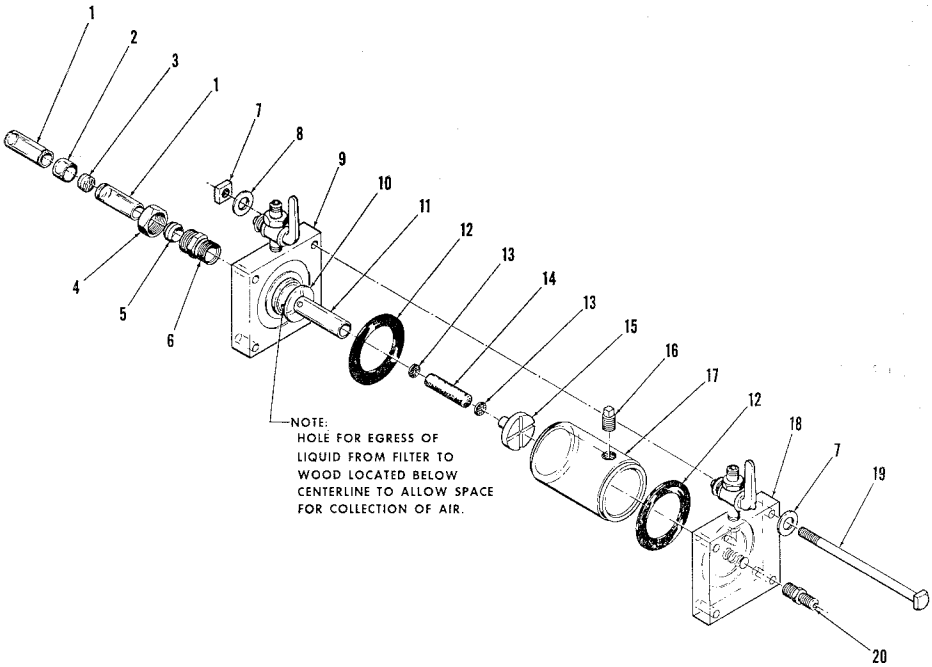

Fig. 2. Exploded view showing methods of mounting cotton filter and wood sample. 1: Plexiglas tube sample mount, ½ inch OD x 2 inches long. 2: cast epoxy seal. 3: wood sample. 4, 5, 6: compression fitting, ½ inch OD to ⅜ inch NPT. 7, 8, 19: ¼-inch nut, washer, and bolt. 9: downstream block. 10: air collection chamber. 11: filter holder. 12: rubber gasket. 13: 80-mesh screen support. 14: cotton filter. 15: filter-retaining plunger. 16: ⅛-inch NPT drain plug. 17: cell cylinder. 18: upstream block. 20: adapter, ¼-inch OD flare to ⅛ inch NPT.

respectively to separate oscillators at the output points of the plate tank circuits.

The oscillators operate at different frequencies to prevent interaction and are tuned to the point of stable oscillation with minimum plate current. When liquid touches the lower electrode, the plate tank circuit becomes nonresonant and the plate current of tube **V1** increases. This results in a corresponding decrease in screen grid current. The drop in screen grid current decreases the voltage across series resistors **R3** and **R4**. This causes a reduction in the negative bias voltage on section **V3b** of tube **V3**. Section **V3b** now conducts and energizes relay **K2**. Contacts **K2a** and **K2b** close and the authority for the eventual energizing of relay **K3** is transferred to relay **K1**.

As the measurement cell fills with liquid, contact is made with the upper electrode, and relay **K1** is energized in exactly the same manner as relay **K2**. **K1b** completes the circuit to the time-

Table 1. Description of parts used in electronic control circuits

Symbol*	Parts required	Description
R1†	2	100K 1W
R2	2	400 1W
R3	2	5K 10W
R4	2	5K 12½W Ohmite type E-0123
R5	1	10 1W
R6	1	10K 4W CTS-IRC—type WR
R7	1	25K 25W
C1, C2, C3‡	6	0.01 paper
C4	2	0.0004 mica padder
C5	2	0.002 mica
C6, C7	2	20 elect. 450 DCWV
C8	1	0.05 600 DCWV
L1	1	25 turns #28 enameled wire close wound on ⅞-in. dia. styrene tube
L2	1	28 turns #28 enameled wire close wound on ⅞-in. dia. styrene tube
L3	1	8 Hy. Stancor C-1709
L4	1	110V solenoid valve ASCO #826231
M1	1	Sarkes-Tarzian M150
K1, K2	2	Potter & Brumfield KCP-11
K3	1	Potter & Brumfield KRP-11A
P1, P2, P3	3	6V
X1	1	3700 KC
X2	1	3655 KC
T1	1	Stancor PC8410 360-0-360V; 6.3V; 5.0V sec.
T2	1	Stancor P6465 used as isolation "step up" transformer for bias supply
V1, V2	2	6F6
V3	1	6SN7 GT
V4	1	6AX5 GT
RFC	2	5 mh.-150 ma.
B+ reg.	1	Heathkit regulated power supply, model PS-4

* As shown in figure 3.
† Value of all resistors is given in ohms.
‡ Value of all condensers is given in microfarads.

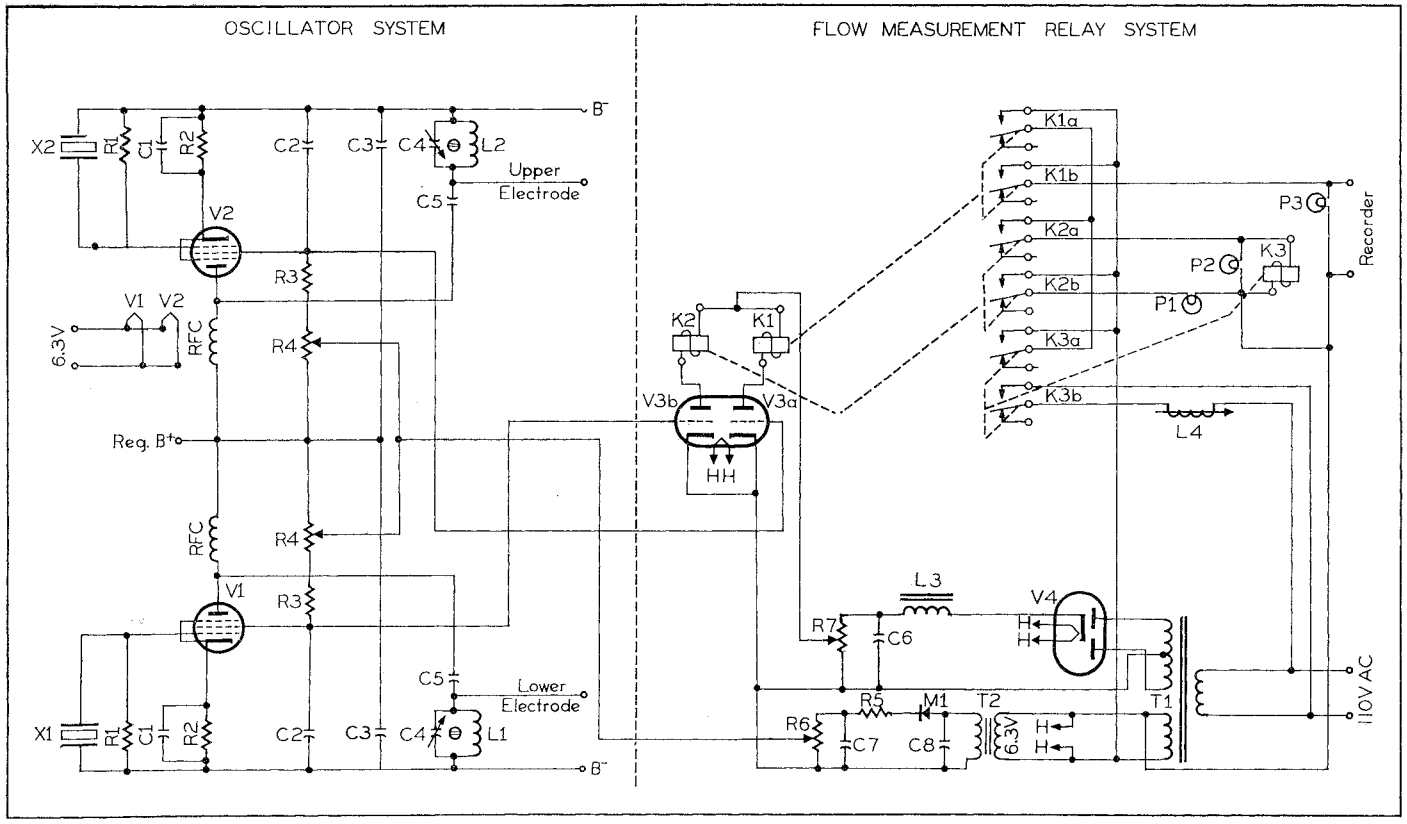

Fig. 3. Electronic control circuits.

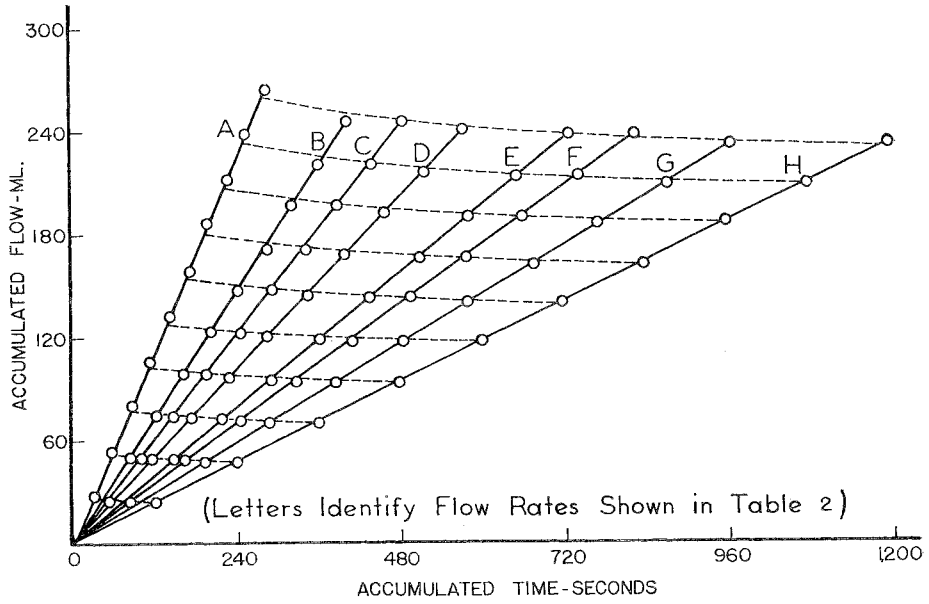

Fig. 4. Calibration of flow measuring and recording equipment against flow from a constant-flow tank.

function recorder (Esterline-Angus Operation Recorder, Model AW, Esterline-Angus Instrument Company, Inc., Indianapolis, Ind.). The time required for the cell to fill is indicated by marks on the recorder chart. Closure of K1a completes the circuit to relay K3; and contacts K3a and K3b close, completing the circuit to the solenoid control valve. The liquid is removed by suction from the flow measurement cell and deposited in the collection flask.

Liquid contact with the upper electrode is broken as the cell is emptied. This reestablishes oscillation which, in turn, breaks the circuit to relay K1. However, relay K3 is still energized by a complete holding circuit through contacts

Table 2. Summary of calibration of electronic flow measuring and recording equipment against flow from a constant-flow tank

Flow rate	Total time for 20 measurement cycles		Total volume for 20 measurement cycles		Standard deviation	
	Duplicate No. 1	Duplicate No. 2	Duplicate No. 1	Duplicate No. 2	Duplicate No. 1	Duplicate No. 2
	seconds		milliliters		seconds	
A	286	288	264	265	0.41	0.51
B	409	402	245	245	0.51	0.32
C	489	488	243	243	0.51	0.61
D	576	573	240	239	0.40	0.51
E	726	728	237	237	0.46	0.51
F	824	829	235	235	0.61	0.61
G	962	964	232	232	0.32	0.61
H	1,196	1,195	232	232	0.46	0.46
Totals	5,468	5,467	1,928	1,928		

K3a and **K2b.** When the liquid breaks contact with the lower electrode relays **K2** and **K3** are released and removal of liquid from the cell is stopped. As liquid continues to flow from the sample, the lower electrode again contacts the liquid and the operational cycle is restaged.

This equipment can detect constant rates of flow over a wide range with a high degree of precision (see the calibration chart, figure 4, and associated table 2). The small variation in time for successive measurement cycles (as indicated by standard deviation) is not related to the electronic equipment but to the precision of removing data from the time-function recorder chart.

The gradual increase in volume of liquid removed from the cell per measurement cycle with rate increases is related to the quantity of liquid flowing into the cell during the time taken to empty it. This characteristic has *no* effect upon the equipment's ability to detect a constant rate of flow—the purpose for which it was designed—and is important *only* when flow rate changes rapidly with time. When the latter condition exists frequent measurement of the water in the collection flask may minimize the error. Or, it may be eliminated by applying a correction factor computed from observed rate of flow and the time required for the cell to empty.

Wood selected for this study was air-seasoned Sitka spruce (*Picea sitchensis*) heartwood, having an average specific gravity (ovendry weight/green volume) of 0.31. It represented a rather impermeable softwood in which air blockage should be more easily demonstrated because of the extremely small opening in its pit membranes.

The liquid used was distilled water. Except where otherwise indicated, it was distilled on day of use.

Experimental Methods

Preparation of Cotton Filters

A known weight of surgical cotton was packed in the filter holder, the cell was assembled, and the entire unit was evacuated over distilled water in a desiccator. The cell was submerged in the water while maintaining the vacuum. The vacuum was released and the filled cell was fastened in the permeability apparatus as shown in figure 1. The filter and all lines up to it in the system were purged with 600 ml. of distilled and Millipore-filtered water before fastening the sample to the downstream block of the filter cell.

Preparation and Evacuation of Permeability Specimens

Wafers approximately 10 mm. in length in the fiber direction were cut from the test piece and divided into individual specimen blanks. These were stored so that end-matched specimens could be identified.

In a typical preparation, the specimen blank was evacuated over distilled water which had been filtered through the Millipore filter, submerged in the water, and the vacuum released. One surface was shaved on a sliding microtome and the blank was dried under cover to equilibrium with room conditions. It was then placed over water in a closed desiccator jar until its moisture content was approximately 20 percent.

A ⅝-inch diameter test specimen was then cut from its center with a gasket cutter and assembled in the Plexiglas tubes (No. 1, figure 2) with one-third of its length exposed between tube ends. The assembly was returned to the desiccator jar for an additional 12 hours to allow the moisture content to approach fiber saturation. The consequent additional swelling was sufficient to secure the wood against the tube walls so the casting resin would not contact end surfaces of the wood.

The wood and tubes were sealed together with Scotchcast Resin No. 5 (Minnesota Mining and Manufacturing Co., St. Paul, Minn.). An aluminum foil and masking tape form was placed over the tubes and adjusted so that resin could be retained in the desired area as it cured (see figure 13). During the curing period the shaved end of the sample was protected from dust by placing the assembly upright with the shaved end in a petri dish containing a little water.

Samples prepared by this technique were tested for leakage at 44 psi pressure. No leakage around the sample was detectable at this pressure.

The mounted sample was evacuated for 15 minutes over freshly distilled and filtered water and then submerged in it while maintaining the vacuum. The vacuum was released and the sample allowed to stand in the water for 30 minutes before being attached to the downstream block (figure 2) of the cotton filter cell.

Care was taken that air did not contact either sample face. The Plexiglas tube on the downstream end was placed over the flow measurement cell. Since the Plexiglas was not wetted by the water, a meniscus could be maintained at the outflow end to prevent contact of air with this end of the sample during a run. This technique allowed reversing the sample with assurance that air did not contact either surface.

Operational Techniques

The assembled cell was mounted in the system and the pressure quickly raised to the desired value. The shaved end of a sample was always upstream unless otherwise indicated.

When only the Millipore filter was used the pressure control point was immediately upstream of the sample (figure 1). When both filters were used in series the pressure control point was either immediately upstream of the sample or the Millipore filter, as demanded by the experiment. Any change in permeability during a run was detected by observing the cycle time on the recorder chart. If the sample permeability was changing with time, the effluent water was measured at the end of each 10th measurement cycle. For constant rates of flow the effluent was measured either at the end of each 10th or 20th measurement cycle.

Experimental Results

PART I

The following results represent only a few of the experiments conducted to satisfy this study's objectives. Only experiments which demonstrate the fundamental principles associated with each objective are included. Each experiment was duplicated. Results are presented with full confidence that they illustrate the basic phenomena controlling permeability of wood to liquids. Experiments will not necessarily be presented in the order of execution. They are arranged in a sequence which progressively leads to elucidation of the effect of air blockage upon the longitudinal permeability of wood to liquids.

In many instances the points plotted in the figures represent only a fraction of the observations recorded on the time-function recorder chart.

Constant Flow of Distilled Water through Wood

The first problem was that of obtaining a constant rate of liquid flow through the wood. Analysis of the literature suggested, and results of exploratory experiments confirmed, that an absolutely constant rate of flow of distilled water through wood should be possible if one could control: (1) air in the wood, (2) air in the liquid, and (3) particulate

Table 3. Summary of data for run No. 17A (sample No. 6-3, length = 0.826 cm., diameter = 0.950 cm.; Millipore filter only; pressure = 48 lb./sq. in.)

Direction of flow					
Original →		Opposite ←		Original →	
Accumulated time	Accumulated flow	Accumulated time	Accumulated flow	Accumulated time	Accumulated flow
seconds	milliliters	seconds	milliliters	seconds	milliliters
21*	15.3*	21	15.5	21	15.1
41	30.6	42*	30.9*	42*	30.3*
62*	45.9*	63	46.4	62	45.4
82	61.2	84*	61.8*	83*	60.6
103*	76.4*	105	77.3	104	75.7
123	91.8	126*	92.7*	125*	90.8*
144*	107.1*	147	108.2	145	106.0
164	122.4	169*	123.6*	166*	121.1*
185*	137.7*	190	139.1	187	136.3
206	153.0	211*	154.5*	207*	151.4*
227*	168.3*	233	170.0	228	166.5
248	183.6	254*	185.4*	248*	181.7*
268*	198.9*	275	200.9	269	196.8
289	214.2	296*	216.3*	289*	212.0*
310*	229.5*	318	231.8	310	227.1
331	244.8	340*	247.2*	331*	242.2*
352*	260.1*	361	262.7	351	257.4
374	275.4	383*	278.1*	372*	272.5*
394*	290.7*	404	293.6	393	287.7
415	306.0	426	309.0	413	302.8
Average rate of flow—ml./sec.					
0.74		0.73		0.73	

* Points plotted in figure 5.

matter in liquid which would serve as nuclei for bubble formation.

Removal of particulate nuclei presented no great problem. All particles down to 0.45 microns or less in diameter could be removed by passing the liquid through the Millipore filter prior to its passage through the wood.

The majority of the air in the wood could be removed by evacuation. But air dissolved in the liquid presented a more difficult problem since prolonged boiling or evacuation could not be relied upon to produce the quality of deaeration necessary. The classic work of Harvey and his coworkers (Part I, II, 1944) suggested, however, that dissolved air could be retained in solution, even to a degree of supersaturation, as it passed through wood if: (1) all active nuclei for bubble formation could be removed from both the liquid and the wood, and (2) the velocity of flow in the smallest wood capillary could not reduce local pressure on the liquid to the extent that local stress would exceed tensile strength. Cavities resulting from such localized ruptures in liquid would serve as centers for diffusion of air out of the liquid and result in bubble formation.

Rough calculations indicated that the possibility of the latter occurring was remote. Distilled and denucleated water, having a minimum of supersaturation, should pass through wood which had been exposed only to such water without any deposition of air in the wood—provided no effective nuclei existed in the wood. If a constant rate of flow resulted from a technique taking these factors into account, one could conclude:

1. No air evolved from the liquid as it passed through the wood.

2. No effective nuclei for bubble formation existed in the wood *under the prevailing hydrodynamic conditions.*

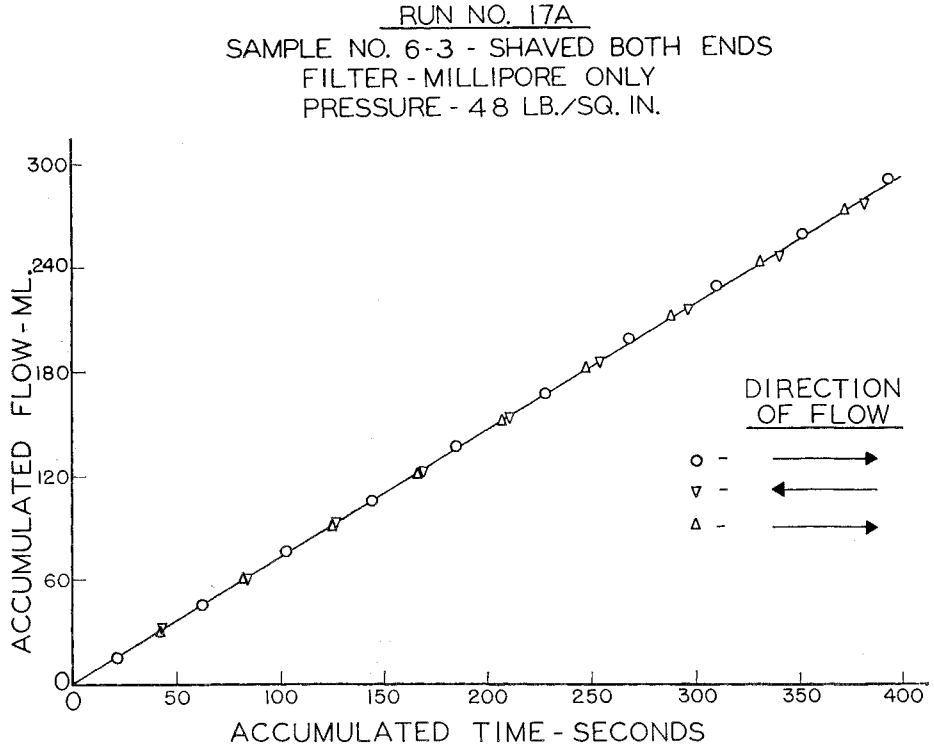

Fig. 5. Longitudinal flow rate of distilled and filtered water through Sitka spruce heartwood.

Such an experiment was performed. Results are given in table 3 and plotted in figure 5. This experiment demonstrates that:

- An absolutely constant rate of flow of distilled water could be obtained at high pressure through seasoned wood by using special handling techniques.
- The same flow would result regardless of direction of flow.
- Filtration and handling techniques employed would remove from the liquid nuclei which might serve as centers for evolution of air from the liquid.
- The wood contained no effective nuclei under the prevailing hydrodynamic conditions.

Repetition of this experiment through a pressure range from 14.13 to 236.13 cm. Hg. gave the results summarized in table 4 and figure 6. These results appear to be the first reported data in which constant rates of flow of a liquid through wood were obtained throughout a wide range of pressures. Individual flow rates could be maintained for extended periods of time.

Darcy's Law and the Pressure-Rate Relationship in Wood

An interesting development from data in table 4 is the relationship between rate of flow and pressure (see figure 7). A direct proportionality between pressure and flow is indicated with the plot of the function passing through the origin. This relationship suggests that a quantitative representation of permeability of wood to liquids should be possible

Table 4. Summary of data for run No. 17B (sample No. 6-3, length = 0.826 cm., diameter = 0.950 cm.; Millipore filter only)

Curve	Pressure	Total time of flow	Total volume of flow	Average rate of flow
	cm. Hg.	seconds	milliliters	ml./min.
1	14.3	1,323	52.7	2.4
2	25.5	1,739	123.3	4.3
3	36.1	1,224	124.2	6.1
4	46.7	932	125.1	8.1
5	57.4	759	126.0	10.0
6	68.0	636	126.0	11.9
7	77.9	553	128.7	14.0
8	98.5	757	213.2	16.9
9	123.1	624	222.2	21.4
10	147.7	565	242.7	25.8
11	172.3	517	258.7	30.0
12	197.0	462	262.5	34.1
13	221.6	418	266.4	38.2
14	236.3	439	295.0	40.3

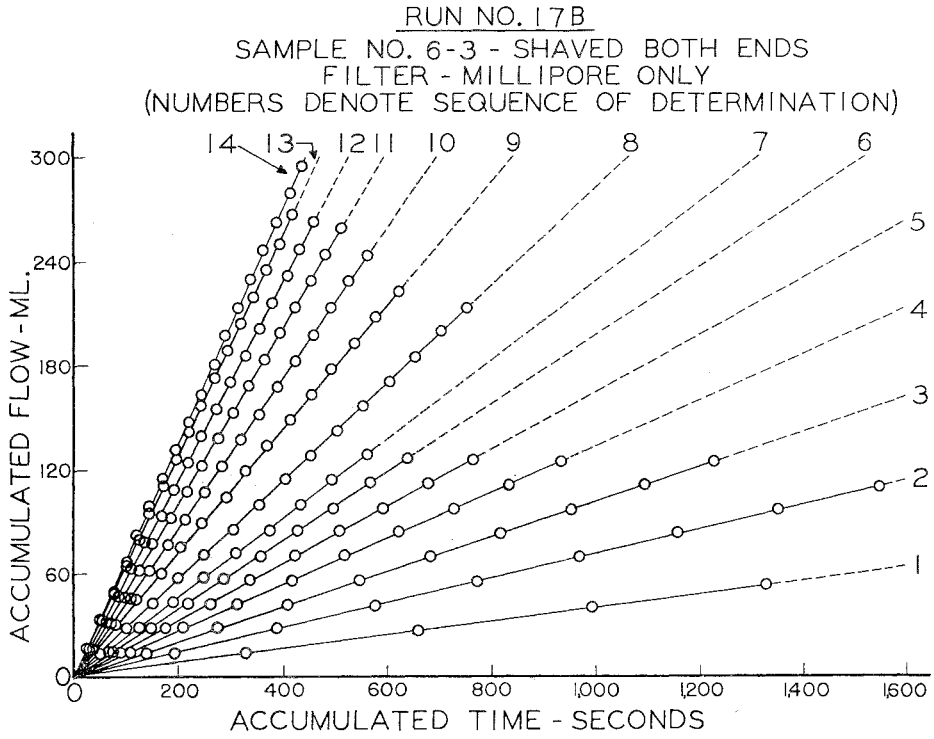

Fig. 6. Longitudinal flow rate of distilled and filtered water through Sitka spruce heartwood at various pressures.

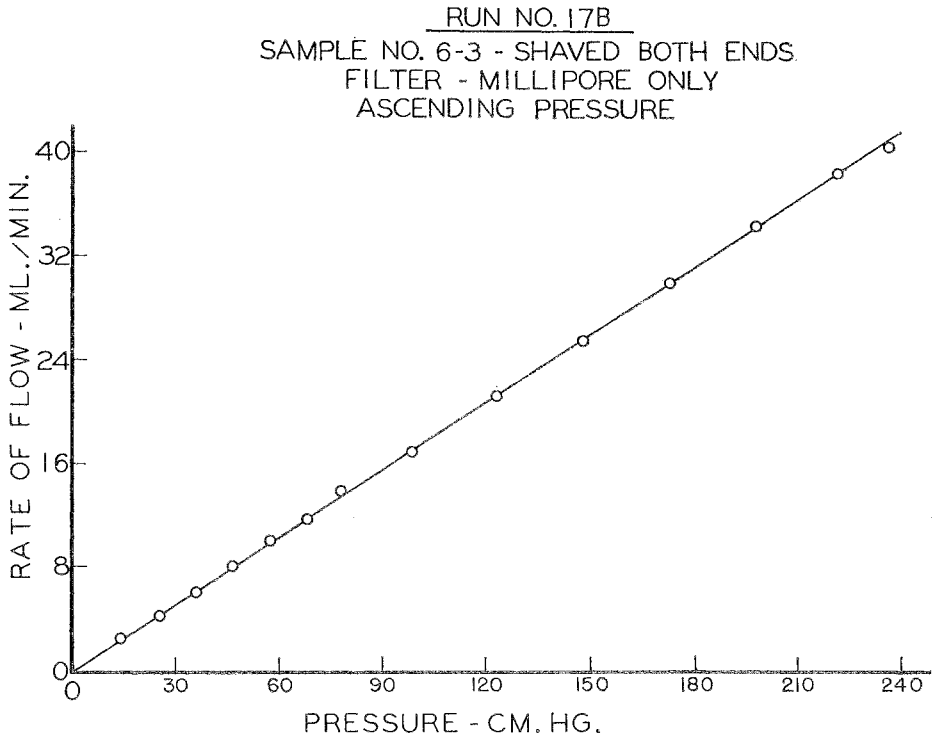

Fig. 7. Pressure-rate relationship for the longitudinal flow of distilled and filtered water through Sitka spruce heartwood.

through application of Darcy's law (Muskat, 1946):

Darcy's Law

$$K = \frac{U\ Q\ L}{A\ (\triangle P)}$$ where:

K = permeability in Darcy units.
U = absolute viscosity in centipoises.
Q = rate of flow in ml./sec.
L = length of material in cm.
A = cross sectional area of material in sq. cm.
$\triangle P$ = pressure drop across material in atm.

The following conditions must be satisfied for application of this law:

1. The liquid must be incompressible.

2. Steady-state flow must be a characteristic of the medium, i.e., flow must be independent of time.

3. Flow must be viscous, i.e., not turbulent.

4. Both liquid and porous material must be homogeneous. The liquid must not liberate an appreciable quantity of gas in the material so as to reduce its permeability for the liquid. The porous material must have the same permeability from end to end.

Most of these conditions are satisfied by results just described for the wood used in this study. The viscous nature of the flow is indicated by the fact that it is proportional to the pressure. Homogeneity of the wood's permeability is not apparent from data given in figures 6 and 7 but is illustrated by the uniform permeability of end-matched samples noted in other experiments.

Although the Darcy expression for permeability is open to question where an

unsteady flow prevails, it has been uniformly applied in this study to all conditions with explicit acknowledgment that its use is technically correct only where above conditions are fulfilled. This procedure was followed for purpose of uniformity of expression.

The Jamin Effect and the Pressure-Rate Relationship in Wood

The proportionality of flow to pressure indicated in figure 7 merits further consideration. In softwoods the disproportionality reported by others was attributed to a stretching of the pit membranes. If this explanation is correct, the phenomenon should have occurred in the present experiment. A possible reason for this difference was observed in some exploratory experiments when preexposure of a sample to a high pressure increased its permeability at a subsequent lower pressure. During the same experimental series it was also noted that if a decrease in permeability preceded an increase in pressure, air bubbles frequently appeared at the downstream end of the sample shortly after the pressure increase. When interpreted according to the Jamin effect, these observations suggested that air was being expelled from the wood by the increased pressure. Thus, if a small amount of air remained in wood after evacuation, the preexposure of the sample to 48 psi pressure as in figure 5 prior to the pressure sequence of figure 6 could have expelled this air. Therefore, this could have been responsible for the proportionality represented in figure 7.

Two experiments were designed to evaluate these observations. Matched samples were prepared and evacuated by the usual procedure. Permeability of each sample was determined at various pressures in an ascending sequence. The sequence on one sample was started 30 minutes after evacuation (normal procedure). The other sample was allowed to stand in the water in the closed desiccator jar for 24 hours after evacuation before being subjected to the same pressure sequence. The purpose of this delay was founded upon the premise that if air bubbles remained in the wood after the normal evacuation procedure, they would enlarge upon standing as air diffused back into the water. This would magnify any disproportionality traceable to expulsion of air from the wood as the pressure was increased. Results are summarized in table 5 and plotted in figure 8. For comparison, the effect of pressure is related both to rate of flow in ml./min. and to permeability in millidarcys.

A disproportionality of both flow and permeability to pressure is evident, but only up to a maximum pressure of 120 cm. Hg. for the normal sequence and 150 cm. Hg. for the delayed sequence. Above these critical limits the proportionality observed earlier is apparent for both runs with identical permeabilities indicated for each sample. Standing for 24 hours after evacuation greatly increased the degree of disproportionality up to the critical pressure but did not affect permeability above this limit.

The writers suggest that this series of experiments confirm the applicability of the Jamin effect, in relation to existing or evolved air bubbles, as a proper explanation of the observed flow-pressure disproportionality. If stretching of the pit membrane was responsible for the disproportionality, one would *not* expect that standing for 24 hours in filtered water at atmospheric pressure would increase the amount of stretching. The occurrence of the Jamin effect is further confirmed by the observation throughout this study that permeability lost during storage could be largely or completely regained by briefly exposing the sample to a higher pressure. A typical experiment representing this observation is recorded in table 6 and in figure 9 and is described as follows:

The permeability of the sample was first determined with both the Millipore filter and a 1.1 gm. cotton filter in the system, and with pressure controlled at 90 cm. Hg. upstream to the Millipore filter. The assembled sample was then stored for 3 weeks over filtered water in a closed desiccator jar. Then permeability

Table 5. Summary of data for runs No. 37A and 39A (run No. 37A: sample No. 12-4,* length = 0.907 cm., diameter = 0.953 cm.; run No. 39A: sample No. 12-1,* length = 0.886 cm., diameter = 0.950 cm.; Millipore filter only)

Run No. 37A			Run No. 39A		
Pressure	Rate of flow	Wood permeability	Pressure	Rate of flow	Wood permeability
cm. Hg.	ml./min.	millidarcys	cm. Hg.	ml./min.	millidarcys
25.9 (9)†	3.8	238	26.5 (19)†	3.1	187
59.5 (20)	9.8	268	51.7 (9)	7.4	229
80.1 (14)	13.5	274	77.6 (9)	12.8	262
98.2 (20)	17.2	284	103.4 (9)	18.1	277
129.3 (20)	23.7	298	129.3 (9)	23.4	288
155.1 (21)	28.4	299	155.1 (9)	29.1	297
181.0 (20)	33.4	300	181.0 (9)	33.8	297
206.8 (20)	37.9	298	206.8 (9)	38.8	298
228.2 (20)	42.1	300	227.5 (20)	42.5	297

* The permeability of sample No. 12-1 was determined 24 hours following evacuation and that of sample No. 12-4 immediately following evacuation.

† Numbers in parentheses indicate the number of measurements of the rate of flow at each pressure.

was again determined under the same conditions. It was found to be only about 60 percent of the original. The cotton filter was then eliminated and the pressure on the sample increased to approximately 229 cm. Hg. The resulting increase in permeability was to within 2.5 percent of the original. Pressure was then returned to the original value with both filters in the system. The permeability

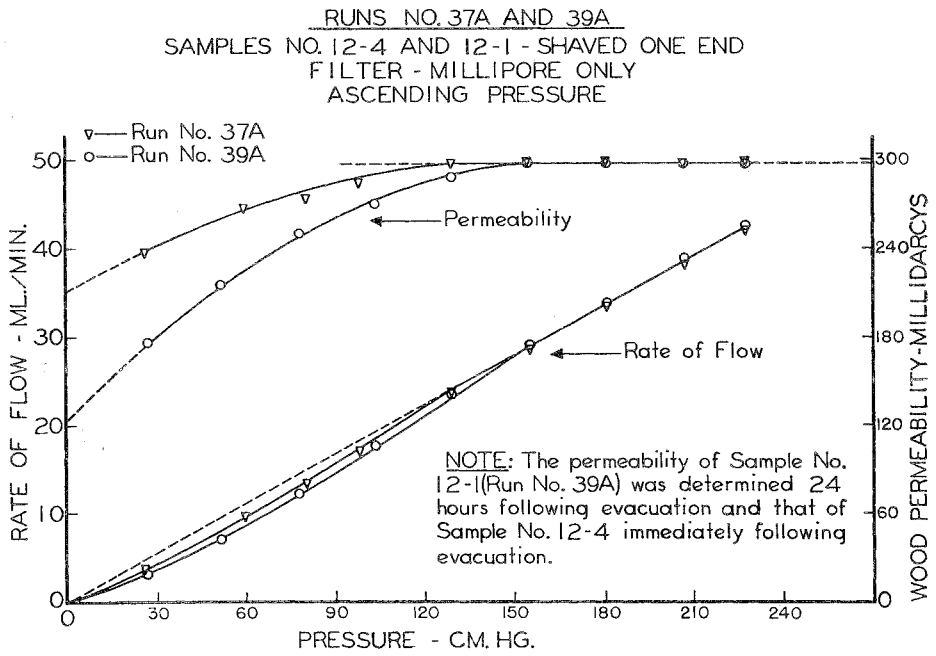

Fig. 8. Effect of standing after evacuation on the pressure-rate relationship for the longitudinal flow of distilled and filtered water through Sitka spruce heartwood.

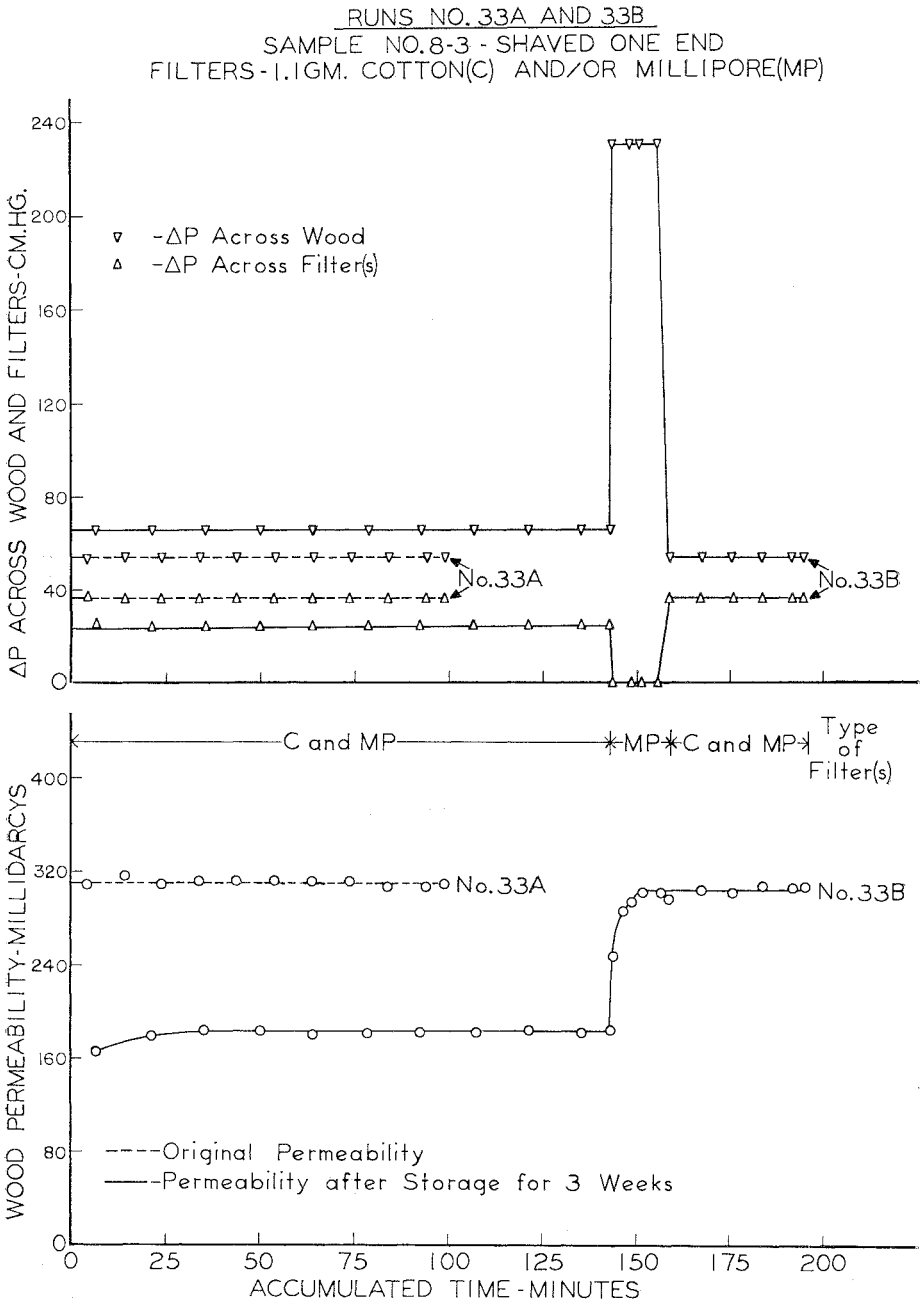

Fig. 9. Effect of pressure upon recovery of permeability lost in storage.

returned to within 1 percent of the original until the end of the experiment.

It does not appear logical that growth of microbiological agents could be the basic cause of this decrease in permeability upon storage. If such agents were responsible one would *not* expect application of a higher pressure to facilitate complete recovery of permeability.

Deposition of Air in Wood under Dynamic Conditions

The outcome of each exemplary experiment already presented illustrates an influence on the fluid flow which may be explained by the presence of air bubbles in the wood. The bubbles may have been either initially present or gradually

Table 6. Summary of data for runs No. 33A and 33B (sample No. 8-3, length = 0.803 cm., diameter = 0.950 cm.)

Accumulated time	Wood permeability	Pressure drop across wood	Pressure drop across filter(s)
min.-sec.	millidarcys	cm. Hg.	cm. Hg.
	run No. 33A		
	cotton (1.1 gm.) and Millipore filters		
4-7	308	53.3	36.7
14-4	317	54.0	36.0
24-2	309	54.0	36.0
33-56	312	54.0	36.0
43-53	311	54.0	36.0
53-49	312	54.0	36.0
63-51	311	54.0	36.0
73-52	311	54.0	36.0
83-55	306	54.0	36.0
93-59	306	54.0	36.0
99-0	309	54.0	36.0
	run No. 33B*		
	cotton (1.1 gm.) and Millipore filters		
6-22	166	65.3	24.7
20-58	179	65.9	24.1
35-21	183	65.7	24.3
49-42	183	65.5	24.5
64-2	180	65.5	24.5
78-24	181	65.5	24.5
92-43	182	65.4	24.6
107-5	181	65.3	24.7
121-25	183	65.3	24.7
135-48	181	65.3	24.7
142-58	183	65.3	24.7
	Millipore filter only		
144-1	248	229.4	0.0
146-29	286	.....	.....
148-52	294	229.4	0.0
151-11	302	229.4	0.0
155-47	302	229.4	0.0
	cotton (1.1 gm.) and Millipore filters		
158-57	296	53.8	36.2
167-13	304	53.8	36.2
175-28	302	53.6	36.4
183-39	307	53.5	36.5
191-53	306	53.5	36.5
194-58	307	53.5	36.5

* Run No. 33B was made 3 weeks after run No. 33A. The sample had been stored during this interval in a closed desiccator jar containing water in the bottom.

evolved from the liquid at hydrophobic surfaces within the wood under *static* conditions. The following experiments, however, consider the possibility of air bubbles arising and accumulating in wood under *dynamic* conditions.

As pointed out in the discusion of the gas blockage theory, it should be possible to establish conditions for dynamic bubble development within the sample by: (1) increasing velocity of flow at a given gas saturation of the fluid, or (2) establishing a critical pressure gradient across the sample. In either case the objective is to establish a hydrodynamic system so that at some point on the pressure gradient through the wood the gas saturation pressure would permit growth of existing nuclei to bubbles of plugging proportions.

The successful establishment of such a hydrodynamic system is illustrated in table 7 and figure 10. In this experiment the sample length of 0.805 cm. was slightly shorter than the maximum length of a tracheid. It was selected so that the

Table 7. Summary of data for run No. 29A (sample No. 8-2, length = 0.805 cm., diameter = 0.953 cm.)

Accumulated time	Wood permeability	Pressure drop across wood	Pressure drop across filter(s)
seconds	millidarcys	cm. Hg.	cm. Hg.
	cotton (1.1 gm.) and Millipore filters		
	shaved surface upstream		
42	503	48.4	46.1
376	495	49.2	45.3
714	473	49.8	44.7
1,077	.....	50.3	44.2
1,260	456	.....	.....
1,444	.....	50.7	43.8
1,812	438	51.2	43.3
2,180	436	51.4	43.1
2,550	433	51.8	42.7
	unshaved surface upstream		
2,744	531	18.9	75.6
3,145	529	19.3	75.2
3,546	512	19.6	74.9
3,946	523	19.7	74.8
4,343	517	19.9	74.6
4,744	520	20.0	74.5
5,140	516	20.3	74.2
	Millipore filter only		
5,368	385	93.2	1.3
5,406	294	.....	.....
5,452	239	.....	.....
5,555	207	94.4	0.1
5,671	186	.....	.....
5,792	.....	94.5	0.0
5,982	172	.....	.....
6,177	.....	94.5	0.0
6,377	164	.....	.....
6,577	.....	94.5	0.0
6,780	159	.....	.....
6,986	.....	94.5	0.0
7,195	155	.....	.....
7,405	.....	94.5	0.0
7,615	155	.....	.....
7,825	.....	94.5	0.0
8,035	155	94.5	0.0

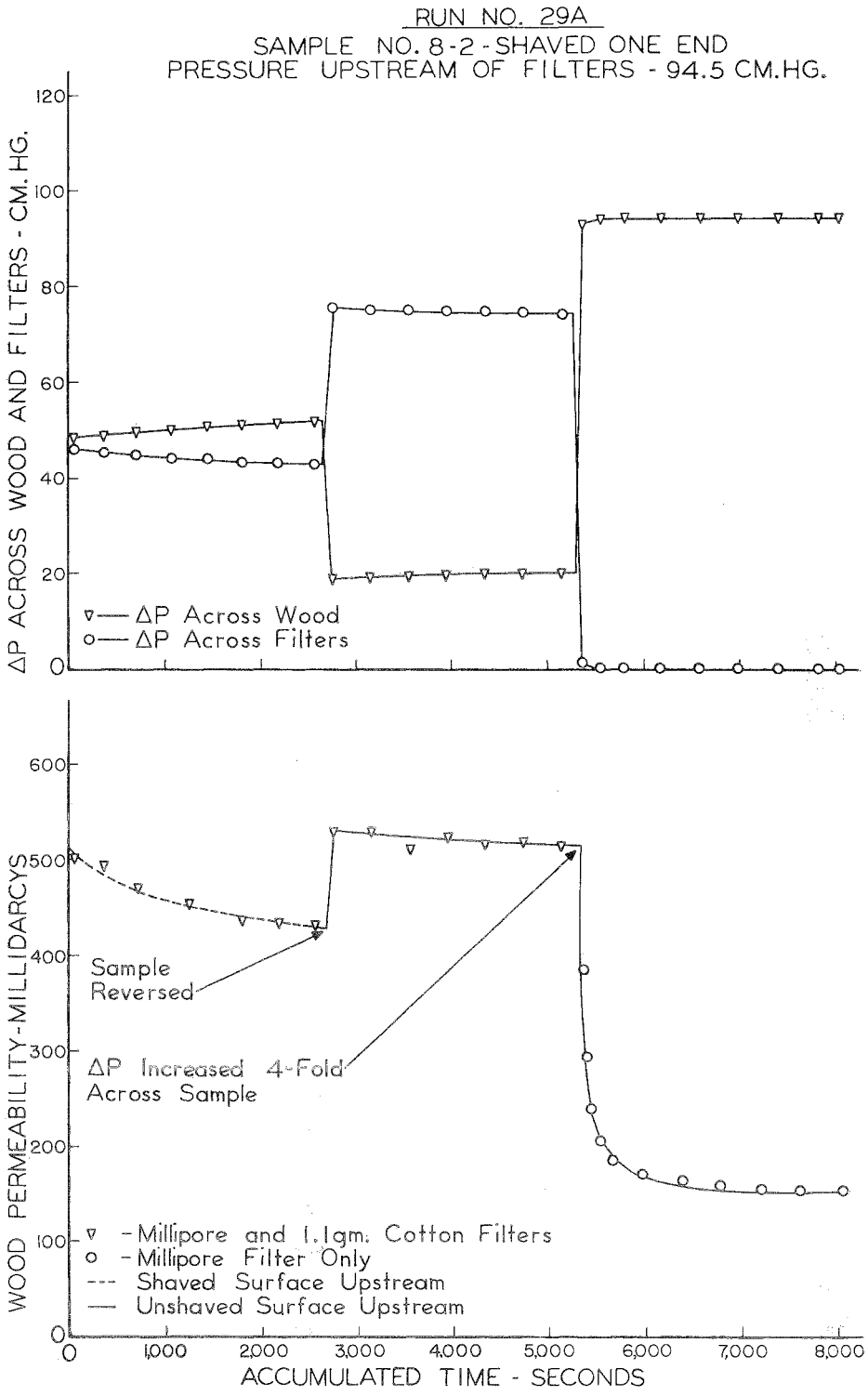

Fig. 10. Effects of reversal of flow direction and a sudden increase in the velocity of flow upon permeability.

linear fluid velocity through the sample would be at a maximum for the pressure used. Yet, the major volume of flow would be through at least two pit openings in series as the fluid traversed the sample.

Flow was started through both filters with the pressure controlled at 94.5 cm. Hg. upstream from the Millipore filter. After 43 minutes the sample was reversed. Flow was continued in the opposite direction for a similar period of time. The cotton filter was then eliminated. For the next 48 minutes the water was filtered only through the Millipore filter. This change allowed the pressure on the sample to increase suddenly from 20.3 to 94.5 cm. Hg.

The gradual decrease in permeability at the start of this run contrasts sharply with the constant rates of flow obtained through slightly longer samples under similar conditions (not shown). The increased and more stable permeability obtained after reversing direction of flow suggests that the blocking agent was located in cell cavities exposed at end surfaces and could be largely flushed out by the flowing liquid.

Here, again, an interpretation could be that the initial decrease resulted from accumulation of solid particles rather than evolved air bubbles in exposed lumens. However, if particulate matter was responsible, the inflow surface of *every* sample would have to be backflushed with the liquid to remove these particles from the open lumens before a constant rate of flow could be obtained. That such action is not necessary where a lower velocity of flow prevails has been adequately demonstrated in preceding experiments (for example, table 5).

The rapid decrease in permeability upon elimination of the cotton filter may be partially explained by the sudden increased velocity resulting from sudden increased pressure on the sample. It may also be explained, however, as resulting from an increase in gas tension of the fluid. The following experiment separates the effect of increased velocity of flow from the effect of increased gas tension.

High velocity flow was started through both filters with pressure controlled at 60.0 cm. Hg. at the upstream face of the sample and maintained for 27 minutes. The pressure was then released and the system held static for 30 minutes. Flow was then resumed with pressure on the sample increased to 80 cm. Hg. and maintained for 20 minutes. After this the cotton filter ($\triangle P - 26$ cm. Hg.) was eliminated from the system. Flow was continued at 80 cm. Hg. upstream to the sample for 40 minutes with the Millipore filter only. Results are shown in table 8 and figure 11.

A gradual decrease in permeability occurred during the initial condition of the experiment as in the previous experiment. Relaxing pressure and maintaining the static condition for 30 minutes reduced permeability by approximately 20 percent. When flow was resumed at a higher pressure, permeability remained constant at this new level.

Increasing gas tension within the liquid by eliminating the cotton filter, and consequent reduction of the pressure on the supply tanks from 106 to 80 cm. Hg., caused the permeability to decrease 52 percent within 2 minutes. After this sudden initial decrease, permeability gradually declined for the next 18 minutes before coming to equilibrium. This was also true in the previous experiment. Equilibrium permeability was approximately 43 percent of that previously maintained using both filters but represented only 30 percent of the initial permeability of the sample. The equilibrium value for the previous sample was equivalent to 29 percent of its initial permeability.

The large decrease in sample permeability upon standing undisturbed for 30 minutes, and the following constancy of flow, again suggest that air nuclei in the wood at the start of flow were responsible for the initial decrease in permeability in both experiments. If plugging by particulate matter originally in the wood was the cause of the initial decrease, one would *not* expect undisturbed standing at atmospheric pressure

Table 8. Summary of data for run No. 12 (sample No. 4-8, length = 0.744 cm., diameter = 0.935 cm.; pressure = 60 or 80 cm. Hg.)

Accumulated time	Accumulated flow	Wood permeability
min.-sec.	milliliters	millidarcys
cotton (5.1 gm.) and Millipore filters		
pressure = 60 cm. Hg.		
2-6*	54	587*
4-13	107	583
6-23*	161	569*
8-35	214	561
10-47*	268	561*
13-1	321	552
15-17*	375	544*
17-34	428	540
19-53*	482	532*
22-13	536	529
24-33*	589	529*
26-58*	643	510*
pressure released for 30 minutes and then increased to 80 cm. Hg.		
29-11*	696	412*
31-23	749	415
33-36*	801	412*
35-49	854	412
38-2*	907	412*
40-15	960	412
42-28*	1,013	412*
44-41	1,066	412
46-55*	1,119	409*
48-35*	1,159	411*
Millipore filter only		
49-25*	1,172	274*
50-35*	1,185	196*
51-46	1,198	193
55-20*	1,238	191*
58-50*	1,278	196*
62-31*	1,317	186*
66-22*	1,357	178*
70-12*	1,397	179*
74-0*	1,437	180*
77-53*	1,476	176*
81-46*	1,516	176*
85-36*	1,556	179*
89-26*	1,595	179*

* Points plotted in figure 11.

to further decrease permeability. Further, if such particles were responsible, the blocking action would have continued when flow was resumed because no approaching equilibrium was evident when pressure was relaxed.

Results of numerous experiments have shown that if flow was initiated through either of these samples without the cotton filter in the system, the initial decrease would have been very rapid. After a few minutes the flow would have approached the same equilibrium value as that indicated for the above experiments.

The large decrease in permeability obtained by eliminating the cotton filter illustrates the principle that changing of gas tension within the liquid allowed air to be deposited in the wood. The appearance of bubbles in the downstream end of the sample tube shortly after the bypassing of the cotton filter indicated that conditions were suitable for air to evolve from the liquid. These bubbles apparently evolved after the liquid passed through the last pit at the downstream sample end.

In contrast to the previous experiment, pressure on the sample was maintained at a constant value while eliminating the cotton filter. Thus, velocity of flow was held constant while gas tension within the liquid was increased. Nuclei were already present in the wood, as evidenced by the initial decrease in permeability. Therefore, an increase in the gas tension of the liquid flowing through the wood at a constant pressure would have the same effect as relaxing the pressure in a static system, i.e., it would allow nuclei to increase in size. However, rate of growth would be faster under dynamic conditions because nuclei would be in continuous contact with supersaturated water.

The foregoing experiments served to demonstrate that air nuclei existed in the wood, even after careful evacuation. Their effectiveness in altering the permeability of the wood depended upon existing hydrodynamic conditions.

Effect of Cavitation by Mechanical Shock

The literature suggests that if nuclei were present in the wood they could be enlarged by subjecting the liquid to a mechanical shock wave as it passed through the wood. If the shock was of sufficient magnitude, the flowing liquid

might be ruptured and caused to cavitate within the wood. The resulting cavities would serve as additional centers for gas to diffuse from the liquid and be deposited in the wood.

The first indication that permeability might be affected by this phenomenon occurred during an exploratory run. It was then observed that the permeability decreased after lightly tapping the Millipore filter with a hammer. Further, if pressure on the sample was increased following these slight shocks, permeability increased and many fine air bubbles issued from the downstream sample end.

Two experiments were performed to verify these observations. Samples used were the same ones used in previous pressure sequences (figure 8) and the water was filtered through the Millipore filter only. Both freshly distilled and aged distilled water were used in the first experiment. The aged water had been stored for 4 months in a sealed, carefully cleaned, polyethylene bottle. It was used because of the higher degree of air saturation and, thus, greater sensitivity to pressure gradient. Because of this experiment's importance in representing a continuous sequence of operations, each dependent upon the other, a general summary of results (table 9 and figure 12) are integrated with the description of procedures used.

At the experiment's start, rate of flow was determined through 20 measurement cycles using the *freshly distilled* water. Pressure was controlled at 229 cm. Hg. immediately upstream to the sample face. A similar number of measurements of the rate of flow of the *aged water* through the wood were recorded at the same pressure. Constant rates of flow and identical permeabilities were obtained in

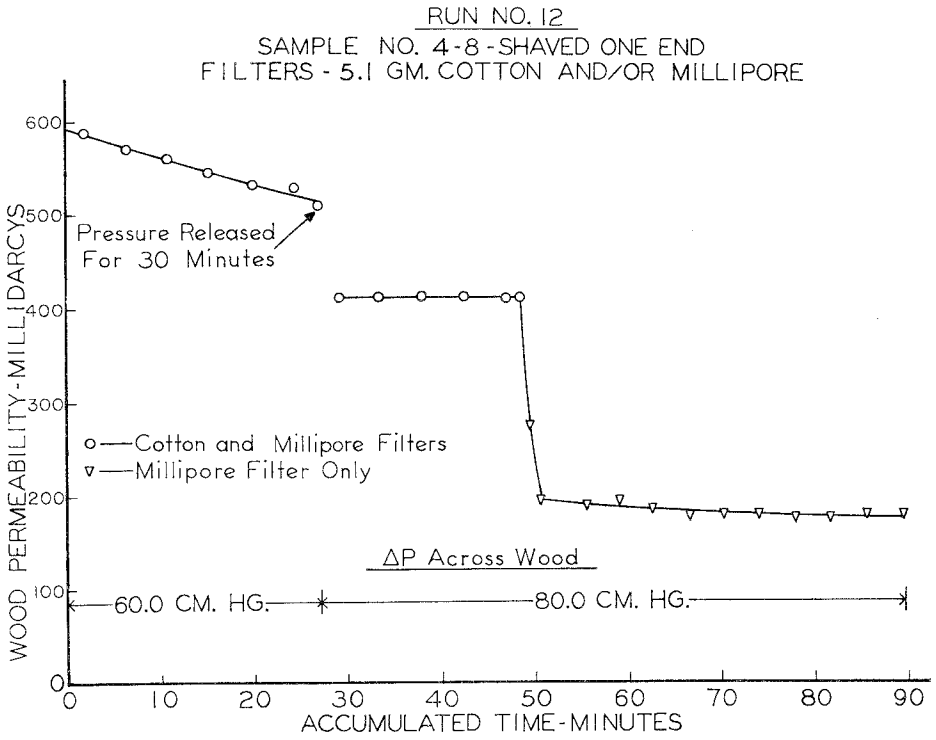

Fig. 11. Effects of a temporary relaxation in pressure and a sudden increase in the gas tension within the liquid upon permeability.

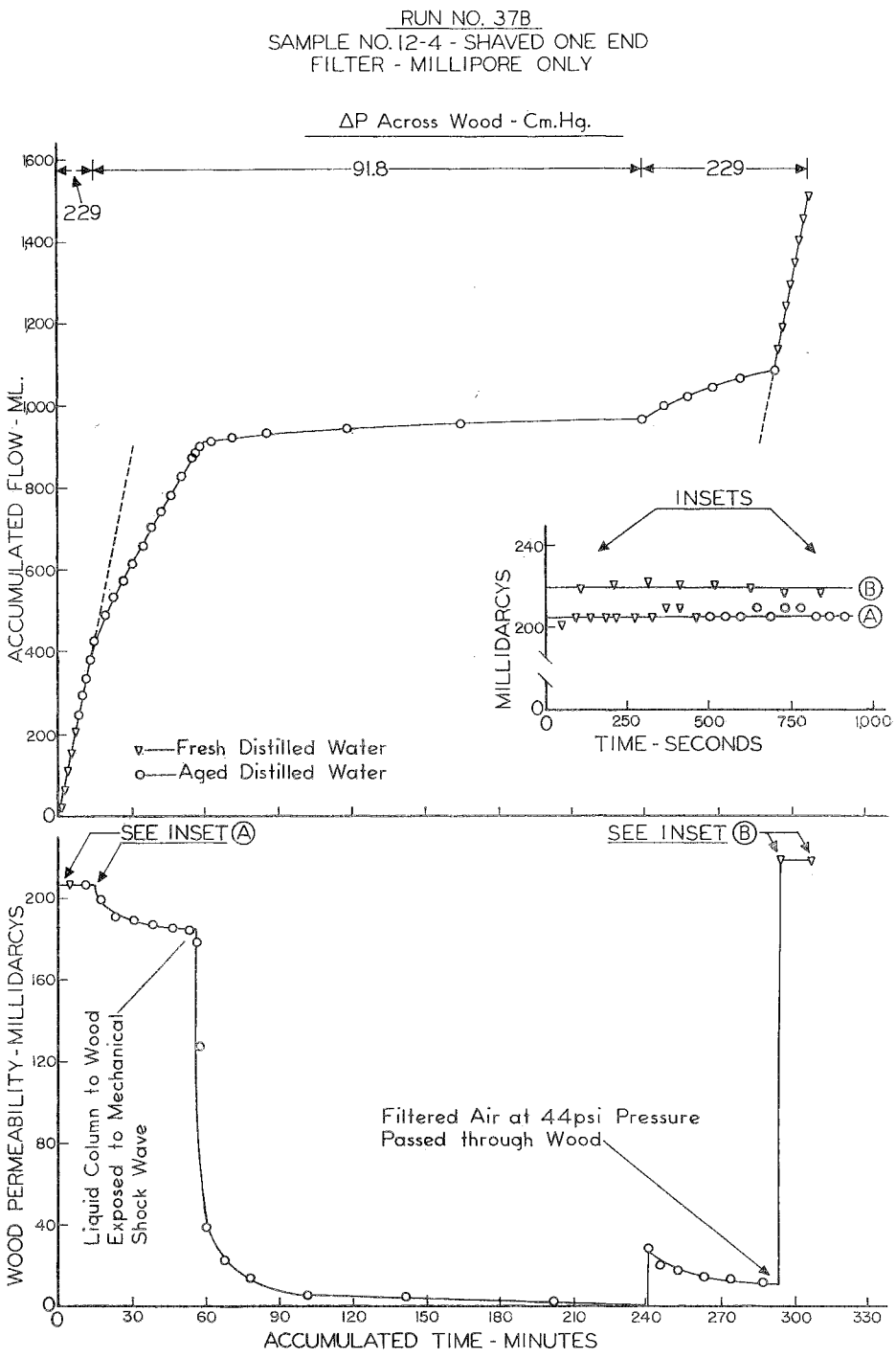

Fig. 12. Effect of mechanical shock upon flow of aged distilled and filtered water through Sitka spruce heartwood.

Table 9. Summary of data for run No. 37B (sample No. 12-4, length = 0.907 cm., diameter = 0.953 cm.; Millipore filter only)

Accumulated time	Accumulated flow	Wood permeability
min.-sec.	milliliters	millidarcys
	fresh distilled water	
	pressure = 229 cm. Hg.	
0.47	22.1	201 (A)*
1-33	44.2†	205 (A)
2-19	66.3	205 (A)
3-5	88.4†	205 (A)
3-51	110.5	205 (A)
4-37	132.6†	205 (A)
5-23	154.7	205 (A)
6-8	176.8†	210 (A)
6-53	198.9	210 (A)
7-39	221.0†	205 (A)
Average		206†
	aged distilled water‡	
	pressure = 229 cm. Hg.	
8-25	243.1	205 (A)
9-11	265.2†	205 (A)
9-57	287.3	205 (A)
10-42	309.4†	210 (A)
11-28	331.5	205 (A)
12-13	353.6†	210 (A)
12-58	375.7	210 (A)
13-44	397.8†	205 (A)
14-30	419.9	205 (A)
15-16	442.0†	205 (A)
Average		207†
	pressure = 91.8 cm. Hg.	
19-3	484.5†	199†
22-53	527.0†	197
26-44	569.6†	190†
30-41	612.1†	190
34-40	654.6†	189†
38-40	697.1†	188
42-42	739.6†	187†
46-45	782.2†	186
50-50	824.7†	185†
54-56	867.2†	184
55-57	877.7†	183†
	liquid column to wood exposed to mechanical shock wave§	
	pressure = 91 cm. Hg.	
57-0	888.2†	178†
58-28	898.7†	127†
63-23	909.2†	38†
71-36	919.7†	22†
84-46	930.2†	13†
118-2	940.7†	5†
164-59	951.2†	4†
239-28	961.7†	2†
	pressure = 229 cm. Hg.	
242-13	972.5†	28†
245-22	983.2	24
249-4	994.0†	20†
253-28	1,004.7	18
258-5	1,015.5†	17†

Table 9 (cont.)

Accumulated time	Accumulated flow	Wood permeability
263-9	1,026.2	15
268-28	1,037.0†	14†
274-4	1,047.7	14
280-1	1,058.5†	13†
286-13	1,069.2	12
293-19	1,080.0†	11†
Filtered air at 44 psi pressure blown through sample for 5 minutes. Sample evacuated.		
	fresh distilled water	
	pressure = 229 cm. Hg.	
295-4	1,133.5†	219 (B)¶
296-48	1,187.0†	221 (B)
298-31	1,240.5†	223 (B)
300-15	1,294.0†	221 (B)
301-59	1,347.5†	221 (B)
303-44	1,401.0†	219 (B)
305-30	1,454.5†	217 (B)
307-16	1,508.0†	217 (B)
Average		220†

* The A in parentheses identifies the points plotted in inset A, figure 12.

† Points plotted in figure 12.

‡ This water was aged for 4 months in a sealed polyethylene jug.

§ The shock was applied by hitting the Millipore filter three sharp blows with a hammer.

¶ The B in parentheses identifies the points plotted in inset B, figure 12.

both cases (figure 12, inset A). Pressure on the supply tank containing the aged water was reduced to 91.8 cm. Hg. Flow was continued at this pressure for 41 minutes during which the permeability decreased slowly and fine air bubbles appeared in the liquid flowing out of the sample.

The liquid column leading to the wood was then exposed to three successive mechanical shock waves by striking the Millipore filter sharp blows with a hammer. Permeability then decreased rapidly and masses of fine air bubbles collected in the downstream end of the sample tube (figure 13). Pressure on the sample was increased to 229 cm. Hg. and maintained at this level for 50 minutes with little effect upon permeability. Air bubbles continued to flow from the downstream end.

The sample remained in the equipment overnight with no pressure on that part of the system downstream of the

Millipore filter. It was then removed and evacuated. The equipment was cleaned, freshly distilled water placed in the supply tanks, and flow initiated through the Millipore filter and sample at 44 psi. Data for this portion of the run are presented as the timed sequence of photographs illustrated in figure 14. Shortly after flow was initiated, masses of air bubbles accumulated downstream from the sample.

At the conclusion of the sequence the sample was removed from the system and purged of liquid in the same direction with filtered air at 44 psi pressure. It was then evacuated, replaced in the system, and its permeability again determined using freshly distilled water. Figure 12, inset B, illustrates recovery by this process of all the permeability lost during the previous part of the experiment.

Recovery of the permeability by passing air through the sample should eliminate any possibility that the shock wave: (1) dislodged particles from cell walls to block flow channels, or (2) caused aspiration of pits.

A similar experiment using freshly distilled water is illustrated in figure 15. The rapid decrease in permeability after mechanical shock was identical with that observed for aged water except afterwards no air bubbles appeared downstream of the sample. However, when the direction of flow through the sample was reversed, fine air bubbles issued from the "now-downstream" original inflow surface. Permeability then increased to 71 percent of that in the original direction. But it again decreased on continued flow to 56 percent.

Direction of flow was again reversed so that the original inflow surface would be upstream. Failure to regain original permeability by backflushing the initial inflow surface suggests that the shock treatment caused the liquid to cavitate beyond the first pit with formation of air bubbles within whole tracheids. Reversal of direction of flow would not then remove them from the wood.

After standing overnight in the equipment at atmospheric pressure, the sample was removed and purged in both directions with filtered air at 44 psi pressure. It was then evacuated and placed again in the system. Flow was continued through several more reversals until permeability in both directions approached that of the original. The gradual decrease in permeability with the shaved surface upstream for the first two reversals after exposing the sample to the filtered air was caused by failure of the reevacuation to remove all air from the sample after purging. An additional evacuation resulted in constant flow in both directions.

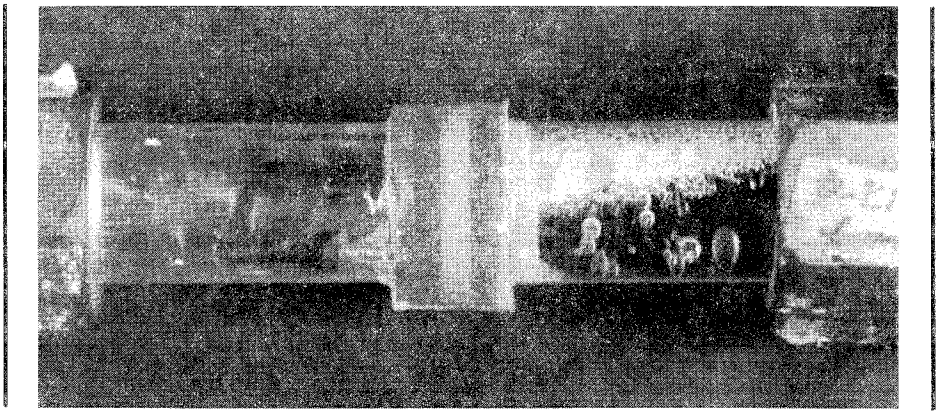

Fig. 13. Air bubbles in downstream end of sample tube after subjecting aged and filtered distilled water to mechanical shock as it passed through the wood.

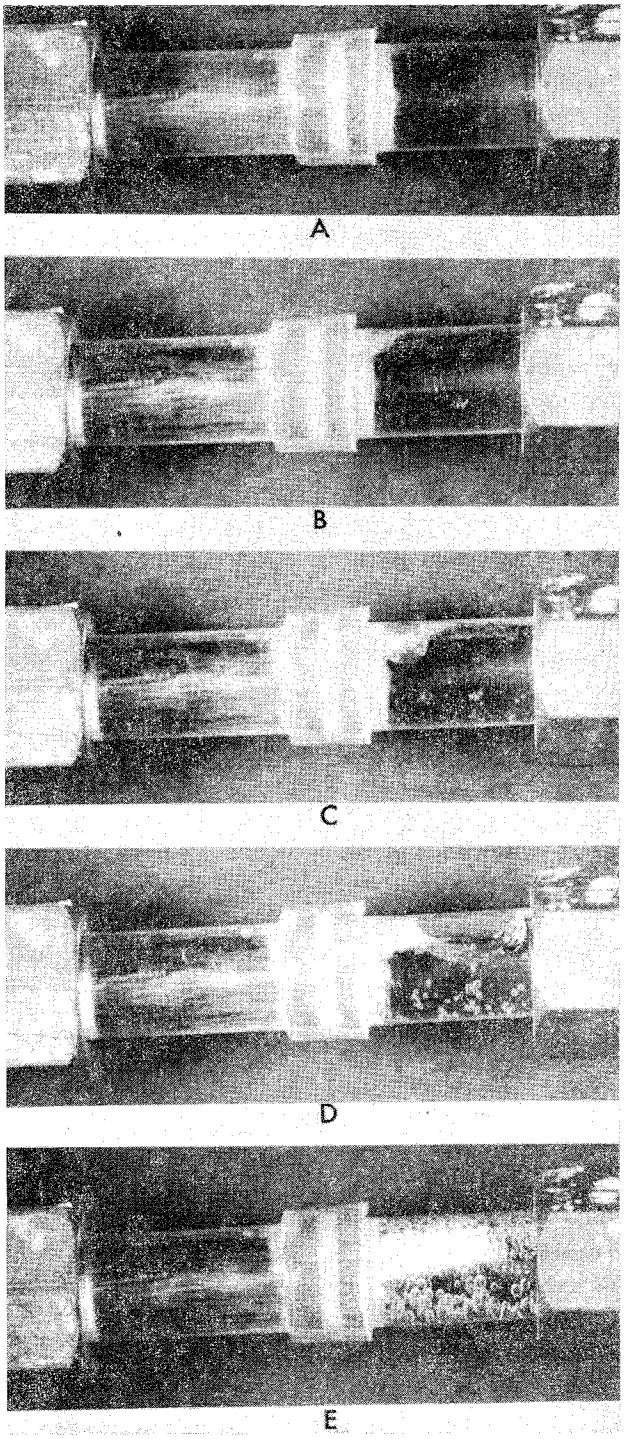

Fig. 14. Rate of accumulation of air bubbles. Sample No. 12-4 had been reduced in permeability to aged and filtered distilled water by exposing the flowing liquid to mechanical shock. After standing flow of freshly distilled water was initiated with consequent downstream bubble formation.

Data for figure 14 (sample No. 12-4, length = 0.907 cm., diameter = 0.953 cm.; Millipore filter only; pressure = 44 psi

Fig. No.	Accumulated time	Accumulated flow
	min.-sec.	milliliters
14A	0-0	0
14B	24-36	136
14C	32-56	181
14D	48-39	271
14E	97-44	555

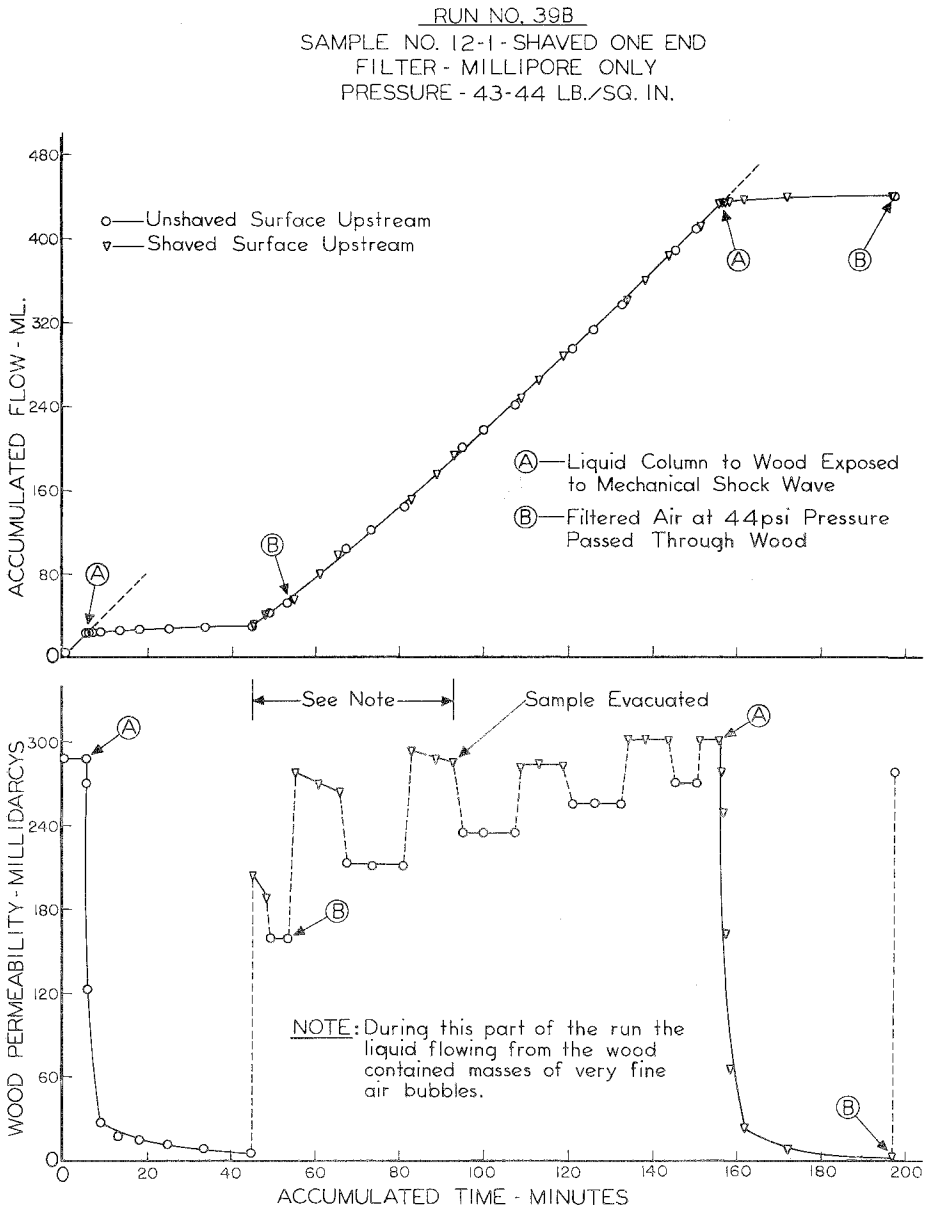

Fig. 15. Effect of mechanical shock upon flow of freshly distilled and filtered water through Sitka spruce heartwood.

When the permeability with the shaved surface upstream became constant, the liquid column to the wood was exposed to the same shock treatment as that applied with the unshaved surface upstream. Permeability decreased rapidly as was true with flow in the opposite direction. Purging the sample again with filtered air returned the permeability to the original value.

Table 10. Summary of data for run No. 39B (sample No. 12-1, length = 0.886 cm., diameter = 0.950 cm.; Millipore filter only; pressure = 43-44 lb./sq. in.)

Accumulated time	Accumulated flow	Wood permeability
min.-sec.	milliliters	millidarcys
	unshaved surface upstream	
0-32	22.0	289
5-22	220.0	289
	liquid column to wood exposed to mechanical shock wave*	
5-38	230.2	270
6-12	240.3	123
8-54	250.5	27
13-16	260.7	17
18-25	270.9	14
24-45	281.0	11
33-39	291.2	8
44-48	301.4	6
	shaved surface upstream	
45-10	312.0	205
48-38	407.4	188
	unshaved surface upstream	
49-6	418.0	161
53-22	513.4	161
	filtered air at 44 psi pressure passed through wood	
	shaved surface upstream	
54-52	572.4	278
60-55	808.4	270
65-34	985.4	264
	unshaved surface upstream	
67-30	1,043.9	214
73-21	1,219.4	211
81-17	1,453.4	211
	shaved surface upstream	
82-45	1,513.9	294
88-39	1,755.9	288
93-10	1,937.4	285
	sample evacuated	
	unshaved surface upstream	
94-57	1,996.4	234
100-15	2,173.4	236
107-22	2,409.4	234
	shaved surface upstream	
108-51	2,468.4	281
113-15	2,645.4	284
119-11	2,881.4	281
	unshaved surface upstream	
120-51	2,940.6	255
125-50	3,118.4	255
132-36	3,355.4	254
	shaved surface upstream	
134-2	2,315.4	303
138-20	3,595.4	303
144-7	3,835.4	296

Table 10 (cont.)

Accumulated time	Accumulated flow	Wood permeability
	unshaved surface upstream	
145-23	3,882.8	271
150-27	4,072.4	268
	shaved surface upstream	
151-34	4,120.4	302
156-20	4,324.4	297
	liquid column to wood exposed to mechanical shock wave*	
156-37	4,335.8	279
156-56	4,347.1	250
157-25	4,358.5	163
158-37	4,369.9	66
162-7	4,381.3	23
171-59	4,392.6	8
196-47	4,404.0	3
	At this point filtered air at 44 psi pressure was passed through the wood to recover the permeability lost by the mechanical shock treatment.	

* The shock was applied by hitting the Millipore filter three sharp blows with a hammer.

Both foregoing experiments demonstrate that exposure of the liquid to an intense shock wave as it passed through the wood caused permeability to decrease within a few minutes to only a small fraction of the original value. The fact that air readily passes through a sample blocked by this technique supports the hypothesis that cavitation of the liquid and consequent air entrainment is largely responsible for this sudden decrease.

PART II

Confirmation of Air Blockage by an Independent Technique

Substantial evidence has already been presented that accumulation of air within a wood sample was responsible for the observed decrease in rate of flow. However, it would be desirable to confirm the presence of air bubbles by an independent technique.

Study of the literature suggested that the most logical method would be to use conductivity measurements; that is, employ the liquid-filled wood as an electrical conductor. Accumulation of air bubbles

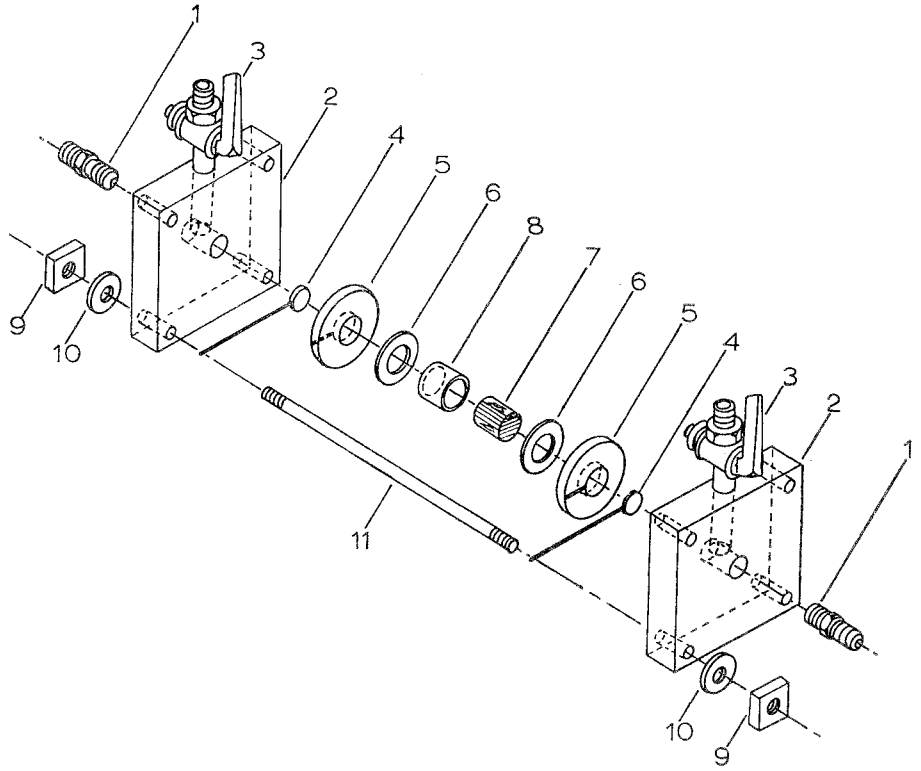

Fig. 16. Exploded diagram of the conductivity cell. 1: ⅛ inch ID flared to ⅛-inch NPT adapter. 2: Plexiglas end plates. 3: two-way ⅛-inch brass valve. 4: 14 karat gold electrodes. 5: Plexiglas flange plates. 6: polyethylene washers. 7: wood sample, 1 cm. in length. 8: ⅜-inch ID polystyrene tube 8 mm. in length. 9: ¼-inch square nut cadmium plated. 10: ¼-inch steel washer cadmium plated. 11: ¼-inch threaded rod cadmium plated.

Flange plates, with electrodes in place, were cemented to the Plexiglas end plates with Plexiglas solvent. Grooves for the gold electrode wires were filled with B7 Plexiglas cement.

would reduce the cross sectional area available for liquid flow and for electric current flow.

Wyckoff (1936), in his study of permeability of various sands to carbon dioxide-saturated electrolyte, employed conductivity measurements to determine the amount of carbon dioxide evolving from the liquid. He observed that conductivity and rate of liquid flow through the sand column decreased as carbon dioxide evolved from electrolyte solution.

Briggs (1928) measured the conductivity of cellulose plugs for computation of zeta potential. He found that the specific conductivity of liquid in cellulose plugs was greater than the specific conductivity of the liquid alone. He attributed this effect to surface conductance along the electrokinetic double layer.

Anderson (1941) studied the effect of electrokinetic phenomena upon flow of distilled water and electrolyte solutions through wood. He found that conductivity decreased as rate of flow decreased. He attributed this to a leaching of electrolytes from cell walls and to a decrease in the cross sectional area of the wood sample. Anderson assumed that he was working in the absence of dissolved air and particulate matter. So he theorized that the decrease in cross sectional area was due to a pivoting of structural units in pit membranes to offer the greatest

resistance to liquid and electrical current flow. Since the present study gives strong evidence that occlusion by air was responsible for the decrease in rate of flow, the decrease in conductivity observed under similar conditions by Anderson was probably due to formation of air bubbles.

Experimental Method and Results

The equipment used in this part of the study was basically the same as that described in figure 1. There were two modifications: (1) a conductivity cell (figure 16) was used in place of the cotton filter cell, and (2) a Heathkit Model 18-2A Impedance Bridge was used for resistance measurements.

The Impedance Bridge was equipped with an internal 1,000 cycle a.c. signal generator and an internal detector circuit. The detector circuit used a meter as a null point indicator. In all resistance measurements the 1,000 cycle a.c. voltage was used in the bridge circuit to prevent polarization of electrodes.

Table 11. Summary of data for run No. 12c (sample No. 11-7, dialyzed, length = 1.06 cm., diameter = 0.945 cm.)

Accumulated time	Permeability	Conductivity
min.-sec.	millidarcys	10^{-6} mho.
7-26	62	4.88
16-17	56	4.76
20-00	102	4.88
23-10	.....	4.44
28-05	96	4.08
36-38	92	3.77
45-20	91	3.60
54-07	88	3.58
62-57	88	3.58
67-36	82	3.38
73-21	78	3.36
77-22	77	3.33
83-36	73	3.29
98-36	.....	3.15
113-36	.....	3.15
130-40	74	3.17
134-55	.....	3.17
139-10	72	3.08
147-45	71	2.96
152-01	72	2.92
158-20	72	2.67

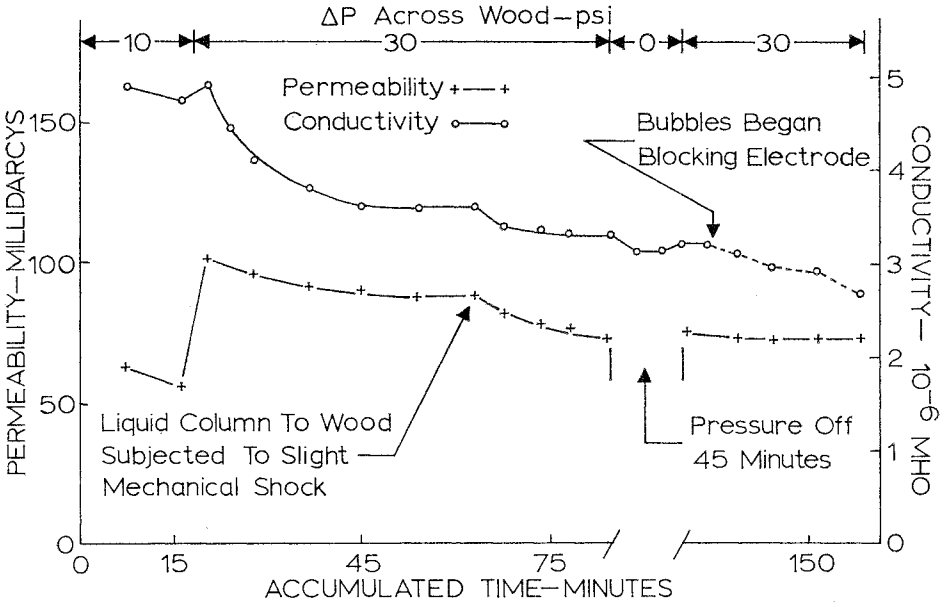

Fig. 17. The relationship between conductivity and permeability of a dialyzed wood sample.

Table 12. Summary of data for run No. 23 (sample No. 12-8, length = 1.06 cm., diameter = 0.945 cm.; 0.01N KCl)

Accumulated time	Permeability	Conductivity
min.-sec.	millidarcys	10^{-5} mho.
1-31	136	50.00
3-48	90	.....
6-52	67	48.08
14-38	50	46.51
23-28	46	45.77
33-42	39	45.35
39-42	34	45.25
42-40	.....	45.66
45-41	48	45.45
53-01	48	45.45
60-23	48	45.45
62-23	.....	44.74
65-23	.....	44.15
69-23	.....	43.76
73-23	.....	44.94
75-23	.....	45.45
80-23	.....	44.25
84-23	.....	43.86
86-53	.....	44.84
89-23	.....	45.45
99-23	.....	43.76

For simplicity and accuracy, resistance was measured during actual flow. However, the possibility that streaming potentials of significant magnitude could develop and thus interfere with the resistance bridge had to be considered. Preliminary experiments with fresh distilled water showed that if flow was stopped and electrodes immediately shorted together and grounded to insure elimination of any electrical charges, resistance was the same as that previously measured during flow. Thus, if streaming potentials were present they were apparently not of sufficient magnitude to interfere with measurements.

An initial experiment confirmed Anderson's (1941) observation that a portion of the conductivity decrease during flow was attributable to leaching of electrolyte from the wood substance. This component of decrease was eliminated from subsequent experiments by predialysis of samples before mounting in the apparatus. Wood samples were prepared for dialysis by evacuating them in the ab-

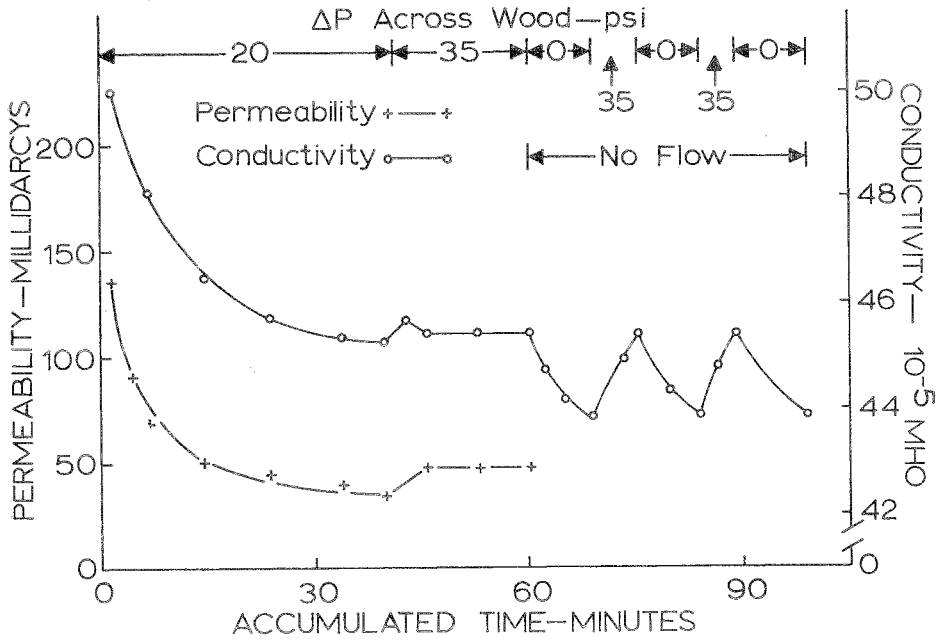

Fig.18. Relation between conductivity of 0.01N KCl and the permeability of a wood sample.

sence of water and then submerging them in distilled and ultra filtered water while still under vacuum. The vacuum was then released to thoroughly penetrate submerged samples. They were then dialyzed against distilled water for 1 week using Visking casing (1⅝-inch diameter cellulose casing, Visking Corporation, Chicago, Ill.) as a semipermeable membrane. The membrane was used primarily to prevent contamination by particulate matter. Dialyzed samples were then air dried and mounted for assembly in the conductivity cell.

Figure 17 and table 11 show results of run No. 12c using a dialyzed sample. Conductivity remained constant during a period of constant rate of flow. Another point of interest (figure 17) was the decrease in conductivity corresponding with the decrease in permeability on subjecting the flowing liquid column to a slight mechanical shock wave.

A third point of significance is found in the final segments of the curves following relaxation of pressure. When pressure was again applied and flow was continued, air bubbles accumulated between the downstream sample end and the electrode. This agrees with the earlier observation illustrated in figures 13 and 14.

Although dialysis of samples eliminated the effect of woodborn electrolytes, the preparation process was time consuming. Another experimental approach would be to substitute a dilute solution of electrolyte as the flowing liquid so the electrolyte concentration effect in wood would be negligible. Preliminary experiments with 0.01N KCl showed that the resistance of the cell was in the appropriate range for accuracy of measurement and that the conductivity followed the permeability in every respect.

After consideration of these results, it was decided that if air bubbles accumulated within a sample that had undergone a decrease in rate of flow, their presence could best be confirmed on the basis of their elastic properties. Figure 18 and table 12 show results of an experiment designed to test this suggestion. After a sample had decreased in permeability as a result of flow, the outflow end of the conductivity cell was capped to prevent flow. Pressure was intermittently applied and released (a pressure sequence). The recorded increase and decrease in conductivity as pressure was applied and relaxed under static conditions confirmed the presence of an elastic system such as air bubbles. This static experiment also eliminated the possibility of streaming potentials interacting with resistance measurements.

If the observed changes in conductivities during static pressure cycles were due to compression and expansion of air bubbles rather than of the wood substance, it should be possible to record a difference in the magnitude of conductivity change when a pressure sequence was performed on a sample at two different permeability values. Figure 19 and table 13 show results of such an experiment.

Table 13. Summary of data for run No. 26 (sample No. 13-3, length = 0.998 cm., diameter = 0.947 cm.; 0.01N KCl)

Accumulated time	Permeability	Conductivity
min.-sec.	millidarcys	10^{-5} mho.
1-27	133	49.75
4-21	.....	49.50
5-49	132	.....
7-17	.....	49.50
10-17	129	49.38
16-17	129	49.38
21-17	.....	49.26
26-17	.....	49.14
31-17	.....	49.26
36-17	.....	49.38
41-17	.....	49.26
46-17	.....	49.14
52-15	118	49.32
58-23	114	49.26
64-45	110	49.20
71-49	102	49.08
80-47	77	49.02
85-47	.....	49.26
90-47	.....	49.38
95-47	.....	49.02
100-47	.....	48.78
105-47	.....	49.14
110-47	.....	49.38
112-53	89	49.26
119-12	89	49.26
123-25	89	49.26

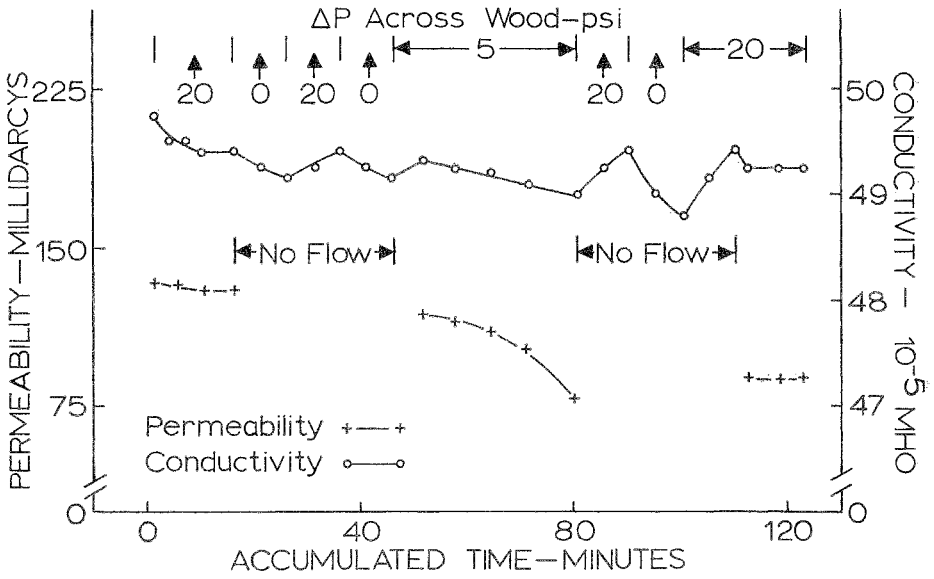

Fig. 19. The effect of static pressure cycling on the conductivity of a sample at different permeabilities.

A constant rate of flow corresponding to the original permeability value was first achieved. Then the pressure cycle was applied under static conditions at 10-minute intervals and the conductivities recorded. Flow was then continued at 5 psi until the sample lost nearly one-half of its original permeability. Static pressure cycles were again applied at 10-minute intervals and the conductivities again recorded.

Data show that a greater change in conductivity occurred in the partially blocked sample. Although changes in conductivity noted initially and prior to plugging could be partially explained by wood compression and relaxation, a more reasonable explanation would be the presence of residual bubbles from the original sample impregnation. The most significant point in this final experiment is that the increase in conductivity range in the second pressure sequence can best be explained by the presence of air bubbles. These accumulated or enlarged in the wood during the period of decreasing rate and were responsible for the decrease in permeability.

Summary of Results and Conclusions

Summary of Results

Results of this representative selection of experiments offer evidence that freshly distilled water will not pass through wood at a constant rate *unless precautions are taken to prevent any dissolved air in the liquid from being deposited as bubbles in the wood.* Figures 10 and 11 show that permeability may be changed drastically by altering either the velocity of flow or the initial gas tension within the liquid. An immediate consequence of these results is that air blockage must be considered as a major factor in accounting for the decreasing rate of flow of liquids through wood, as reported by others. Since such rapid decreases in

permeability were obtained with ultrafiltered water, the role of any particulate matter in freshly distilled water upon the permeability of wood must be reassessed.

Krier (1951) suggested that the principal role of particulate matter is that of a physical occlusion of flow channels. That particulate matter blocks such channels is not questioned. However, the findings of Harvey et al. (Part I, II, 1944) suggest that particulate matter, if present, in freshly distilled water also serves as nuclei for bubble formation. Since decreases shown in figures 10 and 11 for filtered water are as rapid as those obtained in experiments with unfiltered water (not shown), a large amount of the blockage previously attributed to the physical action of particulate matter may actually result from air blockage by bubbles forming on nuclei initially present in the wood.

The exact conditions required for air to evolve from a liquid as it passes through wood cannot be specified. But results of this study indicate that the following variables are important:

1. **Gas Tension within the Liquid**— In presence of a nucleus the possibility of air evolving from the liquid varies directly with the magnitude of gas tension within the liquid. Gas tension within any liquid containing a dissolved gas progressively increases as the flowing liquid is subjected to a negative pressure gradient through a porous material.

This effect is shown in figure 10 by comparing the change in permeability with the pressure drop across the filters. Increasing the pressure drop across the filters by reversing the sample reduced the rate at which permeability declined. Reversal of the sample increased its permeability and shifted a portion of the total pressure drop to the filters. Thus, gas tension decreased in the liquid effluent from the filters. Elimination of the pressure drop by removal of the cotton filter caused the permeability to decrease rapidly before coming to equilibrium. The latter is a true equilibrium and is believed to be directly related to the gas tension within the liquid. For this reason it has been termed a "systemic equilibrium."

Existence of a systemic equilibrium was indicated in a number of experiments, not recorded here. Permeability of the same sample was determined with several cotton filters of progressively increasing density and pressure drop. With the lower density filter the permeability of the wood *decreased* before coming to equilibrium. Insertion of a more dense filter caused the permeability to *increase* before coming to a *higher* equilibrium value. These trends suggest that preexposure to an increasing pressure drop progressively lowered the gas tension of the effluent liquid by deaeration. This, in turn, altered the equilibrium condition in the wood with respect to gas saturation.

2. **Length of Sample** — Numerous trends in data and observations from exploratory runs suggest that the sample's length determines whether the flow of a liquid containing a dissolved gas is constant under given conditions. Rate of flow through samples shorter than approximately 8 mm. almost invariably decreased with time, regardless which filter was used. However, when the cotton filter was used the rate of decrease was less and the final equilibrium value was higher. The tendency for the flow to be unstable below this critical length indicates that the velocity of flow and the associated pressure gradient might be the determining factors. Increasing velocity of flow would reduce pressure in flow channels, in accordance with the Bernoulli equation, and promote evolution of air from the liquid.

These observations suggest that a given porous system may have a critical or "hydrodynamic" length beyond which unstable flow prevails unless all air can be removed from the system. Thus, at a given pressure, the critical length for stable flow through wood should vary depending upon its basic permeability. Additional data are needed to evaluate this concept.

Krier (1951) demonstrated that most blockage occurs near the inflow surface. Resurgence of flow obtained by reversing the sample, as shown in figure 10, supports this conclusion. However, as Krier noted, reversing direction of flow did not produce the expected great response when the sample was more completely blocked. This effect suggests that some blockage must occur downstream of the first pit where it cannot be flushed out upon reversal of flow direction. Air bubbles could accumulate in this region either by evolving from the liquid as it passed through pores in pit membranes or by growth of existing nuclei within a tracheid.

The decrease in permeability upon standing, as indicated in figures 9 and 11, is further evidence that air blockage is involved in most studies of flow of liquids through wood. Neither of these relationships would have occurred as indicated unless an elastic system existed. The same type of elastic system is illustrated in figure 8. This relates the response of flow to pressure for fresh and aged water samples. Since all these conditions are influenced by pressure, this response is a necessary and sufficient reason for suggesting that the elasticity developed because of changes in the amount of free gas in the wood. The proportionality of flow to pressure obtained by preexposure of a sample to high pressure flow before running the lower pressure sequence, as illustrated in figure 7, is also evidence that this elastic effect results from presence of air bubbles.

This elastic effect may also manifest itself during a cyclic pressure sequence, especially if the liquid contains sufficient air to be supersaturated at the lower pressure. Air bubbles would evolve from the liquid upon relaxing of the pressure. They would reduce the permeability at the higher pressure unless the intensity of the pressure would expel or redissolve the bubbles from the wood upon continuation of flow.

The decrease in permeability obtained by exposing the liquid to a mechanical shock wave as it passed through the wood also demonstrates the extent that air bubbles may block flow channels in wood. Permeability can be reduced to near zero by this technique, even at a driving pressure of 44 psi. The recovery of this loss in permeability by passing air through the wood leaves little doubt that blockage was caused by an instantaneous cavitation of the liquid in the wood.

The intensity of the negative component of the shock wave introduced into the system by this technique is not known. Work of Harvey et al. (Part I, 1944) indicates that it must be sufficient to exceed the tensile strength of the liquid. In addition, any existing air bubbles in the wood would be enlarged since the reduction in permeability depended upon the intensity and frequency of striking the filter unit. A slight blow would reduce the permeability only a few percent. An intense blow would produce a much greater reduction. A rapid sequence of blows would reduce the permeability almost to zero. Harvey et al. (Part I, 1944) describe the effect of a sequence of shock waves on bubble growth as follows:

> Inertial resistance determines rate (of bubble growth) where local negative pressures occur in pressure pulses, sound waves, Bernoulli effects, turbulence or from stretching. Even though positive components accompany the negative, as in sound waves, bubbles tend to grow continuously with a succession of pulses, because the surface area is always greater in a bubble during the negative pressure phase when gas moves in as compared with the positive pressure phase when gas moves out. In liquids of low viscosity the net effect is gas diffusion into the bubble.

The fact that water becomes supersaturated with air upon standing is also of interest. Krier (1951) observed that aged distilled water reduced the permeability of wood faster than freshly distilled water. Figure 13 strongly suggests that this action can be attributed to the supersaturated condition of the aged water.

The progressive increase in permeability indicated in figure 15 is unique. Others (Anderson, et al., 1941; Krier, 1951) reported that the response upon reversal *decreased* after one or two reversals. This difference probably results from the fact that constant rates of flow were obtained in the present study. Results reported in the literature were obtained in the presence of unsteady flow. In part II of the experimental work it is also shown that changes in electrical conductivity correspond with changes in permeability of flow to water and electrolyte solutions through wood specimens. These confirmatory results give a large measure of confidence to the disclosure of air bubble blockage as a controlling factor in the permeability of wood to liquids.

Conclusions

1. Air blockage is a common phenomenon when distilled water is passed through wood in response to an externally applied pressure. It is probably a predominant cause of the decreasing rate of flow with time which was previously reported in the literature.

2. A constant rate of flow of distilled water through seasoned wood can be obtained and maintained indefinitely over a wide range of pressures if:

- The liquid is previously passed through an ultrafilter to remove foreign particles. These particles not only physically occlude the capillaries but also function as nuclei for the evolution of air from the liquid; and
- The gas tension within the liquid is sufficiently low so that nuclei present in the wood will not grow significantly under prevailing hydrodynamic conditions. Of the latter, the local reduction in pressure in response to the change in the velocity of flow appears to be the most important consideration.

3. A proportionality of flow to pressure can be obtained through seasoned wood if the wood is preexposed to a high pressure gradient before running the pressure sequence.

4. The disproportionality of flow to pressure frequently observed with wood is probably caused by air bubbles remaining after the usual evacuation procedure.

5. Darcy's law, which was originally developed to describe the flow of fluids through inert porous materials, can also be used to characterize the permeability of wood to liquids.

6. The decrease in the permeability of wood following storage in distilled water probably results from the gradual development of air bubbles from the supersaturated liquid in the wood. These bubbles arise from nuclei in the wood.

7. A mechanical shock wave applied to a liquid, as water, as it passes through wood can cause the liquid to cavitate and deposit air in the wood, greatly reducing the permeability.

Selected Bibliography

ANDERSON, B. E., GORTNER, R. A., and SCHMITZ, H. 1941. Factors Affecting the Decreasing Rate of Flow of Liquids through Wood. Univ. Minn. Agr. Expt. Sta. Bull. 146.

BRIGGS, D. R. 1928. Determination of Zeta Potential on Cellulose. Jour. Phys. Chem. 32:642-675.

BUCKMAN, S. J., SCHMITZ, H., and GORTNER, R. A. 1935. A Study of Certain Factors Influencing the Movement of Liquids in Wood. Jour. Phys. Chem. 39:103-120.

DEAN, R. B. 1944. The Formation of Bubbles. Jour. Appl. Phys. 15(5):446-451.

DE MONTIGNY, R. and MAASS, O. 1935. Investigation of Physicochemical Factors which Influence Sulphite Cooking. For. Ser. Bull. 87, Dept of Int., Canada.

ERICKSON, H. D. 1960. The Effects of Storage Conditions and Time upon Permeability of Green Sapwood. Proc. Amer. Wood-Preservers' Assoc. 56:156-165.

_____ and CRAWFORD, R. J. 1959. The Effects of Several Seasoning Methods on the Permeability of Wood to Liquids. Proc. Amer. Wood-Preservers' Assoc. 55: 210-220.

_____ and ESTEP, E. M. 1962. Permeability of Douglas Fir Heartwood from Western Washington. For. Prod. Jour. 12(7):313-324.

_____, SCHMITZ, H., and GORTNER, R. A. 1937. The Permeability of Woods to Liquids and Factors Affecting the Rate of Flow. Univ. Minn. Agr. Expt. Sta. Tech. Bull. 122.

HARVEY, E. N., BARNES, D. K., MCELROY, W. D., WHITELEY, A. H., PEASE, D. C., and COOPER, K. W. 1944. Bubble Formation in Animals. I. Physical Factors. Jour. Cell. and Compar. Physiol. 24:1-22.

_____, WHITELEY, A. H., MCELROY, W. D., PEASE, D. C., and BARNES, D. K. 1944. Bubble Formation in Animals. II. Gas Nuclei and Their Distribution in Blood and Tissues. Jour. Cell. and Compar. Physiol. 24:23-34.

_____. 1945. Removal of Gas Nuclei from Liquids and Surfaces. Jour. Amer. Chem. Soc. 67:156-157.

JOHNSTON, H. W. and MAASS, O. 1930. The Path of Liquid Penetration in Jack Pine. Can. Jour. Res. 3:140-173.

KING, F. H. 1899. Principles and Conditions of the Movements of Ground Water. U. S. Geol. Survey, 19th Ann. Rpt., Pt. 2:59-294.

KNAPP, R. T. 1958. Cavitation and Nuclei. Trans. ASTM. August (Paper No. 57-A-80).

KRIER, J. P. 1951. Factors Causing Decreasing Rate of Longitudinal Flow of Liquids through Freshly Cut Woody Stems. Unpub. Ph.D. Dissertation, Yale Univ.

LIEBERMANN, L. 1957. Air Bubbles in Water. Jour. Appl. Phys. 28:205-211.

MUSKAT, M. 1946. The Flow of Homogeneous Fluids through Porous Media. J. W. Edwards, Inc., Ann Arbor, Mich.

PEASE, D. C. and BLINKS, L. R. 1947. Cavitation from Solid Surfaces in the Absence of Gas Nuclei. Jour. Phys. and Colloid. Chem. 51:556-567.

RUTH, B. F. 1935. Studies in Filtration: IV. Nature of Fluid Flow through Filter Septa and Its Importance in the Filtration Equation. Ind. Engin. Chem. 27:803-816.

SCHWEITZER, P. H. and SZEBEHELY, V. G. 1950. Gas Evolution in Liquids and Cavitation. Jour. Appl. Phys. 21:1218-1224.

STRASBERG, M. 1956. Undissolved Air Cavities as Cavitation Nuclei. Proc. on Symposium on Cavitation in Hydrodynamics. Nat. Phy. Lab. Her Majesty's Stationery Office, London.

SUTHERLAND, J. H., JOHNSTON, H. W., and MAASS, O. 1934. Further Investigation of the Penetration of Liquids into Wood. Can. Jour. Res. 10:36-72.

WARDROP, A. B., and DAVIES, G. W. 1958. Some Anatomical Factors Relating to the Penetration of Water into Xylem of Gymnosperms. Aust. Jour. Bot. 6(2):96-102.

WYCKOFF, R. D., and BOTSET, H. G. 1936. The Flow of Gas-Liquid Mixtures through Unconsolidated Sands. Physics 7:325-345.

Submitted for publication October 15, 1962
Approved for publication January 3, 1963

3M-1-63