Longitudinal Air Permeability of Lodgepole Pine

by

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(ABSTRACT)

The longitudinal air permeabilities of the wood of 1116 specimens from 279 trees, two sapwood and two heartwood replicates, representing two varieties of lodgepole pine (*Pinus contorta*, vars. *latifolia* and *murrayana*) were measured with a steady state apparatus. It was found that the mean ratio of sapwood to heartwood permeability was ca. 10:1 for both varieties. The mean ratio of var. *latifolia* to *murrayana* was 1.5:5 and 1.75:5 for sapwood and heartwood, respectively.

The most important source of variation following the difference between heartwood and sapwood was that among trees. Geographical locations, such as latitude and elevation did not significantly influence permeability. Tree size did, but only because the small trees (3 inch diameter) showed higher heartwood permeability and lower sapwood permeability than normal. Ca. 20 specimens of *latifolia* heartwood showed extremely high permeabilities. They were also deeply brown in color, which probably was caused by fungal or bacterial infestation.

Pit pore size and number per cm^2 were determined for sapwood by making four permeability measurements, each at a different average pressure on each specimen. A mean pit pore radius of 1.5 µm and 1.3 µm for sapwood of var. *latifolia* and var. *murrayana* was calculated. The median values between 1200-1300 pit pores per cm^2 indicate an average rate of tracheid connection of 1.2-1.3%.

Of the tested wood parameters including moisture content and specific gravity average ringwidth, only the permeability of var. *latifolia* was significantly correlated with moisture content for both heartwood and sapwood, with a negative correlation coefficient.

Water retention measurements were carried out to relate the measured gas permeability of an individual specimen to its ability to absorb water. For both varieties the retention was significantly and quadratically correlated with sapwood permeability ($R^2 = 0.286$ and 0.224) and was linearly correlated with heartwood permeability ($R^2 = 0.488$ and 0.5775). The correlation factors for the regression between retention and the logarithm of permeability were 0.239 and 0.227 for sapwood and 0.447 and 0.420 for heartwood.

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1.0 Introduction

This study on longitudinal gas permeability is part of a decade long project of the Forest Service of the US Dept. of Agriculture to assess the properties of lodgepole pine (*Pinus contorta*) grown in the western parts of the United States and Canada.

Successful impregnation of wood against fire and decay, in situ polymerization of monomers in wood to produce wood-plastic composites, treating of wood chips with pulping agents, and many other processes depend to a large extent on the knowledge of the treatability of a certain species with liquids.

One of the most important indicators of the treatability of wood with liquids is permeability. Both liquid and gaseous permeability have been intensively investigated to predict a species′ ability to absorb liquids. If measured and calculated properly, both permeabilities are regarded equally valuable for this purpose. Since the measurement of gaseous permeability is more economical, both in time and money, determination of gas permeability with air as the fluid was carried out in this work.

Wood, as an anisotropic material has different values of permeability in each of its three dimensional directions. However, the longitudinal permeability is so much higher than the tangential and radial permeability that in most cases only the longitudinal value is of interest. Furthermore, since intertracheid pit pores are the factor determining both longitudinal and transverse permeability of softwoods, the latter can be estimated from the former. Because of the fact mentioned above this study was focussed primarily on measuring the gaseous longitudinal permeability.

To relate the measured permeability of the tested wood to its liquid treatability, a simple arbitrary retention test using water was also carried on all samples.

2.0 Objectives and Purpose

The primary purpose of this study was to determine the longitudinal permeability of lodgepole pine (*Pinus contorta*) from the western portion of the United States and Canada. This study is part of a larger project carried out by the Forest Service of the US Department of Agriculture to assess the overall properties of this species.

The specific objectives are:

1. To build an apparatus for measuring the longitudinal air permeability.
2. To test for various sources of variation in the species, such as tree size, latitude, elevation and botanical variety, for both heartwood and sapwood.
3. To determine the size and abundance of intertracheid connecting pit pores.
4. To relate permeability to the penetration of liquid water into the wood.

3.0 Literature Review

3.1 Permeability

Permeability is a very important property for many wood treatment processes, such as preservation, impregnation, wood-plastic composites production, etc. Many investigations have been undertaken in the last 30 years to increase our knowledge about this property. Siau (1984) summarizes the state of the art concerning the permeability. The following review of permeability related matters are mainly drawn from his treatment of the subject.

3.1.1 Darcy's Law

The bulk flow of fluids through a porous medium such as wood is directly proportional to the pressure gradient and to the permeability of the wood.

Darcy's law defines permeability generally as flux divided by the pressure gradient (Siau 1984):

$$k = \frac{QL}{A\Delta P}. \qquad [1]$$

where k is the permeability [m^3/m Pa s], Q is the flow rate in [m^3/s], L is the length of specimen in [m], A is the area of the specimen perpendicular to flow in [m^2] and ΔP is the pressure differential in [Pa].

In order to apply Darcy's law to a porous body like wood several requirements must be met such as:

1. the flow is viscous and linear, that is that the flow rate is proportional to the pressure differential, and there is no energy loss because of turbulence or non-linearity;
2. the fluid is homogenous and incompressible;
3. the porous body is homogeneous;
4. there is no interaction between fluid and substrate;
5. the flow rate is independent of the length of the flowpath. (Siau 1984)

Clearly wood does not fulfill these assumptions completely. However, due to the small capillary openings which occur in wood the first assumption about viscous flow can be regarded as true. Nevertheless, nonlinear flow has been found even at low Reynold's numbers when a fluid enters a small capillary from a large one. This happens for instance when the fluid moves from a tracheid into a pit opening (Siau and Petty 1979).

The second assumption regarding the incompressibility of the fluid is not true when gas is used as a medium. Therefore, to apply Darcy's law for gaseous permeability the expansion of the gas because of the decrease of pressure along the flowpath must be accounted for. Hence, Darcy's law may be rewritten as:

$$k_g = \frac{QLP}{A\Delta P\bar{P}}. \qquad [2]$$

where k_g is the gaseous permeability in [m^3/m Pa s], P is the pressure at which flow rate is measured [Pa], and $\overline{P}$ is the average pressure in the sample [Pa].

The third assumption about uniformity of the porous body is often violated by wood, especially by hardwoods. Also interaction between the fluid and the substrate may occur if polar substances such as water are used, contrary the fourth assumption.

Bramhall(1970) has shown that the fifth assumption may not hold for wood. He found that the flowrate is not independent of the length of the flowpath, but decreases exponentially with length of the specimen presumably due to the decrease of possible interconnections with length.

Nevertheless, for reason of convenience and convention, Darcy's law continues to be applied to pressure driven gaseous and aqueous flow through wood.

3.1.2 Specific Permeability

Permeability as calculated with Eq.1 or 2 depends not only on the properties of the specimen and on the pressure differential but also on the viscosity of the fluid. Comstock (1968) found that permeability is in fact inversely proportional to the viscosity of the fluids. To obtain the specific permeability of a body regardless of the fluid the permeability is multiplied by the viscosity :

$$K = k\eta \qquad [3]$$

where K is the specific permeability [m^3/m] and η is the viscosity, which is $1.81*10^{-5}$[Pa s] for air at 20°.

Since specific permeability expressed in [m^3/m] or in [cm^3/cm] leads to extremely low numbers, the unit known as the darcy is the commonly used unit for specific permeability in the literature. The permeability in [m^3/]m is converted into the permeability in [darcy] by multiplying with the factor 1.01325*10^{12}.

3.1.3 Poiseuille's law

Poiseuille's law describes viscous flow through a body comprised of parallel uniform circular shaped tubes. It relates the flowrate not only to the pressure differential but also to the size and number of tubes. Poiseuille's law for liquids is:

$$Q = \frac{N\pi r^4 \Delta P}{8\eta L} \qquad [4]$$

where N is the number of parallel uniform circular capillaries and r is the radius of capillary in [m].

As is the case with Darcy's law, Poiseuille's law must be modified when applied to gaseous fluids. Poiseuille's law for gases therefore may be written as:

$$Q = \frac{N\pi r^4 \Delta P \bar{P}}{8\eta L P}. \qquad [5]$$

The combination of Darcy's and Poiseuille's laws leads to the elimination of Q. This shows that the permeability is directly proportional to the size and the number of the openings.

$$k = \frac{n\pi r^4}{8\eta} \qquad [6]$$

where n is the number of openings per unit area [m^{-2}].

3.2 Kinds of Flow

Siau (1984) names four kinds of flows occurring in wood. These are

1. viscous or laminar flow
2. turbulent flow
3. nonlinear flow
4. slip flow or Knudsen diffusion.

Viscous flow is essential for the validity of Darcy's and Poiseuille's law. In straight long capillaries the flow is laminar when the Reynold's number does not exceed 2000. The flow rate is linearly proportional to the pressure differential. Except for hardwood with very large vessels Re is well below 2000 for wood.

However, if a fluid enters a small capillary like a pit opening, nonlinear flow can occur in wood at Reynolds numbers between 0.04 and 16. Nonlinear flow can be distinguished from turbulent flow by the fact that in the former ΔP is proportional to Q^2, while in the latter to $Q^{1.75}$ (Siau and Petty 1979; Siau 1984).

3.2.1 Knudsen Diffusion or Slip Flow

When using gas as a fluid, slip flow or Knudsen diffusion adds to the magnitude of the measured permeability. Slip flow which is essentially the slippage of molecules along the walls of capillaries, occurs when the diameter of the pit pores is in the same order of magnitude as the mean free path of fluid molecules. The mean free path of gas molecules may be obtained from

$$\lambda = \frac{2\eta}{P}\sqrt{RT/M} \qquad [7]$$

where λ is the mean free path [m], R is the universal gas constant [J/mol K], T is the Absolute temperature [K],and M is the molecular weight [kg/mol]. Using air at 20°C and 1 atm the term $\sqrt{RT/M}$ equals 290 [m/s]. Under these conditions the mean free path λ for air is approximately 0.1 μm, based on Eq. 7.

The slip flow may be obtained from Knudsen equation:

$$Q = 3N\sqrt{RT/M}\,\frac{r^3\Delta P}{LP}. \qquad [8]$$

Thus, the total flow is the sum of the Poiseuille flow, given by Eq.5 and the Knudsen flow given by Eq.8 as is discussed in "Klinkenberg Equation" on page 12.

3.3 Permeability and Anatomical Structure of Softwoods

3.3.1 Comstock's Model for Flow in Softwoods

Fluids, driven by a pressure differential, travel through softwoods mainly in the tracheid lumens, which are interconnected with bordered pit pairs. Pit openings are small compared to the lumen diameter so that it is generally assumed that the non-aspirated pits account for all of the flow resiatnce.

Comstock (1970) proposed a model for the flow through softwood (Figure 1 on page 11). This model assumes that the pits are at the tapered ends of the radial wall and that therefore there are two parallel flow paths per tracheid in the longitudinal direction. From Fig.1 it can be clearly seen that the magnitude of the flow increases with the number of pits perpendicular to the flow direction and decreases with the increase in the number of pits in series. This is true for both directions, axial and tangential.

Permeability in the longitudinal k_l and tangential directions k_t may then be calculated as follows:

$$k_l \propto L_t \frac{(1 - \alpha)}{2r_t^2} \qquad [9a]$$

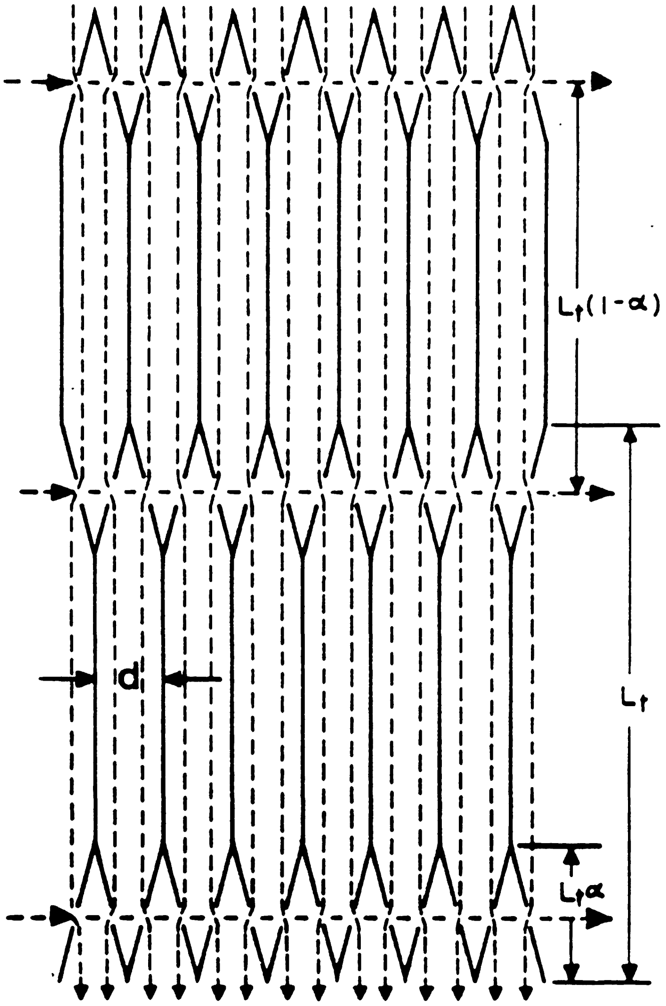
$$k_t \propto \frac{1}{2L_t(1 - \alpha)} \qquad [9b]$$

where L_t is the length and r_t is the radius of a tracheid, and α is the fraction of tracheid overlap.

Combining both equations to get the ratio of k_l to k_t leads to Eq. 10:

$$\frac{k_l}{k_t} = \frac{L_t^2(1 - \alpha)^2}{r_t^2}. \qquad [10]$$

Assuming that the length to diameter ratio is approximately 100 and that α may vary between zero and 0.5 the Comstock ratio varies from 10 000 to 40 000. This ratio therefore permits one to estimate the tangential permeability from the axial permeability. It is difficult to measure tangential permeability, because it is so low. Furthermore, unless the grain angle is absolutely at 90° there is a large component of longitudinal flow. For example, Wengert and Skaar (1978) suggest that even for a grain angle of 85°, approximately 99% of the flow is axial rather than tangential in a typical softwood. It is therefore more expedient to measure axial permeability, and to estimate tangential from their values, using Eq.10.



- L..length of a tracheid
- d...diameter of a tracheid
- α...overlap factor

Figure 1. Comstock's Model for Softwoods

3.3.2 Klinkenberg Equation

Darcy's and Poiseuille's laws, together with Knudsen diffusion are useful tools to estimate the mean size and numbers of connecting pit pores by measuring the flow rate as a function of the mean pressure in the sample.

Adzumi combined the Poiseuille's (Eq.6) and the Knudsen equation (Eq.8) to the so called Adzumi equation. This can be rearranged in the form:

$$\frac{Q}{\Delta P} = \frac{N\pi r^4 \overline{P}}{8\nu LP} + \frac{3Nr^3}{LP}\sqrt{RT/M} \qquad [11]$$

Since all variables in this equation but $\overline{P}$ are constant $Q/\Delta P$ can be described as a linear function of the average pressure in the specimen (Adzumi plot). From the slope and the intercept of such a curve, the magnitude of the mean radius r and of the number of pit pores N can be determined.

Klinkenberg modified the Adzumi Equation such that the permeability k_g is a function of the reciprocal of the average pressure. Thus

$$k_g = \frac{n\pi r^4}{8\eta} + 3nr^3\sqrt{RT/M}\,.\frac{1}{\overline{P}} \qquad [12]$$

Substitution of the mean free path λ in the above equation leads to the so called Klinkenberg equation (Eq.13),

$$k_g = k(1 + \frac{12\lambda\eta}{\pi r}) \qquad [13]$$

where k is the permeability in the absence of slip flow.

The permeability k may be obtained by extrapolation of k_g to zero reciprocal average pressure in the so called Klinkenberg plot (Figure 2 on page 14). Using the term kb for the slope of the Klinkenberg line Eqs.12 and 13 can be rewritten as:

$$k_g = k + \frac{kb}{\overline{P}} \qquad [14]$$

where k is the intercept of k_g vs $1/\overline{P}$ [m^3/m Pa s] and kb is the slope [m^3/m s]. Thus b is the ratio of intercept to slope or,

$$b = \frac{12\lambda\overline{P}\eta}{\pi r} \qquad [15a]$$

and by substituting for λ

$$b = \frac{24\eta}{\pi r}\sqrt{RT/M}\,. \qquad [15b]$$

3.3.3 Pit Pore Radius

The expression pit pore, pit pore size or pit pore radius here refers to the opening of the pit membrane of interconnecting pits. Using the Klinkenberg plot it is possible to calculate the mean radius r of the pit opening in softwoods using Eq.15. Hardwoods which have a higher axial permeability do not obey the linearity of the Adzumi or Klinkenberg equation but rather follow a curvilinear line. This is due to the fact that two conductances in series account for the flow resistance, mostly vessel and intervessel pits (Petty Model, Petty 1970; Siau et al. 1981).

Assuming the Comstock model for softwoods, the intertracheid pit pores are the main limiting factor to the flow (Bolton and Petty 1975). Softwoods therefore obey the Klinkenberg equation which makes possible to calculate the size of the average pit pore opening.

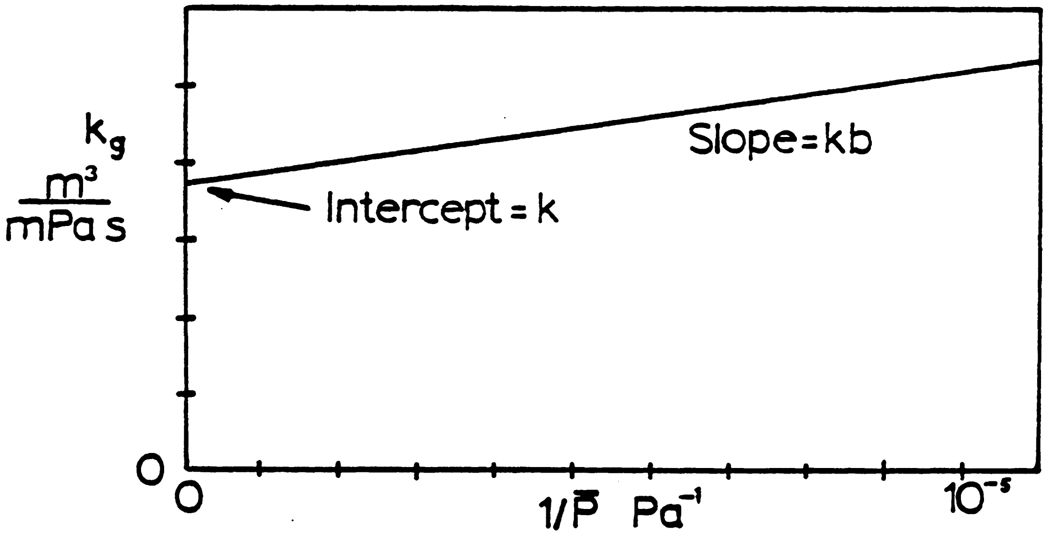


Figure 2. Klinkenberg Plot (Siau 1984)

Eq.15 may be rearranged ansd solved for the mean pit pore radius:

$$r = \frac{24\eta}{\pi}\sqrt{RT/M}\,.\frac{k}{kb} \qquad [16]$$

Since the term $\sqrt{RT/M}$=290 [m/s] and η is $1.81*10^{-5}$ [Pa s] at 20°C and 1 atm the equation may be rewritten as follows to obtain r in [µm]:

$$r = 4.10^4 \frac{intercept}{slope} \qquad [17]$$

where the intercept is expressed in [m^3/m Pa s] and the slope in [m^3/m s]; or if using specific permeability in [m^3/m, darcy] and [m^3Pa/m, darcy Pa], respectively. However, two correction factors must be applied to Eqs. 16 and 17 since pit pores are very short capillaries (Petty and Preston 1969; Sebastian et al. 1965; Petty 1970). These two correction factors, the Couette correction to account for the end resistance and the Clausing factor accounting for the reduction of slip flow in short capillaries, may be combined to give the following overall correction term cc (Siau 1984):

$$cc = \frac{\frac{L}{r} + 1.2}{1.33\frac{L}{r} + 2.67} \qquad [18]$$

where L/r is the ratio of length to radius of a capillary. The pit pore radius calculated with Eqs.16 or 17 must be multiplied by the factor cc.

Assuming a pit membrane thickness of 0.1 µm (Bao et al.1986) and an average pit pore radius from 1 to 5 µm the factor cc ranges from 0.46 to 0.45.

3.3.4 Number of Pit Pores per Unit Area

To obtain the number of pit pores per unit cross-sectional area the intercept of the Klinkenberg plot has to be corrected to get the true permeability of one pit opening path (Siau 1984). On the basis of the Comstock model this can be accomplished by multiplying the intercept permeability k by the ratio:

$$\frac{L_p}{L_t(1-\alpha)} \qquad [19a]$$

where L_p is the thickness of the pit membrane, L_t is the length of the tracheid and α is the overlap according to Comstock's model. Hence k_{lp}, the true permeability of the pit-opening path may be calculated by Eq.19b:

$$k_{lp} = k\frac{L_p}{L_t(1-\alpha)} \qquad [19b]$$

Therefore by rewriting Eq.6 the number of pit openings per unit cross-sectional area may be obtained by the equation:

$$n = \frac{8\eta k_{lp}}{\pi r^4} \qquad [20]$$

Assuming an overlap α of 0.3, a membrane thickness of 0.1 μm and a tracheid length of 3.19 mm for *Pinus contorta* (Panshin and De Zeeuw 1980) k_{lp} equals $10^{-4} * k$.

3.4 Sources of Variation of Permeability

Since it has been shown that permeability in softwoods mainly depends on the size and the abundance of non-aspirated pits it is clear that all circumstances and conditions which change the pit structure are also likely to affect the permeability. The most important of these effects are

- earlywood-latewood differences;
- sapwood-heartwood differences;
- location within the tree;
- specific gravity;
- moisture content;
- drying processes;
- treatments to enhance permeability.

3.4.1 Earlywood-Latewood Differences

Removing water from the wood results in various degrees of pit aspiration. It has been shown that this effect is more pronounced in the earlywood than in latewood. For example, Shaw (1970) reported 25-60% non-aspirated pits in latewood of several coniferous species compared with 1-7% in earlywood. From this it appears that wood samples with higher latewood percent should have higher permeability. However, measurements by several researchers indicate the contrary to be true. Thus other factors may be involved such as the greater numbers and sizes of pits in the earlywood than latewood. Considerable controversy exists concerning this factor and a consensus of opinion has not been achieved as yet (Fogg 1969; Comstock 1965).

3.4.2 Sapwood-Heartwood Differences

When heartwood is treated with liquids it shows significantly less penetration than sapwood. Pit aspiration, extractives, and incrustation, among other factors, are responsible for its smaller permeability. The average ratio of sapwood to heartwood permeability varies from 15.4 to 190 with figures as high as 2000-3000 for individual trees (Fogg 1969).

It seems therefore appropriate to separate the results of permeability measurements on sapwood and heartwood; especially since Fogg (1969) has shown that there is no significant correlation between the permeability of sapwood and heartwood obtained from the same tree.

3.4.3 Location within the Tree

3.4.3.1 Radial Location

Comstock (1965) listed radial location as the most important location factor affecting the permeability of eastern hemlock. He reported that for heartwood the value decreased continuously with distance from the sapwood-heartwood borderline. The same was true for sapwood in that the larger the distance from the pith, the higher was the permeability.

3.4.3.2 Axial Location

Comstock (1965) also undertook measurements to evaluate the significance of height in the tree. He found that for sapwood, permeability increased significantly with height while heartwood permeability was not significantly different at different heights.

3.4.4 Specific Gravity

Various scientists have tried to establish a relationship between average permeability and specific gravity, although in most cases there appeared to be no significant correlation. In particular Resch et al(1964) reported this to be true for redwood; Fogg (1969) came to the same conclusion for southern yellow pine. Comstock (1965) however found that the heartwood permeability of eastern hemlock was significantly related to density but with a low correlation coefficient.

3.4.5 Moisture Content.

Moisture content has an influence on permeability. Above fiber saturation, permeability is very low because high capillary forces must be overcome when forcing air bubbles through the water-filled system.

Below fiber saturation, permeability is negatively correlated with moisture content. Comstock's (1968) findings indicate a two to threefold increase in permeability as the moisture content decreases from 24% to 6%. He explains this by the shrinkage of the microfibrillar strands in the pit margo, thus increasing the pit pore size.

3.4.6 Drying Processes

The high capillary forces occurring during the kiln or air drying of species having bordered pits can cause their aspiration. This happens to a larger extent in earlywood than in latewood due to the higher mechanical rigidity of the latter. Also drying rate and temperature influence the degree of aspiration. It is therefore necessary to know the drying history before comparing permeability results from different measurements.

One way to avoid pit aspiration would be solvent exchange drying. An alcohol-benzene extraction employed by Bramhall and Wilson (1971) led to an increase in the permeability of earlywood samples with a higher permeability than 0.2 darcy. Heartwood and latewood were significantly unaffected due to the already high amount of aspirated and encrusted pits in the non-dried material. Petty and Puritch (1970) report that they found 27 000 connecting pit pores per conducting tracheid for solvent dried wood compared with 600 for air dried samples.

Another method used by several investigators is freeze drying in which capillary water is sublimated in the frozen condition. In this case there are no capillary forces to cause pit aspiration. However, drying is excessively slow since all of the water must diffuse in vapor form from the wood surface at low vapor pressure.

3.4.7 Treatments to Increase Permeability

Siau (1984) lists several other procedures besides special drying techniques which may be used to enhance permeability. These processes involve delignification and degradation of the pit membrane and torus by chemical and biological attack. Treatments with pectinase and ozone-oxygen mixture, as well as exposure to mild bacterial onset have been employed with good results. Steaming causes hydrolysis of the pit membrane and deaspiration of aspirated pits. It may be applicable to the lumber industry at relatively low cost. However some precaution is required to avoid loss of mechanical strength.

3.5 Methods of Measuring Permeability

Since permeability is a variable mainly used to predict treatability of wood with liquids it seems appropriate to determine the liquid rather than the gaseous permeability. However, the use of liquid fluids causes many practical difficulties. Gaseous permeability measurements on the other hand are less difficult to accomplish. However, to make the results comparable to those obtained from aqueous mediums suitable adjustments must be made. Nevertheless, if gaseous permeability is corrected for slip flow, gas expansion, and viscosity it is generally regarded as a reliable indicator of treatability (Comstock 1967; Siau and Shaw 1971; Choong et al 1974). Booker (1977), however contradicts this opinion and does not regard gas permeability as a valid substitute for liquid permeability. He reports that besides correction for slip flow and microtoming the ends, the samples must be at least 20 mm in length. In addition the tested wood must be dried as it would be done commercially prior to treating with liquids. Since these requirements have not been met by most of the studies he doubts the value of gas permeability as an estimator for treatability.

3.5.1 Liquid Permeability

Kelso et al (1963) determined that air blockage of the minute pit structure is responsible for the occurrence of steadily increasing flow rates over time, which had been observed in earlier studies. Ultrafiltering and complete degasification of the liquid is therefore required to obtain a constant flow rate as well as a linear response of the flow rate pressure differential as Darcy's law predicts.

Another problem is the interaction of polar liquids such as water with the hydroxyl groups of the cell wall. Non-polar fluids such as benzene, iso-octane, and n-hexane have been used by several workers with good results.

3.5.2 Gas Permeability

As mentioned above, three adjustments must be made on gas permeability measurements in order to obtain the equivalent liquid permeability:

Gas expansion: The use of the modified Darcy equation (Eq.2) accounts for expansion of gases due to the drop in pressure along the sample.

Viscosity: The specific permeability which is independent of the fluid employed is calculated with Eq.3.

Slip flow or Knudsen diffusion: To adjust for slip flow, measurements must be made at different mean pressure levels in the specimen. The intercept of the Klinkenberg plot may then be assumed to be equal to the liquid permeability.

Gas permeability measurements have the further advantage of providing a means for calculating the mean size and concentration of pit pores.

Three different types of devices are used in general according to the literature.They are:

1. the falling water displacement method;
2. the rising water displacement method;
3. the steady state apparatus designed by Petty(1969).

Methods 1 and 2 are in fact unsteady state methods described by Siau (1971). In a falling water-displacement apparatus the wood sample is connected with a hose to the top of a long vertical glass tube filled with water. Air is removed from the tube; the time the water needs to fall a certain distance by drawing the air through the sample is a measure of the permeability. This method is best suited for woods of high permeabilities such as longitudinal measurements on some hardwoods.

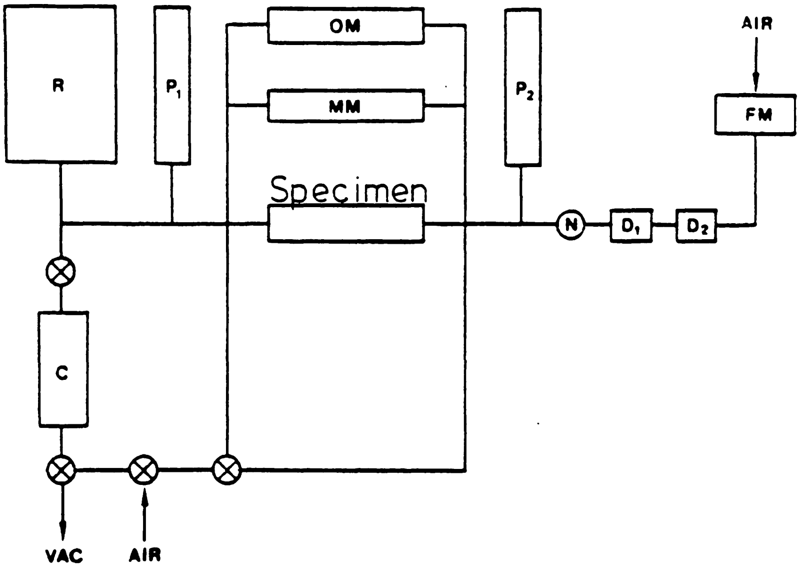
Method 2 is also an unsteady-state method although it is usable for woods of low permeability too. The time required to raise a certain amount of water in capillary tube together with the measured pressure differential enables one to calculate the permeability.

The schematic diagram of the apparatus designed by Petty (1969) is shown in Figure 3 on page 24. It can be seen that two manometric gauges and one flowmeter are necessary to obtain all the variables required to calculate the permeability. The two pressure gauges measure ΔP and P which enables one to calculate $\overline{P}$ by Eq.21.

$$\overline{P} = P + \frac{\Delta P}{2} \qquad [21]$$

Furthermore it is possible to get the Adzumi or the Klinkenberg plot and to calculate the size and abundance of connecting pit pores.

The apparatus has been designed for using a near vacuum on one end of the specimen, which essentially means that the barometric pressure is the force that drives the air through the wood sample. Nevertheless, it may be modified in such a way that high gas pressure is applied, though the connecting tubes and joints must then be made stronger in order to withstand high pressures.



- R ......vacuum reservoir
- P_1 ......open mercury manometer, vacuum end
- P_2 ......open mercury manometer, pressure end
- C ......Cartesian manostat
- OM ......differential oil manometer
- MM ......differential mercury manometer
- N ......needle valve
- D_1,D_2 ......dessicants
- FM ...Flowmeter

Figure 3. Apparatus to Measure Air Permeability (Petty 1970)

4.0 Material and Procedures

4.1 Material

4.1.1 Species

All samples for this investigation came from trees of two varieties of lodgepole pine (*Pinus contorta*) growing in the western portions of the United States and Canada. This species is the focus of a decade long research program of the Forest Service of the US Department of Agriculture intended to improve the utilization of lodgepole pine (Koch 1985).

Lodgepole pine occupies 5.25 million ha throughout the states of Montana, Wyoming, Colorado, and Oregon with a growing stock of 748 million m^3 (71 billion board feet). In Canada it covers 20 million ha, equivalent to 22% of all Canadian forest land. Four varieties have been described but only two, var. *latifolia* and var. *murrayana*, with emphasis on the former, were included in the program.

4.1.2 Geographical Origin

The var. *latifolia* has been sampled in the Rocky Mountains between the latitudes of 40° to 60° at latitudinal increments of 2.5°, and within a longitudinal range of 10° (see Figure 4 on page 27). Within each of these nine latitudes trees were selected at each of three elevations, designated as low, medium, and high. These were not at specific but were relative elevations, depending on the local topography.

Three classes of breast height diameter were chosen (76mm or 3″, 152mm or 6″, 228mm or 9″) with three replicate trees for each class. In summary, 243 trees were taken from the population *latifolia.*

Trees of var. *murrayana* were sampled only at medium elevation and at 37.5°, 40°, 42.5°, and 45° northern latitude, thus constituting a sample size of 36 trees.

4.1.3 Sample Preparation

All of the material provided by the Forest Service was taken from the trunk of the trees at a height corresponding to about 10% of the distance from the stump to the top of the tree. Each sample consisted of 15 cm long pieces of roundwood with a moisture content of 13%, measured on the surface with a resistance moisture meter. Disks, approximately 1.5 cm thick were cut by means of a circular saw after making a cleaning cut at the end of the roundwood piece. With a 3/8″ plugcutter, four dowels were drilled out from each disk, each therefore having a diameter of 0.95 cm. Two of the plugs were taken from sapwood and two from heartwood in each case. To minimize the effect of radial location on permeability replicate dowels were taken opposite each other at definite locations. For the 3 inch class the sapwood samples were taken from the outermost portion of the disk whereas the heartwood samples were taken from as close as possible to the pith. Since the

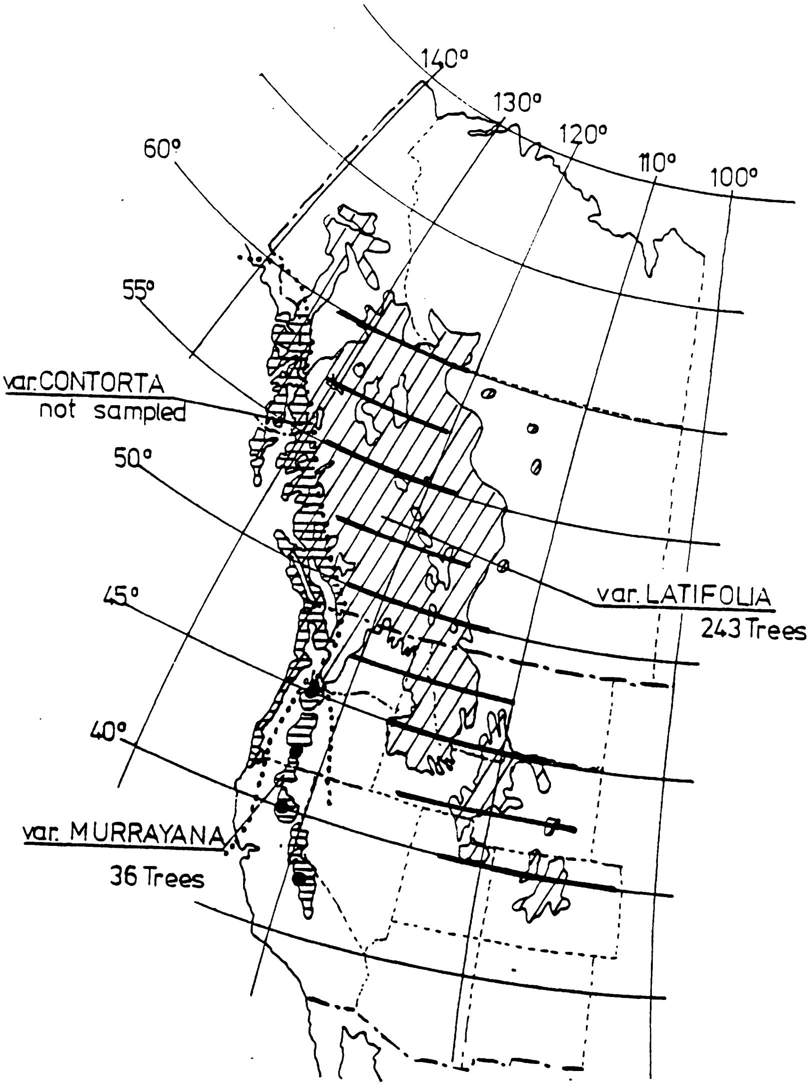


Figure 4. Sampling Sites (Koch 1985)

amount of heartwood varies considerably, from almost no sapwood to almost no heartwood, this method assures that a sapwood sample contains as much sapwood as possible, the same being true for the heartwood dowels. In some cases however, no sample containing only sapwood could be obtained from the three inch trees.

For the 6 inch diameter trees the sapwood samples were taken 1 cm from the cambium line and the heartwood samples 1 cm from the pith. The nine inch trees were sampled similarly, except the distances were 2 cm in each case.

In summary, the var. *latifolia* provided 972 and var. *murrayana* provided 144 test samples.

The length of ca. 1.5 cm was a compromise between the need for a considerably longer specimen than the average tracheid length (3.19 mm) and the need to save material for further investigations. However, it was not possible with the available procedure to obtain a uniform length for all dowels. Thus, it varies from 0.9 to 1.7 cm. According to Darcy's law this should not affect the measured permeability, although Bramhall (1970) has demonstrated some decrease of permeability with length of specimen. A test for the significance of the differences in sample length on permeability was included in the evaluation of results.

Each sample was microtomed on both ends until its cross-sectional surface was completely clean and free of loose fiber bundles which might block the lumens of the tracheids (Choong et al 1975).

The samples were then stored in small labeled polyethylene bags in the same room in which they were tested, thus allowing the sample moisture content to adjust to the room climate. Since drying cracks can occur when using air considerably dryer than that at equilibrium with the specimen (Fogg 1969), this procedure minimizes the risk of cracking. The average room climate was 65 ± 5% humidity and 75 ± 5°F. The minimum duration of exposure before measurements was one week.

4.2 Parameter and Experimental Design

From the above discussed sampling distribution four parameters may be derived for var. *latifolia* (latitude LAT, altitude ALT, diameter DIA, and replicate TREE) and three for var. *murrayana* (LAT, DIA, TREE). All these parameters are considered random effects, hence a three factor random effects model was applied to the analysis of variance (Anova) of the var. *latifolia* and a two factor random effects model for var. *murrayana.* In both cases the factor TREE is nested in all other effects, as can be seen from table 1.

To test for significant differences between the two varieties the two sample populations from the common latitudes (40°, 42.5°, and 45°) and from their common medium elevation were compared. Since the effect VAR would be a fixed one, a three factor mixed model was applied (Sokal and Rohlf 1981; Steel and Torrie 1980).

4.3 Permeability Measurements

The apparatus used in this study to measure longitudinal air permeability was designed after one described by Petty (1969). However, to cover both sapwood and heartwood permeability two modifications of Petty's design have been made, one for sapwood and one for heartwood measurements, respectively. Another modification of Petty's design was that no desiccant was used to dry the air prior to using it. This might have caused drying cracks in the specimen. But to clean the air from dust and small particles, a microfibre filter was used.

Table 1 Experimental Design

A Variety Latifolia (three factor random model)

Source	*df*
LAT	8
ALT	2
DIA	2
LAT x ALT	16
LAT x DIA	16
ALT x DIA	4
LAT x ALT x DIA	32
TREE(LAT x ALT x DIA)	162
ERROR	243

B Variety Murrayana (two factor random model)

Source	*df*
LAT	3
DIA	2
LAT x DIA	6
TREE(LAT x DIA)	24
ERROR	36

Table 1 contd.

C Comparison Latifolia with Murrayana (three factor mixed model)

Source	*df*
VAR[1]	1
LAT	2
DIA	2
VAR x LAT	2
VAR x DIA	2
LAT x DIA	4
VAR x LAT x DIA	4
TREE(VAR x LAT x DIA)	36
ERROR	54

[1] fixed effect

Steele and Torre 1980; Sokal and Rohlf 1981)

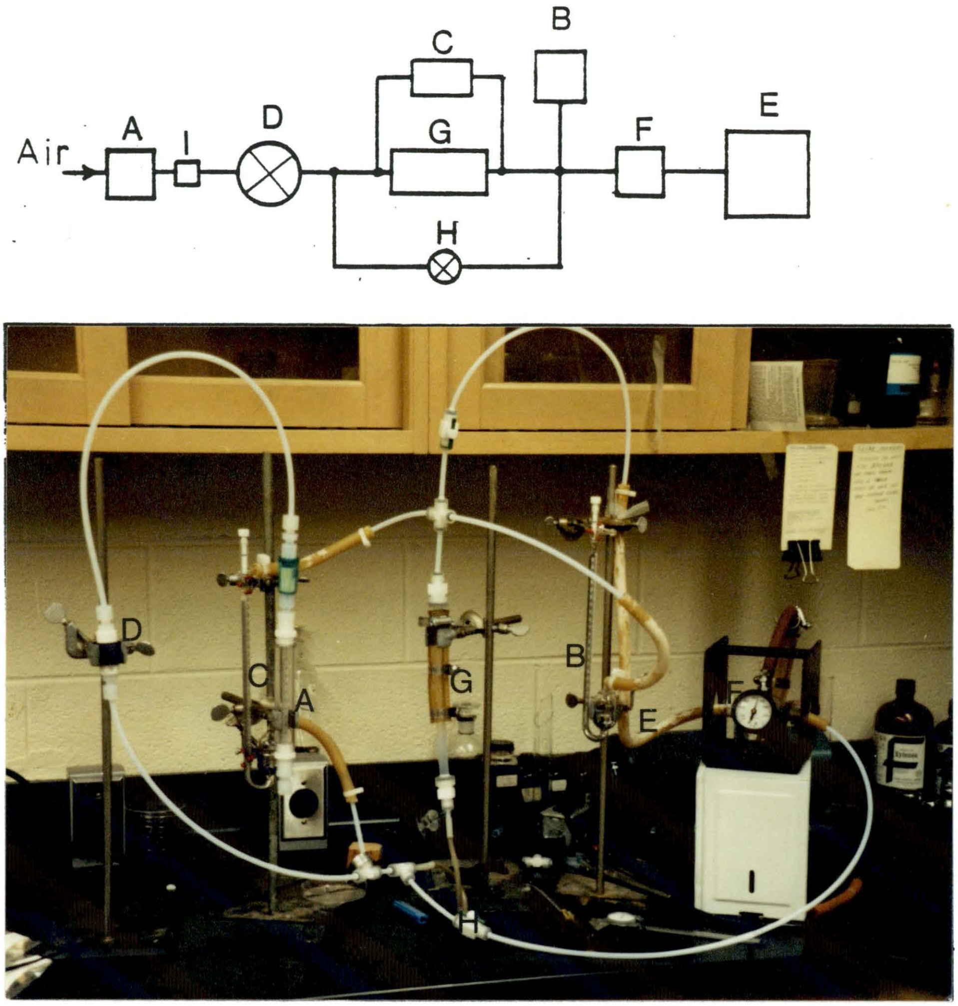
4.3.1 Sapwood Apparatus (Method A)

As seen in Figure 5 on page 33 there are basically three instruments which comprise the apparatus. These are a microflowmeter(A) with a range of 0.03 to 15 ml/min, a mercury pressure gauge(B), used as absolute gauge (0 to 200 mmHg), and a mercury pressure gauge(C), used as differential gauge (0 to 200 mmHg). Gauge B indicates the pressure on the vacuum side of the specimen and gauge C shows the differential pressure across the specimen. The pressure driven flow can be regulated with the needle valve D. The vacuum is provided by pump E and can be adjusted by the manostat valve F. Teflon tubing (OD= 1/4″ ID= 1/5″) and teflon valves and joints are used to connect the instruments. The specimen holder G (see Figure 7 on page 37) is made of a thick walled rubber tube with an ID of 3/8″. The sample is fixed inside the tube with a screw clamp. This design prevents measurable air bypass and also permits short preparation intervals between samples.

According to the range of the instruments mentioned above it was calculated this device is theoretically capable of measuring permeabilities from a maximum of $1.67*10^{9}$ m^3/m or 1695 darcy to a minimum value of $1.67*10^{16}$ m^3/m or $1.7*10^{4}$ darcy. This assumes a sample length of 1.5 cm and a cross-sectional area of 0.71 cm^2. However, for reasons of accuracy and stability this apparatus only was used to measure samples with a permeability above 0.01 darcy (see chapter on "Heartwood Apparatus (Method B)" on page 36).

4.3.2 Sapwood Procedure

Since it was within the scope of this investigation not only to measure permeability of lodgepole pine but also to get the size and abundance of the pit pores, it was necessary to make measurements required to obtain the Klinkenberg plot.



•	A	......microflowmeter
•	B	......mercury manometer, vacuum pressure end
•	C	......mercury manometer, differential pressure
•	D	......needle valve
•	E	......vacuum pump
•	F	......Cartesian manostat
•	G	......Specimen holder
•	H	......bypass valve
•	I	......microfibre filter

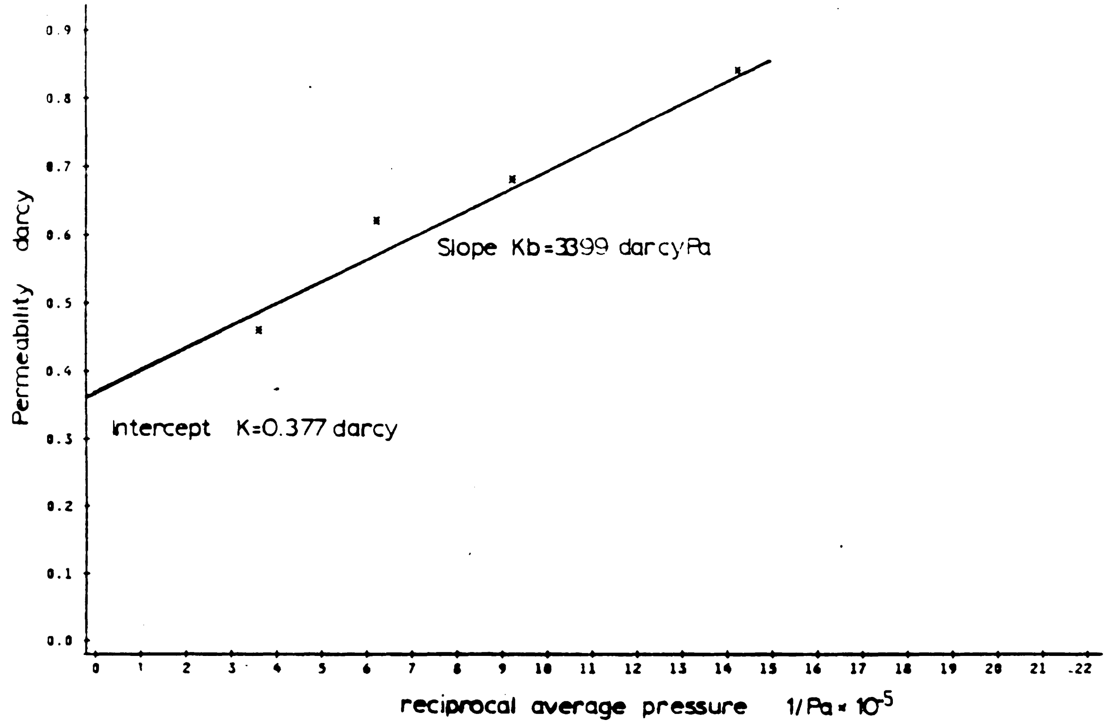
Figure 5. Sapwood Apparatus

Four different levels of vacuum pressure P were established for each sample (0.4, 6.67, 13.33, 26.67 kPa or 3, 50, 100, 200 mmHg). Assuming an average differential pressure ΔP of 13.33 kPa or 100 mmHg the four average pressures $\overline{P}$ were 7.1, 13.7, 20.4 and 33.7 kPa or 53, 103, 153, 253 mmHg, respectively. The four values of reciprocal average pressure $1/\overline{P}$ therefore were calculated to be approximately $15*10^{-5}$, $7.5*10^{-5}$, $5.0*10^{-5}$, and $3.0*10^{-5}$ Pa^{-1} (see Figure 6 on page 35).

The first measurement for each specimen was taken using the lowest possible vacuum level of 400 Pa or 3 mmHg. The valve H was opened to establish the same vacuum on both sides of the sample so that the initial pressure differential was zero. After the vacuum was achieved the valve H was closed and the needle valve D was opened slightly to allow air to flow through the specimen. The pressure differential ΔP then rose and stabilized for a certain flowrate Q by fine tuning the needle valve.

Since the accuracy of the flowmeter is 2% of the end reading a high flowrate was desirable. After recording both ΔP and Q for stable flow the manostat valve F was opened to produce the second level of vacuum. This caused ΔP to drop considerably and the flowrate to drop slightly. The differential ΔP stabilized after a few seconds for specimens of high permeability and after a few minutes for those of low permeability. ΔP and Q were then recorded and and the procedure was repeated for the pressure levels of 100 and 200 mmHg on the vacuum side.

For each of the four values of ΔP and Q, the specific gas permeability K_g was calculated. These were then plotted against $1/\overline{P}$ to obtain the Klinkenberg plot for each specimen (Figure 6 on page 35). The regression equation of K_g against $1/\overline{P}$ was calculated, from which the intercept permeability K, and both r, the mean pit pore radius and n, the mean number of pit pores per unit area, were calculated for each specimen, using Eqs.16 and 19.



ID= 6
LAT=40°
ALT=low
DIA= 3 inch
VAR=latifolia

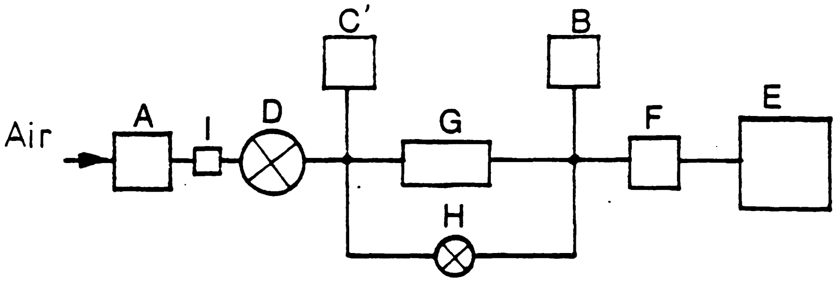
Figure 6. Typical Klinkenberg Plot for Lodgepole Pine Sapwood

4.3.3 Heartwood Apparatus (Method B)

From preliminary screening it was obvious that the permeability of most of the heartwood specimen were too low to be measured by the method A, although in most cases it would be theoretically possible. This was because the flowmeter readings were so low and so unstable that it was not possible to obtain reliable measurements.

Therefore the device was modified to permit reliable measurements of the less permeable samples. Figure 7 on page 37 shows the apparatus used for measurements on low permeability samples which were essentially all of the heartwood specimens. As seen in Figure 7 on page 37 the gauge C was relocated as C′ to record the absolute pressure on the high pressure side ranging from 500 mmHg to 700 mmHg. This was achieved by connecting the system to the upper outlet of the mercury gauge, thus measuring the difference between system pressure and atmospheric pressure. This configuration provides a pressure differential ΔP approximately three times that used in the sapwood apparatus, thus allowing permeability measurements over a range from zero to $2.0*10^{-14}$ m^3/m or 0.02 darcy.

Although the heartwood permeabilities could be measured with this apparatus it was not practical to estimate both the intercept permeability and the mean size and number of pit pores as was done for sapwood. This is because the points of $^1/\bar{P}$ lie too close together and were too far from the intercept so that the extrapolation of the graph would be inaccurate. Therefore only one value of permeability for each heartwood specimen was determined, this at an average pressure of 47.0 kPa or 350 mmHg, the value for $1/\bar{P}$ of is $2.1*10^{-5}$ Pa^{-1}. Those few heartwood samples having a larger permeability than 0.02 darcy were measured by the sapwood method at the same average pressure of 47.0 kPa to make the results comparable with those of the low permeability specimens.



- A ......microflowmeter
- B ......mercury manometer, vacuum pressure end
- C′ ......mercury manometer, high pressure end
- D ......needle valve
- E ......vacuum pump
- F ......Cartesian manostat
- G ......Specimen holder
- H ......bypass valve
- I ......microfibre filter

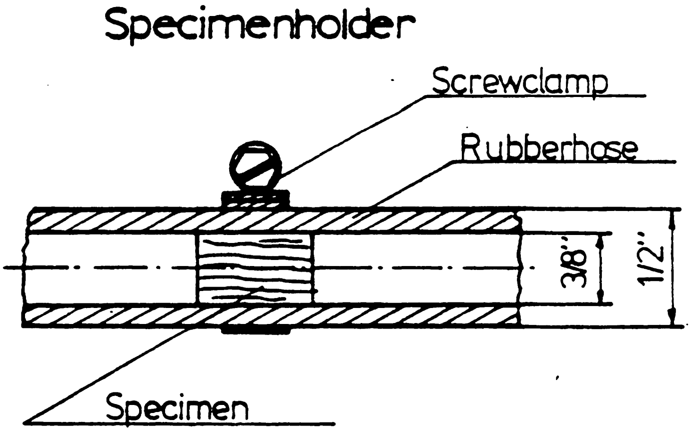


Figure 7. Heartwood Apparatus, Specimen Holder

4.3.4 Heartwood Procedure

After establishing the vacuum level of 400 Pa or 3 mmHg at only the low pressure side of the system the needle valve was opened fully. If the permeability was very low the flowmeter reading was within the range of the meter. The differential pressure then equaled the atmospheric pressure. If the flowrate first exceeded the range of the flowmeter, the needle valve was to be closed slightly till Q was within the flowmeter's range. Closing the needle valve resulted in a decrease of differential pressure thus raising the mercury level in gauge C′. In all cases, a flowmeter reading as high as possible was desired to enhance the accuracy.

4.4 Retention Measurements

It has been demonstrated by several workers that the gas permeability of wood is a good indicator of its treatability with liquids. To confirm this relationship in the present case a simple empirical test was devised to measure the liquid treatability of the same specimens whose permeabilities were measured. Water was chosen as the liquid to be used for this test.

Preliminary experiments suggested that a simple soaking of the specimen in water under a vacuum of 1 kPa (ca.8 mmHg) for five minutes, followed by exposure to atmospheric pressure and then blotting to remove excess surface water, would give a wide distribution in water retention among specimens of high and low permeabilities. Therefore this empirical treatment was chosen for most of the retention tests.

As a variation of the five minute soaking test, a one minute soak test was used for half of the var. *latifolia* sapwood specimen, that is, one of each replicate was subjected to a one minute soak and the other to the standard five minute soak. The reason for using the shorter period for half these samples was to minimize the tendency for the more permeable samples to become completely water-soaked, thus truncating the regression equation at the higher levels of permeability.

There were also two variations of the five-minute soak test which occurred. In one set of tests, those on var. *murrayana*, the samples were allowed to float on the water surface during the test so that fewer of them were completely submerged in water during application of the vacuum. In the second case all of the samples were kept submerged in water during the entire test. Thus they tended to soak up more water during the test than did those which were not completely submerged.

In the discussion of results, the three kinds of soaking tests described above are designated as F5, S5, and S1, referring to the five minute float, five minute submerged, and one minute submerged test, respectively.

After soaking, each sample was reweighed (± 1 mg) to obtain the soaked weight, which is the difference between weight before soaking w_{15} and after. To adjust for sorption of water by the cell wall between the initial average moisture content of 15% and the fiber saturation taken to be 30%, 15% of the dry weight w_0 was subtracted from the water weight (see Eq.23). This was divided by the void volume of wood VVa, where V is the volume of the sample and Va is the porosity estimated for each specimen by use of the equation (Siau 1984):

$$Va = 1 - G(0.667 + 0.01M) \qquad [22]$$

where G is the specific gravity and M the moisture content in %.

The retention Ret, or fraction of void space filled with liquid water was calculated as:

$$Ret = \frac{(w_s - w_{15} - 0.15w_0)}{VVa} \qquad [23]$$

The volume was taken to be equal to the sample length (cm) multiplied by 0.71 cm^2, the assumed cross-sectional area of each test sample prior to soaking.

Eq.23 assumes that the water taken up during soaking was uniformly distributed throughout the specimen which probably was not true, particularly for those of low permeability which have little penetration into the center of the specimen. However, the method was a convenient empirical technique for relating the treatability of the individual specimen to the gas permeabilities. It is believed that the results are qualitatively related to the full scale treatability of larger samples with water-borne and probably also other liquid preservatives. It is similar to techniques used by Graham (1964) and by Chudnoff (1970) to determine the probable treatability of various kinds of wood with preservatives, based on simple soaking tests in water and other liquids.

5.0 Results and Discussion

5.1 Permeability

As it showed in "Permeability Measurements" on page 29 Darcy's law was used to calculate the longitudinal specific air permeability of lodgepole pine, both for sapwood and heartwood from each of the two varieties. The results of the investigations are summarized in tables 2 to 8 as well in Figure 8 on page 46 and Figure 10 on page 62. The tables also include information on sample size, moisture content, specific gravity, and average ringwidth per sample and also the analysis of variance (Anova) tables and Duncan groupings.

There are no reported studies of permeability measurements on lodgepole pine. Hence, literature reported for other pines were compared with the results of this study. For example Bao et al (1986) measured air permeability of Chinese pine (*Pinus koreaensis*) and reported a specific intercept permeability of 0.12 darcy, but did not distinguish between sapwood and heartwood. Choong et al (1975) reported the value of 0.18 darcy for southern yellow pine but they also did not distinguish between sapwood and heartwood. Smith and Lee (1958) measured the air permeability of some pine species with the rising water method. They reported values of 0.0005 darcy for heartwood of

British Honduras pitch pine (*Pinus caribaea*) and 6.69 darcy for sapwood, 4.16 darcy for Scotts pine (*Pinus sylvestris*) sapwood and 7.96 darcy for western white pine (*Pinus monticola*) sapwood. Fogg (1969) reports sapwood permeabilities for the four southern yellow pines ranging from 0.33 to 0.56 darcy and for heartwood permeabilities from 0.0004 to 0.020 darcy. The findings reported here for lodgepole pine agree well with those of Fogg(1969), Bao et al(1986), and Choong et al(1975). However, the figures given by Smith and Lee (1958) are higher than those reported by other studies probably because a rising water method was used which is an unsteady-state method. The other reported studies used steady-state Petty-devices.

5.1.1 Sapwood

Using Eq.2 the specific permeability K was calculated for each of four different average pressures to obtain a Klinkenberg plot for each specimen. The intercept gave the superficial air permeability without slip flow for each sample. Figure 6 on page 35 shows an example of such a plot for a sample from the var. *latifolia*. As noted earlier, air permeability was converted to the specific permeability K by multiplying with the viscosity of air ($\eta = 1.81 * 10^{-5}$ Pa s).

5.1.1.1 Variety Latifolia (Table 2)

The air permeability of 479 samples out of 486 possible specimens of var. *latifolia* were measured. The permeabilities of five samples were too low to be measured reliably by method A, and two samples were missing. The overall mean permeability for latifolia sapwood is 0.133 darcy with a standard deviation of 0.095.

For both varieties, differences among trees account for a large portion of the variability as it can be seen from Table 2. Figure 8 on page 46 shows that the mean permeability varies somewhat with

Table 2 Permeability of Sapwood

Variety Latifolia

sample size	n = 479
moisture content	MC = 13.8% (2.74)[1]
specific gravity	G = 0.443 (0.05245) [0.414][2]
average ringwith per sample	RW = 1.8 mm (1.058)
mean specific permeability	**K = 0.133 darcy** (0.0946)

[1] standard deviation

[2] specific gravity reported by Koch (1985)

mean specific permeabilities for subset **latitude:**

latitude	n	K	Std.Dev.	Duncan Grouping
40.0°	52	0.132	0.0973	B
42.5°	53	0.092	0.0707	C
45.0°	54	0.068	0.0451	B
47.5°	54	0.131	0.0839	B
50.0°	51	0.156	0.1036	A
52.5°	53	0.159	0.1010	A
55.0°	54	0.161	0.1054	A
57.5°	54	0.172	0.1101	A
60.0°	54	0.124	0.0689	D

mean permeabilities for subset **altitude:**

altitude	n	K	Std.Dev.	Duncan Grouping
low	160	0.130	0.0974	A
med	161	0.133	0.0879	A
high	158	0.135	0.0988	A

Table 2 contd.

mean permeabilities for subset diameter:

diameter	n	K	Std.Dev.	Duncan Grouping
3 in	156	0.082	0.0744	C
6 in	162	0.139	0.0868	B
9 in	161	0.178	0.0971	A

Analysis of Variance

Source	*df*	F
LAT	8	2.91**
ALT	2	0.83ns
DIA	2	27.43**
LAT x ALT	16	1.11 ns
LAT x DIA	16	1.33 ns
ALT x DIA	4	0.22 ns
LAT x ALT x DIA	32	1.06 ns
TREE(LAT x ALT x DIA)	160[1]	2.47**

** significant at a 99% level

ns not significant

[1] *df* for TREE are reduced because of missing observations

latitude. Although the influence is significant at a 99% level no trend is apparent. Diameter is a very influential parameter and highly significant. The 9 inch trees have twice the permeability of the 3 inch trees. However, this difference might be explained by the fact that the sampling of the 3 inch sample dowels took place very close to the heartwood-sapwood boundary, some specimens even included portions of heartwood. This, together with the fact that permeability increases with distance from the heartwood-sapwood boundary (Comstock 1965), might well account for the significant effect of diameter. However, from the standpoint of utilization it can be said that small diameter trees generally have less permeable sapwood than those of larger diameter.

Elevation does not seem to have any significant effect on permeability.

5.1.1.2 Variety Murrayana (Table 3)

The average permeability of var. *murrayana* was 0.088 darcy, 67% of that of *latifolia*. Of all the parameters considered, only the difference among trees was significant. Although the tree diameter was not a significant variable, the result of the Duncan test indicated that the 3 inch diameter class was significantly less permeable than the two other classes. This might also be explained by the fact that the sapwood samples were taken so close to the heartwood-sapwood boundary.

5.1.1.3 Comparison of Latifolia and Murrayana (Table 4)

A Students t-test for the differences between means and an analysis of variance were carried out to test for significant difference between the two varieties concerning permeability.

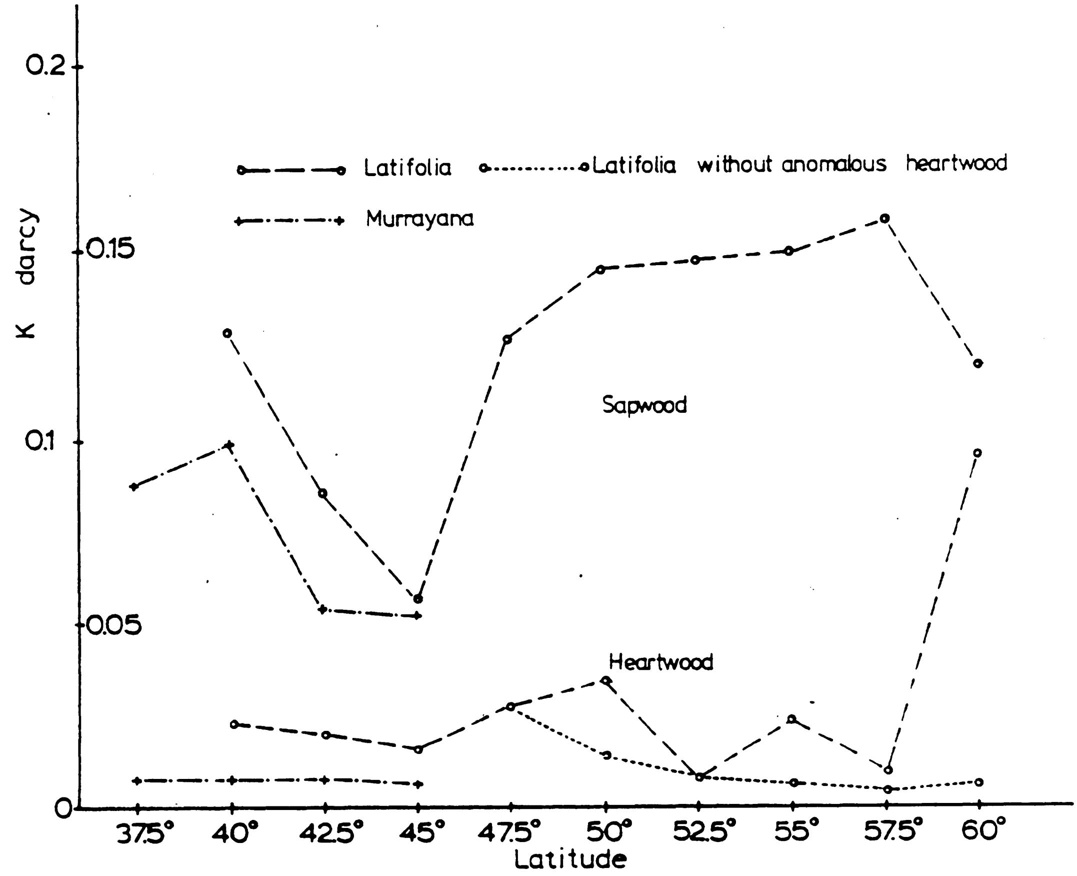


Figure 8. Mean Permeability vs Latitude

Table 3 Permeability of Sapwood

Variety Murrayana

sample size n = 72

moisture content MC = 15.9% (2.90)[1]

specific gravity G = 0.444 (0.0889) [0.437][2]

average ringwidth per sample RW = 1.1 mm (0.71)

mean specific permeability **K = 0.088 darcy** (0.0774)

[1] standard deviation [2] specific gravity reported by Koch(1985)

mean permeabilities for subset **latitude**:

latitude	n	K	Std.Dev.	Duncan Grouping
37.5°	18	0.083	0.0831	A
40.0°	18	0.105	0.0962	A
42.5°	18	0.069	0.0637	A
45.0°	18	0.089	0.0634	A

mean permeabilities for subset **diameter**:

diameter	n	K	Std.Dev.	Duncan Grouping
3 in	24	0.046	0.0479	B
6 in	24	0.100	0.0827	A
9 in	24	0.113	0.0811	A

Table 3 contd.

Analysis of Variance

Source	*df*	F
LAT	3	0.36 ns
DIA	2	2.69 ns
LAT x DIA	6	1.53 ns
TREE(LAT x DIA)	24	2.97 **

** significant at a 99% level

ns not significant

Table 4 Permeability of Sapwood

Comparison variety *latifolia* to *murrayana*

Variety	n	K *darcy*	Std.Dev.
latifolia	479	0.133	0.0946
murrayana	72	0.088	0.0774

A t-test for significant differences between means[1]

Source	*df*	t
Var.Latifolia	478	3.83***
Var.Murrayana	71	

*** significant at a 99.9% level

B Analysis of Variance[2]

Source	*df*	F
VAR[3]	1	2.40ns
LAT	2	0.83ns
DIA	2	12.12*
VAR x LAT	2	3.95ns
VAR x DIA	2	1.00ns
LAT x DIA	4	4.52ns
VAR x LAT x DIA	4	0.21ns
TREE(VAR x LAT x DIA)	36	1.80*

ns not significant, * significant at a 95% level

[1] based on all latitudes and altitudes

[2] based on common latitudes 40.0°, 42.5°, 45° at medium altitude

[3] fixed effect

The t-test was based on the entire sample size of both varieties and showed that the two mean permeabilities were significantly different. However, the analysis of variance, carried out for restricted sample sizes of both varieties - common latitudes (40°, 42.5°, 45°) and common medium elevation - did not show a significant difference. The strong effect the tree diameter showed for var. *latifolia* was also apparent in the comparison Anova. Together with the differences among trees, these two effects accounted for all of the variability. This was also confirmed by a t-test carried out for the same sample size which showed no significant difference between the two means.

5.1.2 Heartwood

The permeability of the heartwood samples was measured by a slightly different method than for sapwood permeability as discussed in "Heartwood Apparatus (Method B)" on page 36. Thus rather than the intercept permeability obtained from the Klinkenberg plot, only the permeability at ca. 47 kPa or 350 mmHg was measured. However, since slip flow was included in this value, the actual superficial permeabilities would be somewhat smaller than the reported permeabilities.

5.1.2.1 Variety Latifolia (Table 5)

Twenty samples from trees of higher latitudes showed anomalies which affected the measured permeabilities considerably. The cross section of these trees showed an irregular shaped brown to deep brown core sometimes occupying the entire heartwood area. The boundary of this brown region did not follow the annual rings and sometimes penetrated into the sapwood. It may be that this was caused by fungal or bacterial infection. Since these samples showed very high permeability values, this would agree with some studies which have reported an increase of permeability after bacterial attack (Siau 1984).

Table 5 Permeability of Heartwood

Variety Latifolia (incl. samples with anomalous heartwood)

sample size	n = 484
moisture content	MC = 14.0% (2.77)[1]
specific gravity	G = 0.418 (0.0449) [0.434][2]
average ringwidth per sample	RW = 0.8 mm (0.580)
mean specific permeability	**K = 0.029 darcy** (0.0884)
[1] standard deviation	[2] specific gravity reported by Koch(1985)

mean specific permeabilities for subset **latitude:**

latitude	n	K	Std.Dev.	Duncan Grouping
40.0°	54	0.021	0.0220	B C
42.5°	54	0.019	0.0197	B C
45.0°	54	0.016	0.0292	B C
47.5°	54	0.028	0.0359	B C
50.0°	52	0.035	0.0966	B
52.5°	54	0.009	0.0223	C
55.0°	54	0.024	0.0938	B C
57.5°	54	0.009	0.0254	C
60.0°	54	0.097	0.2080	A

mean permeabilities for subset **altitude:**

altitude	n	K	Std.Dev.	Duncan Grouping
low	160	0.040	0.1285	A
med	162	0.026	0.0711	B
high	162	0.021	0.0425	B

Table 5 contd.

mean permeabilities for subset **diameter:**

diameter	n	K	Std.Dev.	Duncan Grouping
3 in	160	0.042	0.1209	A
6 in	162	0.026	0.0791	B
9 in	162	0.018	0.0489	B

Analysis of Variance

Source	*df*	F
LAT	8	1.88ns
ALT	2	1.27ns
DIA	2	1.12ns
LAT x ALT	16	0.71 ns
LAT x DIA	16	1.60 ns
ALT x DIA	4	1.03 ns
LAT x ALT x DIA	32	1.05 ns
TREE(LAT x ALT x DIA)	162	3.85**

** significant at a 99% level

ns not significant

Table 5a Permeability of Heartwood

Variety *Latifolia* without samples with anomalous heartwood

sample size	n = 464
moisture content	MC = 14.0% (2.80)[1]
specific gravity	G = 0.419 (0.0449) [0.434][2]
average ringwidth per sample	RW = 2.1 mm (1.27)
mean specific permeability	**K = 0.014 darcy** (0.0231)
[1]standard deviation	[2]specific gravity reported by Koch(1985)

mean specific permeabilities for subset **latitude:**

latitude	n	K	Std.Dev.	Duncan Grouping
40.0°	54	0.021	0.0220	B
42.5°	54	0.019	0.0197	B C
45.0°	54	0.016	0.0292	C
47.5°	54	0.028	0.0359	A
50.0°	51	0.014	0.0185	C
52.5°	53	0.007	0.0020	D
55.0°	52	0.006	0.0145	D
57.5°	52	0.005	0.0126	D
60.0°	40	0.006	0.0120	D

mean permeabilities for subset **altitude:**

altitude	n	K	Std.Dev.	Duncan Grouping
low	153	0.013	0.0230	A
med	155	0.013	0.0219	A
high	156	0.015	0.0245	A

Table 5a contd.

mean permeabilities for subset **diameter**:

diameter	n	K	Std.Dev.	Duncan Grouping
3 in	151	0.012	0.0060	A
6 in	155	0.011	0.0056	A
9 in	154	0.014	0.0064	A

Analysis of Variance

Source	*df*	F
LAT	8	2.00ns
ALT	2	0.72ns
DIA	2	1.26ns
LAT x ALT	16	1.22 ns
LAT x DIA	16	1.13 ns
ALT x DIA	4	0.95 ns
LAT x ALT x DIA	32	1.25 ns
TREE(LAT x ALT x DIA)	162	4.60**

** significant at a 99% level

ns not significant

Therefore two sample sets were created for the heartwood of var. *latifolia.* The original set which included these 'brown' anomalous specimens, (Table 5), and a reduced set which excluded these specimens (Table 5a). These anomalous samples were removed and then treated as a subgroup with a mean permeability of 0.371 (Std.Dev= 0.2440) compared with 0.029 darcy for the entire set and 0.014 darcy for the reduced set excluding the anomalous samples.

As can be seen from Table 5, the anomalous samples had an especially great effect on the means of the three inch diameter trees from the low elevation of the northern latitudes. Although even with the anomalous samples included, no effect besides the effect TREE was significant; the means and their Duncan groupings became more uniform upon removal of these 20 samples.

5.1.2.2 Variety Murrayana (Table 6)

The mean permeability of the heartwood of var. *murrayana* was 0.008 darcy, 57% of var. *latifolia's.* The only significant factor of variation was the difference among trees. The three inch diameter group, however was significantly more permeable than the the two other diameter groups, indicated by the Duncan grouping. As was the case with sapwood, this might also be because samples were taken close to the heartwood-sapwood boundary. In some trees the amount of heartwood was very small, thus sapwood portions were included in heartwood samples. It is also possible that the pits in the younger heartwood of the small trees are less incrusted than those of the larger, older trees.

5.1.2.3 Comparison of Latifolia with Murrayana (Table 7)

Two t-tests were carried out, one comparing the *latifolia* subset including the samples with anomalous heartwood with the *murrayana* subset and one using the reduced subset without anomalous

Table 6 Permeability of Heartwood

Variety Murrayana

sample size	n = 69
moisture content	MC = 15.9% (2.481)[1]
specific gravity	G = 0.476 (0.0784) [0.502][2]
average ringwidth per sample	RW = 2.2 mm (1.23)
mean specific permeability	K = **0.008 darcy** (0.0113)

[1] standard deviation

[2] specific gravity reported by Koch(1985)

mean permeabilities for subset **latitude:**

latitude	n	K	Std.Dev.	Duncan Grouping
37.5°	18	0.0080	0.01419	A
40.0°	18	0.0083	0.01189	A
42.5°	18	0.0083	0.01048	A
45.0°	18	0.0072	0.00858	A

mean permeabilities for subset **diameter:**

diameter	n	K	Std.Dev.	Duncan Grouping
3 in	24	0.0107	0.01456	A
6 in	24	0.0065	0.00113	B
9 in	24	0.0069	0.00699	B

Table 6 contd.

Analysis of Variance

Source	*df*	F
LAT	3	0.01 ns
DIA	2	0.18 ns
LAT x DIA	6	1.81 ns
TREE(LAT x DIA)	23[1]	4.72 **

** significant at a 99% level

ns not significant

[1] *df* reduced because of missing samples

Table 7 Permeability of Heartwood

Comparison variety *latifolia* to *murrayana* 6incl. specimens with anomalous heartwood

Variety	n	K *darcy*	Std.Dev.
latifolia	484	0.0287	0.08841
murrayana	69	0.0079	0.01125

A t-test for significant differences between means

Source	*df*	t
Latifolia	483	1.96*
Murrayana	68	

Comparison variety *latifolia* to *murrayana* excl. specimens with anomalous heartwood

Variety	n	K *darcy*	Std.Dev.
latifolia	464	0.014	0.0231
murrayana	69	0.0079	0.01125

B t-test for significant differences between means

Source	*df*	t
Latifolia	463	2.15*
Murrayana	68	

* significant at a 95% level

Table 7 contd.

C Analysis of Variance[1]

Source	*df*	F
VAR[2]	1	15.88**
LAT	2	2.23ns
DIA	2	2.93ns
VAR x LAT	2	0.31ns
VAR x DIA	2	0.41ns
LAT x DIA	4	0.26ns
VAR x LAT x DIA	4	4.13*
TREE(VAR x LAT x DIA)	36	2.36*

ns not significant

* significant at a 95% level

** significant at a 99% level

[1] common latitudes are 40.0°, 42.5°, 45° and medium altitude

[2] fixed effect

specimens. The Anova was based only on samples taken from the common latitudes (40°, 42.5°, 45°) and from the common medium elevation as it was done for the sapwood comparison.

Both the t-tests and the analysis of variance showed significant differences in permeability between the varieties. The three factor interaction is also significant at a 95% level. This may be caused by the difference in how mean permeability change with diameter in the two varieties at the three different latitudes. From Figure 9 on page 61 it can be seen that the curves of var. *latifolia* showed the opposite trend with latitude than did those of var. *murrayana*

Figure 10 on page 62 is a summary of the permeability measurements in the form of boxplots for the sapwood and heartwood permeabilities of both varieties (Tukey 1977). The borders of the boxes indicate the first Q1 and third quartile Q3 (Q3-Q1 = IQR inter quartile range), and the middle line the median M of the population; the + marks the arithmetic mean. The line on both sides are extended to Q3 + 1.5*IQR and Q1-1.5*IQR and mark the inner fences. For a normal distribution this would include the range from $\mu + 2.69\sigma$ and $\mu - 2.69\sigma$, thus containing 99.3% of the data. Mild outliers designated by circles lie within the outer fences ranging from M3 + 3*IQR to M1-3*IQR ($\mu + 4.7\sigma$ and $\mu - 4.7\sigma$) Extreme outliers ($P = 2*10^{-7}$) are designated by asterisks and lie beyond the outer fences.

In Figure 10 on page 62 the boxplot diagrams are shown for the four permeability subsets (*latifolia* sapwood and heartwood [excl. specimens with anomalous heartwood]; *murrayana* sapwood and heartwood). In addition the distribution of the logarithms of the permeabilities for all subsets can be seen below.

From Figure 10 it can be clearly seen that the permeability distributions show skewness toward higher values. Median and mean lie apart from each other in all four subsets as well as all have more outliers than the normal probability would predict. Sapwood permeability distribution is less skewed than is heartwood distribution, however.

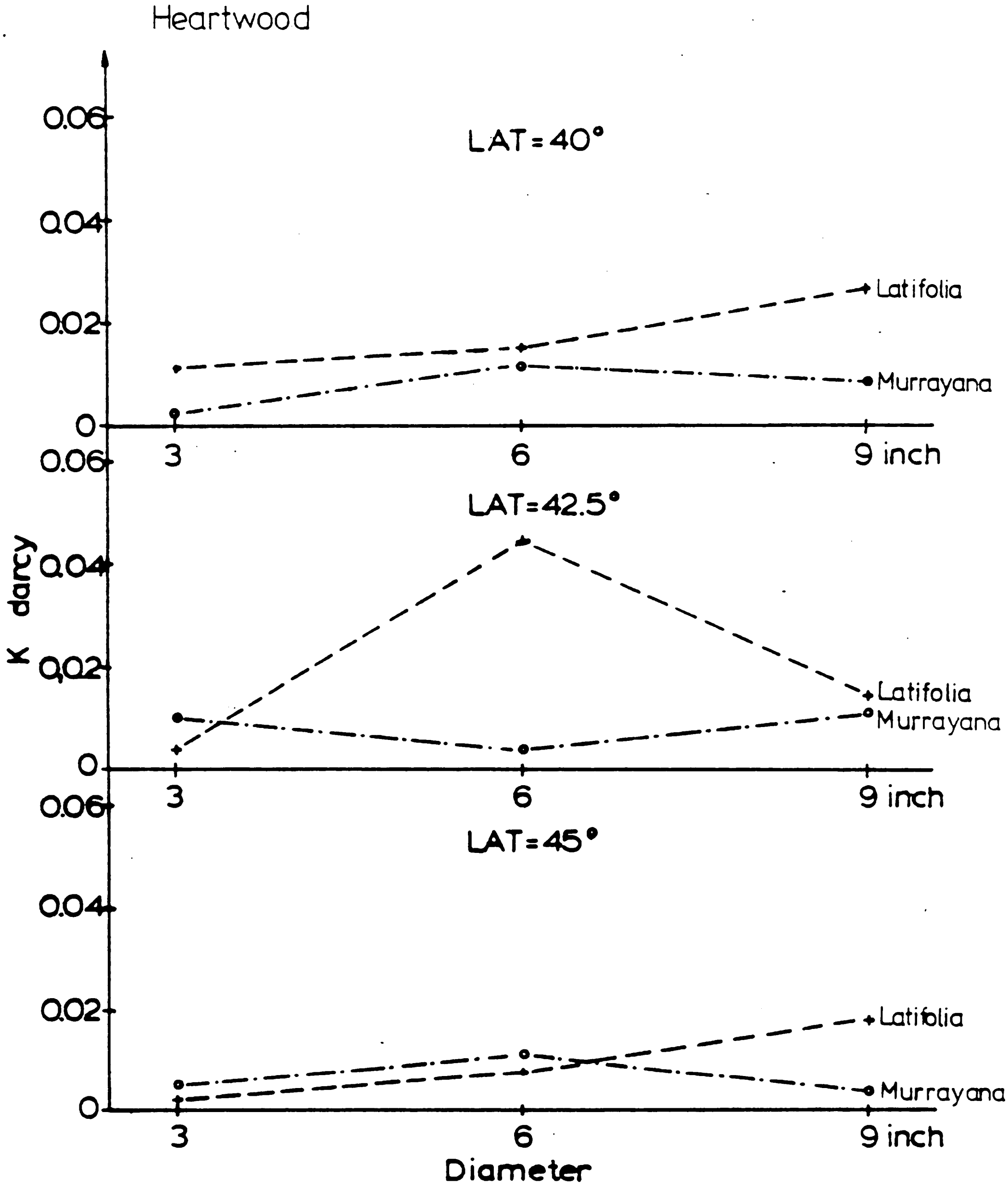


Figure 9. Mean Permeability vs Diameter

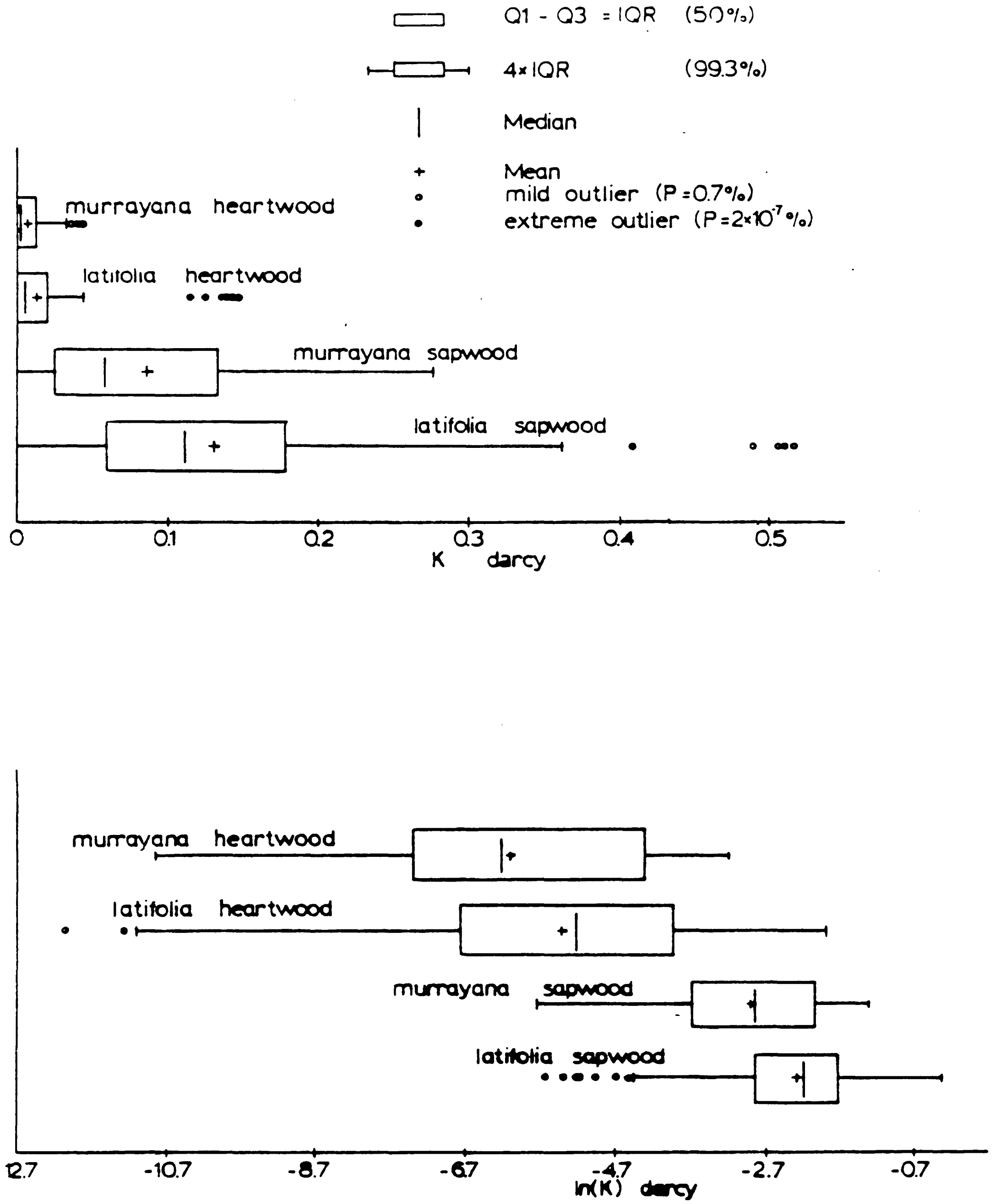


Figure 10. Boxplot Diagrams for Permeability Distribution

Also on Figure 10 on page 62 boxplot diagrams for the logarithmic the distributions of the logarithms of the permeabilities are shown. These come much closer to a normal distribution than do the non-logarithmic distributions. Median and mean lie close together, the tails are approximately equal, and there are no extreme outliers and fewer mild ones.

5.2 The Effect of Woodparameters on Permeability

The measured permeabilities were tested as function of moisture content, specific gravity, average ringwidth, and sample length. The mean values for all parameters are shown in Table 2 trough 7. Table 8 summarizes the values of R and R^2 as well as their significance for each parameter. All coefficients are very low, thus explaining very little of the variation.

Moisture content was significantly correlated with heartwood and sapwood permeability for var. *latifolia*. The regression slope is negative, thus indicating a rise in permeability with decreasing moisture content. From the regression equation given at Figure 11 on page 64 it can be calculated that the the rise in *latifolia's* permeability over a drop in moisture content from 24% to 6% would be 280%, which is in good agreement with the findings of Comstock (1968). However, for the var. *murrayana* no significant trend could be observed. The rise of the log of permeability of var *latifolia* over the same range is 177%.

The same was observed for the relationship of the logarithm of permeability versus moisture content. While regression for the var. *latifolia* was significant no significance could have been observed for the var. *murrayana*(see Figure 12 on page 65).

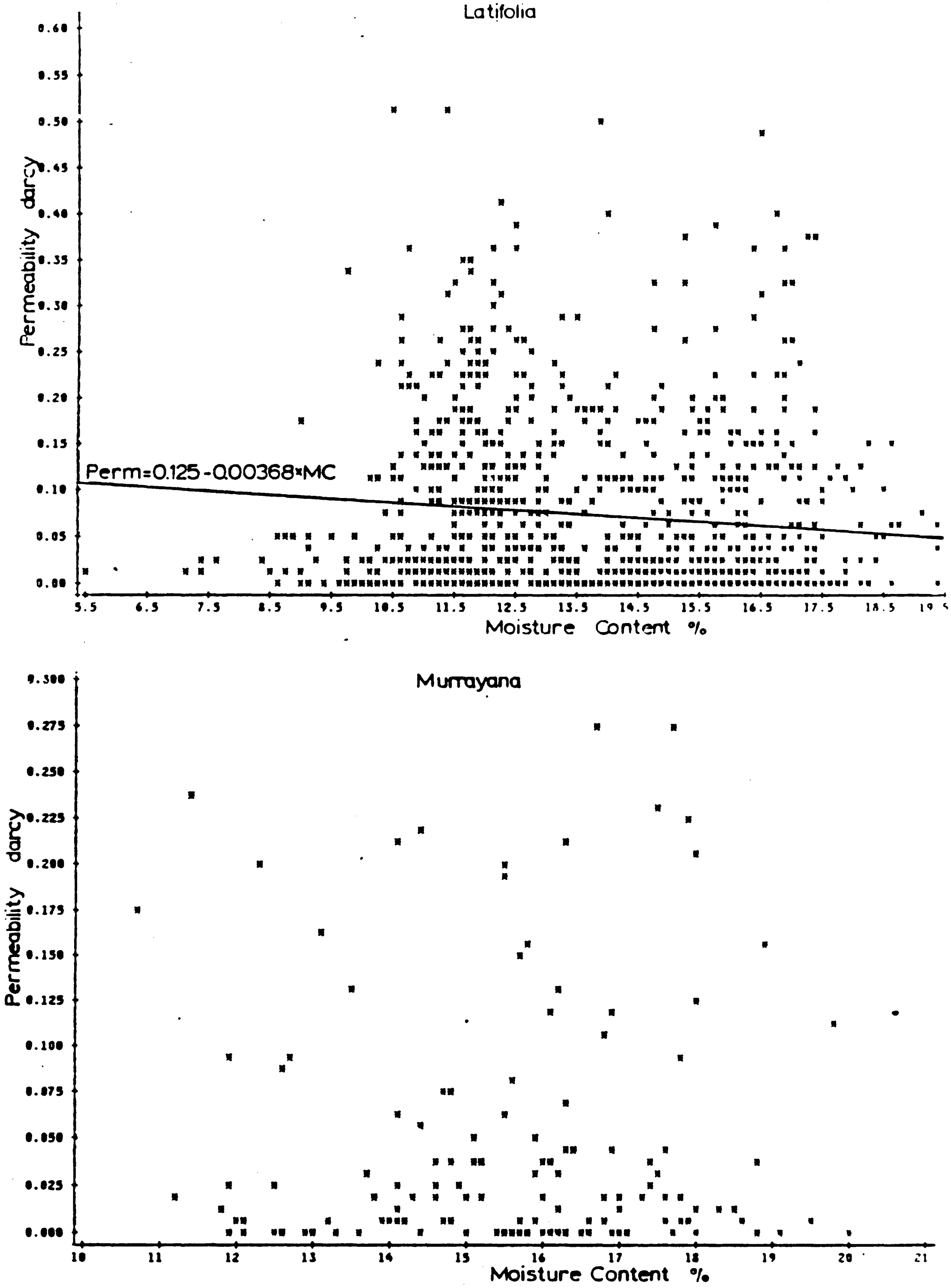
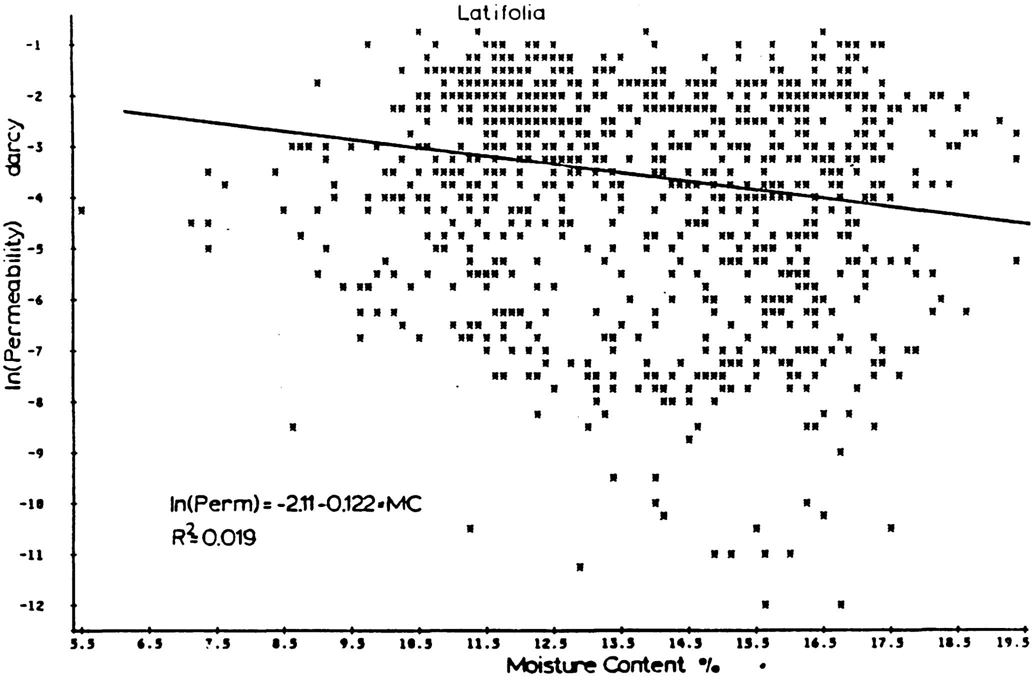


Figure 11. Moisture Content vs Permeability



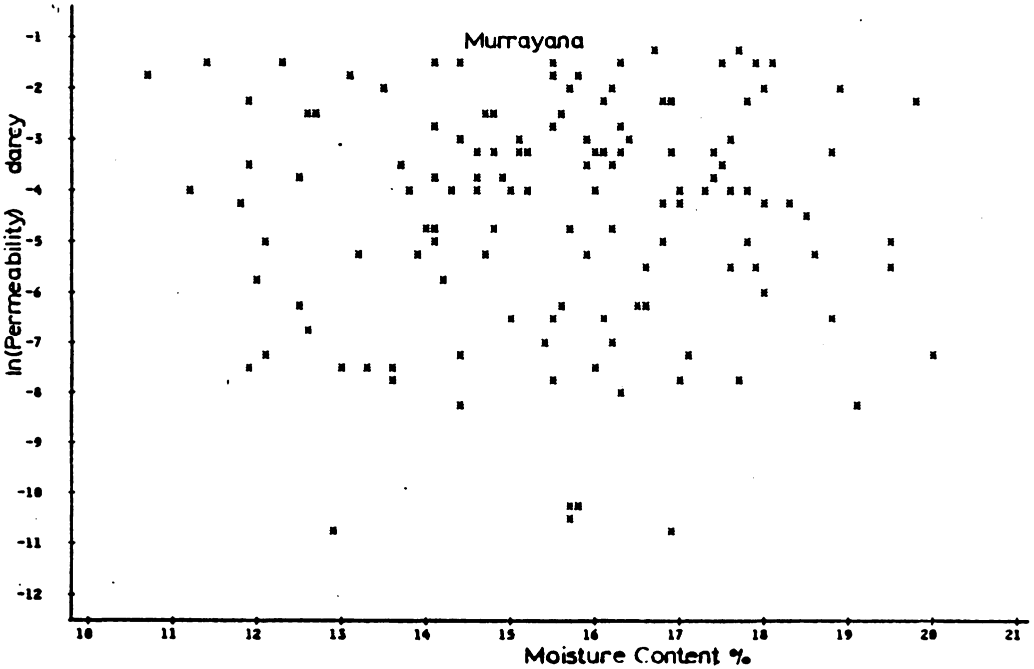


Figure 12. Moisture Content vs Log(Permeability)

Table 8 Permeability, Log of Permeability and Moisture Content MC, Average Ringwidth RW, Specific Gravity G, Length of Specimen L

A Sapwood

var. *latifolia*

Parameter	linear: R	R^2	Sig[1]	log: R	R^2	Sig[1]
MC	-0.129	0.017	*	-0.116	0.013	*
RW	-0.081	0.007	ns	-0.115	0.013	*
G	0.038	0.001	ns	0.021	0.0	ns
L	0.098	0.010	*	0.141	0.020	*

var. *murrayana*

Parameter	linear: R	R^2	Sig[1]	log: R	R^2	Sig[1]
MC	-0.002	0.0	ns	0.041	0.002	ns
RW	0.048	0.002	ns	0.0145	0.0	ns
G	-0.184	0.034	ns	-0.261	0.068	*
L	-0.037	0.001	ns	-0.054	0.003	*

[1] H0: $\rho \neq 0$

ns not significant

* significant at a 95% level

Table 8 contd.

A Heartwood

var. *latifolia* (incl. specimen with anomalous heartwood)

Parameter	linear: R	R^2	Sig[1]	log: R	R^2	Sig[1]
MC	-0.073	0.005	ns	-0.194	0.038	*
RW	-0.073	0.005	ns	-0.043	0.002	ns
G	-0.115	0.013	ns	-0.256	0.066	*
L	-0.028	0.001	ns	-0.120	0.014	*

var. *latifolia* (excl. specimens with anomalous heartwood)

Parameter	linear: R	R^2	Sig[1]	log: R	R^2	Sig[1]
MC	-0.107	0.011	*	-0.188	0.036	*
RW	-0.068	0.002	ns	-0.037	0.001	ns
G	-0.105	0.011	*	-0.216	0.046	*
L	-0.114	0.013	*	-0.111	0.012	*

-var. *murrayana*

Parameter	linear: R	R^2	Sig[1]	log: R	R^2	Sig[1]
MC	0.056	0.003	ns	0.105	0.011	ns
RW	-0.146	0.021	ns	0.028	0.001	ns
G	-0.056	0.003	ns	-0.155	0.024	ns
L	-0.015	0.0	ns	-0.161	0.042	ns

[1] H0: $\rho \neq 0$

ns not significant * significant at a 95% level

Green specific gravity G_g was estimated individually from the measured specific gravity G_{15} at the actual moisture content for each sample by means of Eq.24 (Siau 1984). A fiber saturation point of 30% was assumed for both, heartwood and sapwood, as well as constant lumen size with change in moisture content.

$$G_g = \frac{G_{15}}{1 + G_{15}(0.3\text{-}mc)} \qquad [24]$$

where mc is the moisture content in fraction of the dry weight. The only deviation from the values determined by the Forest Service on the green material was that the specific gravity for *latifolia* sapwood was higher than Koch(1985) reported. Specific gravity only was significantly and negatively correlated with heartwood permeability of var. *latifolia*, the 20 anomalous specimens excluded, thus indicating an increase of permeability with decreasing specific gravity. This trend was also reported by Comstock (1965).

Specimen length was a significant factor for both heartwood (without anomalous samples) and sapwood permeability of var. *latifolia*. However, for sapwood the correlation was positive while for heartwood it was negative. Clearly length of specimen should be negatively correlated (Bramhall 1970), and there is no simple explanation for the opposite effect on sapwood. It is possible that systematic effects during sample preparation might have biased the results in this way.

The average ringwidth per sample was not significantly correlated with permeability in any case, nor has any literature reference been found to indicate that it should be.

Table 9 Permeability and Pore Size

Sapwood

var. *latifolia*	
sample size	n = 479
permeability	K = 0.133 darcy
mean pore radius	r = 1.29 μm
median number of pores per cm^2	n = 1293 (1616)[1]
var. *murrayana*	
sample size	n = 72
permeability	K = 0.088 darcy
mean pore radius	r = 1.52 μm
median number of pores per cm^2	n = 1210 (1722)[1]
var. *latifolia*, anomalous heartwood	
sample size	n = 9
permeability	K = 0.371 darcy
mean pore diameter	r = 3.75 μm
median number of pores per cm^2	n = 68 (69)[1]

[1] values in brackets represent means of logarithmic distribution

5.3 Pit Pore Size and Number

As discussed in "Permeability and Anatomical Structure of Softwoods" on page 9 gas permeability measurements provide a useful method to estimate the pit pore size and the number of pit pores per unit cross-sectional area. Table 9 gives a summary of the results of the pit pore size investigation. 0.45, the combined Couette and Clausing factor cc, was used to correct the calculated pit pore radius (see"Pit Pore Radius" on page 13). The pit pore radius for sapwood of var. *latifolia* was 1.29 µm, slightly lower than that of var. *murrayana* (1.52 µm). However, because of a high standard deviation the means were not significantly different. Bao et al (1986) calculated an average pore radius of 0.95 µm for Chinese pine (*Pinus koreaensis*), but did not distinguish between heartwood and sapwood. Sebastian et al (1965) calculated a pit pore radius of 1.25 µm for sapwood of white spruce (*Picea glauca*), while Petty and Preston (1969) calculated an average pit pore radius of 0.85 µm for Sitka spruce (*Picea sitchensis*). These findings are in good agreement with the results of this study. Petty (1970) however, reporting that the assumption that all the flow in coniferous wood is limited by the pit pores may not be true, gave an average pore radius of 0.14 µm for Sitka spruce. This is considerable lower than those values reported in the other studies.

The distribution of the numbers of pit pores per cm^2 as calculated with Eq.19 is very much skewed toward higher numbers. Since r^4 is part of the denominator, the equation used to calculate the average number is very sensitive to the radius. The distribution of the radii is the same as the distribution of permeability, and therefore as discussed in "Comparison of Latifolia with Murrayana (Table 7)" on page 55, they are skewed toward higher values. To correct for this skewness the median of the pit pore number and the mean of the natural logarithm are reported in Table 9. The two varieties are not significantly different with respect to pore numbers. The median values of 1293 and 1210 pit pores/cm^2 are higher than the figure of 605 reported by Bao et al (1986) for Chinese pine possibly because his reported pit pore radius was lower. Assuming 10^5 tracheids per cm^2, 1.2 - 1.3% of all tracheids in sapwood would be connected with a single pore.

Nine samples from the anomalous wood described in "Heartwood" on page 50 were tested using the sapwood measuring method to calculate the pore size. The average radius of the pit pores was 3.75 μm, almost three times higher than the mean sapwood pit pore radius of var. *latifolia.* Since the sapwood radii are believed to be larger than the heartwood radii (Petty and Preston 1969) this result is a strong indicator that the pit pores were altered in these samples. The number of connecting pit pores per cm^2 (68) is fairly small compared with the sapwood figure, but taking into account that the specimens are made from heartwood the figure might be reasonable.

5.4 Retention Measurements

As described in "Retention Measurements" on page 38 soaking tests under vacuum were carried out to relate the measured gaseous permeability to the ability of the wood to absorb water. Table 10 includes average retention in g water per cm^3 void space as calculated with Eq.23. In addition, three regression models -- linear, quadratic, and logarithmic -- were evaluated and the R^2 values were included in the table. All correlation coefficients are significant at a 99.9% level. Since no study relating water uptake and permeability was found, no direct comparison can be made. However, Graham (1964) and Chudnoff (1970) used simple water soaking tests to predict the treatability of a certain species. Siau and Shaw (1971), Tesoro (1964), Joslyn (1972) related permeability to treatability with non-aqueous liquids. In all cases highly significant relations between the liquid retention and the logarithm of gaseous permeability were obtained. This accords fairly well with the findings of this study although the linear model has a somewhat higher R^2 than the logarithmic model for heartwood.

Figure 13 on page 76 and Figure 14 on page 77 show the linear and logarithmic regression of retention over sapwood air permeability for both varieties. The one minute experiment (S1) is re-

Table 10 Retention Measurement

Correlation between water absorpion per void volume of wood and gas permeability

A Sapwood

var. *latifolia*	S1[1]	R^2	
n=237		linear:	0.1875
K=0.136 darcy		quadr.:	0.2861
Ret=0.570 g/cm^3		log.:	0.2392

var. *latifolia*	S5[1]	R^2	
n=240		linear:	0.1922
K=0.129 darcy		quadr.:	0.2243
Ret=0.675 g/cm^3		log.:	0.2274

var. *murrayana*	S5[1]	R^2	
n=72		linear:	0.1606
K=0.088 darcy		quadr.:	0.2021
Ret=0.400 g/cm^3		log.:	0.2145

[1] S1, S5, F5 refer to 1 minute soaking time, 5 minutes soaking time, and 5 minutes floating time

Table 10 contd.

B Heartwood

var. *latifolia* S5[1] incl. specimen with anomalous heartwood	R^2	
n = 484	linear:	0.4726
K = 0.029 darcy	quadr.:	0.5718
Ret = 0.195 g/cm^3	log.:	0.3604 (log quadr.:0.6184)

var. *latifolia* S5 excl. specimen with anomalous heartwood	R^2	
n = 464	linear:	0.4876
K = 0.014 darcy	quadr.:	0.5161
Ret = 0.182 g/cm^3	log.:	0.4474

var. *murrayana* F5	R^2	
n = 69	linear:	0.5767
K = 0.008 darcy	quadr.:	0.5775
Ret = 0.140 g/cm^3	log.:	0.4195

[1] S1, S5, F5 referr to 1 minute soaking time, 5 minutes soaking time and 5 minutes floating time

Table 10 contd.

C Heartwood and Sapwood Pooled

var. *latifolia* S5[1] incl. specimen with anomalous heartwood	R^2	
n = 717	linear:	0.4375
K = 0.0 darcy	quadr.:	0.5979
Ret = 0.195 g/cm^3	log.:	0.5673 (log quadr.:0.6824)

var. *latifolia* S5 excl. specimen with anomalous heartwood	R^2	
n = 697	linear:	0.5996
K = 0.0 darcy	quadr.:	0.7215
Ret = 0.195 g/cm^3	log.:	0.5696 (log quadr.:0.7114)

var. *murrayana* F5	R^2	
n = 134	linear:	0.4159
K = 0.0 darcy	quadr.:	0.5877
Ret = 0.195 g/cm^3	log.:	0.6274 (log quadr.:0.6667)

[1] S1, S5, F5 referr to 1 minute soaking time, 5 minutes soaking time and 5 minutes floating time

presented as dotted line indicating the lesser amount of water absorbed. Also the slope of the regression line is somewhat smaller, indicating that the void spaces of the more permeable samples were not completely filled whereas they had already reached saturation (1.0 g/cm^3) in the five minute treatment (S5).

Figure 15 on page 78 and Figure 16 on page 79 show the equivalent plots for the heartwood specimens. However, The entire set of heartwood samples of var. *latifolia*, including the anomalous samples, is best described by a quadratic regression line which is also true for the logarithmic regression ($R^2 =$ 0.572 and 0.618).

From the plots of *latifolia* and *murrayana* it can be observed that both varieties have different intercepts. This is probably caused not by natural differences between the varieties but rather by slightly different procedures (see "Retention Measurements" on page 38). While the specimens of the var. *latifolia* were submerged below water surface during the soaking period (S1,S5), the samples of *murrayana* were permitted to float on the surface (F5). Nevertheless, regression lines show that the trend of retention vs gaseous permeability is the same for both varieties.

All three models (linear, quadratic, logarithmic) for the retention of the heartwood samples have correlation coefficients twice as high as those of the sapwood samples. Nevertheless, the models were significant at a 99.9% level for both varieties.

The pooled regression (sapwood and heartwood) for both varieties is shown in Figure 17 on page 80 and Figure 18 on page 81. Over the wide range of permeabilities asymptotic curves best describe the regression of retention over permeability. The highest theoretical value for retention is 1.0 g/cm^3. However, there are some outliers with a higher retention than 1.0 g/cm^3 especially in the case of var. *latifolia*. This might be because the value for the fiber saturation point was assumed to be 30% which may not be true for these outliers which are mostly samples with anomalous heartwood.

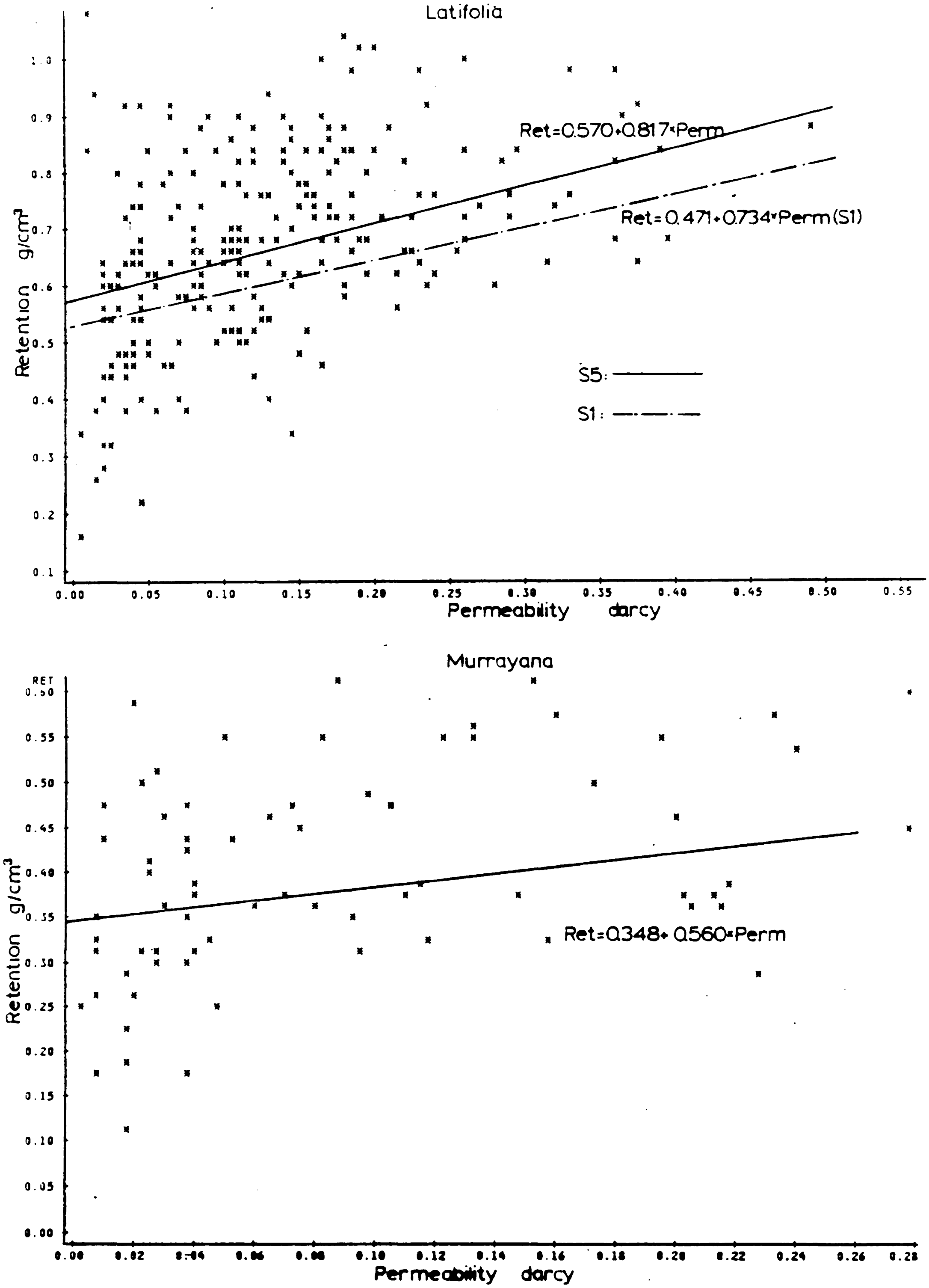


Figure 13. Retention vs Gas Permeability for Sapwood

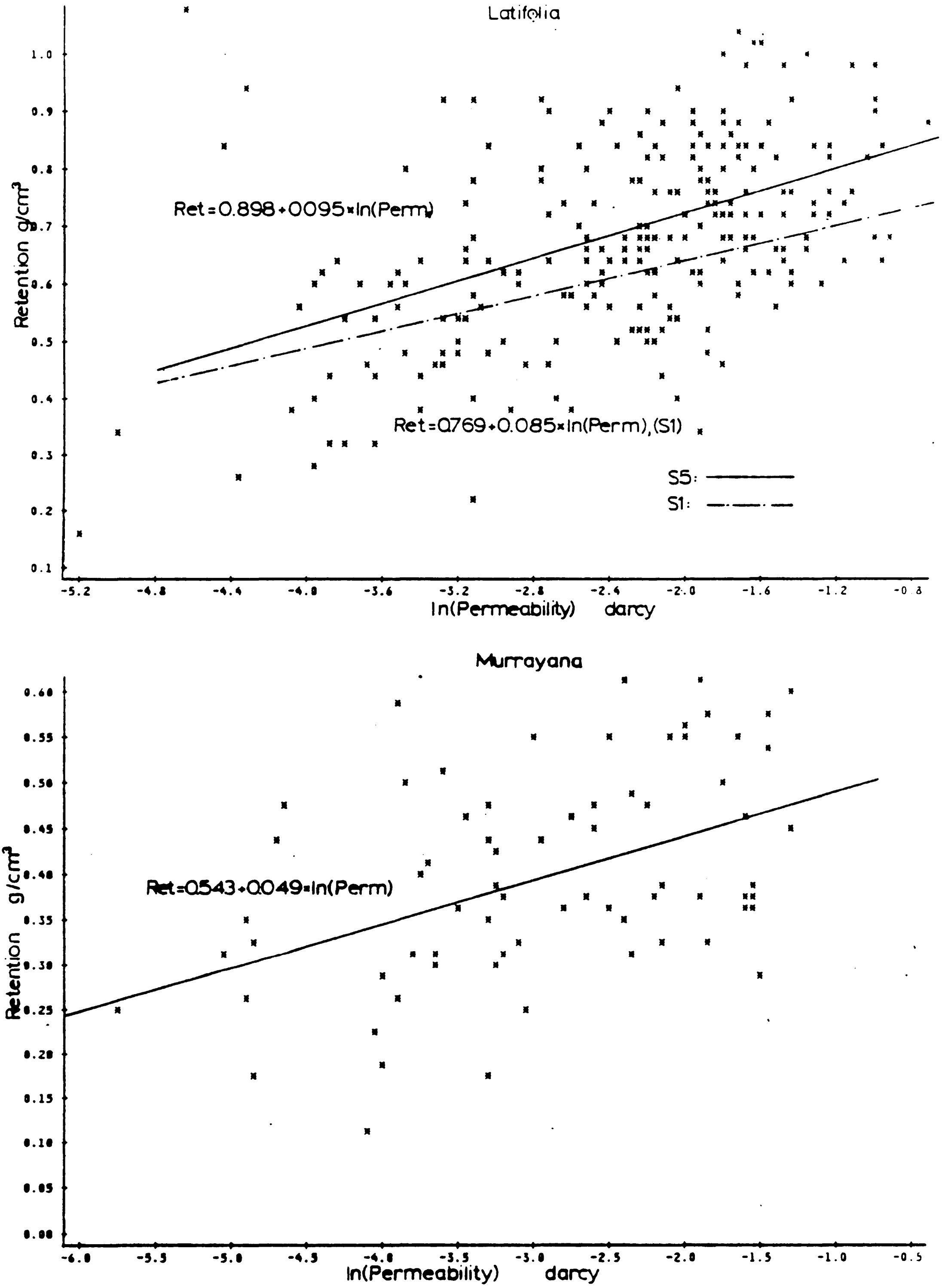


Figure 14. Retention vs Logarithmic Gas Permeability for Sapwood

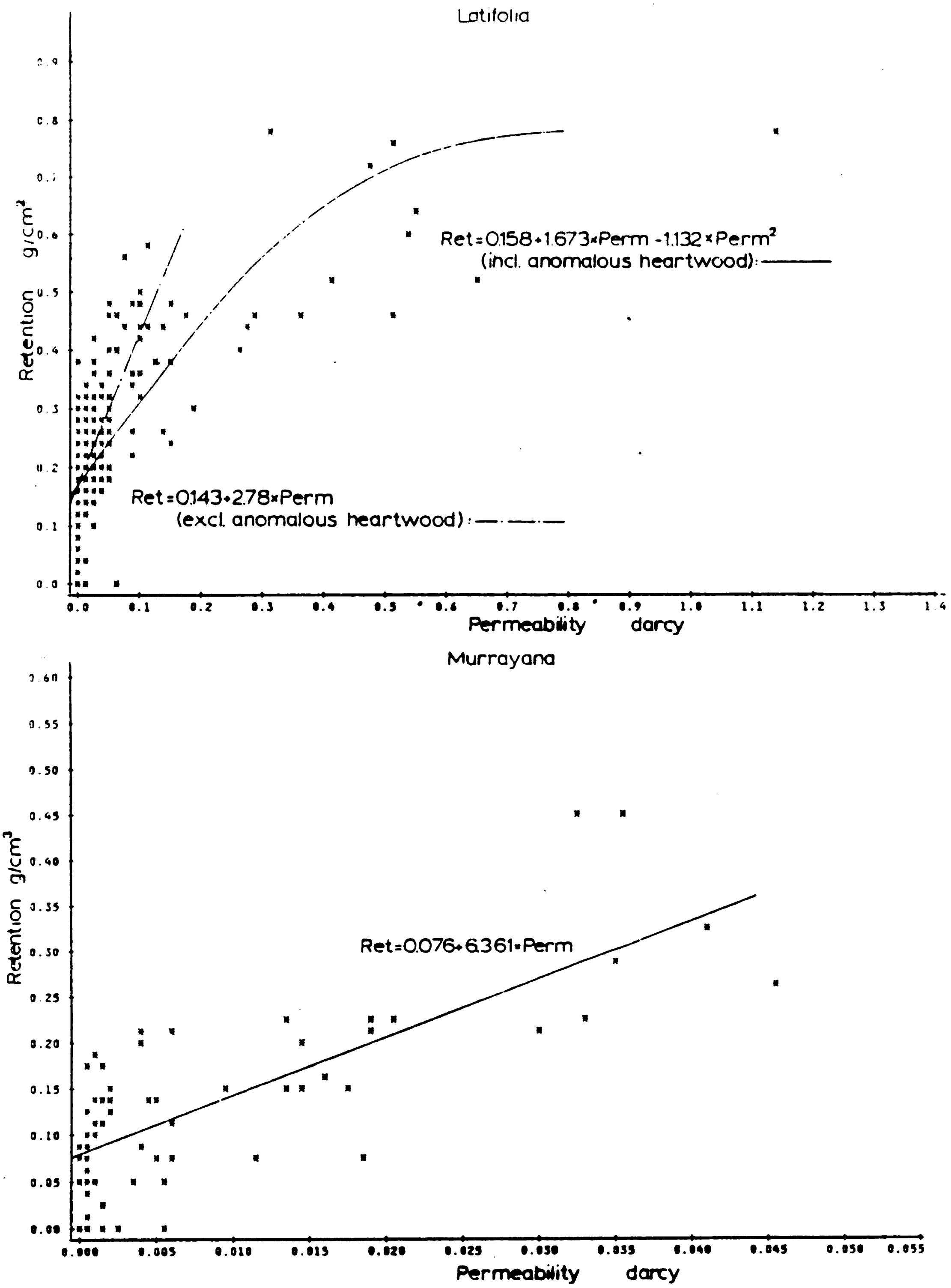


Figure 15. Retention vs Gas Permeability for Heartwood

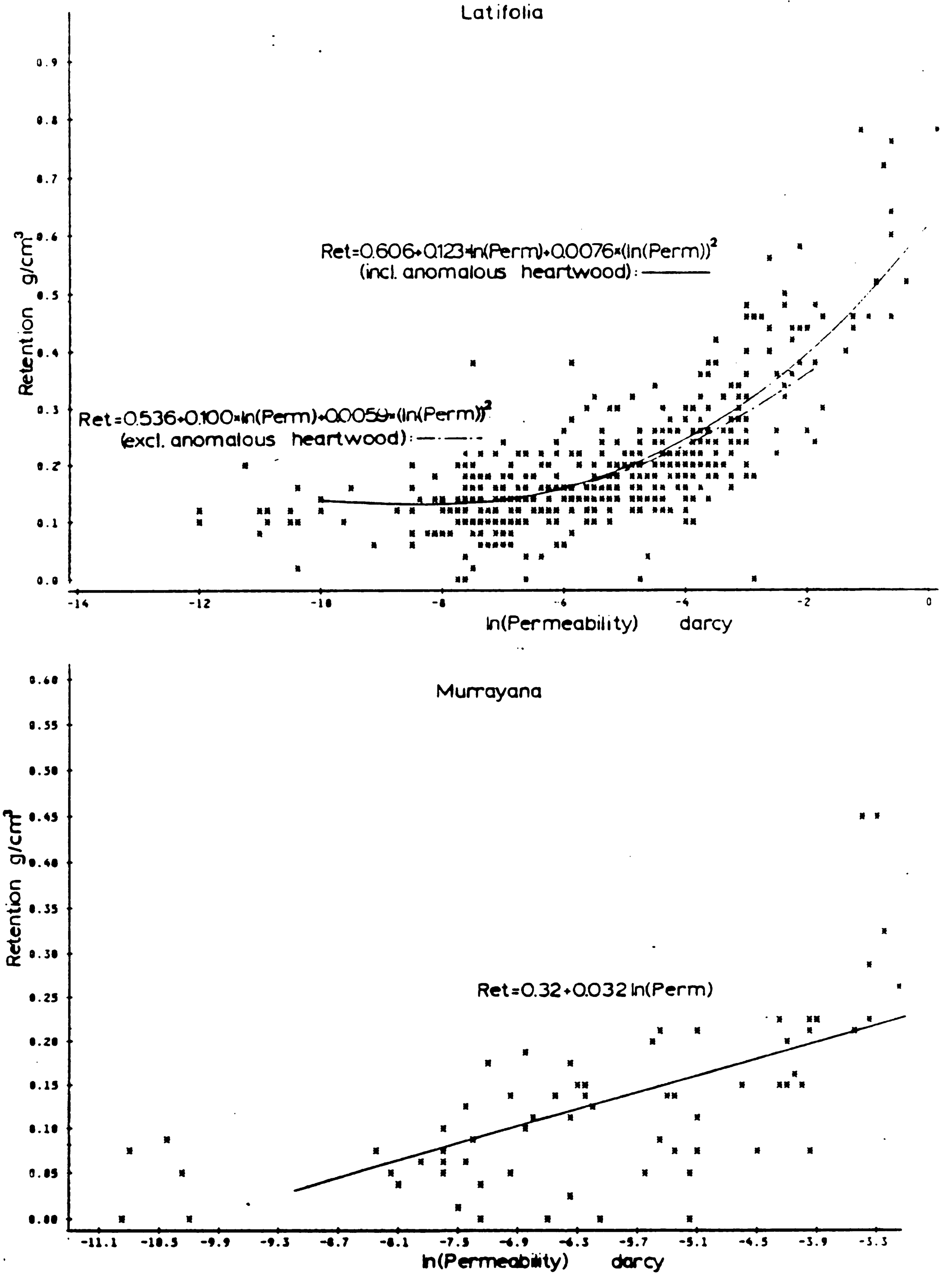


Figure 16. Retention vs Logarithmic Gas Permeability for Heartwood

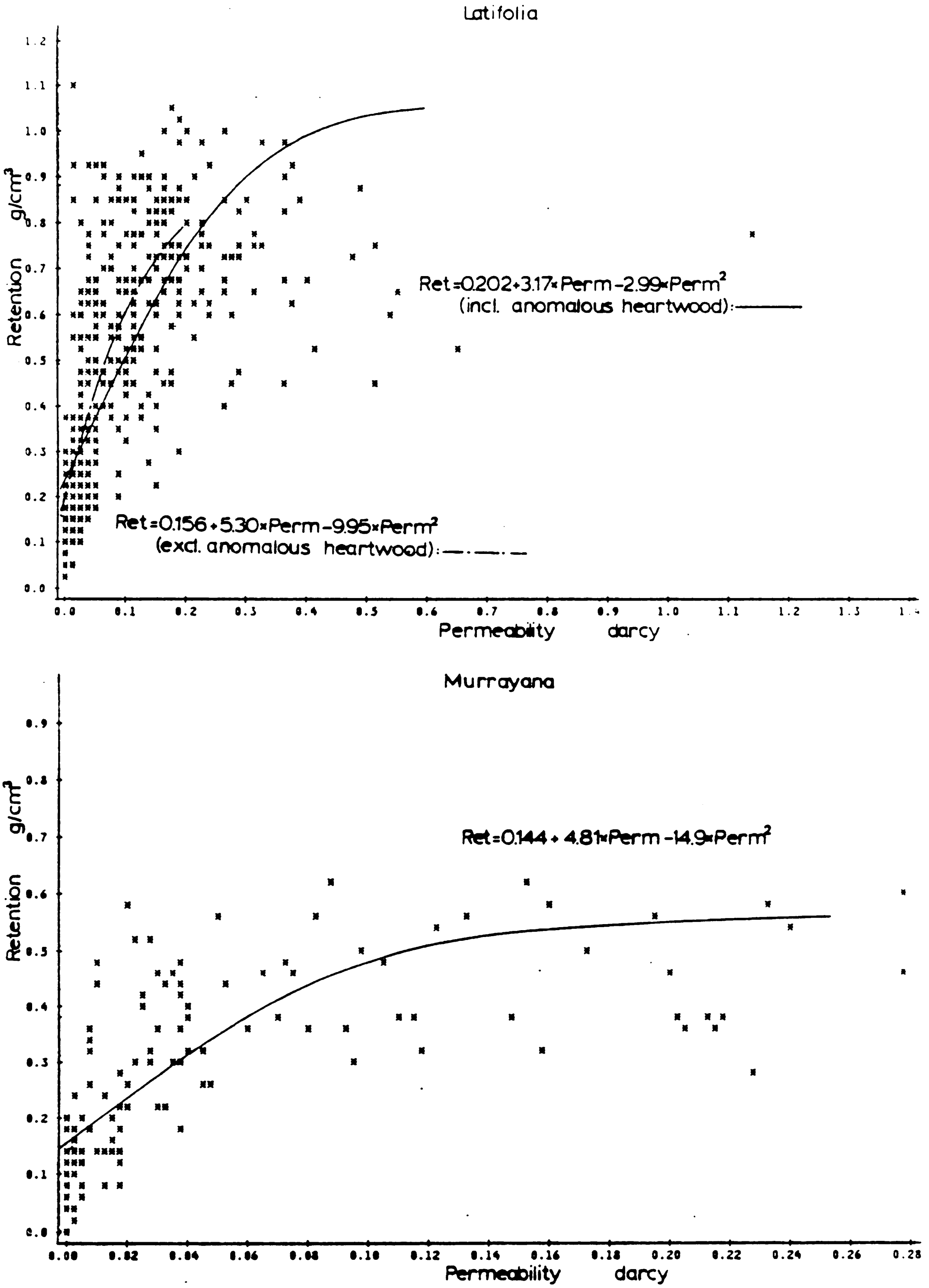


Figure 17. Retention vs Gas Permeability, Heartwood and Sapwood pooled

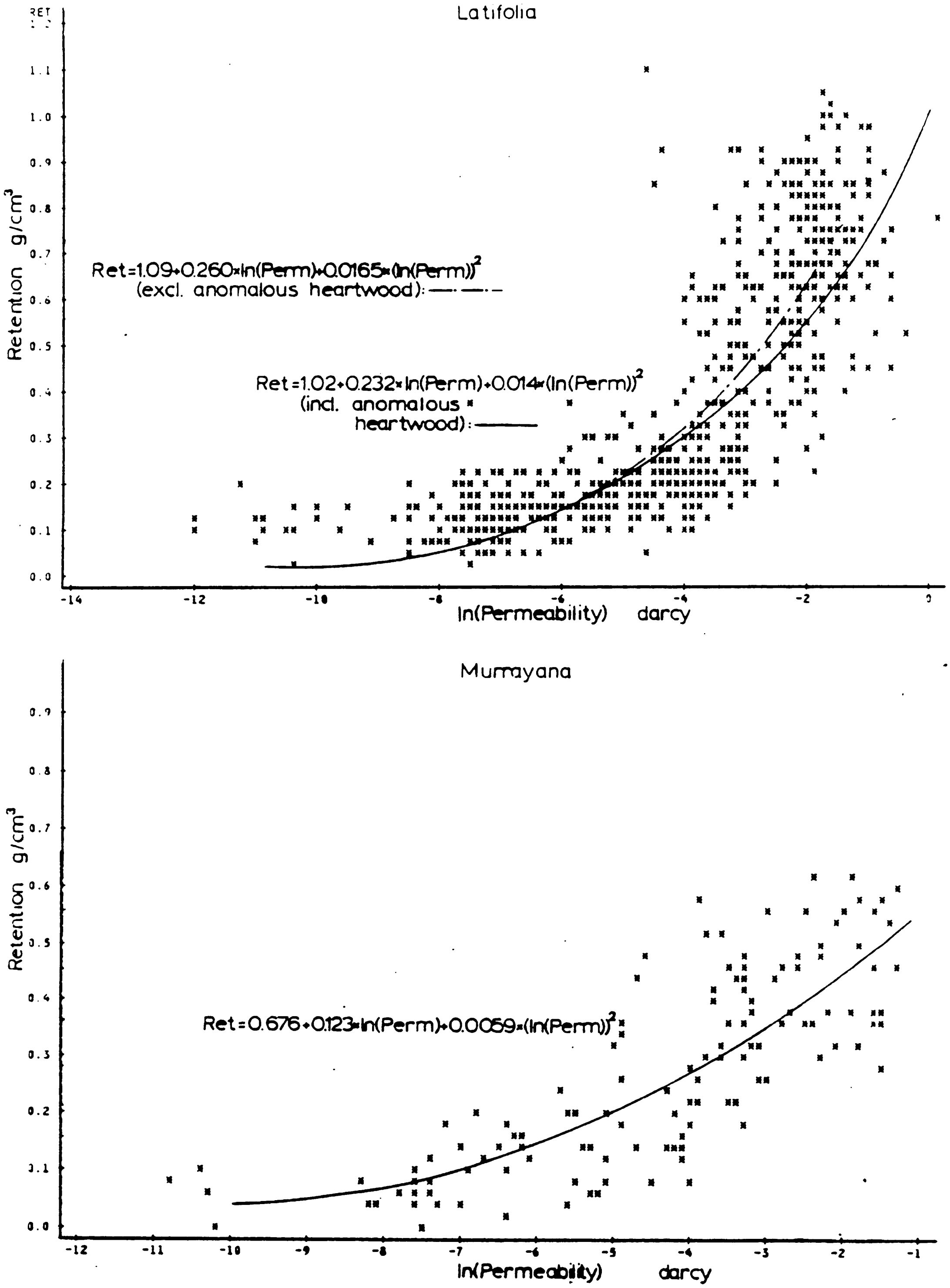


Figure 18. Retention vs Logarithmic Gas Permeability, pooled

6.0 Summary

The longitudinal air permeabilities of the wood of 1116 specimens from 279 trees, two sapwood and two heartwood replicates, representing two varieties of lodgepole pine (*Pinus contorta*, vars. *latifolia* and *murrayana*) were measured with a steady state apparatus. It was found that the mean ratio of sapwood to heartwood permeability was ca. 10:1 for both varieties. The mean ratio of var. *latifolia* to *murrayana* was 1.5:5 and 1.75:5 for sapwood and heartwood, respectively.

The most important source of variation following the difference between heartwood and sapwood was that among trees. Geographical locations, such as latitude and elevation did not significantly influence permeability. Tree size did, but only because the small trees (3 inch diameter) showed higher heartwood permeability and lower sapwood permeability than normal. Ca. 20 specimens of *latifolia* heartwood showed extremely high permeabilities. They were also deeply brown in color, which probably was caused by fungal or bacterial infestation.

Pit pore size and number per cm^2 were determined for sapwood by making four permeability measurements, each at a different average pressure on each specimen. A mean pit pore radius of 1.5 μm and 1.3 μm for sapwood of var. *latifolia* and var. *murrayana* was calculated. The median values between 1200-1300 pit pores per cm^2 indicate an average rate of tracheid connection of 1.2-1.3%.

Of the tested wood parameters including moisture content and specific gravity average ringwidth, only the permeability of var. *latifolia* was significantly correlated with moisture content for both heartwood and sapwood, with a negative correlation coefficient.

Water retention measurements were carried out to relate the measured gas permeability of an individual specimen to its ability to absorb water. For both varieties the retention was significantly and quadratically correlated with sapwood permeability ($R^2 = 0.286$ and 0.224) and was linearly correlated with heartwood permeability ($R^2 = 0.488$ and 0.5775). The correlation factors for the regression between retention and the logarithm of permeability were 0.239 and 0.227 for sapwood and 0.447 and 0.420 for heartwood.

7.0 Practical Considerations

This study was focussed on the determination of the permeability of lodgepole pine. The measurements showed that the sapwood of this species has a permeability, which lies in the lower third of the permeability range of southern yellow pine, indicating a reasonable good treatability of the wood with liquids. But unlike southern yellow pine, lodgepole pine has a fairly high amount of heartwood, especially in trees with small diameter. Since heartwood is approximately ten times less permeable than sapwood,it is probable that lodgepole pine is not very suitable for treated lumber, fence posts, poles, etc, unless the heartwood is naturally decay resistant or there is a larger than normal volume of sapwood.

Further research might study the effects of solvent exchange drying, steaming and other treatments for enhancing the permeability of lodgepole pine heartwood. Also the fact that the heartwood of trees from the northern region of the growing area was apparently infested by fungi or bacteria is worth further investigation. This anomalous heartwood is three times more permeable than sapwood, which indicates that some alteration of the wood structure has occurred. If the cause of this phenomenon could be understood and taken advantage of industrially, lodgepole pine might be better utilized,it does not decrease mechanical properties seriously.

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