# LONGITUDINAL WATER PERMEABILITY OF WESTERN HEMLOCK[1] II. UNSTEADY-STATE PERMEABILITY

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## ABSTRACT

A mathematical model was developed and used as the basis for constructing two experimental apparatuses to investigate the permeability of western hemlock to water. When unsteady-state and steady-state permeability were compared, the unsteady-state permeability of both sapwood and normal heartwood was found to be higher than the steady-state permeability, but that of wetwood was generally lower than the initial steady-state permeability and was of the order of the final steady-state permeability. The permeability of western hemlock to water, regardless of whether it is measured by steady-state or unsteady-state techniques, is the highest for sapwood, followed by wetwood and normal heartwood.

Under unsteady-state conditions, sapwood permeability is time-independent, but wetwood exhibits time-dependent behavior, probably caused by blocking of the openings on pit membranes by movable extractives when water flows through the cell lumen. Storing western hemlock wetwood in water at room temperature reduces its water permeability. Wet pockets that form when wetwood of western hemlock is subjected to kiln-drying have lower permeability than the dried portion of the lumber.

*Additional keywords:* Tsuga heterophylla, sapwood, heartwood, wetwood, kiln-drying, wet pockets.

## INTRODUCTION

Steady-state techniques for determining specific permeability coefficients using constant pressure differences across test specimens are widely adopted because of simplicity in theory and execution of experiment. Yet actual industrial processes include unsteady-state conditions where there is a continuous change in the pressure differences. Determination of permeability by the unsteady-state method, however, has seen little use because of difficulty in obtaining exact solutions for the second-order differential equation. The solution of the differential equation can be estimated by numerical methods, for a given boundary condition. However, to use the method as the basis to calculate permeability requires measurement of pressure at three equally spaced points along the flow paths in the test specimen and makes the experiment difficult to perform on small test specimens.

The present investigation was undertaken, first, to develop a simplified unsteady-state technique for determining the permeability of wood to liquid, in this study, water; second, to enlarge the list of known properties of wetwood[2] in western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) by using newly developed measuring techniques.

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[1] Paper 858, School of Forestry, Oregon State University.

[2] Wetwood is heartwood that has a much higher moisture content than normal heartwood in the never-dried condition, appearing as a wet zone under naked eyes.

## THEORY

Consider a pressure cell (Fig. 1) that contains a known volume of air space, separated from a volume of water by a corrugated dental-rubber membrane having negligible resistance to pressure. When the air chamber is pressurized to provide the force necessary to cause water to flow through a porous wood specimen that contains a continuous column of water, the amount of water that passes through the specimen is equivalent to the increase in the volume of air in the air pocket over the rubber membrane. If the water is an incompressible fluid and the flow of water through a small wooden specimen at an instantaneous moment obeys the integral form of Darcy's law, then:

$$\frac{dV}{dt} = \frac{k\,AP}{\eta L},\qquad(1)$$

where $dV$ is the volume of liquid that flows through wood in a small time interval $dt$; $k$ is the specific permeability; $A$ is the cross-sectional area of liquid flow; $P$ is the gage pressure inside the pressure cell with respect to that at the outside of the cell, which is held constant; $\eta$ is the viscosity of the flowing liquid; and $L$ is the specimen length through which the liquid must flow.

Another assumption is that air in the upper compartment of the cell behaves as an ideal gas according to the ideal gas equation:

$$PV = nRT = \text{Constant} = C\qquad(2)$$

Differentiation of equation (2) yields:

$$dV = -\frac{C}{P^2}\cdot dP,\qquad(3)$$

which indicates the expansion in volume of air associated with decrease in the pressure of the cell. Constant $C$ can be determined by knowing the initial pressure, $P_i$, and volume, $V_i$, of the air chamber.

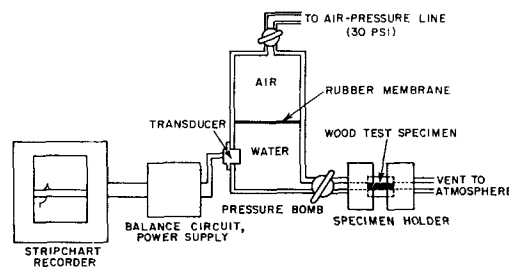Because the increase in volume of the air chamber corresponds to the volume



Fig. 1. Flow diagram of the first unsteady-state permeability apparatus.

of water that passes through the wood specimen, equation (1) can be equated to (3) and rearranged to give:

$$-\frac{dP}{P^3} = \frac{k\,A}{C\eta L}\,dt\qquad(4)$$

Integrating (4) and applying the initial conditions that at $t = 0$, $P = P_i$, the initial pressure inside the cell, yields:

$$\frac{1}{P^2} = \frac{2\,k\,A}{C\eta L}\cdot t + \frac{1}{P_i{}^2}\qquad(5)$$

Equation (5) suggests that the specific permeability, $k$, can be calculated from the slope of the plot of $1/P^2$ versus time provided that $A$, $\eta$, $L$, and $C$ are known.

## EXPERIMENT

### Unsteady-state versus steady-state water permeability

The initially designed experimental system contains three components (Fig. 1): a stainless steel pressure cell, the specimen holder, and a transducer-recorder. The pressure cell is a two-piece unit and, when bolted together, consists of two compartments separated by a corrugated dental-rubber membrane. Its lower compartment is connected to the upstream end of the specimen and a pressure transducer. The transducer is connected to a stripchart recorder by way of a balance circuit and a DC power supply for the transducer. In operation, the lower compartment of the pressure cell is filled with water. The upper compartment contains air under pres-
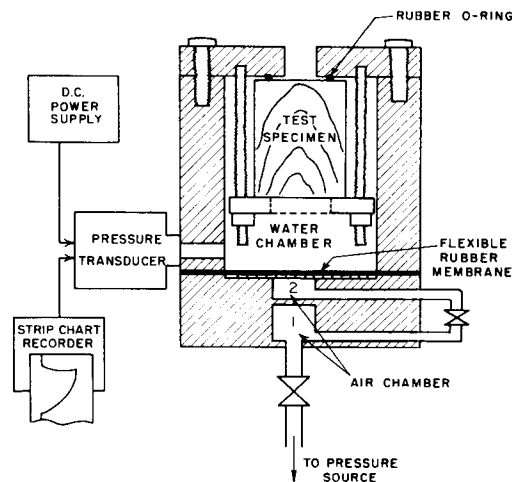
Fig. 2. Diagram of the second unsteady-state permeability apparatus.

sure, which acts as a driving force to cause the water to flow through the test specimen. As the volume of the air compartment increases, pressure in both the air and water compartments decreases and is recorded on a stripchart.

Test specimens were never-dried western hemlock consisting of 10 sapwood, 7 normal heartwood, and 10 wetwood dowels, made from wood collected from a sawmill in Turner, Oregon. The dowels were 1 cm in diameter and 2 cm along the grain and were imbedded into Lucite tubes with epoxy resin as binder. After steady-state permeability measurement (which is the first part of the series of this paper by Lin et al. 1973), an unsteady-state experiment was conducted. The unsteady-state permeability coefficient of each specimen was calculated from the slope of the linear relation between $1/P^2$ versus time using the least-squares method.

### Improved design of unsteady-state permeability test

a. *Apparatus*: The difficulty of the previous design was that it required from one-half to 6 hr of testing to complete a measurement, depending on the permeability of the specimen. A second unsteady-state permeability device was developed

(Fig. 2). The differences between the two are: The second device has two air chambers rather than one; the total volume of air space in the air chambers of the second device (5 cc) is very much smaller than that of the first device (95 cc), so that a small flow of water through a test specimen would result in considerable change in the pressure inside the pressure cell; and the test specimen is immersed in the water of the liquid chamber of the second device. This method eliminated encapsulating the test specimen in a Lucite tube, thus simplifying specimen preparation.

After the first air chamber is pressurized, the apparatus is isolated from the line pressure. When air chamber 2 is connected to chamber 1 (Fig. 2), it provides hydraulic force, which pushes liquid through the test specimen. Change in the pressure in the pressure cell is recorded on a potentiometric stripchart recorder. A difficulty in this device is often caused by introducing air pockets inside the liquid chamber when a specimen is placed in it, and this affects the volume of the air space in the chamber and constant $C$ in equation (5). Therefore, the amount of water flowing through the test specimen is collected in a 10-ml graduated cylinder from which $C$ and the total volume of air space in the test cell at $t = 0$ are calculated.

The test lasted from about 2 to 10 min, depending upon permeability of test specimens. An initial pressure of 30 psi was applied throughout the study. This experimental arrangement was made to determine the effect of frequency of testing, ponding, and drying on the water permeability of western hemlock.

b. *Test specimens*: All test specimens were never-dried western hemlock of approximately 2.5 by 2.5 by 4 cm along the grain. The four side-surfaces of the specimens were flash-dried with a high-intensity infrared lamp and were coated with molten paraffin wax. Specimens then were placed in a desiccator and subjected to evacuation under distilled water that was freshly made, boiled, and cavitated as in Part I

(Lin et al. 1973). All test specimens were stored in such condition until testing to ensure complete saturation with water. Three specimens that did not sink in water after storage for more than 4 days in evacuated, degassed distilled water were discarded because of the possibility that air blockage in wood would prevent measurement of true permeability (Kelso et al. 1963).

c. *Effect of frequency of testing*: Lin et al. (1973) observed that the permeability of sapwood and wetwood of western hemlock deteriorates with time. For sapwood, it was theorized that time-dependent pit aspiration took place during the steady-state experiment, which mainly caused a decrease of flow. In wetwood, the movement of extractives under hydraulic gradients in specimens caused incrustation of pit membranes, which was considered the major cause for the consistent decrease in permeability. To examine the existence of similar time-dependency under unsteady-state conditions, 11 sapwood and 13 wetwood specimens were prepared as described in b and a. One-way analysis of variance was performed for sapwood and wetwood separately.

d. *Effect of storage*: Permeability of wood changes during storage, depending upon the conditions under which wood is stored. Ten test specimens of western hemlock wetwood were selected and saturated with distilled water. The time between felling of the trees and the first testing of permeability was estimated as one month. The permeability of specimens to water was measured by the second apparatus. They then were stored in freshly boiled distilled water at room temperature. The permeability of test specimens was measured again after 2 weeks, after 1 month, and after 1 year of storage. The test results were analyzed using one-way analysis of variance.

e. *Effect of drying on the permeability of wetwood of western hemlock*: When western hemlock lumber containing wetwood
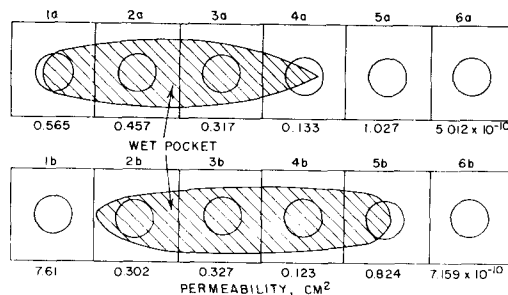


Fig. 3. Unsteady-state longitudinal water permeability (the numbers under the figure) of western hemlock heartwood after kiln-drying. The shaded areas denote the formation of wet pockets after drying.

is dried under a commercial schedule, it usually results in lumber containing wet pockets. The moisture content of wet pockets is usually higher than fiber saturation (Kozlick et al. 1972). A charge of 2 by 8-inch western hemlock lumber was dried under a commercial hemlock schedule for 120 hr in a laboratory kiln. Two boards from which test specimens were cut contained at least 75% wetwood while green. Wet pockets remained after drying, and specimens 4 cm in length along the grain were cut from the center of each board. A total of 12 test specimens was obtained, and the distribution of wet pockets across the boards is shown in Fig. 3. The specimens were immersed in distilled water and subjected to five cyclic treatments of evacuation and pressure of 70 psig to restore water into the wood. The unsteady-state water permeability of the specimens was measured using the second device. None of the test specimens showed formation of air bubbles at the exit end of wood during the test.

### RESULTS AND DISCUSSION

#### Steady-state versus unsteady-state water permeability

The linear regression analysis of $1/P^2$ versus time, $t$, showed that all the coefficients of determination ($R^2$) were greater than 0.9, and the majority of these were 0.98 or higher (Fig. 4). Therefore, the
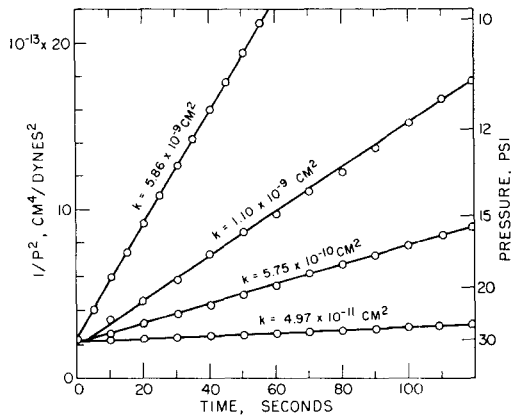
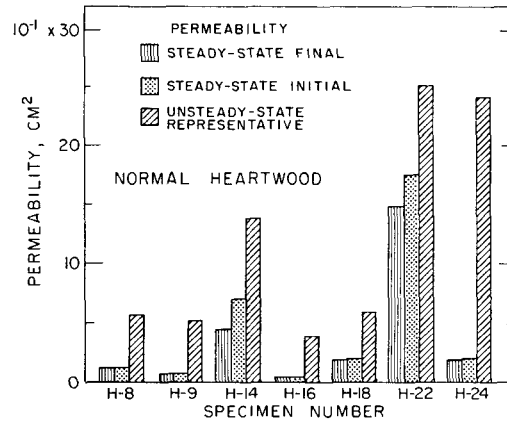Fig. 4. Typical plot of $1/P^2$ vs. time for unsteady-state flow of water through a short test specimen.



Fig. 6. A comparison of permeability values derived by steady-state and unsteady-state methods for western hemlock normal heartwood.

relation predicted by equation (5) appears to be acceptable.

Figures 5 to 7 show the comparison between steady-state and unsteady-state water permeability of western hemlock. Generally, the unsteady-state permeability is much higher than the steady-state permeability for sapwood and normal heartwood. The cause of the differences in permeability is not exactly known, but it can be caused by differences in the techniques of measurement and the recovery from partial pit aspiration. In wetwood, unsteady-state permeability is lower than the initial steady-state values and approxi-

mately equal to the final steady-state permeability. This was considered the result of incrustation of pit membranes during test by extractives, which migrated with the flow of water through the specimen.

## Effect of frequency of testing

Table 1 shows the statistical summary of the effect of frequency of testing on the unsteady-state water permeability of sapwood. Analysis of variance indicated that the $F$-ratio is not significant at all. Examination of individual data and average permeability revealed that there is no tendency to show a decreasing trend in water permeability.

In the steady-state experiment, the flow rates of water through sapwood specimens
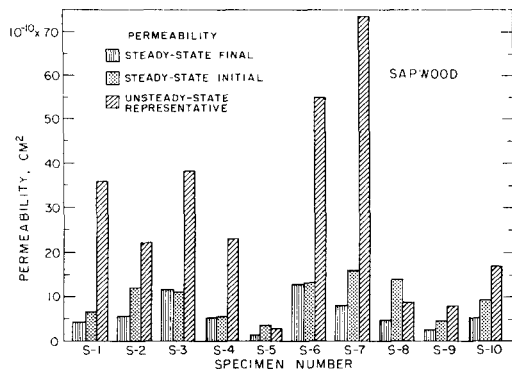


Fig. 5. A comparison of permeability values derived by steady-state and unsteady-state methods for western hemlock sapwood.
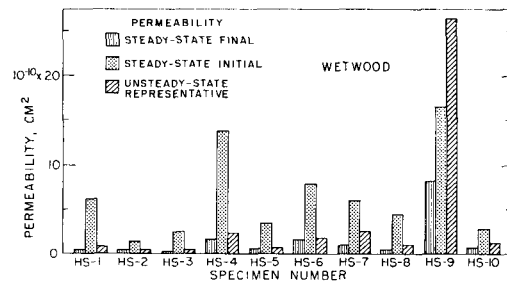


Fig. 7. A comparison of permeability values derived by steady-state and unsteady-state methods for western hemlock wetwood.

TABLE 1. *Summary of the effect of frequency of testing on the unsteady-state longitudinal water permeability of western hemlock sapwood*

| Testing order | Mean | Degrees freedom | Standard deviation |
|---|---|---|---|
| 1 | $228.09 \times 10^{-10}$ | 10 | $91.22 \times 10^{-10}$ |
| 2 | $243.17 \times 10^{-10}$ | 10 | $102.51 \times 10^{-10}$ |
| 3 | $241.26 \times 10^{-10}$ | 10 | $106.99 \times 10^{-10}$ |
| 4 | $232.70 \times 10^{-10}$ | 10 | $99.22 \times 10^{-10}$ |
| 5 | $229.71 \times 10^{-10}$ | 10 | $101.57 \times 10^{-10}$ |

TABLE 2. *Summary of the effect of frequency of testing on unsteady-state longitudinal water permeability of western hemlock wetwood*

| Testing order | Mean | Degrees freedom | Standard deviation |
|---|---|---|---|
| 1 | $11.03 \times 10^{-10}$ | 12 | $3.18 \times 10^{-10}$ |
| 2 | $10.53 \times 10^{-10}$ | 12 | $3.40 \times 10^{-10}$ |
| 3 | $9.48 \times 10^{-10}$ | 12 | $2.86 \times 10^{-10}$ |
| 4 | $8.76 \times 10^{-10}$ | 12 | $2.79 \times 10^{-10}$ |
| 5 | $8.16 \times 10^{-10}$ | 12 | $2.56 \times 10^{-10}$ |
| Total | $9.59 \times 10^{-10}$ | | |

Analysis of Variance

| Source | d.f. | SS | MS | F[1] |
|---|---|---|---|---|
| Between Testing Time | 4 | $74.47 \times 10^{-20}$ | $18.62 \times 10^{-20}$ | 2.113 |
| Within Test | 60 | $528.72 \times 10^{-20}$ | $8.812 \times 10^{-20}$ | |
| Total | 64 | $603.20 \times 10^{-20}$ | | |

[1]Confidence limit = 91%.

decreased with time and finally reached a constant flow rate. The phenomena were explained as caused by time-dependent pit aspiration, which took place during the test because of hydrostatic pressure. If the hydrostatic force is removed, some recovery, or movement of the membrane back towards median position in the pit, should follow. Because of a decreasing pressure gradient with time during the unsteady-state permeability experiment, pit membranes in sapwood specimens are subjected to creep, but also experience rapid recovery; hence, the effect of rheological nature of pit membranes on the flow rate should diminish.

Table 2 shows the statistical analysis of the effect of frequency of testing on the unsteady-state longitudinal water permeability of western hemlock wetwood. The analysis of variance revealed that the confidence of the F-ratio is significant at the 91% level. Examination of individual test specimens as well as the mean indicates that the longitudinal water permeability of western hemlock wetwood decreases consistently with testing frequency. The deterioration of steady-state permeability in wetwood was considered to be caused mainly by extractives that migrate through wood carried by moving fluid and deposit on pit membranes, to reduce the flow path. This deposition of extractives also should occur in wetwood under the unsteady-state condition; hence, the permeability deteriorates with the frequency of testing.

### Effect of storage

When wetwood of western hemlock is stored at room temperature, its permeability to water decreases as duration of stor-

age increases. The F-ratio of analysis of variance in Table 3 indicates that the decrease in permeability is significant at the 98% confidence limit. This result agrees with the finding by Erickson (1960), who studied the effect of storage at 5 C in a plastic bag on the water permeability of sapwood of Douglas-fir and western hemlock. Because the magnitude of decrease in permeability after 1 month and after 1 year of storage is very much higher than the effect caused by frequency of testing of wetwood, the effect is caused mostly by storage conditions and storage time on test specimens. Deterioration in permeability could occur from dissolved air that diffuses into water in the test specimens during storage and causes air blockage during testing. It also could be caused by the chemistry of extractives existing in wood, or it could be caused by the growth of microorganisms existing in wood, which effectively block the passage of water through test specimens. Erickson (1960) demonstrated that when specimens were stored in freezing conditions or stored aseptically, there is no deterioration in water permeability of wood. Therefore, when a high degree of penetration of fluid into western hemlock is desired, wood should be processed as soon as possible to take advantage of its high natural permeability.

TABLE 3. *Summary of the effect of storage on unsteady-state water permeability of wetwood from western hemlock*

| Duration of storage | Mean | Degrees freedom | Standard deviation |
|---|---|---|---|
| 0 week | $4.70 \times 10^{-10}$ | 9 | $4.531 \times 10^{-10}$ |
| 2 weeks | $3.060 \times 10^{-10}$ | 9 | $2.697 \times 10^{-10}$ |
| 1 month | $2.056 \times 10^{-10}$ | 9 | $2.447 \times 10^{-10}$ |
| 1 year | $0.291 \times 10^{-10}$ | 9 | $0.443 \times 10^{-10}$ |
| Total | $2.537 \times 10^{-10}$ | | |

| Analysis of Variance | | | | |
|---|---|---|---|---|
| Source | d.f. | SS | MS | F[1] |
| Between test | 3 | $104.00 \times 10^{-20}$ | $34.67 \times 10^{-20}$ | 4.079 |
| Within test | 36 | $305.98 \times 10^{-20}$ | $8.50 \times 10^{-20}$ | |
| Total | 39 | $409.98 \times 10^{-20}$ | | |

[1]Confidence limit of F-ratio is 98%.

### Effect of kiln-drying on water permeability of western hemlock wetwood

Figure 6 shows the result of longitudinal water permeability of kiln-dried western hemlock in which moisture has been restored through cyclic evacuation and pressurization. The circles in the figure represent the area where permeability was measured. The permeability of wood to water within wet pockets is small compared to that of dried specimens. The test did not prove or disprove the theory developed by the previous paper (Lin et al. 1973) that the formation of wet pockets is caused by formation of an impermeable zone in the lumber through incrustation of pit membranes in wetwood. The area where permeability was measured for specimens 1a, 4a, and 5b was too large and contained both the wet pocket zone and the dried zone, so that it did not reveal such a trend of formation of an impermeable zone. The result shows, however, that the permeability of wet pockets ($k = 0.381 \times 10^{-10}$ cm$^2$) is clearly lower than the permeability of wetwood ($k = 9.59 \times 10^{-10}$ cm$^2$) that never has been subjected to drying. This could have been caused by the movement of extractives, which incrusted the pit membrane. A systematic investigation of pit structure using a scanning electron microscope or transmission electron microscope may prove or disprove the accuracy of the theory of wet-pocket formation developed by Lin et al. (1973).

Because of the lower water permeability of wet pockets and lower drying rate of wetwood (Lin and Kozlik 1971), the movement of moisture through western hemlock wet zones probably is controlled by diffusion of water through the wet zones.

### CONCLUSIONS

Unsteady-state water permeability of wood can be measured by the technique developed here. The unsteady-state permeability of both sapwood and normal heartwood is higher than the steady-state permeability, but that of wetwood is generally lower than the initial permeability under steady-state conditions and is of the order of the final steady-state permeability. The unsteady-state permeability obtained agrees with the findings of steady-state measurements in that the sapwood has the highest permeability, followed by wetwood; heartwood has the lowest permeability.

Under unsteady-state conditions, sapwood permeability is time-independent, but wetwood exhibits time-dependent behavior that is considered mainly caused by time-dependent incrustation of pit membranes by extractives. Storing of western hemlock wetwood at room temperature reduces water permeability. One should process western hemlock as soon as possible when a high degree of penetration of liquid is desired.

When wetwood is subjected to kiln drying, the permeability of the wet-pocket portion of western hemlock lumber is lower than the part that can be dried normally.

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