VARIATIONS IN CONIFEROUS WOOD MOISTURE ESTIMATION BY ELECTRICAL TECHNIQUES

by

I-CHEN WANG

B.Sc. Taiwan Provincial Chung Hsing University, 1970

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Department of Forestry

The University of British Columbia
2075 Wesbrook Place
Vancouver, Canada
V6T 1W5

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ABSTRACT

Electrical moisture meters have certain advantages over other techniques for determining wood moisture content. Variability associated with such meter measurements has not been thoroughly investigated. This study examined some sources of this variability that arise between species, between trees and within stem which relate to wood electrical properties.

Wood samples included portions of seven recently felled full-tree coniferous logs. This provided comparison as: between species (lodgepole pine (Pinus contorta var. latifolia Engelm.), western white spruce (Picea glauca (Moench.) Voss.), Douglas-fir (Pseudotsuga menziesii var. glauca (Beissn.) Franco) and subalpine fir (Abies lasiocarpa (Hook.) Nuttl.); within species (four lodgepole pine); and within individual stem (four to five in height series, two to five in radial series). In addition, one lodgepole pine stump displaying reaction wood was included. Direct current resistance (Delmhorst RC-1B) and power-loss (Moisture Register, Model L) meters were used to estimate moisture. Radial specimens (2.5 cm x 2.5 cm x 40 cm) were subdivided into four 10 cm lengths and placed side by side to expose radial or tangential faces that accommodated the power-loss meter head. This provided a novel way for collecting and replicating data with regard to position within stem, as well as minimizing the influence of defect. Specimens were tested at 21°C for nominal moisture levels ("green", 19% and 12% for resistance meter, 19%, 12% and 6% for power-loss meter) and meter readings were compared with calculated moistures.

Direct current resistance moisture meter measurements did not appear to be related to wood specific gravity. Between tree measurements within lodgepole pine showed less variation than measurements between the four

species. Within tree height contributed little to variation, but radial direction did provide discernible variation, especially at low moisture contents. Precision of the resistance measurements was good, but accuracy was poor.

Power-loss type moisture meter measurements were influenced by specific gravity. Regression lines of meter readings and moisture content approached quadratic functions, with the notable exception of Douglas-fir. Regression equations containing moisture content, moisture content squared and specific gravity as independent variables accounted for 92% of the total variability for all seven trees studied, and 96% among the four lodgepole pine trees.

Between species variations in power-loss meter measurements were prominent and highly significant. There were also significant differences for between tree measurements. Within tree height contributed little, but radial direction did contribute to variation. Exposure of radial or tangential faces gave significantly different readings.

Better understanding of the contribution of such variables could increase usefulness of moisture estimations by electrical meters.

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1.0 INTRODUCTION

Moisture level seriously affects wood properties and uses. In addition, there are constant interactions between ambient humidity and wood which changes its moisture content. In operations of drying, machining and wood treatments, moisture content has large importance. It also affects transportation costs to the lumber and paper industries. A fast and reliable means of determining moisture content, is therefore vital for wood product quality control.

Several conventional means of wood moisture content determination are used currently. These include oven-drying, distillation, titration, hygrometric methods and electrical moisture meters. Most of these methods operate only on small sample quantities, while some are destructive in nature and are time consuming to use. Newer means of moisture determination have been suggested, such as beta ray adsorption and neutron scattering (66). These are either not developed for practical application or require expensive and bulky equipment.

In 1972, Stamm (80) first suggested that the relationship between moisture content and direct current resistance of wood could be used to determine its moisture contnet. Since then numerous studies have been made in this field, and a variety of instruments have been devised for estimating moisture. Electrical meters offer the advantages of speed, economy, mobility non-destructiveness and reasonable accuracy, and have little restriction on sample size. These benefits put electrical moisture meters in favour over other conventional methods of determining moisture, especially in regard to continuous monitoring and automatic control.

More recently, the trend is toward the use of dielectric properties to assess moisture content. Two types of dielectric moisture meters, capacity and radio-frequency power-loss are in use. These are more effective in assessing low moisture, leave no pin marks on the specimen, are capable of continuous measurements and do not depend on good contact between the electrodes and specimen. The meter readings are affected, however, by the specimen density which may cause substantial deviations. The use of high frequency microwaves may ameliorate this situation, as there is less interaction between specimen density and the dielectric properties at high frequencies.

Explorations in dielectric properties of wood have opened up some other possible applications. McLauchlen et al. (55) have patterned a device using the dielectric anisotropy to measure the grain angles of wood. Pande (68) suggested using the dielectric constant to assess cellulose crystallinity. Venkateswaran (92), after observing a linear relationship between the lignin content of wood and the dielectric constant, has commented on the possibility of applying these polarization properties to measure lignin content. However, the complexity of wood and its overlapping polarization spectra demand more study before practical applications of these discoveries can be established.

Although there are tables available for adjusting electrical moisture meter readings as regards species, very little attention has been paid to other facets of wood variability. It was a purpose of this study to investigage the relationship between electrical moisture meter performance and some aspects of wood origin, such as differences between coniferous species, between stems of the same species, and between height levels, wood zones and anisotropy within the same stem. Another purpose was to recognize for further study, wood specimens varying greatly from established norms.

Comercially available direct current resistance type and radio-frequency power-loss type moisture meters were used in the study. This fulfilled the idea of practicality, although the precision of these may be less satisfactory than sophisticated laboratory instruments.

Through a special sampling scheme and specimen arrangement, all measurements were carried out on comparatively small samples. This allowed analyses and presentation of data in ways not done previously.

2.0 LITERATURE REVIEW

Moisture content is one of the most important wood property parameters. It has great significance on economic and technical aspects of the material utilization. Therefore, it is deemed appropriate to examine first the definition and interaction of moisture on wood.

2.1 Moisture and its Interaction with Wood.

2.1.1 Wood moisture definitions.

The moisture content of a material may be defined in a variety of ways, depending on the purpose of definition and the field of technology to which it is applied. Most frequently, moisture content is expressed by calculation based on original weight (relative moisture content), whereas in the wood and textile industries, the calculation is based on oven-dry weight (absolute moisture content). In either case, the separation of dry material portion from water portion and accurate measurement of at least one of them is essential in determining moisture content (31). This is mostly done by oven-drying the material according to certain specifications to obtain its dry weight (1).

Various methods and instruments have been devised to measure moisture content of wood based on the relationship between moisture content and certain physical properties of wood, but all these measurements have to be calibrated according to the dry weight. The importance of a proper and universal drying method is evident. Accordingly, it is one of the central issues of moisture content definition (41). Both oven-drying and high vacuum drying have the problem of being time consuming. Also, the accuracy suffers when the wood contains volatile substances like fats and oils (41).

Wood is a complex fibrous material mainly composed of hollow, elongated cells oriented parallel to the lonitudinal axis of the tree. The cell walls in turn are formed by lamination of numerous thin layers. Also, wood has both colloidal properties and an infinite number of capillary pores. In such an intricate material, water interacts with wood substance in a complicated manner. In addition to these complications, it is commonly assumed that moisture content refers to a definite and implicitly defined quantity of moisture present in a material. However, much careful study may be necessary in order to be able to define moisture content usefully for any given purpose, or to interpret the results obtained from a particular method of measurement. For instance, measurements based on dielectric constants have to take into consideration the great variability of water, which may adjust constants from 9 (bonded water) to 81 (bulk, free water) (31).

Water may be held in wood in different states as a result of different modes of interaction with wood substance. These interactions often alter the physical and chemical properties of both water and wood. Most apparent of all, for example, are the sorption isotherm and dimensional change of wood (22). It is difficult to differentiate between different states of water in wood, although it is classified into three types according to one system. Based on the bonding force between water molecules and wood substance, there are chemical, physico-chemical and physical bondings (31).

Chemically bonded waters, such as hydrates and crystalline compounds, are absorbed on to the molecular structure to form a solid solution, and become a portion of the wood constitution, hence the term "water of consitution". Stamm (82) considered this portion not water at all but hydroxyl groups that split out under high temperature. Generally, this form is excluded from the definition of moisture content.

Physico-chemically bonded water refers to a monomolecular surface adsorption layer. Macro- and microstructures of the wood surface or the geometric configuration of the space water molecules may occupy have a profound effect on the strength and quantities of bonds. Langmuir (46), who first proposed theoretical explanation of this monomolecular adsorption layer, believed that the bonding energy is about the same order as a covalent bond. On the other hand, Stamm (82) considered that this monomolecular adsorbed water or "surface bound" water is held by hydrogen bonds which have about one-fourth of the covalent bond energy. This strongly held water is one of the reasons that oven-dry weight of a piece of wood is an arbitrarily determined weight.

Physically bonded water is considered to be the result of the imbalance of force exerted on water molecules from the surface of the adsorbent. In other words, this portion of water is held by long range weak links due to polarization or Van der Waals forces (41). The water adsorbed in this range is multi-molecular. Three widely received theories have been proposed for the multi-molecular adsorption.

Zsigmondy (102), who proposed the capillary condenstation theory, attributed adsorption to condensation of water vapor in the capillary pores. The pressure of condensation is proportional to the radius of liquid meniscus in a capillary, therefore the smaller the capillary radii, the faster condensation occurs. This theory can not account for unimolecular adsorption, and is applicable only to relative humidities of 90% or more.

Polarization theory (10) considers adsorption as a result of induced dipole attractions propagated from the adsorbent surface over several layers. It was used to explain the sorption isotherm quantitatively, but is now obsolete largely because it fails to account for the binding energy between layers.

Brunauer, Emmett and Teller (13) proposed a theory to account for multi-molecular adsorption based on the assumption that the same forces that produce condensation are also chiefly responsible for the binding energy of multi-molecular adsorption and only the first adsorbed layer is surface bound. The subsequent layers are adsorbed not by the surface but by the preceeding layers. This is known as the BET theory.

Kollmann and Cote (41) classified water held within wood in four phases: water of constitution; surface bound, monomolecular layer; multi-molecular layers of decreasing order of dipole; and capillary condensed water. Transition between the different phases is not sharp. Kollmann (39) further divided the capillary condensation curve into "apparent" capillary condensation in submicroscopic structure and real capillary condensation in the microscopic pores. A three component furmula was proposed to describe the total range of relative humidity sorption isotherm.

2.1.2 Interaction between wood moisture and electrical properties

Dry wood is an excellent electrical insulator. The electrical conductivity is almost entirely due to adsorbed moisture (82). Resistivity of oven-dry wood has been obtained by extrapolation as 3×10^{17} to 3×10^{18} ohm-centimeter (16, 82). The resistivity is inversely proportional to moisture content. From oven-dry to about 7% moisture content, there is a linear relationship between the logarithm of resistivity and moisture content (16,38,70). Stamm (82), estimated the change in resistivity in this range as about 100,000-fold. From 7% to fiber saturation (28%), the logarithm of resistivity relates linearly to moisture content with a different slope (38,82). Above the fiber saturation point, the change in resistivity is relatively small (38, 80).

The breaking of linearity at 5 to 8% moisture content was thought to correspond to the transition zone from monomolecular to multi-molecular adsorption. Moisture would be a disrupted film at moisture contents below this range. This provided some explanation as to the drastic change in resistivity below and above this transition zone (82).

Lehmann (51) studied the dependence of the electrical conductivity of some hygroscopic fibers on their water content. He found that below fiber saturation point, the moisture sorption curves and d.c. conductivity of different natural fibers plotted against moisture content are very similar. In low moisture content range, the water molecules were held by chemisorption in amorphous regions of the fibers, hence had no effect on conductivity. Further, as water adsorption penetrated by capillary condensation into intermecellar crevices, with increasing hydrogen bonding, the d.c. conductivity also increased.

The comparative electrical conductivity of pure water held in a porous body compared with conductivity of the same amount of water in bulk, i.e., the relative conductivity may be as high as a factor of 10. This indicates ten times higher conductivity for surface bound water then bulk water (82,100). This is attributable to zeta-potential at one hand and less association between adsorbed water molecules than bulk water on the other hand.

At a given temperature and frequency, the dielectric constant increases with moisture content (12,27,78). The increase is attributed to the high dielectric constant of water (ca. 80) compared with the low dielectric constant of wood substance. Also high moisture content contributes to freedom of rotation for the cell wall polar groups. This dielectric contant of wood increases exponentially with moisture content below the fiber saturation point and increases linearly above this point (78, 88). Venkateswaran and Tiwari (93) studied the moisture content and dielectric property relationship by employing a binary system of water and wood, and assuming that the macroscopic polarization of the system follows chemical rate theory. Fair agreement was obtained for calculated values and experimental observations.

A disruption has been observed at about 6% moisture content for both dielectric constant and dielectric loss tangent of wood. The underlying significance is correlation between the Langmuir monomolecular adsorption layer and the inflection point. Trapp and Pungs(84) and Tsutsumi and Watanabe (86) both have observed this phenomenon.

Kajanne and Hollming (32) observed abrupt change in dielectric constant (ε') of wood when moisture content was around 4.5%. They accounted for it as hydrogen bonding and by assuming a 4 to 5% hydrogen bonding rate. The bonding energy was shown to be 3 to 4 kcal per mole through calorimetric measurement.

Tsuge and Wada (85) explained this inflection of dielectric dispersion of paper and cellophane at 3 and 6% moisture content, respectively, as a result of rotational segmental motions caused by sorbed water molecules breaking the inter-and intramolecular hydrogen bonds.

Norimoto and Yamada (62) studied dielectric properties of wood in relation to wood moisture content in the microwave range (ca. 10 GHz, or 1×10^{10} Hz). They found that the wood dielectric constant and loss factor in radial direction increased slightly up to 5% moisture content, then increased rapidly with increasing moisture content. They also divided moisture according to its interaction with wood as surface bound, multimolecular and capillary condensed water and analyzed these accordingly. Their results indicated a clear dependence of electrical properties on other physical parameters. The values obtained for surface bound, multi-molecular and capillary condensed water as regard specific gravity, dielectric constant, loss factor and specific polarization were given. Dielectric constants were shown to change from 7.1 to 63.5, loss factor from 1.6 to 6.5 and specific polarization from 1.1 to 14.0 for surface bound and capillary condensed water, respectively.

2.2 Effect of Wood Variability on Electrical Properties

The complexity of wood structure makes the study of its properties difficult. Nevertheless, the interdependence of certain wood properties and wood components such as density, fiber length, grain angle and chemical composition is well recognized. Due to the complexity of each individual property, interactions between them are often subtle and ill-defined. In many case, only phenomenal or qualitative interdependence can be observed (23).

Little work has been done relating wood electrical properties to other wood physical, chemical or morphological properties. Practically no literature is available dealing with wood electrical properties in terms of wood zones and tree height levels. Only indirect inferences may be drawn on electrical behaviour in regard to the position of wood sampled from a tree. Here, provisions have to be made for considerable speculation, since most of these studies were done on disintegrated wood or wood components, such as pulps and electrical condenser papers.

Some between tree and between species differences on electrical properties of wood have been studied, but these were not directed to the present specific interest. In fact, knowledge at this level arises as by-product of studies on other affilated subjects.

In the following review, wood characteristics which are reported to affect wood electrical behaviour are discussed.

2.2.1 Wood physical properties in relation to electrical properties

A most prominent subject in wood physical properties is specific gravity, which is the ratio of wood oven-dry weight and the weight of an equal volume of displaced water. Wood density is defined as weight per unit volume.

There is no final agreement on the effect of specific gravity on wood direct current conductivity. Yavorsky (99) and Stamm (82) both considered that wood conductivity should show a positive correlation with specific gravity. Hart (25) theorized the effect of gross anatomy upon conductivity of wood with the same underlying assumption of a positive specific gravity-conductivity correlation. However, little experimental evidence has been given in support of this view. Data from the Wood Handbook (2) and a recent study by Venkateswaran (91) indicate that differences due to species effects are much stronger than the specific gravity effect.

Also, because of the logarithm relationship between moisture content and direct current conductivity of wood, differences in specific gravity have a minor effect upon conductivity, e.g., a two fold difference in specific gravity may result in a 1 to 2% meter reading difference for moisture content (82).

The effect of wood density on its dielectric properties has been well recognized. Peterson (70) studied the relationship for Douglas-fir (Pseudotsuga menziesii) (Mirb.)Franco) wood and found a curvelinear relationship. When moisture content is above 6%, there is a linear relationship between dielectric constant (ε') and density (ρ) (18, 63, 78).

Delevanti and Hansen (18) found that the ξ' of kraft paper was related to density ρ by the Clausius-Mosotti relation:

$$(\xi' - 1)/(\xi' + 2) \propto \rho \quad \ldots\ldots\ldots\ldots \quad [1]$$

Skaar (78) discovered a correlation between density and the transverse loss tangent of oven-dried wood. Peterson (70) supported these findings that a positive correlation exists between the dielectric loss and density of wood. However, he noted that the effect is not so marked as between dielectric constant and density. Delevanti and Hansen (18) also noted a linear relationship between the loss factor and density. Norimoto and Yamada (63) found a similar linear relationship between loss factor in longitudinal direction (ξ''), loss factor of wood substance (ξ_{1}'') and specific gravity (ρ), and gave the equation as:

$$\xi'' = \frac{\rho}{1.53} \times \xi_{1}'' \quad \ldots\ldots\ldots\ldots \quad [2]$$

However, the function was found to be affected by temperature and frequency.

Hearmon and Burcham (29), on the other hand, have decided that the relationship between loss tangent and density for air-dried wood was ambiguous. Lin (54) in a recent work, in which he assumed wood to be an orthogropic dielectric material and calculated the results by stepwise regression analysis, also found that moisture content contributed 94% of the variability in dielectric constant and 84% for a.c. resistivity and loss tangent. Incorporation of density as an additional independent variable improved the regression very little. Specific gravity had virtually no effect on the regression model.

It is likely that the effect of density or specific gravity on dielectric properties of wood is positive only at oven-dry condition. At other moisture contents, the effect is largely masked by the predominance of moisture and thereby difficult to assess.

2.2.2 Wood anatomical properties in relation to electrical properties

Morphological properties have attracted the least attention in this regard, and frequently studies were done on separated fiber, rather than on wood itself.

Some studies on fiber length in relation to electrical properties have been done in connection with condenser papers.

Callinan (14) studied the electrical properties of handsheets made from unbleached kraft, semibleached kraft and mechanical pulp and found that dielectric constant and loss factor varied not only with chemical composition of the pulps, but also were correlated to fiber length. The explanation was that longer fibers contained less extractives and ash than short fibers. In other similar studies (101), the same conclusion was reached but with explanation that short fibers are more likely to form a continuous monomolecular adsorption layer under low moisture content. Long fibers would have discontinued water film, separated by air bubbles, thus contributing to poorer polarization and lower values of ε' and ε'' in long fibers.

Gallay (23) pointed out the importance of fiber length in correlating various paper properties. This appears to be a critical parameter in various physical properties.

Due to the elongated shape of most wood elements, their alignment according to the tree longitudinal axis and the near orthotropic alignment of microfibril angle, there is anisotropy of wood properties parallel and perpendicular to the grain direction.

Hart (25) theorized on effects of gross wood anatomy on conductivity and showed that by assuming an anisotropic cell wall substance, the transverse conductivity of wood specimens would be only one-half of the longitudinal conductivity. This arises simply as a result of the gross cellular structure of wood.

It has been well established that the direct current resistivity of wood across the grain is about 2.3 to 4.5 times higher than along the grain. For some pored wood species, the ratio may reach 8 times (38, 72, 82). These differences are reflections of structural variations, and are independent of moisture content (53, 82).

In perpendicular to grain direction, there is a 10 to 12% conductivity reduction in tangential direction as compared with radial direction. This is attributed to cellular misalignment in tangential direction of conifers, and the presence of rays (25).

The same phenomena also prevail in dielectric properties. Dielectric constant of wood along the grain direction is always higher than in the transverse direction. Skaar (78) considered the difference attributable to molecular structure of the cell wall. Orientation of the cellulose chains is largely orthotropic, with the hydroxyl groups of cellulose having more freedom along the grain than across the grain.

Lin (54) found that wood behaved as an orthotropic dielectric material without serious deviation when the moisture content was below 15%. Above 15% moisture content, the deviation of theoretically calculated values from experimental values became significant in the longitudinal-radial plane, the maximum then coincided to microfibril angle.

An anisotropy of dielectric properties is also present between radial and tangential directions. The origin of these variations were considered by Uyemura (88) and Kröner and Pungs (45) as resulting from cell wall orientation, rather than from microstructural differences. Nanassy (60) made similar observations. Rafalski (74) demonstrated that by compressing beech wood specimens along both radial and tangential directions, the dielectric property differnces between the two directions gradually reduced, finally reaching the same value as the specific gravity of the specimens became 1.45.

McLauchlen et al. (55) recently patented a grain slope indicator based on this anisotropic dielectric property. However, as pointed out by Lin (54), at high moisture content microfibril orientation has a significant effect on wood dielectric behaviour. Further studies were urged.

Fainberg et al. (21) discussed electrical anisotropy of cellulose materials, especially regenerated celluloses. Difficulties in determining dielectric anisotropy were thought due to the presence of water and the porous nature of the hydrophilic fibers. Calculated anisotropy values for non-drawn viscose rayon cord fiber and high-tenacity rayon cord fiber varied from 5.23 to 6.15, as compared with optical birefringence values of 0.0202 to 0.0395. Correlations between the orientation, dielectric permittivity and optical birefringence were suggested

Norimoto and Yamada (64) found a frequency dependency in dielectric anisotropy. At high frequency no difference was observed between parallel and perpendicular to grain directions. This was interpreted as indicating that dielectric anisotrpy is caused mainly by macroscopic structural differences. At low frequency, a large anisotropy difference was observed. which corresponded to polarization of hydroxyl groups in the disoriented regions of cellulose chains. This indicated a dependence of dielectric anisotropy on microstructure and movement of molecules in wood.

2.2.3. Wood chemical composition in relation to electrical properties

A brief review of the wood direct current conduction mechanism is warranted here in order to comprehend significance of chemical composition on wood electrical conduction.

The mechanism of d.c. conduction in wood is thought to be ionic rather than electronic (3, 12, 27, 52). The migration of ions in wood, under an electrical field has been demonstrated by various experimental evidence, such as the use of radioactive isotopes (52), color reactions of metallic ions (58), pH value change near the electrodes (30) and neutron activation analysis (47).

Ito (30) believed that in additoin to the usual ionic conduction, the electrokinetic phenomenon (zeta-potential) played an important role, since the wood specimen is equivalent to a binary system composed of membrane and water. Yurev and Pozin (100) demonstrated the importance of surface conductivity associated with zeta-potential, which is substantially higher than water conductivity of the same volume.

Murphy (59) applied the theory of electrical conduction in ionic crystals to cellulose and proposed that cellulose conductivity is the sum of intrisic and extrinsic conduction. The former are the ionized part of cellulose. These ions are either bounded on the surface of cellulose micelles or exist as free ions. Lin (52) proposed a model for ionic conduction in wood and pointed out that the number of charge carriers in wood is the major factor in determining conduction mechanism across the moisture range from oven-dry condition to 20% moisture. At higher moisture contents, the degree of dissociation of adsorbed ions and the mobility of these ions become determining factors.

The presence of water soluble electrolytes in wood is, therefore, very important to d.c. conductivity. One likely source of these ions is the ash content of wood. Ash is usually low in most woods, and a good portion of it is in water insoluble forms (38, 81). Consequently, it may have only minor effect on the electrical properties. Cellulose chains are thought to contain some highly polar groups which are available as ion exchange sites. Metallic ions adsorbed on these sites are held by strong bonds with bonding energy approximately the same as covalent bonds (12, 17). Under the influence of moisture, activation energy is reduced substantially and water itself is added to metallic ions to form charge carriers (28, 52).

Weatherwax and Stamm (98) found that deposition of nonhygroscopic, low conductivity materials, such as phenolic resins,in wood reduced d.c. conductivity because these substances reduced wood hygroscopicity.

As a long chain polyer composed of numerous hydroxyl groups, also of variable packing density, cellulose has been the subject of dielectric studies for some time, especially due to its importance as insulation paper in electric capacitor.

Bolotova and Sharkov (8) and Verseput (95) both found that the dielectric constant (ε') of cellulosic materials decreased with increasing crystallinity. Kane (33) employed a binary system and found a good regression between vapor accessibility of cellulose and ε', with small deviation from the least square regression line. The ε' of accessible cellulose was about 9, that of inaccessible cellulose 4. The reason for a high dielectric constant and loss factor of amorphous cellulose is thought to result from greater mobility or polarizability of hydroxyl groups in these regions, whereas hydroxyl groups in crystalline regions are hydrogen bonded and require extra energy for polarization.

Pande (68) described a theoretical approach for evaluating cellulose crystallinity through dielectric constant measurement. Gladstone and Dale's law for refractive index and density of a substance was used to derive an equation relating average dielectric constant with volume fraction of cellulose crystallinity. However, Venkateswaran (89) later pointed out that the Gladstone-Dale law is independent of cellulose crystalline content, thus it is invalid to calculate cellulose crystallinity via dielectric measurement.

Norimoto and Yamada (65) compared the dielectric constant and loss tangent of nine dry cellulose preparations and their corresponding crystallinity degrees as determined from moisture regain and x-ray diffraction. They were able to derive and experimentally verify a relationship between dielectric properties and cellulose amorphous content.

The effect of lignin content on dielectric loss factor has been a subject of interest in insulating paper research.

Borodulina et al. (9) and Delevanti and Hansen (18) pointed out the detrimental effect of lignin in contributing to loss factor. Nekrasov et al. (61) studied dielectric constant of lignin solutions in dioxane by assuming a lignin-dioxane-water ternary system. The results followed the Clausius-Mosotti relation (Eq.1). The polarizability of lignin molecules, as calculated from the experimental data, was higher by a factor of 1000 than that of water.

More recently, Venkateswaran (92) found a linear relationship between percentage lignin and dielectric permittivity (dielectric constant ε'). Woods with lignin contents ranging from 15 to 35% were studied. The higher the klason lignin content, the lower the specific permittivity as measured perpendicular to the grain. No explanation was given for this phenomenom, but a suggestion was made to develop this relationship into a non-destructive means for lignin measurement.

Venkateswaran (90) has found little association between the hemicellulose fraction and wood permittivity. Borodulina et al. (9) found that the pentosan content of kraft pulp had an inhibitory effect on sodium ions as to reduce dielectric losses. If pentosan content was lower than 5 to 6% the presence of sodium ions increased dielectric loss substantially, especially at high temperature.

Hemicellulose has been treated as a relatively short chained amorphous compound with some branching and containing polar groups, like hyroxyl, acetyl and carboxyl. These features may contribute to the dielectric relaxation behaviour as such.

Lazarev (49) in a study of rosin used for insulating purposes, found that abeitic acid contributed significantly to lower dielectric losses, whereas the rosin volatiles were detrimental to insulating qualities. Vermaas(94) studied the dielectric properties of cluster pine (*Pinus pinaster* Fram.) as a function of its alcohol-benzene soluble content. No significant influence on dielectric constant was found for wood extractives. The influence of extractives on the loss tangent depended upon the grain direction, where loss tangent along the grain was not influenced, while in the radial direction it increased and in the tangential direction it decreased with increasing extractive content. Norimoto and Yamada (63) found little difference between dielectric loss factor(ε'')of untreated and extracted wood samples. Kusunoki (*Cinnamomum camphora* Sieb.) was the only exception. This was thought to be due to the presence of conductive impurities like camphor, which were removed by extraction. Uyemura (88) also found little influence of organic extractives on dielectric properties.

Mineral content in wood, according to Skaar (78) does not affect to any significant extent the dielectric constant at radio frequency, but has influence on the power loss and loss tangent which are a function of a.c. conductivity. Venkateswaran (92) suggested that in dry wood, ash content does not seem to have any effect on dielectric permittivity and d.c. conductivity, due to the random distribution of metallic elements in wood.

On the other hand, researchers on insulating papers always stress importance of these impurities to dielectric losses. Delevanti and Hansen (18) showed that acid extraction, salt content and especially metallic ions contributed a large portion of the loss factor. Among the metallic ions, bivalent ions like calcium and magnesium have less influence on paper dielectric properties than monovalent ions like sodium and potassium (6).

The above review, hopefully, provides a background for understanding results of the present study.

3.0 MATERIALS AND METHODS

3.1 Sample Collection

Through arrangements made by CLMA and the efforts of Mr. M. Noel of the Merrill and Wagner Lumber Co., Williams Lake, B. C., the samples were collected from the company woodyard on June 4th, 1974. Fresh felled whole-tree lengths were selected. For within species comparisons, four stems and one compression wood stump of lodgepole pine (Pinus contorta var. latifolia Engelm.) were chosen. One stem each of white spruce (Picea glauca (Moench.) Voss.), Douglas-fir (Pseudotsuga menziesii var. glauca (Beissn.) Franco) and subalpine fir (Abies lasiocarpa (Hook.) Nuttl.) were also chosen for between species comparisons. All these species are important to the British Columbia Interior lumber industry.

A systematic sampling scheme was used. Each tree stem was sampled at five height levels. Internodal segments of ca. 45 cm were cut from each height level. Two segments were cut from the living crown part of the stem. Distances between the segments were adjusted slightly to avoid serious defects and branch whorls. Data on samples are given in Appendix I. Each segment was marked and wrapped in saran film and stored in a polyethylene bag to prevent moisture loss. After transporting samples to the Faculty of Forestry, University of British Columbia, they were stored in a coldroom at 2°C.

3.2 Specimen Preparations

The wood segments were sawn longitudinally into halves across the centers. Then along one of the two halves from each segment a 3 cm thick slab was cut. Each slab was further sawn longitudinally and parallel to the tangential faces into halves through the pith to give two radial series counterparts. The sample slabs were jointed on the edges and planed to give parallel surfaces. The slabs were marked into two to five 2.5 cm wide strips as radial series. Sapwood and heartwood zones were separated. The central growth increment of each marked strip was counted from the pith and recorded (see Appendix II). Each strip was further marked and coded into four 10 cm long specimens. Defects such as knots, pitch pockets and bark pockets were excluded from specimens as much as possible. The specimen pieces were then prepared by sawing the slabs into strips along the marked lines and dividing them longitudinally into four 2.5 x 2.5 x 10 cm pieces. These four specimen pieces were considered as one group. Specimens from the same radial series were put in one polyethylene bag and kept in the coldroom. A schematic diagram for specimen preparation is presented as Fig 1.

3.3 Moisture Measurements

3.3.1 Instruments and calibration

Commercial resistance and power-loss type moisture meters were used to assess specimen moisture contents. The resistance type moisture meter used was a Delmhorst RC-1B model, equipped with 26E electrodes of 1-inch pins. The power-loss meter used was a Moisture Register, Model L (see Appendix III for the meter circuitry).

The resistance type moisture meter was corrected before the experiment with standard resistances. Readings on some test pieces were compared with meter readings of a similar model from the Western Forest Products Laboratory. Tests showed good agreement.

The power-loss type moisture meter (Moisture Register, Model L) has a built-in standard. Before each series of measurements the meter was standardized and zeroed according to instructions. Necessary adjustments were made by tuning the trim.

3.3.2 Moisture conditioning and measurement

At first, "green" specimens were weighed individually and dimensions were measured to the nearest 0.1 mm by micrometer. These were used later to calculate actual initial moisture contents and specific gravities.

All "green" specimens had moisture contents above 25% and were thereby beyond the range of the power-loss meter scale. Only the resistance type moisture meter was used in this instance. Measurements were taken with the electrode aligned parallel to the grain direction and perpendicular to the radial faces. The depths of penetration were 0.5 and 1.2 cm. The former measurements at 1/5 of the specimen thickness corresponded to the over-all moisture content (11). The latter was a measure of the core moisture content. Differences between the two measurements were generally small, indicating a fairly even moisture gradient.

Subsequently, the specimens were conditioned stepwise to nominal 19%, 12% abd 6% moisture contents. The specimen pieces were placed on wooden trays with vinyl screen bottom, which provided good ventilation. Trays were stacked inside an Aminco constant temperature and humidity (CTH) chamber. Each conditioning took two to three weeks. The requirement of moisture content uniformity was compromised a little in order to conserve time. Stable moisture content levels were established as shown by fairly constant specimen weight at consecutive weighings.

Following each conditioning, the specimens were weighed in groups of four as representing the same radial series strips. Use of the resistance type moisture meter followed the same practice as described for the "green" condition, except in addition to measurements made on the radial faces, tangential faces were investigated as well. The nominal 6% moisture level was beyond the capacity of the resistance moisture meter. All measurements were made at 21°C.

The power-loss type moisture meter had an 8.6 cm diameter circular electrode, and demanded an even larger specimen surface to accommodate the electrode. This posed a problem on matched radial series measurements, since the largest diameter of those stems sampled was less than 40 cm. One pith to periphery radial series could at most accommodate two measurements which were far from adequate for establishing within stem data of analytical value.

To overcome the problem, a novel method of specimen arrangement was devised. The group of four specimens were aligned side by side, exposing either radial or tangential surfaces to provide a 10 x 10 cm surface. Pressure was exerted laterally to minimize gaps between specimens. The measurements could then be made on this improvised surface. After measurements were taken on both radial faces, the specimens were turned 90° and again measurements were made on the two tangential surfaces. The method not only provided a feasible way to assess a radial series and provide matched anisotropy measurements, but by shifting specimen alignments minor defects could be excluded from directly contacting the electrode, thereby minimizing influence of the wood defects.

Preliminary tests were run to determine the effects of "reconstituting" a board by putting specimens back together. Two-and-half centimeter thick lodgepole pine boards were alternately cut into 10 x 10 cm blocks and specimen-size pieces. The comparable sets of blocks and specimen-size pieces were conditioned at three distinct humidity levels (approximately

0%, 50% and 100%). After one month the power-loss meter readings on each set showed very small deviations between intact blocks and reconstituted blocks.

The power-loss moisture meter was designed to work on a 5 cm thick board. Since 2.5 cm thick specimens were used, a styrofoam insulating piece was placed beneath the specimens to prevent any external influence from causing erratic results.

3.3.3 Oven-drying and calculations

Eventual oven-drying was used to obtain specimen weights. Following the last batch of moisture measurements, specimens were stacked in ovens with wire mesh separating each layer for better ventilation. The ovens were adjusted and maintained at 102°C for three days.

A glove box with air lock was set up, and a well adjusted electrical balance was placed inside the glove box. Glass trays containing silicon gel and P_2O_5 were put under the false bottom of the glove box and air lock to give a dry atmosphere inside. After removal from ovens, specimens were put in a desccicator and carried to the glove box, where they were stored in the air-lock and allowed to cool. Then the individual specimen pieces were weighed. The balance readings were recorded vocally on a tape-recorder. At the end of each batch of measurements, the data were transcribed onto data sheets.

For control, the actual moisture content (U) was computed as follows:

$$U\% = \frac{Wu - Wo}{Wo} \times 100 \quad \ldots\ldots\ldots\ldots [3]$$

where:

Wu = weight with moisture content U (original weight); and

Wo = weight following oven-drying (41).

Data on wood specific gravity (G) were calculated as follows:

$$G = \frac{W_o}{V_g} \quad . . . . [4]$$

where:

W_o = oven-dry weight; and

V_g = "green" dimension of the specimen.

4.0 RESULTS

Data of the experiment were treated according to the following three headings. Raw data not discussed here appear in Appendices IV and V.

4.1 Specific Gravity

Specific gravities of specimens based on oven-dry weight and green volume were obtained through use of Equation [4]. There were four measurements for each set of specimens. Since the power-loss meter head covered all four pieces, the mean of the four measurements was used to represent the specific gravity of a particular specimen set. Variations in specific gravities within the specimen set could be substantial. In some cases up to 0.04 in value, even though they came from the same longitudinal strip and were no more than 30 cm apart. The causes of this variation were mainly minor defects and uneven wood texture.

The specific gravities of the samples are presented in Appendix V. accompanying the power-loss meter results.

The specific gravity variations for between species and within lodgepole pine comparisons are presented in Fig 2 and 3. The plotted points are the means of two replicates. In some cases there were substantial differences between the two replicates, due to uneven growth patterns and the sample selection imposed. Plots are intended to show the trend of specific gravity variations within the stem at different height levels and wood zones. In lodgepole pine reaction wood samples, only the compression wood results are plotted, instead of averaging opposite wood values with those of compression wood.

4.2 Resistance Type Moisture Meter

Resistance meter data are presented in Appendix IV. Three sample moisture content levels were examined, i.e., "green", nominal 19% and 12%. It is beyond the limit of the resistance meter to measure moisture content at 6%, hence no data were collected at that level.

The relationship between electric conductivity and wood moisture content is known to be curvelinear with the inflection point around the fiber saturation point of the wood. Since in this experiment only two levels of moisture content were below the fiber saturation point, it is not feasible to fit a line regressing meter readings on moisture content. Free hand regression lines intended for qualitative discussion of the data are presented in Fig 4 and 5. In these, the lines were fitted through data points of the two moisture content levels below the fiber saturation point and a point in the vacinity of the fiber saturation.

4.3 Power-loss Meter

Data on power-loss moisture meter measurements at nominal moisture content of 19%, 12% and 6% are presented in Appendix V.

Results of analysis of variance and covariance tables for between species, between trees and within stem factors are presented in Table 1 to 19. These tables are not inclusive, and all the non-significant interactions have been entered into the error terms. The power of the analysis of variance was not ideal, due to empty cells, unequal replications, missing levels and uncertainty in expected mean squares used for testing each factor. Many of these problems were intrinsic and unavoidable, like tapering of trees, unequal growth patterns to the left and right of the pith and large defects.

Simple and multiple regressions of important independent variables are presented as Fig 6 to 10.

Calibration charts generated by these regression equations are presented as Table 20 to 23. Comparison with data provided by the manufacturer and that established by Bramhall and Salamon (11) are given.

5.0 Discussion

5.1 Moisture Contents

The choice of moisture content levels in the experiment, i.e., nominal 19%, 12% and 6% represented a range in which lumber manufacturing, seasoning and transportation are most likely to be interested. The 12% level may represent the air-dried moisture content.

The oven-drying method used in obtaining moisture content values is conventional and easily applicable. Most woods investigated in this study have extraneous materials, some fraction of which must have been lost during drying to give slightly higher apparent moisture values (41). Since there is no easy way of establishing this deviation, no attempt was made to correct the oven-dry moisture values. Conditioned values were 1 to 2% higher than the intended or the nominal moisture content levels. More time might have been taken to allow specimens to reach equilibrium conditions in the CTH chamber. This was evidenced by the moisture gradient of 0.1 to 0.5% in the resistance meter measurements taken at 1/5 of specimen thickness and at the core.

The sample "green" condition turned out to be lower than from freshly felled trees, a consequence of sampling log decks. While some results were barely above the fiber saturation point, others ranged up to 150% or so for some sapwood specimens. Nevertheless, the purpose of the study was served by providing a moisture content level above the fiber saturation point in all cases and a basis for "green" volume used in specific gravity calculations.

5.2 Specific Gravities

From review of literature, the subject of density or specific gravity effects on power factor of wood is observed to be controversial. Some investigators considered that the correlation between power factor and wood density is weak or ambiguous (29, 41, 54). On the other hand, evidence exists in support of a positive correlation between the two (63, 70, 78). In any event, inclusion of specific gravity as an independent variable may help to account for part of the variability experienced with power-loss meter readings.

As showed in Fig 2 and 3, there are substantial specific gravity variations among species, within lodgepole pine species, and with height levels and wood zones within individual stems.

Such variations in conifers have been studied extensively by various authors. A general pattern for coniferous wood has evolved as: in radial direction, specific gravity either increases all the way from pith to periphery or decreases from pith in the corewood zone then increases to a maximum at the periphery; while in axial direction, specific gravity decreases from the base to top of these stems (69). Some of the factors affecting specific gravity of wood have been established. For instance, diameter, volume to age ratio and age of Douglas-Fir contribute significantly to its specific gravity (57). However, lack of agreement in certain cases is confusing. Radial direction specific gravity variations of Douglas-fir have been reported as increasing from pith to periphery, as decreasing from pith in the corewood zone then increasing to a maximum at the periphery, and as increasing in the corewood zone then remaining constant or decreasing slightly at the periphery (71, 72, 76).

Due to these uncertainties, references made for specific gravity variations should be treated with some reservation. The variability of wood power factor at various stem levels as related to specific gravity variations will be discussed.

5.3 The Power Factor

When an alternate current is applied to two parallel plates, with a dielectric sandwiched between, the electric current can be imaged as a continuous sine wave. In an ideal condenser, the charging current on the plate surfaces leads the applied alternating potential by 90°. When the frequency of the current increases, the charging current will be slightly out of phase, and adsorptive polarization occurs. The current then leads the voltage by ($\pi/2 - \delta$); δ is called the loss angle. The tangent of this angle is termed dissipation factor or loss tangent. The complementary angle of δ, ϕ is the phase angle. The cosine of ϕ is called the "power factor", since it expresses the ratio of power dissipated to the total power led into the system. When δ is small, tan δ is equivalent to cos ϕ. The power factor of wood increases with its moisture content at a given frequency, and the moisture meter was designed according to this principle.

Power factor of wood is also dependent on other factors like temperature and frequency. Proper choice of frequency to ensure maximum response between the power factor and moisture content of wood and converting charts accommodated with temperature changes are important considerations in the design and use of the power-loss type moisture meter.

5.4 Moisture Meter Variables

A main objective of this study was to investigate some of the variables associated with electrical means of moisture measurements. External factors like temperature, frequency, wood treatment and weathering may have significant interactions with meter readings, but were beyond the scope of the present study.

De Zeeuw (19) pointed out the uniqueness of individual pieces of wood. Cell walls are variable in chemical composition and in organization on the molecular level, compounded with variations between several parts of individual trees in cell sizes, wall thickness and tissue organization. All these features directly influence its physical behaviour and cause variability in these latter characteristics. Many of the controversial questions of wood variability may simply be inter-specific differences or other variations which cause discrepancies as reported in the literature.

5.4.1 Between species varaibility

The resistance moisture meter is in fact a microampere meter which registers the strength of electric current passing between the two electrode pins. The meter is logarithmically scaled to accommodate the logarithm relationship between d.c. resistance of wood and its moisture content. For measurements below the fiber saturation point and above ca. 7% moisture content, a good linear relationship can be obtained between meter readings and moisture contents. However, the data here tended to underestimate the actual moisture content by 2 to 6% (Appendix IV and Fig 4 and 5). Since the meter had been calibrated with standard resistances before the experiment, the cause of these discrepancies may come from configuration of the electrode pins. Through prolonged usage, the tips of the pins may wear off and become blunt, creating small crevices between the electrode and wood substance. Also, this reduced area of pins exposed decreases contact area. These would increase resistance and lower the readings.

Kozlik (42) used both resistance and power-loss type moisture meters to measure moisture content of western hemlock (<u>Tsuga heterophylla</u> (Raf.) Sarg.) dimension lumber. The former tended to underestimate actual moisture content slightly.

In general, resistance moisture meter readings showed less variation compared with the power-loss meter. Nevertheless, between species differences did exist, as showed in Fig 4. These differences are strong enough to overshadow the specific gravity effect (53, 91) and have warranted the use of adjusting tables for different species.

Interspecific variations did not quite follow the specific gravity ranks shown in Fig 2. Besides moisture content, the most significant variable affecting electrical resistance of wood is thought to be the amount of water-soluble eletrolytes (82). Thereby, variation may be attributed largely to extraneous material content. Organic polar substances would have some effect on electrical resistance of the wood. The ranking in Fig 4 seems to match suspected extractive contents (15, 69, 75), at least to some extent.

Venkateswaran (92) proposed that wood lignin content has a significant effect on wood electrical resistivity. The correlation between lignin content and electrical conductivity (d.c.) of wood was a positive linear one. The lignin contents of the species investigated here are quite similar. According to literature values they are in the range of 26 to 30% (69,79). Therefore, the lignin content may not have contributed much to the species variations.

Kollmann (39) considered that numerous wood properties, such as density, fiber length, vessel width variation, sorption and rheology of wood follow Gaussian distributions. Electrical properties of wood are profoundly interrelated with such properties, therefore, should exhibit normal distribution.

The analysis of variance of power-loss meter results (Table 1) showed highly signficant difference between species. In order to eliminate the possible specific gravity effect as the cause of this difference, covariance analyses were carried out, using specific gravity values of each specimen as covariate (Table 2). The correlation coefficient between power-loss meter readings and specific gravities was .3494 and the F value was still highly significant. A draw-back of the covariance analysis, as used here, was the requirement of homogeneous slopes for regression equations of individual cells. There were not enough replications per cell for an F-test. Since many factors were presented in the analysis of variance table, the reliability of the covariance analysis became doubtful. Nevertheless, the results may lend some support to the significance of differences between species. The Studentized Newman-Keul multiple range test in unadjusted (specific gravity) data showed that there were no two species having similar response to power-loss moisture meter readings at comparable moisture ranges.

Parallelism of power-loss moisture meter readings and specific gravity graphs (Fig 6 and 8 _vs_. Fig 2), suggested that specific gravity may have some influence on the power factor of wood. Unlike the results obtained by Lin (54), which indicate practically no effect of density on power factor of wood, the multiple regressions for all trees carried out here indicated that specific gravity was an independent variable making significant contribution to the regression equation. Quantities obtained by multiplying apparent moisture percentage of the specimen and its specific gravity, which is an expression of absolute amount of water per unit volume, was the single most important independent variable in the regression, accounting for 88.1% of the total variability. Inclusion of other potential independent variables, as moisture content and its transformed form, moisture content squared, accounted for 91.7% of the total variability. In multiple regression equations with all potential independent variables forced in, the least significant variables may be dropped out stepwise. Here, the product of moisture content and specific gravity was the first independent variable to drop out. This quantity was a linear combination of moisture content and specific gravity and was highly correlated with either moisture content or specific gravity.

The remaining portion of variability unaccounted for by the regression equation seems to have arisen in part from experimental errors and some other variables not investigated in this study. The precision of the instrument was not ideal and may have contributed to experimental errors. The presence of specimen defects could cause some deviation, as well.

Contribution of other variables was not investigated in this study and there must be complex interactions among these. Only speculations based on literature information will be offered for the ensuing discussion to explain some differences observed. A particular tendency of variation usually resulted from overall effects of these variable components.

The power factor of wood was suspected to be affected by anatomical and chemical features of the wood. Among these wood characteristics, fiber length, cellulose crystallinity, lignin content, amount and type of inorganic inclusions and extractive content have been reported as major variables (14,78,92,94,95). Their involvement in wood power factor variability has been discussed earlier. A brief discussion of these variables as related to species of the present study is now included.

Tracheid lengths for all four species studied were more or less comparable, as they appear in literature data (69, 83). In case no direct reference was available for a particular species, data for other species of the same genus are available. Even varaitions within species could be considerable. Growth factors and genetic factors contribute most to this variation (19). Tracheid length varaition may reflect other facets of varaition like ash content and extractive content (14), but probably has little significance of its own.

Differences in chemical composition could be the most important variable still to be accounted for.

Cellulose crystallinity of wood has been shown to relate positively with wood density (50,67). Power factor of wood, in turn, was related negatively with cellulose crystallinity (95). Therefore, there is conflict here and the specific gravity effect would be partly cancelled. Data of cellulose crystallinity for the species studied was not available.

As mentioned above, lignin contents of the species examined would be expected to be similar. According to Venkateswaran (92), there is negative correlation between lignin content and dielectric permittivity (dielectric constant) of the wood. The evidence from condenser paper research indicates that lignin has a detrimental effect on power factor. Thus, the higher the lignin content, the higher the power factor of wood (96).

Ash contents of coniferous woods are usually quite minute, normally 0.1 to 0.5% of the oven-dry weight of domestic coniferous woods (20). Even so this could contribute significantly to dielectric loss of cellulose materials (96). Monovalent ions of the ash had the most detrimental effect on power loss, while bivalent ions were far less harmful. The latter presented in low concentrations, however, could reduce power factor slightly under certain temperature and frequency conditions (6).

Noble fir (Abies procera Rehd.), grand fir (Abies grandis Dougl.), Douglas-fir, slash pine (Pinus elliotti Engelm) and Engelmann spruce (Picea engalmaii Parry) have ash contents reported at 0.4, 0.4, 0.2 0.2 and 0.2%, respectively (20,69). Of these, calcium, potassium and magnesium generally comprised 70% of the total ash content. The composition could depend much on growth factors and geographic distribution and could be quite variable (17). The highly significant relationship of ash content to power factor with condenser papers does not necessarily mean that it will dictate power factor of wood significantly, especially at high moisture content. Moisture contents of condenser paper research were usually set at oven-dry condition to eliminate external variables. The amount of ash and its composition in wood may still affect dielectric loss of wood at low moisture content. The higher ash content of fir wood, however, seemed not to affect its variability in this way.

Vermaas (94) provided some evidence that alcohol-benzene soluble content affected dielectric loss of the wood. He pointed out that dielectric loss is in the form of heat absorbed by wood, and that heating results from dipole movements. Polar extractives could be the source of such dipoles and contribute to the loss tangent. The value of loss tangent increased linearly with extractive content in radial direction at moisture range between 0 and 25%, while in tangential direction there was little correlation at low moisture contents and slight decrease in loss tangent with increasing extractive content levels.

The extractive contents for the species examined were given as: lodgepole pine (Pinus contorta Dougl.), 4.7% (acetone fraction); white spruce (Picea glauca (Moench.) Voss.), 1.98% (acetone fraction) (75); Douglas-fir, 4.45% (ethanol-benzene); and for noble fir, 2.7%

(ethanol-benzene) (69). Although the data came from different sources and represent different extractions, the extractive contents showed similar rank to between species power-loss moisture meter readings.

The regression line for Douglas-fir has a unique slope, which was quite different from the rest of the samples examined (Fig 6 and 8). Consider that Douglas-fir samples had the highest average specific gravity, abrupt earlywood-latewood transitions and some polyphenolic extractives which are absent in the other woods examined. All these may have contributed to the differences observed. Specific gravity has comparatively less influence on power factor than moisture content. At low moisture content, however, it contributed very significantly to higher readings (larger intercept, Fig 6 and 8), but at high moisture content its effect diminished and caused the regression line to be more flat than for other species.

5.4.2 Between tree variability

As shown in Fig 5, resistance meter reading variations between four lodgepole pine samples were quite small. No relation between specific gravity ranking (Fig 3) and the meter reading variations was discernible. Poor relationship of wood electrical resistance to specific gravity changes renders the resistance meter more precise than the power-loss moisture meter (41).

Since wood properties exhibit Gaussian distribution, variations among samples are inevitable. To establish a reliable conversion for power-loss meter readings, large sample sizes are called for. Means and standard deviations obtained through these samplings would be useful to establish confidence intervals for the estimations.

The analysis of variance presented in Table 3 showed that highly significant differences existed among lodgepole pine tree power-loss measurements studied. Covariance analysis (Table 4), using specific gravity as the covariate showed poor correlation between meter readings and specific gravities, with coefficient of correlation, $r = 0.1286$. In addition, no F test for comparing the regression equation of each cell was available, so the usefulness of covariance analysis was doubtful. The Studentized Newman-Keul multiple range test indicated that lodgepole pine No. 1 and No. 2, also lodgepole pine No. 3 and No. 4 belonged to the same homogeneous subsets, and were not significantly different, but lodgepole pine No. 1 and No. 2 were significantly different from lodgepole pine No. 3 and No. 4.

Differences between lodgepole pine trees were partly attributable to specific gravity variations among them. Data needed to test homogeneity among slopes were lacking, therefore slopes were not compared. The variations among slopes of Fig 9 seemed to be less divergent as compared with the between species variations.

The pooled data for lodgepole pine trees is also plotted as Fig 8. The R^2 values for pooled data were fairly good, indicating good fit of the regression equation.

5.4.3 Within tree height variability

The "green" sample moisture varied, and meter readings at this level were not comparable. At nominal 19% and 12% moisture levels there was a tendency for measurements taken at the lowest tree segment of all species to be slightly higher than measurements from higher segments. The differences, nevertheless, were small and did not affect precision.

Coniferous woods with regular resin ducts have higher resin contents at the stem base. Presumably total ash content has a similar distribution

(35), which contributes to higher readings for measurements made low in the trunk.

From analysis of variance (Table 5 to 19) for all the species studied, the between height level power-loss meter variations were mostly not significant, with or without specific gravity adjustment (again, the analysis of covariance may not be valid). The trend of variations in meter readings taken at different height levels had the qualitative characteristic of being higher at the two extremities, i.e., the first and fifth segments, while minima occurred at intermediate segments, usually below live crown samples. This slight variation may be accounted for in part by considering specific gravity variation. Furthermore, tracheid lengths increase directly with increasing height in the stem to a maxima part way up the trunk (below the live crown), then further decrease with increasing height to the top of the tree (19,69). Longer fibers have given lower dielectric loss in papers (14), which is in keeping with the patterns of variation here.

For practical purposes, it is justifiable to claim that height levels contributed little to power-loss meter variations.

5.4.4 Within tree radial variability

Little has been done on wood zone variation in relation to its electrical properties. Beldi et al. (4) found that differences in dielectrical properties resulting from structural variation within a given oak stem was negligible. No previous work on coniferous wood within tree variation has been found.

Referring to Fig 4 and 5, the dashed lines indicate sapwood readings which were slightly higher than the corresponding solid line heartwood readings. Differences were more prominent at low moisture contents, i.e., nominal 12% moisture content. The wood zone differences were especially well defined in the cases of white spruce, Douglas-fir and lodgepole pine. Since no sapwood readings at green condition were near fiber saturation point, a higher level for sapwood was not available, causing lines to be truncated.

The qualitative difference in resistance moisture meter readings in radial direction may result from some chemical variation, which will be discussed more fully. The variation in this case was generally less than 1% in moisture, as translated from the meter reading. If the requirement for accuracy is not so critical, this wood zone variation may be neglected. Compared with between tree variation, the amount from this source was minor.

Corewood samples showed no distinct difference from other heartwood samples at low moisture level, but readings tended to decrease slightly from the pith to the end of heartwood zones.

Analysis of variance (Table 1 to 19) indicated that there were significant differences for wood zone samples power-loss measurements.

Sapwood samples had the highest power-loss meter readings, followed by corewood samples, then by decreasing order from inner to outer heartwood. The trend is practically the same as that for resistance meter readings.

Examining the specific gravity graphs in Fig 2 and 3, the higher readings in sapwood can be attributed in part to higher specific gravities for white spruce and Douglas-fir. For lodgepole pine trees, the sapwood tended to have lower specific gravity than the heartwood. Readings, however, showed the same trends as when sapwood zones had higher specific gravity. The underlying causal factors must come from anatomical and chemical variations, possibly as discussed in the Literature Review. This particular effect contributed to lower correlation coefficients between specific gravity and meter readings for lodgepole pine. Subalpine fir, on the other hand, showed corewood with the highest readings among radial series.

Coniferous wood tracheid length varaitions in radial direction have been studied extensively. At any given height, tracheid length increases rapidly across the corewood zone then increases more slowly until a maximum is reached, after which there will be fluctuation about a mean maximum length. Eventually in very old trees, the tracheid length may decrease slightly (69). Literature information on the species studied was: for lodgepole pine, Douglas-fir and white spruce tracheid lengths increased from pith to periphery (19,83,87); while for subalpine fir, tracheid lengths increased from pith to about 10 cm diameter, then decreased slightly outward (36). This trend would explain the higher power-loss meter readings for corewood in part, but would contradict the higher meter readings for sapwood. Evidently, other factors must also be considered.

Preston _et al_. (73) compared Cross and Bevan cellulose crystallinity taken from different rings of monterey pine (_Pinus radiata_ D. Don). They found crystallintiy decreased from pith to periphery. Lee (50), on the other hand, studied the same relationship, using holocelluloses and pulps from western hemlock and found that crystallinity increased from pith to periphery. These conflicting results may be simply due to species differences or cellulose preparation differences. The cellulose content in radial direction tended to increase from the pith outward, then level off gradually (34,87). If the fractions for crystalline and amorphous cellulose were relatively constant, then the amount of crystalline cellulose would be expected to be higher at the periphery. This would mean a trend for decreasing power factor from the pith outward.

Red pine (Pinus resinosa L.), Norway spruce (Picea abies L. (Karst.)) and Japanese red pine (Pinus densiflora L.) have been shown to have decreasing lignin content from the pith to periphery (26,27,48). Again, this implies a decreasing trend for d.c. conductivity and power factor of wood from the pith to periphery. All these considerations seem to indicate that sapwood should have lower resistance and power-loss meter readings than that of sapwood. On the grounds that specific gravities were higher in the sapwood, the argument would hold for Douglas-fir and white spruce, but leave lodgepole pine samples a paradox.

Extraneous substances may be the remaining key to the variation. Ash distribution in radial direction has been shown to be uniform in pine wood (44), whereas in another study (43), Karelian pine (Pinus spp.) was shown to have highest ash content at the external layer of sapwood, with the exception of calcium and manganese which were highest in heartwood. Since calcium has been shown to have little effect on dielectric loss (6) and manganese is thought to be chelated by wood substances and thereby does not participate in charge carrying migration under an electric field (47), these should not much influence wood electrical properties. Bergström (5) studied the distribution of ash and phosphorus in Swedish pine and spruce (scientific names not given). He found considerable variation in ash content among trees, as affected by locality and other factors. Phorphorus content was five times higher in the sapwood than heartwood. Heartwood had higher alkali earth metals, while the sapwood had higher alkali metals.

McMillin (56), on the other hand, found that the ash content of loblolly pine (Pinus taeda L.) tended to decrease from the pith outward. However, he did note that sodium content of the wood showed negative correlation with specific gravity. If his finding is applicable to lodgepole pine, the lower specific gravity would still mean higher monovalent ion content. Since ash content has a strong influence on both d.c. conductivity and dielectric power loss (77,96), it is likely that higher ash concentrations in the sapwood zone contribute significantly to the higher readings of resistance and power-loss moisture meters.

Organic extractive contents have been long recognized as concentrated in the heartwood zone. Campbell et al. (15) compared wood zone resinous extracts in Douglas-fir. The extractive content (ethanol-benzene) was found to decrease from the pith outward, being 6%, 5% and 2% for corewood, heartwood and sapwood, respectively. The same pattern holds for pine (75,87) and spruce (97). Polyphenols, such as dihydroquercetin in Douglas-fir, had a differnt pattern. This increased from pith to the transition zone of heartwood and sapwood then decreased rapidly and disappeared in the sapwood (24). If all other variables were constant, the general trend of variation due to extractive content would be to decrease power factor and d.c. conductivity from the pith outward.

Composition and amount of extractives are quite variable (75). As an example, rosin from coniferous wood is a good insulator and dielectric, and can help to reduce dielectric losses. Literature evidence (49) showed that abietic acid has a beneficial effect on reducing dielectric loss. This contradiction may relate to state in wood, which is dispersed as a liquid and is easily polarizable. In solid rosin, resin acid molecules are rigidly held in a crystalline lattice and can not contribute to polarization or ionization phenomenon.

In summary, the inorganic ash content in wood may be the single, most important, variable controlling unexplained variability of power-loss and d.c. resistance readings in the radial direction. Other variables may further effect patterns from the pith to outer heartwood.

5.4.5 Within tree anisotropy.

Although measurements were taken on both radial and tangential specimen faces with the direct current resistance meter, they were in fact both measured along the grain. Variations among these two sets of readings simply mean localized moisture content differences and does not signify anisotropy between radial and tangential direction.

Analysis of variance results (Tables 1 to 19) indicate that there were significant differences for power-loss meter readings taken on radial and tangential faces. This clearly shows an anisotropy effect. The direction of electrical field in both cases was perpendicular to the grain direction. Measurements taken on radial faces meant the field direction as tangential, and vice versa. Measurements from radial direction were distinctly higher than corresponding measurements made in tangential direction. This confirms results of several other studies (45,65,74). The interactions between directions and moisture contents are also significant. This means that the difference between directions changes with changing moisture content.

Reasoning behind the power-loss anisotropic phenomenon has nothing to do with the above mentioned variables. Evidence indicates dependency of anisotropy with gross wood anatomy (88). Cell wall orientation rather than microscopic structural differences in wood, are thought to be the cause of anisotropy (45, 88).

In tangential direction, the ray cells run parallel to the electrical field, whereas in the radial direction, the ray cells run perpendicular to the field direction. Ray cells are rich in cell contents which may be easily polarizable under an alternating electric field. In the former case the polarization would exhibit strata along the plane of ray cells. In the latter case, polarization would be in the same direction as the electric field, induced resonance would increase power loss and render radial direction measurement higher than those of tangential direction.

5.4.6 Compression wood

A reaction wood sample was included to investigate the effect of high lignin content as found in a specific wood zone on electric moisture meter measurements. According to Venkateswaran (92), higher lignin content increased wood d.c. conductivity, thus at the same moisture content, compression wood should give higher meter readings than the corresponding regular wood. Examining data of Appendix IV does not show any pronounced difference on reaction wood resistance meter readings. The correlation between lignin content and specific conductivity of wood must be weak, indeed. Under oven-dry conditions wood lignin content may contribute to its d.c. conductivity. At high moisture contents, however, the overwhelming influence of moisture could completely mask the lignin effect. This argument is supported by the evidence that only at nominal 12% moisture content, did the measurements show a slight increase as compared with average regular wood readings.

The power-loss meter readings on lodgepole pine compression wood were noticeably higher than the corresponding lodgepole pine regular wood samples. As shown in Fig 7 and 10, the intercept of reaction wood power-loss meter reading regressed against moisture content and moisture content squared, was higher than other lodgepole pine samples. Also, in Appendix V, the matched opposite wood provided a further contrast between the two.

One reason for the differences could be the much higher specific gravity of compression wood. Thick wall, small lumen compression wood cells give higher wood substance per unit volume, hence higher specific gravity. Lignin content may be the causal factor in higher meter readings, but its effect is confounded with specific gravity.

It has been shown in insulation paper research that 3 to 4% residual lignin content in kraft papers did not show appreciable deterioration in dielectric loss. Further increase in lignin content started to affect paper dielectric losses (45). Judging from this quantitative difference, wood lignin content probably only has a comparatively small effect on power-loss meter readings.

When only moisture content squared was presented as an independent variable in the regression equation, coefficient of determination (R^2) was .9181. When specific gravity was also entered as another independent variable, the coefficient of determination then increased to .9838. From these results, the role of specific gravity was quite apparent in contributing to high compression wood power-loss meter readings.

5.5 Regressions and Comparisons

On the basis of individual trees, regression equations including moisture content, moisture content squared and specific gravity as independent variables can describe power-loss moisture meter variability without large error. The residuals (differences between data points and regression lines) of these regression equations for lodgepole pine No. 3 and No. 4, white spruce and Douglas-fir were plotted with moisture contents. These showed essentially horizontally distributed data. No remaining trends among the data were discernible, indicating that no additional variable was needed to improve the prediction. Within tree variability contributed to dispersion of the data, and addition of other variables, i.e., anatomical and chemical variability, would probably narrow the magnitude of dispersion, but may not contribute further to improving the prediction. The error of estimate changed with changing moisture content levels. The higher the moisture content, the more dispersed the power-loss meter measurements.

In the experimental moisture content range, quadratic equations of moisture content on meter readings gave the best fit, if specific gravity was not considered. Blodgett (7) reported that the relationship between loss tangent ($\tan\delta$) and moisture content (M) of oil impregnated paper can be expressed as:

$$\tan\delta = a + bM^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad [5]$$

This is similar to the present study. Here, R^2 values with moisture content squared as independent variable were .94 for lodgepole pine pooled data, up to .97 for individual lodgepole pine trees, .95 for subalpine fir and .90 for white spruce. The only low value was for Douglas-fir at .73. Peculiarity of the Douglas-fir regression equation has been explained on the basis of specific gravity in a previous section.

Using the multiple regression equations, inverse predictions were produced, as summarized in Table 20 to 23. Power-loss meter readings from 15 to 34 and specific gravity range from 0.25 to 0.49 for lodgepole pine pooled data, white spruce, Douglas-fir and subalpine fir were obtained. Specific gravity ranges for each species were chosen and reuslts are listed together with those of Bramhall and Salamon (11) and as supplied by the manufacturer at 21°C.

These tables are not aimed at replacing existing ones, since the sample size was far from adequate for such purpose. The idea is to show the variability of measurements. Bramhall and Salamon (11) gave 2 percent variability either way for their tables. This is generally correct for most of the readings, but substantial differences were also present here, especially at moisture extremities. The large sample size for lodgepole pine provided results comparable to those from other sources, while white spruce, Douglas-fir and subalpine fir showed more deviation, probably partly attributable to smaller sample sizes. Examining Appendix V shows that Douglas-fir sapwood readings were often immensely higher than the corresponding heartwood readings. When taking measurements stradling different wood zones, awareness of this kind of variability would help in making proper adjustment to the readings and more accurate results could arise.

5.6 Further Work

This study reports certain effects on electrical moisture meter measurements attributable to wood variability. Causal factors for these have been speculated through interpretation of the literature. Such causal factors need to be further explored. For example, some chemical analyses of wood showing wide variation may contribute to better understanding, especially if related to more precise electrical measurements.

6.0 CONCLUSIONS

The study showed that there are certain trends of variability in resistance and power-loss type moisture meter measurements on coniferous woods which can be summarized as follows:

1. The direct current resistance type moisture meter showed less unexplained variability in measurement, and was not affected by specific gravity differences to any discernible extent. Readings tended to underestimate the actual moisture contents. The radio frequency power-loss moisture meter, on the other hand, gave more variable results, and was much affected by sample specific gravity variations and other wood variables.

2. By introducing moisture content, specific gravity and moisture content squared in regression equations, 96.48% of the total variation between samples from four lodgepole pine trees was accounted for. The same test for woods from four species gave 91.67% of the variation accounted for.

3. There were significant differences between species for both types of moisture meter. Variation in the resistance type meter may have been due to differing amounts of electrolytes in the woods.

4. There were minor differences between lodgepole pine tree resistance meter measurements, compared to between species adjustments. Power-loss meter variations were more pronounced, partly due to specific gravity differences among the lodgepole pine samples.

5. Height within tree contributed very little variation to either moisture meter measurement.

6. Radial direction within tree did provide discernible variation

for both types of moisture meter. Measurements tended to be higher in corewood, decrease outward to the heatwood-sapwood boundary, then increased to a maximum in sapwood. Higher monovalent metallic ion concentrations in the sapwood may explain the higher sapwood readings.

7. There was a distinct anisotropic phenomenon for power-loss meter measurements at all moisture levels. Radial direction measurements tended to be higher than those made in tangential direction.

8. Only at low moisture content did resistance meter measurements on compression wood show slightly higher readings. Any correlation between lignin content and wood d.c. conductivity would seem to be overshadowed by mosture. Higher power-loss moisture meter readings on compression wood could have been due to higher specific gravity of the samples.

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Table 1. Analysis of variance table for between species power-loss meter measurements. Lodgepole pine No. 4, lodgepole pine reaction wood, white spruce, Douglas-fir and subalpine fir data were used.

Source of variation	Df	Mean squares	Test term+	F	Significance
Between species	4	850.09	Height/tree	35.37	**
Height within tree (H/T)	16	24.03	Sample/H/T	1.49	N.S.
Sample / height (S/H/T)	59	16.10		25.59	**
Moisture content (MC)	2	12077.00		19203.98	**
Tree x MC	8	140.90		244.05	**
H/T x MC	32	3.47		5.52	**
S/H/T x MC	118	4.67		7.43	**
Radial vs. tangential	1	54.61		86.84	**
Direction x MC	2	8.93		14.20	**
Error	657	0.63			
Total	899				

Studentized Newman-Keul's test, level of significance = 0.05

Species	lod. pine Rw.	lod. pine No. 4	D-fir	a-fir	w. spruce
Frequencies	48	210	216	180	246
Means	29.33	26.27	25.92	24.27	22.22

Any two means differ significantly.

* indicate significance at 0.05 level
** indicate significance at 0.01 level
N.S. is not significant.

+ Designate term for F-test. Blank indicates the test term is "Error".

Table 2. Analysis of covariance table for between species power-loss meter measurements. Specific gravity is the covariate. Lodgepole pine No. 4, lodgepole pine reaction wood, white spruce, Douglas-fir and subalpine fir data were used.

Source of variation	Df	Mean squares	Test term+	F	Significance
Between species	4	61.64	Height/tree	11.06	**
Height within tree (H/T)	16	5.57	Sample/H/T	0.48	N.S.
Sample/height (S/H/T)	59	11.78		26.12	**
Moisture content (MC)	2	12068.00		26771.97	**
Tree x MC	8	141.73		313.42	**
H/T x MC	32	3.80		8.43	**
S/H/T x MC	118	4.76		10.56	**
Radial *vs.* tangential	1	54.61		121.15	**
Direction x MC	2	8.93		19.81	**
Error	656	0.45			

Common slope of adjustment = 33.53

Studentized Newman-Keul's test, level of significance = 0.05

Species	l. pine 4	l. pine Rw.	a-fir	w. spruce	D-fir
Frequencies	210	48	180	246	216
Adjusted means	25.71	25.42	24.65	24.59	24.31

Means underlined by the same line are not significantly different from each other.

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant.

+Designate term for F-test. Blank indicates the test term is "Error".

Table 3. Analysis of variance table for within lodgepole pine regular wood power-loss meter measurements.

Source of variation	Df	Mean squares	Test term+	F	Significance
Between tree	3	328.40	Height/tree	30.58	**
Height within tree (H/T)	15	10.74	Sample/H/T	2.39	*
Sample/height (S/H/T)	55	4.49		13.47	**
Moisture content	2	15244.00		45773.92	**
Tree x MC	6	19.61		58.88	**
H/T x MC	30	2.72		8.18	**
S/H/T x MC	110	2.48		7.44	**
Radial *vs.* tangential	1	45.74		137.35	**
Direction x MC	2	9.42		28.30	**
Error	591	0.33			
Total	815				

Studentized Newman-Keul's test, level of significance = 0.05

Trees	l. pine 3	l. pine 4	l. pine 2	l. pine 1
Frequencies	204	210	204	198
Means	26.59	26.27	24.43	24.08

(Underline spans l. pine 3 – l. pine 4; separate underline spans l. pine 2 – l. pine 1.)

Means underlined by the same line are not significantly different from each other.

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant

+Designate term for F-test. Blank indicates the test term is "Error".

Table 4. Analysis of covariance table for within lodgepole pine regular woods power-loss meter measurements. Covariate is specific gravity.

Source of variation	Df	Mean squares	Test term[+]	F	Significance
Between tree	3	25.71	Height/tree	4.66	*
Height within tree (H/T)	15	5.52	Sample/H/T	1.13	N.S.
Sample/height (S/H/T)	55	4.87		17.25	**
Moisture content (MC)	2	15244.00		53953.42	**
Tree x MC	6	19.71		69.75	**
H/T x MC	30	2.83		10.03	**
S/H/T x MC	110	2.47		8.74	**
Radial vs. tangential	1	45.74		118.17	**
Direction x MC	2	9.42		33.35	**
Error	590	0.28			

Common slope for adjustment = 23.38

Studentized Newman-Keul's test, level of significance = 0.05

Trees	l. pine 3	l. pine 4	l. pine 2	l. pine 1
Frequencies	204	210	204	198
Adjusted means	26.05	25.95	24.89	24.51

Underlined means are not significantly different from one another.

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant.

[+]Designate term for F-test. Blank indicates the test term is "Error".

Table 5. Analysis of variance for lodgepole pine No. 1 power-loss meter measurements.

Source of variation	Df	Mean squares	Test term[+]	F	Significance
Between height	3	7.03	Sample/H	1.39	N.S.
Sample within height (S/H)	13	5.04		2.36	**
Moisture content (MC)	2	3749.10		1755.27	**
Height x MC	6	1.57		0.74	N.S.
S/H x MC	26	5.25		2.46	**
Radial vs. tangential	1	5.47		2.56	N.S.
Direction x MC	2	3.60		1.68	N.S.
Error	144	2.14			
Total	197				

Table 6. Analysis of covariance for lodgepole pine No. 1 power-loss meter measurements. Covariate is specific gravity.

Source of variation	Df	Mean squares	Test term[+]	F	Significance
Between height	3	5.52	Sample/H	1.23	N.S.
Sample within height (S/H)	13	4.49		2.10	*
Moisture content (MC)	2	3749.70		1758.79	**
Height x MC	6	1.56		0.73	N.S.
S/H x MC	26	5.22		2.45	**
Radial vs. tangential	1	5.47		2.56	N.S.
Direction x MC	2	3.60		1.69	N.S.
Error	143	2.13			

Common slope of adjustment = 14.79

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant.

[+]Designiate term for F-test. Blank indicates the test term is "Error".

Table 7. Analysis of variance table for lodgepole pine No. 2 power-loss meter measurements.

Source of variation	Df	Mean squares	Test term+	F	Significance
Between height	4	4.59	Sample/H	0.89	N.S.
Sample within height (S/H)	14	5.15		20.20	**
Moisture content (MC)	2	3562.60		13968.61	**
Height x MC	8	0.40		1.58	N.S.
S/H x MC	28	1.65		6.46	**
Radial *vs.* tangential	1	13.05		51.17	**
Direction x MC	2	2.03		7.96	**
Error	144	0.26			
Total	203				

Table 8. Analysis of covariance for lodgepole pine No. 2 power-loss meter measurements. Covariate is specific gravity.

Source of variation	Df	Mean squares	Test term+	F	Significance
Between height	4	3.97	Sample/H	0.75	N.S.
Sample within height (S/H)	14	5.32		22.36	**
Moisture content (MC)	2	3564.00		14991.77	**
Height x MC	8	0.39		1.62	N.S.
S/H x MC	28	1.66		6.98	**
Radial *vs.* tangential	1	13.05		54.90	**
Direction x MC	2	2.03		8.54	**
Error	143	0.24			

Common slope for adjustment = 17.12

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant.

+Designate term for F-test. Blank indicates the test term is "Error".

Table 9. Analysis of variance table for lodgepole pine No. 3 power-loss meter measurements.

Source of variation	Df	Mean squares	Test term[+]	F	Significance
Between height	4	12.41	Sample/H	4.67	*
Sample within height (S/H)	14	2.66		6.00	**
Moisture content (MC)	2	3468.50		7838.53	**
Height x MC	8	3.50		7.90	**
S/H x MC	28	2.82		6.37	**
Radial vs. tangential	1	9.84		22.23	**
Direction x MC	2	3.35		7.56	**
Error	144	0.44			
Total	203				

Studentized Newman-Keul's test, level of significance = 0.05

Heights	1	5	3	4	2
Frequencies	54	30	42	36	42
Means	27.30	26.81	26.50	26.17	26.00

Means underlined by the same line are not significantly different from each other.

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant.

[+] Desigiate term for F-test. Blank indicates the test term is "Error".

Table 10. Analysis of covariance for lodgepole pine No. 3 power-loss meter measurements. Covariate is specific gravity.

Source of variation	Df	Mean squares	Test term+	F	Significance
Between height	4	3.58	Sample/H	1.06	N.S.
Sample within height (S/H)	14	3.39		9.09	**
Moisture content (MC)	2	3452.90		9251.17	**
Height x MC	8	3.85		10.31	**
S/H x MC	28	2.85		7.63	**
Radial vs. tangential	1	9.84		26.36	**
Direction x MC	2	3.35		8.96	**
Error	143	0.37			

Common slope for adjustment = 24.33

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant.

+ Designate term for F-test. Blank indicates the test term is "Error".

Table 11. Analysis of variance table for lodgepole pine No. 4 power-loss meter measurements.

Source of variation	Df	Mean squares	Test term[+]	F	Significance
Between height	4	21.44	Sample/H	4.51	*
Sample within height (S/H)	14	4.75		9.92	**
Moisture content (MC)	2	4572.10		9544.09	**
Height x MC	8	5.71		11.93	**
S/H x MC	28	2.83		5.91	**
Radial _vs_. tangential	1	9.18		19.16	**
Direction x MC	2	3.53		7.37	**
Error	150	0.48			
Total	209				

Studentized Newman-Keul's test, level of significance = 0.05

Height	5	1	3	2	4
Frequencies	30	54	42	48	36
Means	27.23	26.90	26.04	25.73	25.52

Means underlined by the same line are not significantly different from each other.

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant.

[+] Designiate term for F-test. Blank indicates the test term is "Error".

Table 12. Analysis of covariance for lodgepole pine No. 4 power-loss meter measurements. Covariate is specific gravity.

Source of variation	Df	Mean squares	Test term+	F	Significance
Between height	4	7.96	Sample/H	1.34	N.S.
Sample within height (S/H)	14	5.93		17.73	**
Moisture content (MC)	2	4577.10		13684.56	**
Height x MC	8	5.89		17.61	**
S/H x MC	28	2.76		8.26	**
Radial vs. tangential	1	9.18		27.44	**
Direction x MC	2	3.53		10.56	**
Error	149	0.33			

Common slope for adjustment = 36.96

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant

+ Designiate term for F-test. Blank indicates the test term is "Error".

Table 13. Analysis of variance table for lodgepole pine reaction wood power-loss meter measurements.

Source of variation	Df	Mean squares	Test term[+]	F	Significance
Sample	4	6.09		1.33	N.S.
Moisture content (MC)	2	755.10		164.84	**
Sample x MC	8	1.49		0.32	N.S.
Radial *vs.* tangential	1	2.48		0.54	N.S.
Direction x MC	2	0.41		0.09	N.S.
Error	30	4.58			
Total	47				

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant.

[+] Designate term for F-test. Blank indicates the test term is "Error".

Table 14. Analysis of variance table for white spruce power-loss meter measurements.

Source of varaition	Df	Mean squares	Test term[+]	F	Significance
Between height	4	30.54	Sample/H	2.87	N.S
Sample within height (S/H)	16	10.64		36.70	**
Moisture content (MC)	2	3232.70		11146.21	**
Height x MC	8	3.64		12.56	**
S/H x MC	32	2.25		7.76	**
Radial *vs.* tangential	1	25.63		88.36	**
Direction x MC	2	4.53		15.60	**
Error	180	0.29			
Total	245				

Table 15. Analysis of covariance for white spruce power-loss meter measurements. Covariate is specific gravity.

Source of variation	Df	Mean squares	Test term[+]	F	Significance
Between height	4	16.51	Sample/H	2.49	N.S.
Sample within height (S/H)	16	6.64		22.88	**
Moisture content (MC)	2	3230.10		11126.53	**
Height x MC	8	3.61		12.43	**
S/H x MC	32	2.25		7.73	**
Radial *vs.* tangential	1	25.63		88.28	**
Direction x MC	2	4.53		15.59	**
Error	179	0.29			

Common slope for adjustment = -3.29

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant.

[+] Designate term for F-test. Blank indicates the test term is "Error".

Table 16. Analysis of variance table for Douglas-fir power-loss meter measurements.

Source of variation	Df	Mean squares	Test term+	F	Significance
Between height	4	29.97	Sample/H	0.67	N.S.
Sample within height (S/H)	14	45.07		74.75	**
Moisture content (MC)	2	1310.00		2172.79	**
Height x MC	8	2.47		4.10	**
S/H x MC	28	9.61		15.94	**
Radial _vs_. tangential	1	10.89		18.06	**
Direction x MC	2	2.93		2.43	N.S.
Error	156	0.60			
Total	215				

Table 17. Analysis of covariance for Douglas-fir power-loss meter measurements. Covariate is specific gravity.

Source of variation	Df	Mean squares	Test term+	F	Significance
Between height	4	1.08	Sample/H	0.06	N.S.
Sample within height (S/H)	14	16.65		29.87	**
Moisture content (MC)	2	1291.00		2316.06	**
Height x MC	8	2.79		5.01	**
S/H x MC	28	9.26		16.62	**
Radial _vs_. tangential	1	10.89		19.54	**
Direction x MC	2	1.46		2.62	N.S.
Error	155	0.56			

Common slope for adjustment = 51.98

* indicate significance at 0.05 level.
** indicate significance at 0.01 level
N.S. indicate not significant.

+ Designiate term for F-test. Blank indicates the test term is "Error".

Table 18. Analysis of variance table for subalpine fir power-loss meter measurements.

Source of variation	Df	Mean squares	Test term[+]	F	Significance
Between height	4	14.20	Sample/H	2.71	N.S.
Sample within height (S/H)	11	5.23		12.74	**
Moisture content (MC)	2	2770.50		6747.96	**
Height x MC	8	2.06		5.01	**
S/H x MC	22	5.41		13.19	**
Radial *vs.* tangential	1	8.45		20.58	**
Direction x MC	2	0.33		0.81	N.S.
Error	129	0.41			
Total	179				

Table 19. Analysis of covariance for subalpine fir power-loss meter measurements. Covariate is specific gravity.

Source of variation	Df	Mean squares	Test term[+]	F	Significance
Between height	4	1.83	Sample/H	0.44	N.S.
Sample within height (S/H)	11	4.21		13.07	**
Moisture content (MC)	2	2774.40		8619.85	**
Height x MC	8	2.15		6.69	**
S/H x MC	22	5.57		17.31	**
Radial *vs.* tangential	1	8.45		26.25	**
Direction x MC	2	0.33		1.03	N.S.
Error	128	0.32			

Common slope for adjustment = 43.53

* indicate significance at 0.05 level.
** indicate significance at 0.01 level.
N.S. indicate not significant.

[+] Designate term for F-test. Blank indicates the test term is "Error".

Table 20. Comparison of power-loss moisture meter (Moisture Register Model L) correction tables for lodgepole pine pooled data. Manufacturer supplied data and the table prepared by Bramhall and Salamon (11) are given for comparison. Underlined data are extrapolated.

	Lodgepole pine									
	Moisture Content									
Meter	Radial faces				Tangential faces				Manu-	B & S*
reading G	0.36	0.39	0.42	0.45	0.36	0.39	0.42	0.45	fact.	
15	1.7	....	....	....	1.3	....	....	....	6.6	5.5
16	5.3	1.3	....	....	5.0	0.9	....	....	7.7	6.7
17	7.2	5.2	2.9	....	7.0	5.0	3.1	....	8.8	7.8
18	8.8	7.2	5.1	2.4	8.5	6.9	4.9	1.0	9.9	8.9
19	10.1	8.7	7.1	5.0	9.8	8.5	6.9	4.8	10.9	9.9
20	11.3	10.1	8.7	7.0	11.0	9.8	8.4	6.8	11.8	10.9
21	12.3	11.2	10.0	8.6	12.0	10.9	9.7	8.4	12.7	11.8
22	13.3	12.3	11.2	10.0	12.9	12.0	10.9	9.7	13.5	12.7
23	14.2	13.3	12.2	11.1	13.8	12.9	11.9	10.8	14.2	13.7
24	15.1	14.2	13.2	12.2	14.7	13.8	12.9	11.9	15.0	14.7
25	15.9	15.0	14.1	13.2	15.4	14.6	13.8	12.8	15.6	15.5
26	16.6	15.8	15.0	14.1	16.2	15.4	14.6	13.7	16.2	16.3
27	17.4	16.6	15.8	15.0	16.9	16.2	15.4	14.6	16.8	16.9
28	18.1	17.3	16.6	15.8	17.6	16.9	16.1	15.4	17.3	17.5
29	18.7	18.0	17.3	16.5	18.3	17.6	16.9	16.1	17.8	18.1
30	19.4	18.7	18.0	17.3	18.9	18.2	17.6	16.8	18.4	18.7
31	20.0	19.4	18.7	18.0	19.5	18.9	18.2	17.5	....	19.2
32	20.6	20.0	19.3	18.7	20.1	19.5	18.9	18.2	19.2	19.7
33	21.2	20.6	20.0	19.3	20.7	20.1	19.5	18.8	....	20.1
34	21.8	21.2	20.6	19.9	21.3	20.7	20.1	19.4	19.9	20.6

* Temperature used is 20°C.

Table 21. Comparison of power-loss moisture meter (Moisture Register Model L) correction tables for white spruce data. Manufacturer supplied table and the table prepared by Bramhall and Salamon (11) are given for comparison. Underlined data are extrapolated.

Meter reading	White spruce — Moisture content: Radial faces, G: 0.30	0.32	0.34	0.36	Tangential faces, 0.30	0.32	0.34	0.36	Manu-fact.	B & S*
15	8.6	5.6	....	....	8.0	5.1	3.1	....	5.4	4.4
16	10.2	7.9	4.4	2.3	9.7	7.4	6.0	4.6	6.5	5.5
17	11.7	9.6	7.1	5.7	11.1	9.1	7.9	6.5	7.5	6.5
18	12.9	11.1	9.0	7.2	12.3	10.6	8.6	6.9	8.4	7.5
19	14.1	12.5	10.6	8.3	13.4	11.9	10.1	8.0	9.4	8.5
20	15.1	13.6	12.0	10.0	14.5	13.0	11.5	9.6	10.3	9.4
21	16.1	14.7	13.2	11.5	15.4	14.1	12.7	11.0	11.1	10.3
22	17.1	15.8	14.3	12.8	16.3	15.1	13.8	12.3	11.9	11.2
23	17.9	16.7	15.4	13.9	17.2	16.0	14.8	13.4	12.5	12.1
24	18.8	17.6	16.4	15.0	18.0	16.9	15.7	14.4	13.2	12.9
25	19.6	18.5	17.3	16.0	18.8	17.7	16.6	15.4	13.9	13.7
26	20.4	19.3	18.2	16.9	19.6	18.5	17.5	16.3	14.4	14.4
27	21.1	20.1	19.0	17.8	20.3	19.3	18.3	17.2	14.9	15.0
28	21.8	20.8	19.8	18.7	21.0	20.0	19.0	18.0	15.4	15.6
29	22.5	21.6	20.6	19.5	21.7	20.7	19.8	18.8	16.0	16.2
30	23.2	22.3	21.3	20.3	22.3	21.4	20.5	19.5	16.6	16.9
31	23.9	23.0	22.0	21.0	23.0	22.1	21.2	20.3	....	17.3
32	24.5	23.6	22.7	21.7	23.6	22.7	21.9	21.0	17.2	17.8
33	25.1	24.3	23.4	22.5	24.2	23.4	22.5	21.6	....	18.3
34	25.8	24.9	24.0	23.1	24.8	24.0	23.2	22.3	18.1	18.8

* Temperature used is 20°C.

Table 22. Comparison of power-loss moisture meter (Moisture Regi-ster Model L) correction tables for Douglas-fir data. Manufacturer supplied table and the table prepared by Bramhall and Salamon (11) are given for comparison. Underlined data are extrapolated.

Meter reading	Douglas-fir									
	Moisture content									
	Radial faces				Tangential faces				Manu-fact.	B & S*
	G: 0.40	0.43	0.46	0.49	0.40	0.43	0.46	0.49		
15	....	....	....	....	....	....	....	....	5.5	4.7
16	....	....	....	....	....	....	....	....	6.3	5.6
17	3.8	2.2	....	....	4.1	2.5	....	....	7.0	6.3
18	6.1	5.2	4.2	2.8	6.2	5.3	4.2	2.7	7.7	7.1
19	8.2	7.1	6.3	5.5	7.9	7.0	6.2	5.4	8.4	7.8
20	10.1	8.8	7.9	6.3	9.7	8.0	7.3	6.1	9.1	8.5
21	11.2	9.2	8.2	7.7	10.8	8.7	8.0	7.5	9.7	9.1
22	13.1	10.8	9.6	8.9	12.6	10.3	8.9	8.6	10.3	9.8
23	14.7	11.8	10.5	9.9	14.1	11.3	10.1	9.7	10.9	10.5
24	16.1	13.6	11.5	10.6	15.5	13.0	10.9	10.1	11.5	11.3
25	17.4	15.1	12.4	10.9	16.8	14.5	11.8	10.4	12.1	12.0
26	18.6	16.5	14.1	11.6	18.0	15.9	13.4	11.5	12.7	12.8
27	19.8	17.8	15.6	13.0	19.1	17.1	14.9	12.2	13.2	13.3
28	20.9	19.0	16.9	14.6	20.1	18.3	16.2	13.8	13.7	13.9
29	21.9	20.1	18.2	16.0	21.1	19.4	17.4	15.2	14.4	14.7
30	22.9	21.2	19.4	17.3	22.1	20.4	18.6	16.5	15.1	15.5
31	23.8	22.2	20.5	18.6	23.0	21.4	19.7	17.8	....	16.1
32	24.7	23.2	21.5	19.7	23.9	22.3	20.7	18.9	16.0	16.8
33	25.6	24.1	22.5	20.8	24.7	23.3	21.7	19.9	....	17.5
34	26.5	25.0	23.5	21.8	25.6	24.1	22.6	21.0	17.2	18.2

* Temperature used is 20°C.

Table 23. Comparison of power-loss moisture meter (Moisture Register Model L) correction tables for subalpine fir data. Manufacturer supplied table and the table prepared by Bramhall and Salamon (11) are given for comparison. Underlined data are extrapolated.

Meter reading	Subalpine fir									
	Moisture content									
	Radial faces				Tangential faces				Manu-* fact.	B & S**
	G: 0.35	0.37	0.39	0.41	0.35	0.37	0.39	0.41		
15	1.5	....	....	....	3.4	....	....	....	7.2	2.2
16	5.3	3.7	....	....	4.5	2.5	1.3	....	8.1	3.3
17	7.4	6.3	5.0	3.1	6.8	5.6	4.2	1.9	9.0	4.5
18	9.0	8.1	7.1	6.0	8.5	7.6	6.6	5.4	9.9	5.7
19	10.4	9.6	8.8	7.9	9.9	9.1	8.3	7.4	10.7	6.8
20	11.6	10.9	10.2	9.4	11.1	10.4	9.7	9.0	11.4	7.9
21	12.7	12.0	11.4	10.7	12.2	11.6	11.0	10.3	12.1	8.9
22	13.7	13.1	12.5	11.9	13.2	12.7	12.1	11.5	12.8	9.9
23	14.6	14.1	13.5	13.0	14.2	13.7	13.1	12.6	13.5	11.1
24	15.5	15.0	14.5	13.9	15.0	14.6	14.1	13.6	14.1	12.2
25	16.3	15.8	15.3	14.8	15.9	15.4	15.0	14.5	14.7	13.2
26	17.1	16.6	16.2	15.7	16.7	16.2	15.8	15.3	15.2	14.3
27	17.8	17.4	17.0	16.5	17.4	17.0	16.6	16.2	15.7	15.0
28	18.6	18.1	17.7	17.3	18.2	17.8	17.4	16.9	16.2	15.7
29	19.3	18.9	18.5	18.0	18.8	18.5	18.1	17.7	16.7	16.5
30	19.9	19.5	19.2	18.8	19.5	19.2	18.8	18.4	17.2	17.4
31	20.6	20.2	19.8	19.4	20.2	19.8	19.5	19.1	....	18.0
32	21.2	20.8	20.5	20.1	20.8	20.5	20.1	19.8	17.9	18.7
33	21.8	21.5	21.1	20.8	21.4	21.1	20.7	20.4	....	19.3
34	22.4	22.1	21.7	21.4	22.0	21.7	21.4	21.0	18.6	19.8

* Data for subalpine fir (Abies lasiocarpa (Hook.) Nutt.) is not available. Readings for "white fir" are used.

** Temperature used is 20°C.

Table 24. List of regression equations.

Fig 6.

Radial faces

Lodgepole pine 1-4

$$Y = 19.12 - 0.448\ MC + 0.0557\ MC^2 \quad (SE_E = 1.52)$$

Lodgepole pine No. 4

$$Y = 20.45 - 0.627\ MC + 0.0662\ MC^2 \quad (SE_E = 1.06)$$

White spruce

$$Y = 15.76 - 0.174\ MC + 0.0372\ MC^2 \quad (SE_E = 1.68)$$

Douglas-fir

$$Y = 21.44 - 0.124\ MC + 0.0270\ MC^2 \quad (SE_E = 2.13)$$

Subalpine fir

$$Y = 14.26 + 0.273\ MC + 0.0284\ MC^2 \quad (SE_E = 1.26)$$

Tangential faces

Lodgepole pine 1-4

$$Y = 19.52 - 0.507\ MC + 0.0597\ MC^2 \quad (SE_E = 1.49)$$

Lodgepole pine No. 4

$$Y = 20.67 - 0.681\ MC + 0.0706\ MC^2 \quad (SE_E = 1.02)$$

White spruce

$$Y = 15.86 - 0.175\ MC + 0.0396\ MC^2 \quad (SE_E = 1.68)$$

Douglas-fir

$$Y = 22.46 - 0.271\ MC + 0.0337\ MC^2 \quad (SE_E = 2.26)$$

Subalpine fir

$$Y = 14.27 + 0.313\ MC + 0.0278\ MC^2 \quad (SE_E = 1.16)$$

Fig 7.

Radial faces

Lodgepole pine No. 1

$$Y = 20.32 - 0.848\ MC + 0.0691\ MC^2 \quad (SE_E = 0.66)$$

Lodgepole pine No. 2

$$Y = 18.68 - 0.502\ MC + 0.0571\ MC^2 \quad (SE_E = 0.86)$$

Lodgepole pine No. 3

$$Y = 17.63 + 0.063\ MC + 0.0350\ MC^2 \quad (SE_E = 1.02)$$

Lodgepole pine No. 4

$$Y = 20.45 - 0.627\ MC + 0.0662\ MC^2 \quad (SE_E = 1.06)$$

(Continue next page)

Table 24. Continued.

Lodgepole pine reaction wood

$Y = 19.12 + 0.237\ MC + 0.0295\ MC^2\ (SE_E = 1.86)$

Tangential faces

Lodgepole pine No. 1

$Y = 20.60 - 0.853\ MC + 0.0706\ MC^2\ (SE_E = 0.73)$

Lodgepole pine No. 2

$Y = 19.41 - 0.604\ MC + 0.0625\ MC^2\ (SE_E = 0.82)$

Lodgepole pine No. 3

$Y = 18.10 - 0.024\ MC + 0.0403\ MC^2\ (SE_E = 1.02)$

Lodgepole pine No. 4

$Y = 20.67 - 0.681\ MC + 0.0706\ MC^2\ (SE_E = 1.02)$

Lodgepole pine reaction wood

$Y = 18.73 + 0.311\ MC + 0.0286\ MC^2\ (SE_E = 1.74)$

Fig 8.

Radial faces

Lodgepole pine 1-4

$Y = 16.31 + 0.0401\ MC^2\ \ (SE_E = 1.55)$

Lodgepole pine No. 4

$Y = 16.58 + 0.0442\ MC^2\ \ (SE_E = 1.13)$

White spruce

$Y = 14.64 + 0.0313\ MC^2\ \ (SE_E = 1.68)$

Douglas-fir

$Y = 20.65 + 0.0228\ MC^2\ \ (SE_E = 2.26)$

Subalpine fir

$Y = 15.94 + 0.0380\ MC^2\ \ (SE_E = 1.27)$

Tangential faces

Lodgepole pine 1-4

$Y = 16.34 + 0.0421\ MC^2\ \ (SE_E = 1.52)$

Lodgepole pine No. 4

$Y = 16.46 + 0.0467\ MC^2\ \ (SE_E = 1.11)$

White spruce

$Y = 14.73 + 0.0337\ MC^2\ \ (SE_E = 1.67)$

Douglas-fir

$Y = 20.75 + 0.0243\ MC^2\ \ (SE_E = 2.26)$

Table 24. Continued.

Subalpine fir

$Y = 16.20 + 0.0388\ MC^2$ ($SE_E = 1.17$)

Fig 9.

Radial faces

Lodgepole pine No. 1

$Y = 14.99 + 0.0399\ MC^2$ ($SE_E = 0.87$)

Lodgepole pine No. 2

$Y = 15.54 + 0.0396\ MC^2$ ($SE_E = 0.92$)

Lodgepole pine No. 3

$Y = 18.03 + 0.0371\ MC^2$ ($SE_E = 1.02$)

Lodgepole pine No. 4

$Y = 1\ [illegible].58 + 0.0442\ MC^2$ ($SE_E = 1.13$)

Tangential faces

Lodgepole pine No. 1

$Y = 15.23 + 0.0412\ MC^2$ ($SE_E = 0.93$)

Lodgepole pine No. 2

$Y = 15.64 + 0.0414\ MC^2$ ($SE_E = 0.91$)

Lodgepole pine No. 3

$Y = 17.95 + 0.0395\ MC^2$ ($SE_E = 1.01$)

Lodgepole pine No. 4

$Y = 16.46 + 0.0467\ MC^2$ ($SE_E = 1.11$)

Fig 10.

Radial faces

Lodgepole pine 1-4

$Y = 16.31 + 0.0401\ MC^2$ ($SE_E = 1.55$)

Lodgepole pine reaction wood

$Y = 20.63 + 0.0376\ MC^2$ ($SE_E = 1.83$)

Tangential faces

Lodgepole pine 1-4

$Y = 16.34 + 0.0421\ MC^2$ ($SE_E = 1.52$)

Lodgepole pine reaction wood

$Y = 20.72 + 0.0393\ MC^2$ ($SE_E = 1.71$)

Fig 1. Schematic diagram of sample preparation and scheme of measurements.

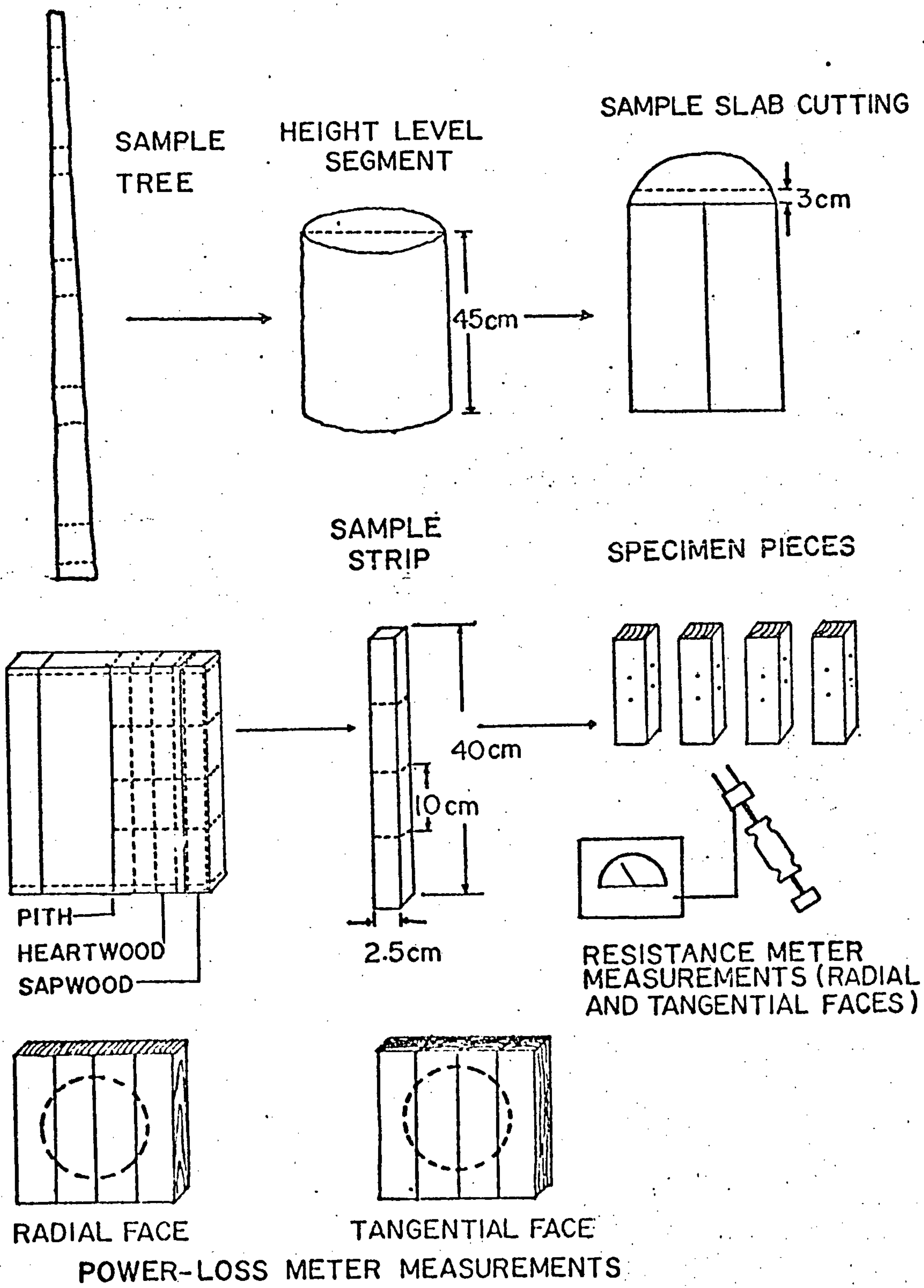


Fig 2. Specific gravity (oven-dry weight and "green" volume) variations among speices. Lodgepole pine No. 4, white spruce, Douglas-fir and subalpine fir sample specific gravities at 5 height levels and radial series are presented. Right-most points at each height level are the sapwood samples. Number of observation is eight for each point.

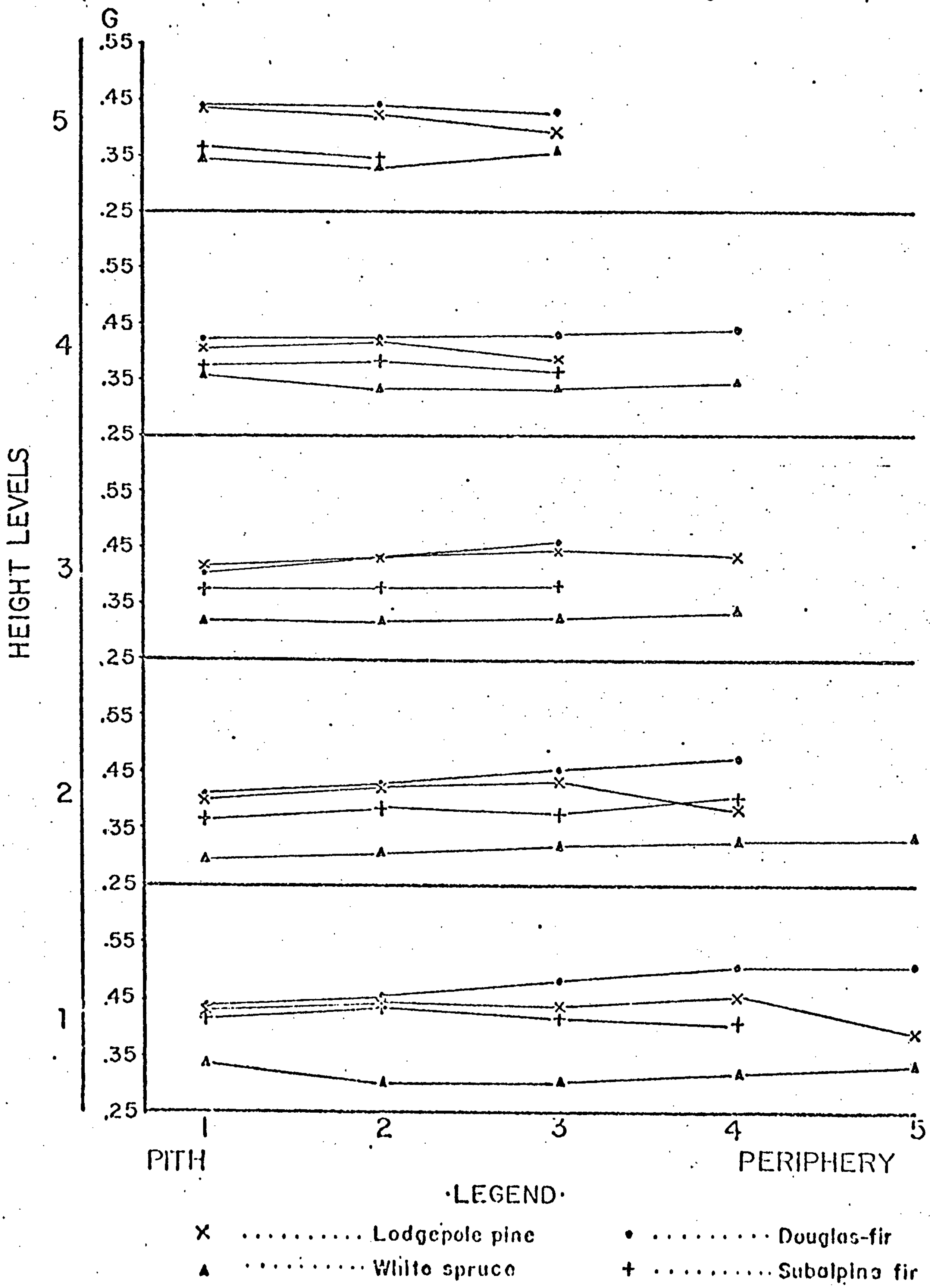


Fig 3. Specific gravity (oven-dry weight and "green" volume) variations among lodgepole pine trees (including compression wood) at 5 height levels and radial series are presented. Right-most points at each height level are the sapwood samples. Number of observation is eight for each point.

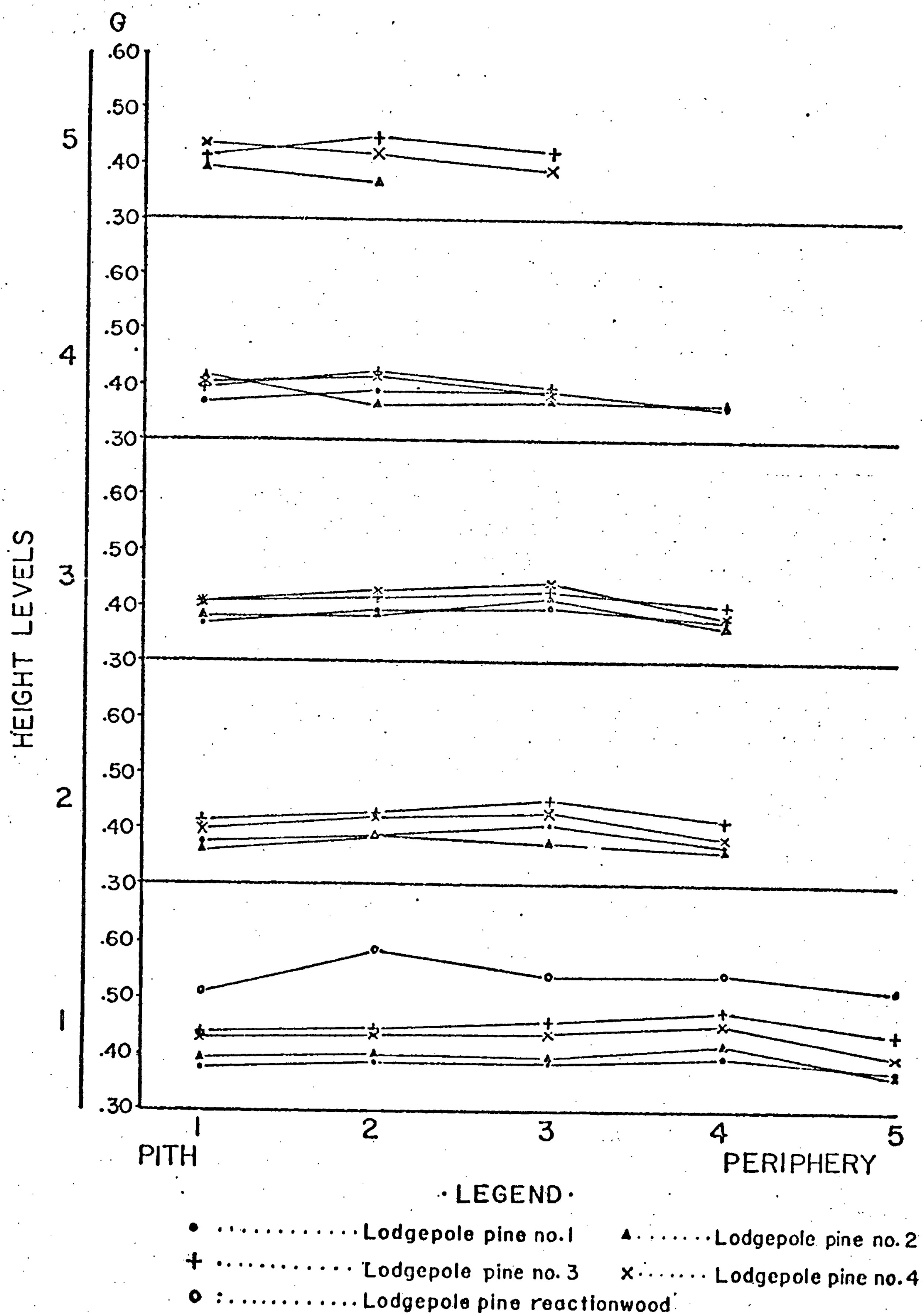


Fig 4. Resistance moisture meter measurements vs. moisture contents (oven-dry basis) for between species comparison as lodgepole pine No. 4, white spruce, Douglas-fir and subalpine fir. (Solid lines represent heartwood samples and dashed lines represent sapwood samples. Symbols on lines serve to distinguish between lines and are not data points.)

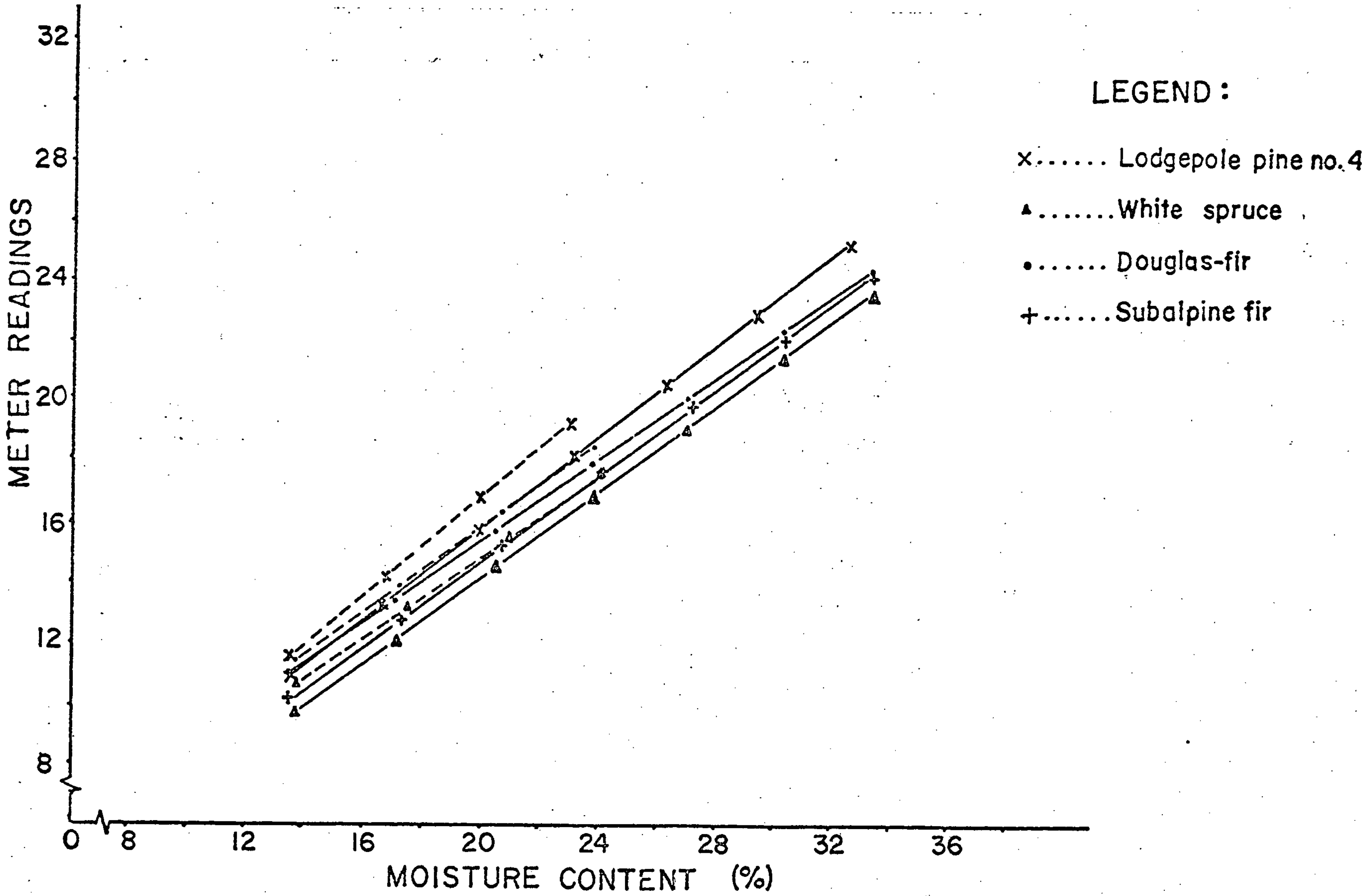


Fig 5. Resistance moisture meter measurements on lodgepole pine samples *vs*. moisture contents (oven-dry basis). (Solid lines represent heartwood samples, and dashed lines represent sapwood samples. Symbols on lines serve to distinguish between lines and are not data points.)

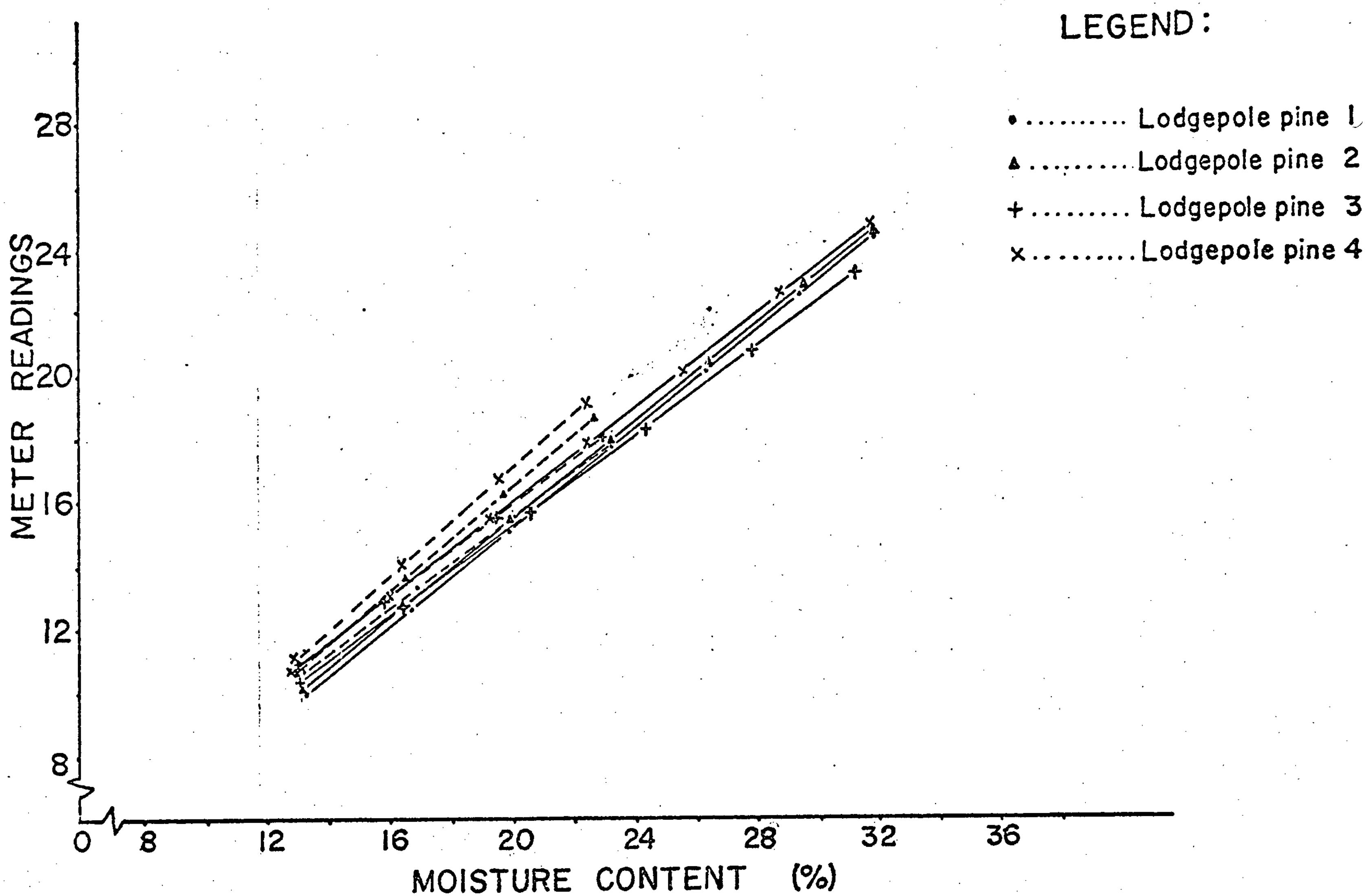


Fig 6. Graph showing the relationship between power-loss meter readings and moisture contents (oven-dry basis) of lodgepole pine pooled (L1-4), lodgepole pine No. 4 (L 4), white spruce (W.S.), Douglas-fir (D.F.) and subalpine fir (A.F.). (Symbols on regression lines serve to distinguish between lines and are not data points.)

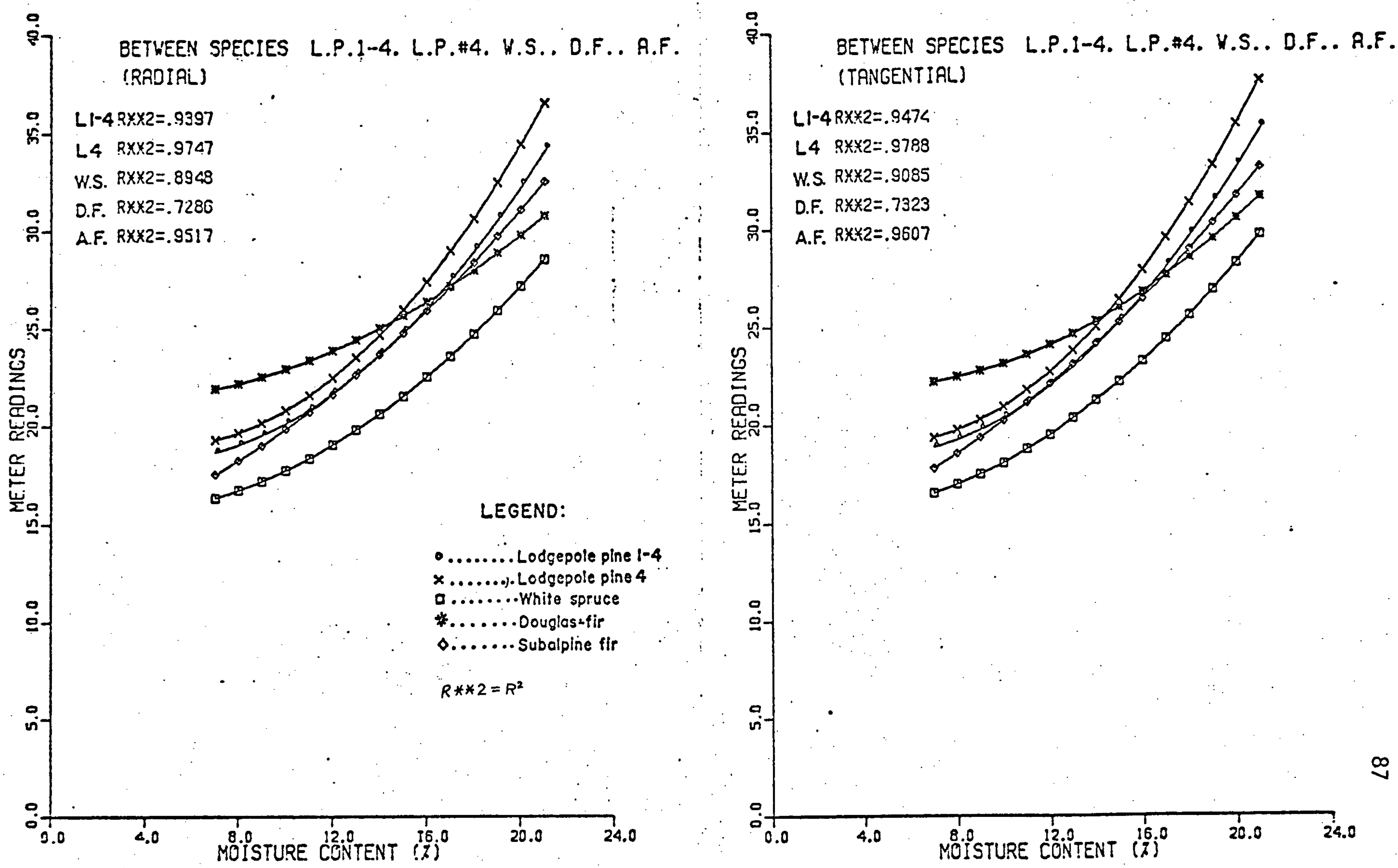
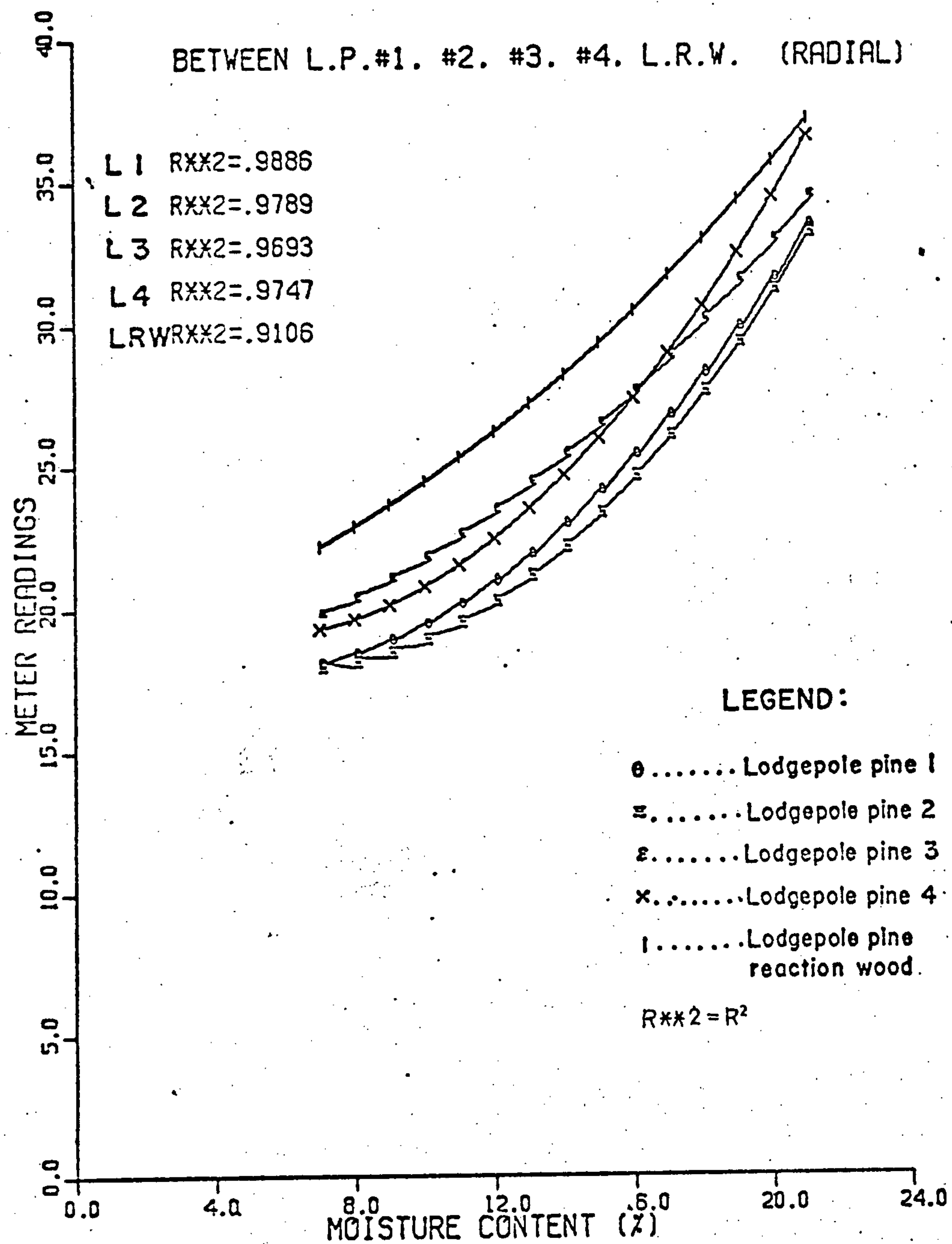


Fig 7. Graph showing the relationship between power-loss meter readings and moisture content (oven-dry basis) of lodgepole pine No. 1 (L 1), lodgepole pine No. 2 (L 2), lodgepole pine No. 3 (L 3), lodgepole pine No. 4 (L 4) and lodgepole pine compression wood (LRW). (Symbols on lines are not data points.)



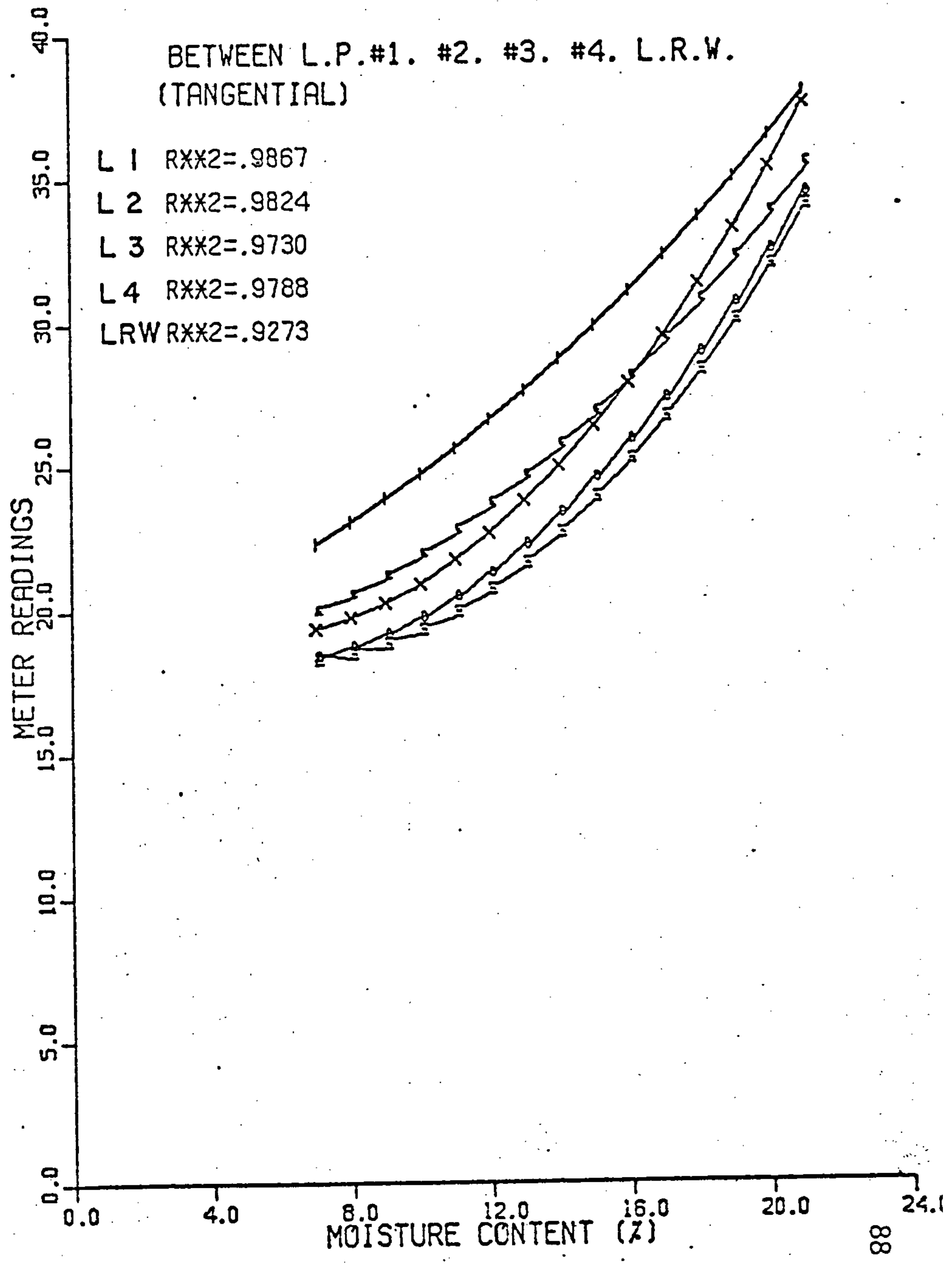


Fig 8. Graph showing the relationship between power-loss meter readings and moisture content squared (oven-dry basis) of lodgepole pine No. 4 (L 4), lodgepole pine pooled (L1-4), white spruce (W.S.), Douglas-fir (D.F.) and subalpine fir (A.F.). (Symbols on regression lines serve to distinguish between lines and are not data points.)

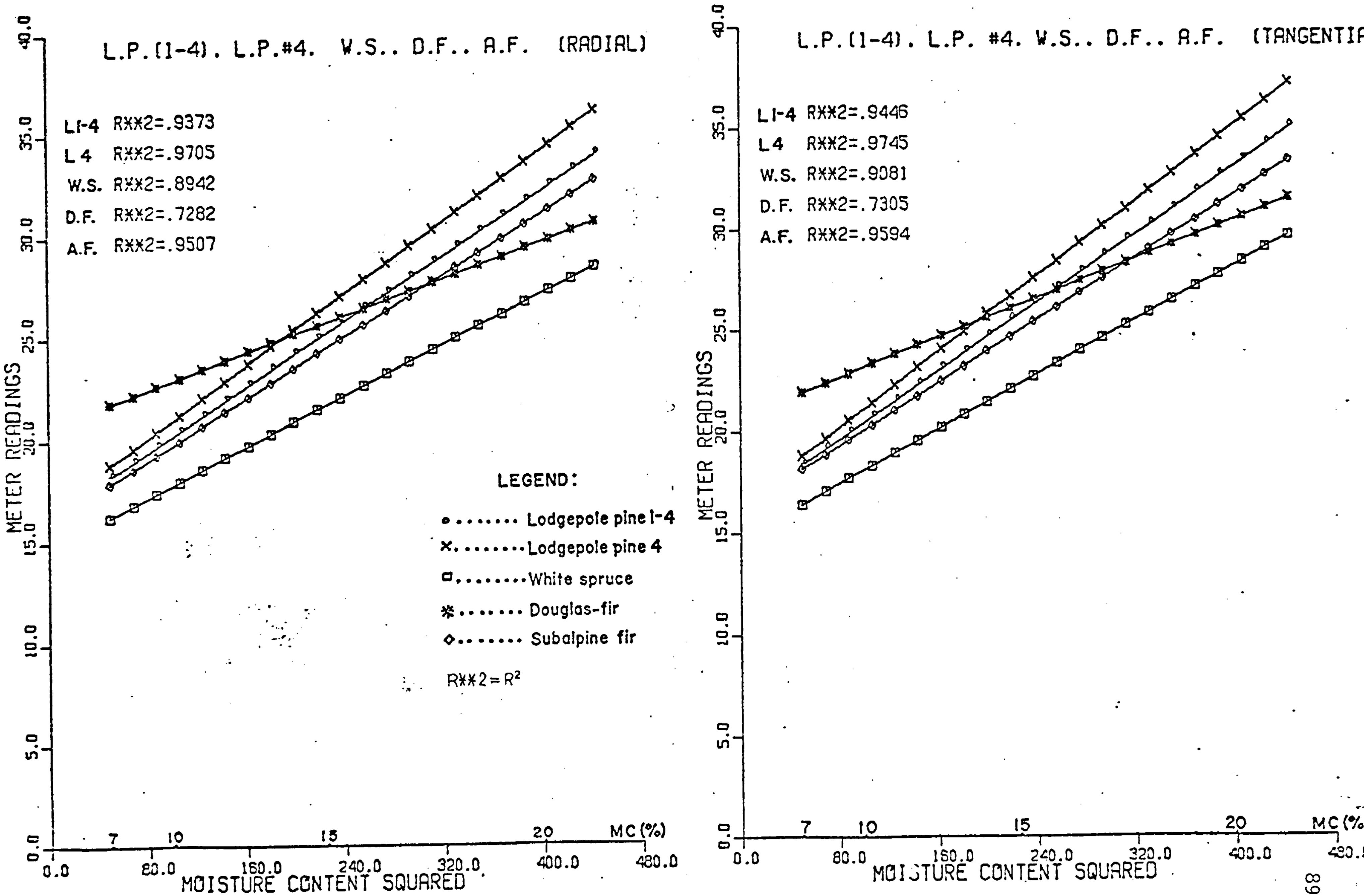
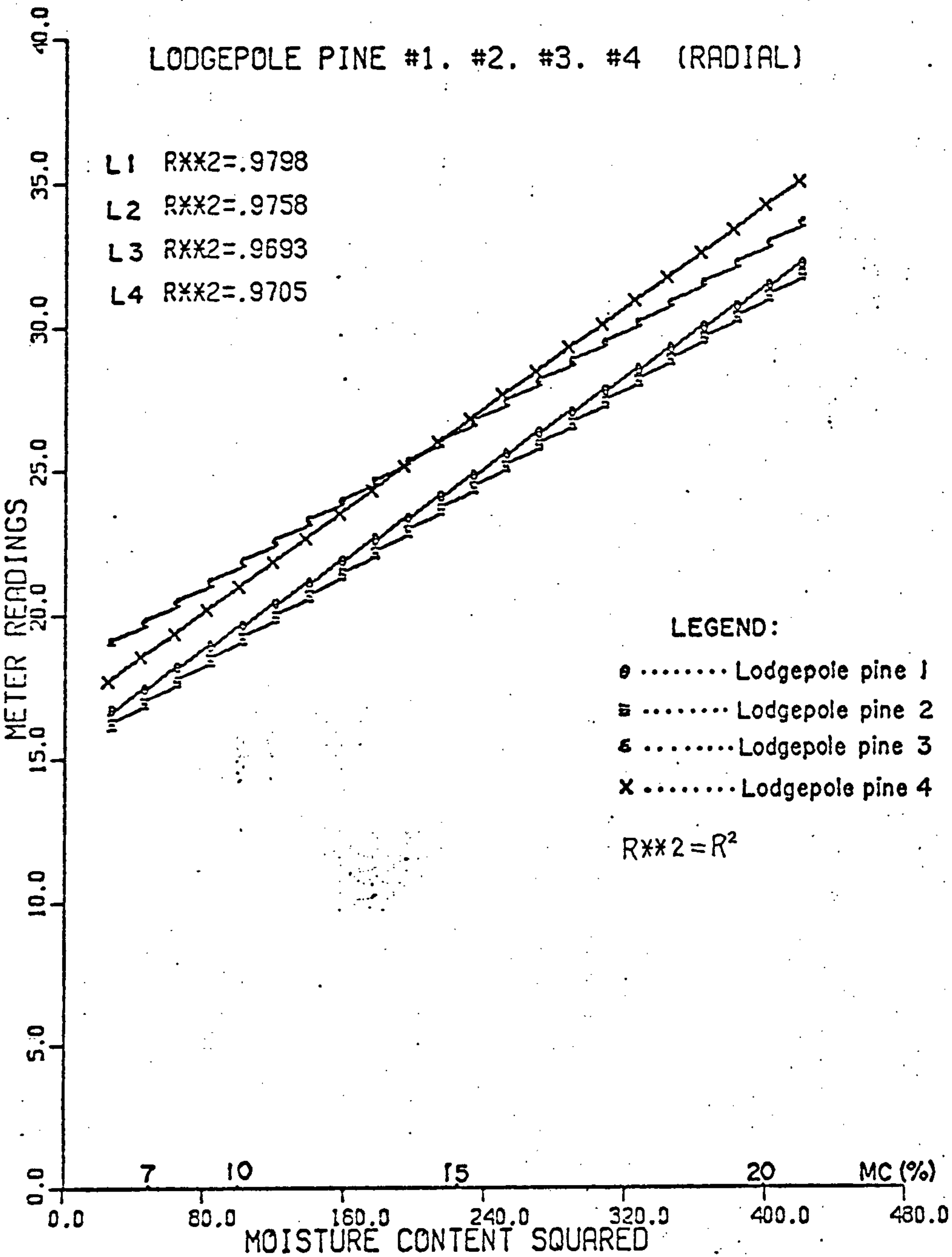


Fig 9. Graph showing the regression of lodgepole pine tree power-loss meter readings on moisture content squared (oven-dry basis). These two variables exhibit quadratic relationships. (Symbols on regression lines serve to distinguish between lines and are not data points.)



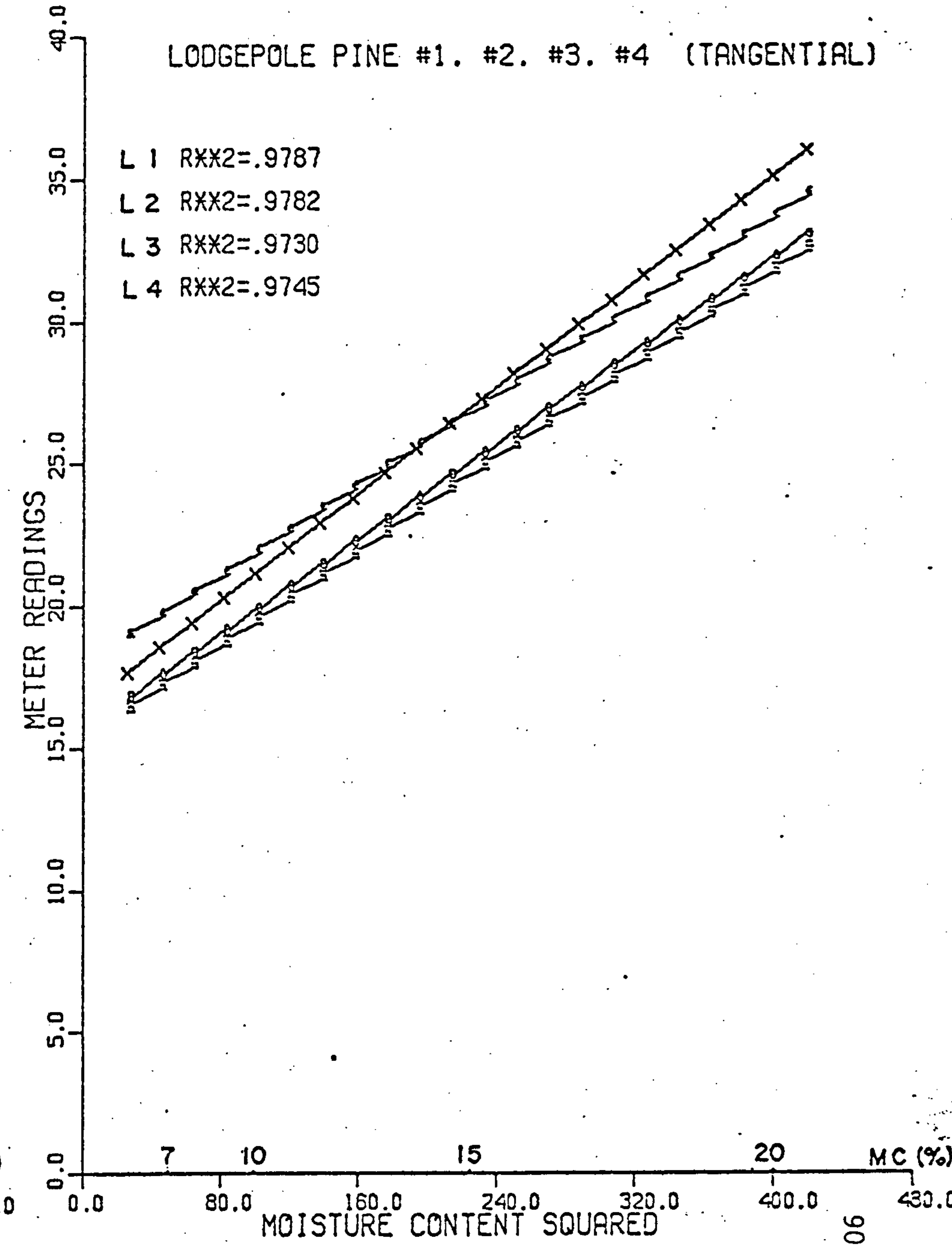
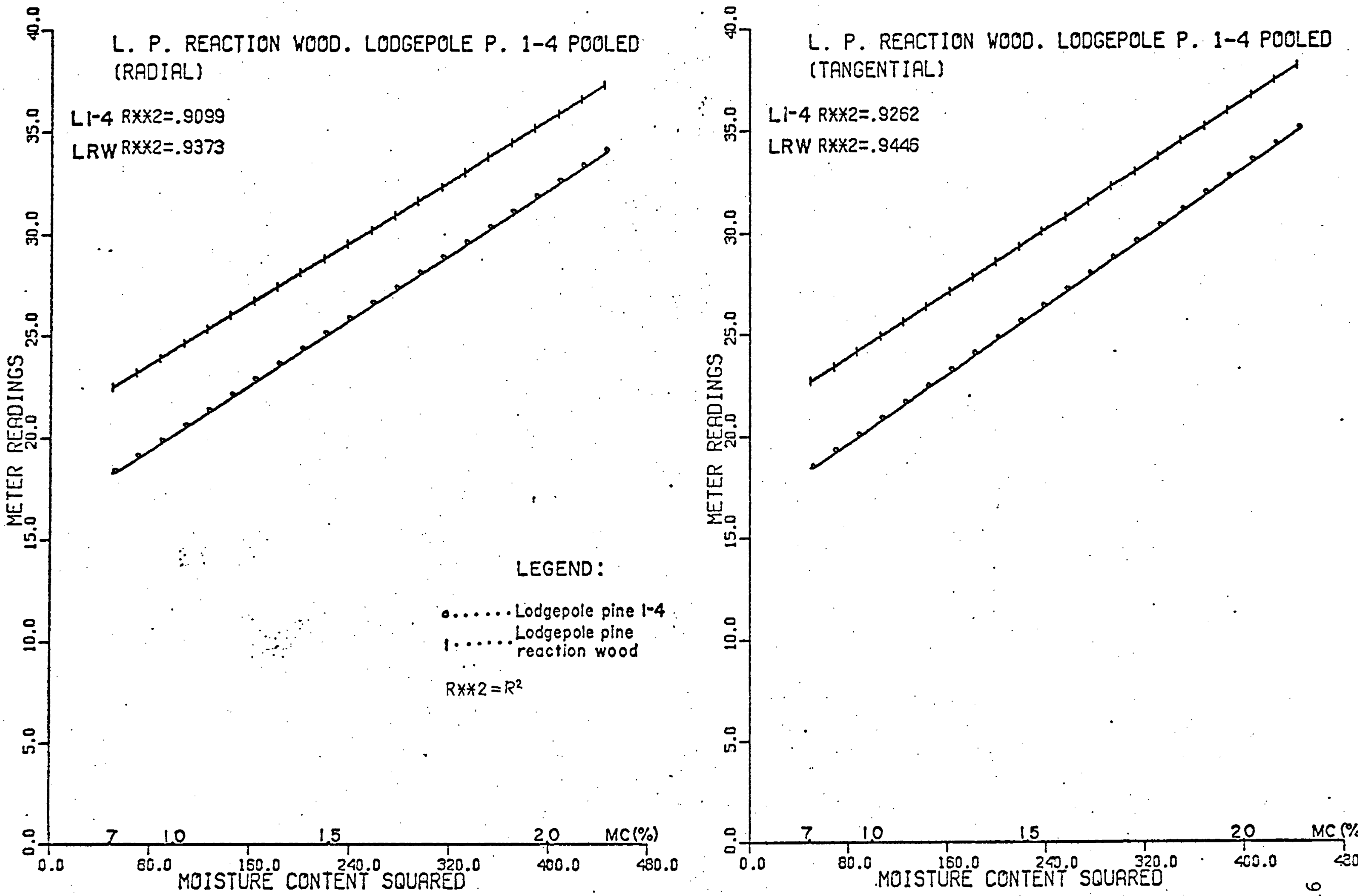


Fig 10. Graph showing the relationship between power-loss meter readings and moisture content squared (oven-dry basis) of lodgepole pine compression wood (LRW) and regular woods (L 1-4). (Symbols on regression lines serve to distinguish between lines and are not data points.)



Appendix I. Characteristics of sample tree stems showing total stem length, diameter and segments according to height level (measured in meters from stem base).

Stem	Length, m	Diameter, cm (base)	Height Level, m				
			1	2	3	4	5
Lodgepole pine No. 1	12.45	36.9 x 36.3	0.70	4.67	7.42	10.05	—
Lodgepole pine No. 2	16.47	35.6 x 36.3	0.84	4.05	7.71	9.85	14.69
Lodgepole pine No. 3	14.84	33.1 x 34.4	1.15	5.32	7.56	10.00	13.77
Lodgepole pine No. 4	16.12	35.6 x 35.6	1.45	5.16	7.25	10.16	13.34
Lodgepole pine RW	—	31.8 x 36.9	0.95	—	—	—	—
White spruce	13.47	38.2 x 38.2	0.89	4.84	7.06	9.75	12.03
Douglas-fir	14.74	38.2 x 39.5	1.06	4.92	7.55	10.14	13.11
Subalpine fir	14.95	33.1 x 32.8	1.21	5.04	7.40	10.08	13.24

Appendix II. Growth zone numbers in the center of each specimen cross section. Radial series No. 1 represents corewood, No. 2 to 4 represent heartwood and No. 5 represents sapwood wood zones.

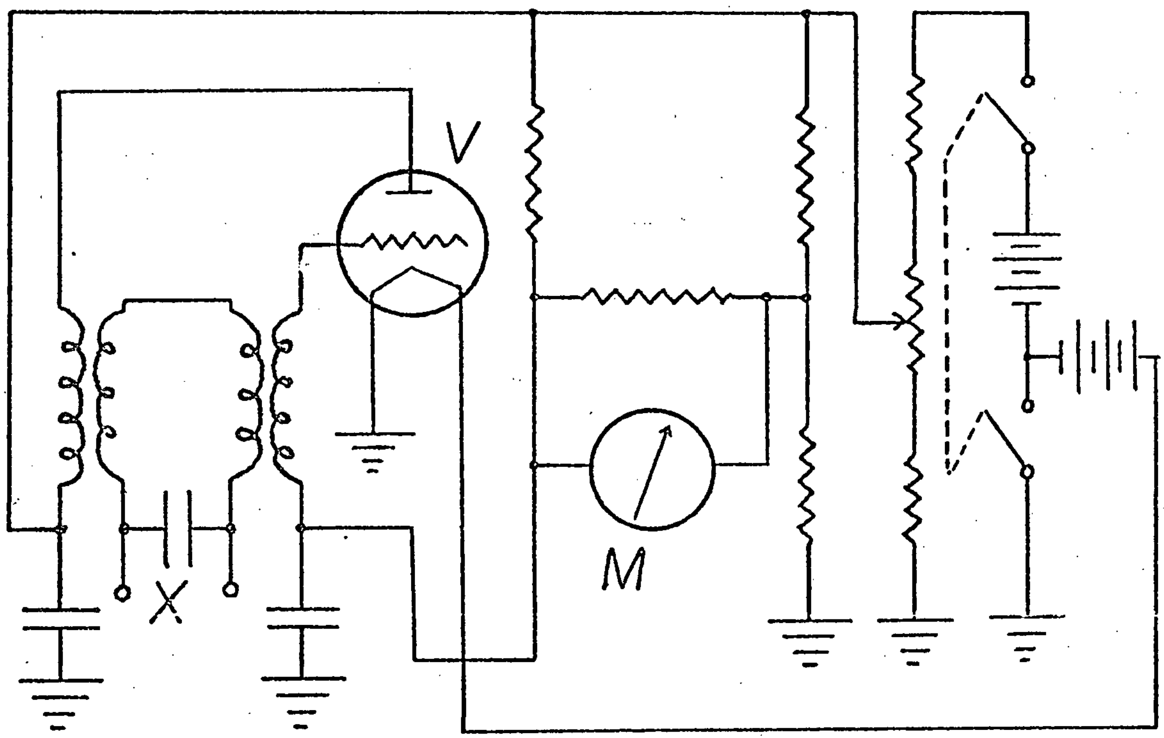
Sample Tree	Height Level	Radial series No. growth zone				
		1	2	3	4	5
Lodgepole pine No. 1	1	8	27	45	75	90+
		12	30	51	70	90+
	2	7	30	52	—	69
		10	25	44	—	72
	3	9	28	48	—	65
		7	24	44	—	61
	4	13	27	—	—	52
		7	18	33	—	64
Lodgepole pine No. 2	1	11	24	48	70	100+
		9	30	56	—	95+
	2	13	25	43	—	70
		15	46	—	—	80+
	3	9	23	40	—	65
		8	37	—	—	74
	4	7	18	33	—	65
		8	27	—	—	60
	5	12	—	—	—	48
		13	—	—	—	45
Lodgepole pine No. 3	1	8	28	51	73	100+
		11	45	68	—	100+
	2	7	25	44	—	74
		9	36	—	—	80
	3	5	20	33	—	62
		9	31	—	—	67
	4	11	36	—	—	62
		7	24	—	—	50
	5	13	35	—	—	43
		15	—	—	—	37
Lodgepole pine No. 4	1	9	23	45	—	80
		7	21	34	54	85
	2	8	26	47	—	74
		10	22	38	—	79
	3	8	25	44	—	80
		13	35	—	—	76
	4	9	35	—	—	67
		15	30	—	—	70
	5	7	27	—	—	51
		5	—	—	—	60
Lodgepole pine reactionwood	1	5	16	27	40	68
		6	25	—	—	55

(continue next page)

Appendix II.(continued)

Sample trees	Height levels	Radial series				
		1	2	3	4	5
White spruce	1	8	21	31	43	55
		8	18	28	39	54
	2	6	16	26	37	50
		10	18	31	—	53
	3	6	14	27	—	46
		6	15	29	—	44
	4	4	12	24	—	41
		6	14	25	—	45
	5	10	22	—	—	41
		9	22	—	—	43
Douglas-fir	1	10	22	36	55	74
		9	24	43	—	68
	2	12	24	45	—	65
		10	27	47	—	63
	3	10	29	—	—	54
		11	35	—	—	55
	4	8	24	38	—	49
		8	33	—	—	46
	5	7	23	—	—	38
		11	31	—	—	44
Subalpine fir	1	16	38	66	—	90+
		14	32	63	—	100+
	2	16	48	—	—	80
		13	38	64	—	88
	3	17	45	—	—	72
		19	44	—	—	74
	4	14	39	—	—	55
		15	41	—	—	60
	5	13	—	—	—	43
		14	—	—	—	45

Appendix III. Circuitry of the power-loss moisture meter, (Moisture Register). Where M is the meter, V is a vacuum tube and X is the sampling electrodes. Adopted from Uyemura (88).



Appendix IV. Resistance moisture meter (Delmhorst RC-1B) measurements (MT) on wood samples from trees of the study compared to oven-dry (OD) calculations; including nominal moisture level (N MC), at stem heights (Ht.) and for two radial replications (1-4 heartwood, 5 sapwood). Observations are 16 for each reading at 19 and 12% nominal moisture level, and 8 for each reading at "green" condition.

Lodgepole pine 1

Ht.	N MC (%)	Repl.	1 OD	1 MT	2 OD	2 MT	3 OD	3 MT	4 OD	4 MT	5 OD	5 MT
1	G	1	33.0	24.7	31.6	22.3	29.4	21.5	30.0	21.8	102.3	35.2
		2	31.8	23.6	30.9	22.7	30.5	22.1	28.5	20.7	84.5	31.6
	19	1	20.7	16.2	20.5	16.2	20.2	15.9	19.6	15.1	20.7	16.6
		2	21.1	17.0	20.8	16.5	20.3	15.8	19.9	15.6	20.5	16.5
	12	1	13.6	10.7	13.6	10.6	13.3	10.2	13.2	10.1	13.7	10.8
		2	13.8	11.1	13.5	10.7	13.4	10.4	13.3	10.1	13.7	10.7
2	G	1	32.8	23.6	29.7	21.3	30.2	22.0	....	....	95.9	34.1
		2	31.8	23.3	30.2	22.0	28.3	21.0	....	....	67.6	29.5
	19	1	20.5	16.0	19.8	15.7	20.4	15.6	....	....	20.9	15.9
		2	20.6	16.1	20.4	15.8	19.7	15.4	....	....	20.7	15.9
	12	1	13.5	10.6	13.3	10.4	13.6	10.3	....	....	13.8	11.2
		2	13.5	10.7	13.5	10.7	13.0	10.1	....	....	13.6	10.9
3	G	1	32.3	23.8	31.2	24.0	30.8	23.2	....	....	86.7	32.5
		2	32.2	24.4	30.5	23.1	29.6	21.8	....	....	79.1	31.2
	19	1	21.4	17.0	20.6	16.6	20.7	16.2	....	....	21.2	16.8
		2	21.2	16.8	19.8	16.2	20.3	16.2	....	....	20.8	16.5
	12	1	13.9	10.8	13.2	10.4	13.2	10.4	....	....	13.8	11.0
		2	13.5	10.7	13.1	10.4	13.5	10.7	....	....	13.7	11.1
4	G	1	29.3	22.6	29.0	22.5	28.6	21.7	....	....	70.7	29.5
		2	27.4	21.1	27.5	20.9	....	....	....	....	68.0	31.5
	19	1	20.9	16.5	20.9	16.5	20.1	15.8	....	....	20.9	16.4
		2	20.8	16.4	20.8	16.7	....	....	....	....	20.9	16.7
	12	1	13.6	10.7	13.2	10.4	13.1	10.2	....	....	13.6	10.9
		2	13.2	10.6	13.6	10.6	....	....	....	....	13.5	11.3

(Continue next page)

Appendix IV. Continued.

Lodgepole pine 2												
Ht.	N MC (%)	Repl.	Moisture content measurements									
			1		2		3		4		5	
			OD	MT	OD	MT	OD	MT	OD	MT	OD	MT
1	G	1	62.5	32.4	44.7	29.5	34.1	26.0	29.2	24.2	111.8	36.7
		2	46.7	29.5	37.7	27.4	31.8	25.3	....	....	91.3	35.5
	19	1	20.0	16.1	19.7	15.8	19.8	15.4	19.4	15.3	20.1	15.4
		2	20.3	16.5	20.2	16.2	19.6	15.7	....	....	20.4	16.0
	12	1	13.8	10.8	13.5	10.8	13.6	10.6	13.4	10.3	14.0	11.5
		2	13.8	10.9	13.7	10.7	13.5	10.5	....	....	13.8	11.1
2	G	1	42.2	30.5	30.9	24.6	27.7	21.5	....	....	79.6	33.6
		2	33.3	25.5	32.8	24.8	....	....	....	....	80.8	30.8
	19	1	20.4	15.8	19.2	15.0	20.3	15.7	....	....	20.1	15.6
		2	20.6	16.4	20.4	16.0	....	....	....	....	20.2	16.0
	12	1	13.2	10.5	12.8	10.0	14.0	10.7	....	....	13.5	11.2
		2	14.0	11.0	13.9	10.8	....	....	....	....	13.8	11.4
3	G	1	35.1	24.6	32.0	23.6	28.9	22.8	....	....	114.3	32.4
		2	31.6	24.1	29.3	23.4	....	....	....	....	97.7	30.8
	19	1	20.6	16.5	20.3	15.9	20.0	16.0	....	....	20.1	16.5
		2	21.1	17.0	20.7	16.4	....	....	....	....	20.1	16.6
	12	1	13.5	10.7	13.1	10.2	13.3	10.2	....	....	13.2	11.6
		2	13.6	10.8	13.3	10.3	....	....	....	....	13.4	11.8
4	G	1	36.1	26.0	28.1	22.4	28.4	22.7	....	....	64.6	32.1
		2	30.3	23.7	29.5	23.0	....	....	....	....	67.8	31.8
	19	1	21.2	17.3	20.8	16.4	19.8	15.6	....	....	20.6	16.6
		2	20.6	16.2	20.6	15.8	....	....	....	....	20.5	16.2
	12	1	13.7	10.6	13.5	10.4	13.3	10.3	....	....	13.8	11.7
		2	13.9	10.8	13.9	10.5	....	....	....	....	13.5	11.1
5	G	1	35.4	24.5	....	....	....	....	....	....	125.4	39.5
		2	29.4	22.4	....	....	....	....	....	....	97.4	33.4
	19	1	20.1	16.0	....	....	....	....	....	....	20.3	16.2
		2	20.5	16.2	....	....	....	....	....	....	20.5	16.3
	12	1	13.5	10.4	....	....	....	....	....	....	13.4	11.8
		2	13.2	10.3	....	....	....	....	....	....	13.3	11.7

(Continue next page)

Appendix IV. Continued.

			Lodgepole pine 3									
Ht.	N MC (%)	Repl.	Moisture content measurements									
			1		2		3		4		5	
			OD	MT	OD	MT	OD	MT	OD	MT	OD	MT
1	G	1	40.6	27.8	36.7	26.7	35.2	26.4	34.2	23.6	104.0	35.8
		2	45.9	28.1	40.3	27.5	33.4	24.7	....	....	136.6	39.2
	19	1	21.5	17.1	21.2	16.8	21.2	16.9	20.7	16.3	21.0	17.0
		2	20.5	15.8	20.4	15.7	20.0	15.5	....	....	20.3	16.2
	12	1	13.9	11.0	13.7	10.9	13.6	10.8	13.4	10.5	13.7	11.6
		2	13.6	10.9	13.4	10.8	13.2	10.5	....	....	13.7	11.7
2	G	1	35.4	25.9	32.6	24.4	28.5	21.5	....	....	102.4	34.5
		2	45.8	27.9	31.3	22.5	....	....	....	....	134.6	37.3
	19	1	20.6	16.1	20.0	15.4	20.3	15.8	....	....	20.3	15.7
		2	20.4	15.7	20.2	15.1	....	....	....	....	20.1	15.6
	12	1	13.2	10.5	13.5	10.5	13.6	10.4	....	....	13.7	10.9
		2	13.7	10.7	13.6	10.3	....	....	....	....	13.7	11.2
3	G	1	31.4	23.3	28.2	21.3	27.4	20.9	....	....	72.4	29.1
		2	48.3	32.7	35.2	25.7	....	....	....	....	120.1	39.3
	19	1	21.3	16.8	21.2	16.6	21.2	16.7	....	....	20.8	16.5
		2	21.4	16.7	20.7	16.0	....	....	....	....	20.5	16.2
	12	1	14.1	10.7	13.8	10.5	13.7	10.4	....	....	13.7	11.0
			13.9	10.7	13.7	10.4	....	....	....	....	13.9	11.3
4	G	1	34.7	25.0	32.4	24.0	....	....	....	....	136.4	40.2
		2	32.9	24.5	32.1	24.1	....	....	....	....	96.8	34.5
	19	1	21.0	16.5	20.3	15.5	....	....	....	....	20.5	15.7
		2	20.9	16.5	20.4	15.6	....	....	....	....	20.7	16.0
	12	1	13.9	10.5	13.7	10.4	....	....	....	....	13.8	11.1
		2	13.7	10.4	13.5	10.3	....	....	....	....	13.9	10.9
5	G	1	30.8	22.0	29.3	21.8	....	....	....	....	110.1	35.0
		2	30.1	22.1	....	....	....	....	....	....	52.8	30.8
	19	1	21.4	16.6	20.0	15.4	....	....	....	....	20.3	15.9
		2	20.4	16.0	....	....	....	....	....	....	21.1	16.2
	12	1	14.1	10.6	13.2	10.1	....	....	....	....	13.5	11.1
		2	13.9	10.7	....	....	....	....	....	....	13.3	10.7

(Continue next page)

Appendix IV. Continued.

Lodgepole pine 4												
Ht.	N MC (%)	Repl.	Moisture content measurements									
			1		2		3		4		5	
			OD	MT	OD	MT	OD	MT	OD	MT	OD	MT
1	G	1	36.3	27.1	33.1	25.3	31.2	24.5	27.9	23.1	114.7	37.4
		2	65.5	37.2	66.4	36.1	28.1	23.0	....	....	119.0	36.5
	19	1	20.4	17.4	19.7	17.0	19.3	16.6	19.4	16.6	20.9	16.8
		2	20.7	17.7	20.3	17.8	19.3	16.4	....	....	20.5	16.7
	12	1	13.6	11.2	12.9	10.9	12.7	10.8	13.0	10.6	13.9	11.4
		2	13.2	10.9	12.9	10.8	12.6	10.2	....	....	13.5	11.3
2	G	1	30.4	24.5	29.3	23.8	28.0	22.9	....	....	119.7	36.2
		2	32.7	25.3	31.3	24.5	29.8	23.2	....	....	133.6	39.3
	19	1	20.1	16.6	19.5	16.2	19.1	15.9	....	....	20.9	16.6
		2	20.8	16.9	20.1	16.5	19.6	16.0	....	....	20.5	16.3
	12	1	13.0	10.6	12.7	10.4	12.6	10.3	....	....	13.9	11.1
		2	13.5	10.8	13.1	10.6	12.9	10.4	....	....	13.6	11.5
3	G	1	29.4	23.4	28.1	22.8	27.9	21.8	....	....	111.5	35.1
		2	31.7	24.3	29.6	23.2	....	....	....	....	141.5	37.6
	19	1	20.6	17.3	20.3	16.8	19.4	16.4	....	....	20.5	16.9
		2	20.3	16.6	19.6	15.7	....	....	....	....	20.4	16.3
	12	1	13.6	11.0	13.6	10.7	12.9	10.7	....	....	13.7	11.5
		2	13.4	10.8	12.9	10.3	....	....	....	....	13.5	11.5
4	G	1	29.0	24.3	29.3	23.2	....	....	....	....	133.7	36.6
		2	28.6	23.0	27.6	22.7	....	....	....	....	112.8	35.7
	19	1	20.8	17.0	20.4	16.5	....	....	....	....	20.9	16.8
		2	20.9	16.9	19.6	15.9	....	....	....	....	19.6	16.1
	12	1	13.6	11.1	13.3	10.7	....	....	....	....	13.9	11.8
		2	13.8	11.2	12.9	10.5	....	....	....	....	13.8	11.8
5	G	1	31.7	25.5	31.1	24.9	....	....	....	....	130.7	40.0
		2	31.2	26.1	....	....	....	....	....	....	150.2	42.0
	19	1	20.6	17.7	19.9	16.1	....	....	....	....	20.8	17.2
		2	20.3	16.5	....	....	....	....	....	....	20.5	16.6
	12	1	13.8	11.1	13.3	10.7	....	....	....	....	14.0	12.0
		2	13.1	10.8	....	....	....	....	....	....	13.7	12.0

(Continue next page)

Appendix IV. Continued.

Lodgepole pine compression wood											
Ht.	N MC (%)	Moisture content measurements									
		1		2		3		4		5	
		OD	MT	OD	MT	OD	MT	OD	MT	OD	MT
		Compression wood									
1	G	27.9	21.8	26.5	19.8	26.5	20.8	26.5	19.5	28.0	22.4
	19	20.7	16.1	20.1	16.4	20.5	16.1	20.5	15.9	20.3	16.0
	12	13.6	10.5	13.3	10.4	14.0	10.9	13.9	10.8	14.5	11.7
		Opposite wood									
1	G	28.4	22.4	26.8	20.5	....	....	....	....	70.3	29.9
	19	20.5	16.2	19.9	15.5	....	....	....	....	14.5	11.7
	12	13.9	11.3	13.5	11.2	....	....	....	....	13.6	10.9

Appendix IV. Continued.

			White spruce									
Ht.	N MC (%)	Repl.	Moisture content measurements									
			1		2		3		4		5	
			OD	MT	OD	MT	OD	MT	OD	MT	OD	MT
1	G	1	28.9	20.6	28.2	19.8	27.3	19.6	26.8	19.2	94.2	32.5
		2	28.0	19.8	28.6	20.3	28.7	20.0	28.0	19.7	73.5	30.2
	19	1	21.0	15.3	20.4	14.8	20.0	14.6	20.8	14.9	20.6	15.5
		2	21.2	15.9	20.6	15.1	20.7	14.9	20.6	15.0	20.3	15.2
	12	1	14.0	10.0	13.8	9.8	13.8	9.7	14.3	9.9	13.7	10.7
		2	14.0	10.0	13.8	9.8	13.9	9.8	13.8	9.8	14.0	10.9
2	G	1	34.7	24.3	33.2	23.5	32.7	22.8	37.7	24.2	103.7	31.9
		2	32.5	22.9	32.2	23.0	30.9	21.8	....	....	57.5	28.4
	19	1	20.7	14.9	20.6	14.5	20.6	14.5	20.5	14.7	20.6	15.2
		2	20.5	14.7	20.7	14.4	20.5	14.5	....	....	20.7	15.1
	12	1	13.8	10.1	13.8	10.0	13.7	9.9	13.6	10.0	13.6	10.8
		2	14.0	10.2	13.8	9.9	13.7	10.0	....	....	13.8	10.7
3	G	1	32.8	23.7	31.8	23.5	31.0	22.6	....	....	57.0	27.9
		2	34.0	23.9	34.1	24.0	32.4	23.4	....	....	73.1	29.2
	19	1	20.0	14.9	20.4	14.7	20.2	14.6	....	....	20.3	15.3
		2	21.0	15.5	21.1	15.2	21.1	15.4	....	....	21.2	15.7
		1	14.1	10.3	13.9	10.0	13.8	10.0	....	....	13.9	10.7
		2	14.0	10.1	13.9	10.0	13.8	10.0	....	....	13.9	10.9
4	G	1	29.5	21.4	30.2	22.4	30.3	22.3	....	....	35.5	25.0
		2	32.7	22.7	33.2	23.8	32.3	23.0	....	....	83.9	32.4
	19	1	21.5	15.5	21.1	15.0	20.8	15.0	....	....	20.5	15.6
		2	21.0	15.1	21.5	15.3	21.0	15.2	....	....	21.0	16.0
	12	1	14.1	10.3	13.9	10.1	13.8	10.0	....	....	13.8	10.9
		2	14.2	10.4	13.8	10.0	13.7	10.0	....	....	13.7	10.9
5	G	1	30.2	21.4	30.8	21.5	....	....	....	....	67.6	28.3
		2	29.2	21.5	30.9	22.3	....	....	....	....	91.4	32.8
	19	1	20.7	14.8	20.4	14.7	....	....	....	....	20.7	15.6
		2	20.9	15.1	20.7	14.7	....	....	....	....	20.8	15.8
	12	1	14.0	10.3	13.8	10.1	....	....	....	....	14.1	11.2
		2	14.0	10.1	13.8	10.0	....	....	....	....	13.8	11.1

(Continue next page)

Appendix IV. Continued.

			Douglas-fir									
Ht.	N MC (%)	Repl.	Moisture content measurements									
			1		2		3		4		5	
			OD	MT	OD	MT	OD	MT	OD	MT	OD	MT
1	G	1	27.8	21.0	26.4	19.5	27.5	19.9	26.6	19.7	61.4	33.5
		2	32.1	24.0	30.8	23.1	29.8	22.4	....	....	38.0	28.6
	19	1	20.9	17.1	20.7	16.9	20.2	16.5	19.9	15.9	21.6	17.1
		2	21.3	17.0	20.4	16.5	20.3	16.1	....	....	21.2	17.0
	12	1	13.4	11.4	13.2	11.5	13.1	11.1	13.0	10.9	13.8	11.8
		2	13.6	11.5	13.0	10.9	13.1	10.8	....	....	13.9	11.5
2	G	1	29.9	21.8	30.2	21.8	29.0	20.9	....	....	64.1	36.8
		2	28.2	20.3	30.0	21.7	29.4	20.5	....	....	60.0	32.8
	19	1	21.1	16.4	20.9	16.6	20.7	16.2	....	....	21.3	17.5
		2	21.6	17.0	20.5	15.8	20.1	15.2	....	....	20.7	16.6
	12	1	13.6	11.5	13.1	10.9	13.2	10.6	....	....	13.5	11.4
		2	13.4	11.4	13.2	11.0	13.0	10.8	....	....	13.4	11.3
3	G	1	29.7	21.4	28.0	20.5	....	....	....	....	42.5	31.7
		2	31.4	23.0	30.7	21.9	....	....	....	....	64.8	34.2
	19	1	20.5	16.5	20.0	15.5	....	....	....	....	20.4	16.6
		2	20.4	16.0	20.3	16.3	....	....	....	....	20.6	17.1
	12	1	13.5	11.3	13.2	11.1	....	....	....	....	13.5	11.0
		2	13.5	11.0	13.2	10.7	....	....	....	....	13.7	11.2
4	G	1	29.3	21.0	30.7	22.2	30.5	21.4	....	....	71.4	37.5
		2	29.6	20.7	27.1	19.8	....	....	....	....	58.4	34.0
	19	1	20.7	16.6	20.4	16.4	20.3	15.9	....	....	20.8	16.7
		2	20.6	16.3	20.3	15.8	....	....	....	....	19.9	15.7
	12	1	14.0	11.3	13.7	11.1	13.7	10.6	....	....	14.0	11.4
		2	13.6	10.9	13.5	10.6	....	....	....	....	13.8	11.1
5	G	1	29.9	21.6	29.8	21.7	....	....	....	....	80.5	39.8
		2	30.1	22.5	29.0	21.5	....	....	....	....	81.8	40.5
	19	1	20.0	15.9	20.1	15.6	....	....	....	....	20.4	16.0
		2	20.6	16.0	19.7	15.5	....	....	....	....	21.0	16.6
	12	1	13.4	10.9	13.3	10.7	....	....	....	....	13.7	11.2
		2	13.6	11.1	13.1	10.5	....	....	....	....	13.4	11.1

(Continue next page)

Appendix IV. Continued.

Subalpine fir

Ht.	N.MC (%)	Repl.	Moisture content measurements 1 OD	1 MT	2 OD	2 MT	3 OD	3 MT	4 OD	4 MT	5 OD	5 MT
1	G	1	45.3	27.5	28.1	21.3	28.1	20.7	....	....	34.3	24.5
		2	55.9	29.6	29.4	20.9	29.5	21.4	....	....	65.4	30.8
	19	1	20.7	16.1	20.0	15.3	20.0	15.2	....	....	20.5	15.7
		2	20.8	16.8	20.2	15.3	20.2	15.1	....	....	20.3	15.7
	12	1	13.4	10.8	13.0	10.2	13.1	10.2	....	....	13.4	10.6
		2	12.8	10.8	13.3	10.2	13.4	10.1	....	....	13.6	10.6
2	G	1	38.2	25.8	37.5	26.4	29.7	21.9	....	....	60.4	29.6
		2	35.3	23.6	34.4	24.3	....	....	....	....	48.7	29.1
	19	1	20.5	15.9	20.2	15.3	20.1	15.2	....	....	20.4	16.2
		2	20.3	15.8	20.3	15.3	....	....	....	....	20.2	16.1
		1	13.2	10.2	13.2	10.1	13.3	10.0	....	....	13.6	10.4
		2	13.0	9.9	13.3	10.2	....	....	....	....	13.5	10.5
3	G	1	48.2	28.3	27.4	20.2	....	....	....	....	40.1	26.4
		2	48.3	27.8	35.1	24.7	....	....	....	....	43.8	27.1
	19	1	19.9	16.0	19.6	15.3	....	....	....	....	19.8	15.5
		2	20.0	16.2	19.5	15.4	....	....	....	....	19.6	14.8
	12	1	13.3	10.9	13.2	10.2	....	....	....	....	13.3	10.7
		2	13.1	10.7	13.0	10.2	....	....	....	....	13.1	10.5
4	G	1	36.2	26.1	36.4	28.0	....	....	....	....	30.6	21.5
		2	39.2	28.5	....	....	....	....	....	....	34.6	23.3
	19	1	20.0	16.2	19.6	15.6	....	....	....	....	19.4	15.1
		2	20.4	16.5	....	....	....	....	....	....	20.0	15.3
	12	1	13.7	10.6	13.4	10.5	....	....	....	....	13.3	10.3
		2	13.5	10.3	....	....	....	....	....	....	13.4	10.4
5	G	1	35.7	28.4	....	....	....	....	....	....	65.8	30.8
		2	37.1	29.1	....	....	....	....	....	....	49.8	30.5
	19	1	20.5	16.4	....	....	....	....	....	....	20.4	16.2
		2	20.6	16.5	....	....	....	....	....	....	20.6	16.5
	12	1	13.4	11.0	....	....	....	....	....	....	13.3	10.6
		2	13.5	11.0	....	....	....	....	....	....	13.4	10.9

(End)

Appendix V. Power-loss moisture meter (Moisture Register, Model L) measurements (MT-radial, MT-tangential) on wood samples from trees of the study compared to oven-dry (OD) calculations; including nominal moisture levels (N MC) at stem heights (Ht.) and for two radial replications (1-4 heartwood, 5 sapwood). Observations are 2 for each reading.

			Lodgepole pine 1															
			Moisture content measurements															
Ht.	N MC (%)	Repl.	1			2			3			4			5			
			OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	
1	19	1	20.7	33.2	34.2	20.5	30.9	31.5	20.2	30.2	31.2	19.6	29.9	29.6	20.7	33.5	34.0	
		2	21.1	33.8	34.9	20.8	31.4	31.9	20.3	30.8	31.6	19.9	30.0	31.0	20.5	33.2	33.8	
	12	1	13.6	21.9	22.2	13.5	20.8	21.3	13.3	20.9	21.2	13.2	20.5	21.0	13.7	22.4	22.6	
		2	13.8	21.5	22.5	13.6	21.3	21.5	13.4	20.9	21.2	13.3	20.6	21.7	13.7	22.6	23.0	
	6	1	7.7	17.8	18.0	7.9	17.5	17.8	7.6	17.4	17.5	7.6	17.5	17.9	7.8	18.4	18.5	
		2	7.8	17.6	18.2	8.0	17.5	17.9	7.8	17.7	18.1	7.7	17.9	18.4	7.6	18.2	18.5	
G		1		0.377			0.378			0.382			0.396			0.363		
		2		0.371			0.386			0.380			0.388			0.369		
2	19	1	20.5	32.0	32.8	19.8	29.7	30.6	20.4	31.8	32.9	....	....	....	20.9	34.2	34.7	
		2	20.6	32.4	33.1	20.4	30.5	31.6	19.7	31.2	31.9	....	....	....	20.7	33.8	34.3	
	12	1	13.5	21.6	21.8	13.3	20.9	21.0	13.6	22.4	22.7	....	....	....	13.8	23.0	22.8	
		2	13,5	21.3	21.4	13.5	21.1	21.1	13.0	21.7	22.1	....	....	....	13.6	22.0	22.5	
	6	1	7.6	17.6	17.8	7.8	18.0	18.5	7.8	17.8	18.0	....	....	....	7.8	17.8	18.3	
		2	7.7	18.0	18.3	7.6	17.7	18.2	8.0	18.3	18.5	....	....	....	7.7	18.2	18.5	
G		1		0.380			0.373			0.397			....			0.370		
		2		0.375			0.403			0.423			....			0.373		
3	19	1	21.4	34.4	36.0	20.6	30.6	31.3	20.7	32.4	33.8	....	....	....	21.2	33.6	33.6	
		2	21.2	33.6	34.0	19.8	31.5	32.6	20.3	32.0	33.3	....	....	....	20.8	33.4	33.6	
	12	1	13.9	22.3	22.5	13.2	20.9	21.4	13.2	21.1	22.5	....	....	....	13.8	21.9	22.2	
		2	13.5	21.5	22.1	13.1	21.1	22.5	13.5	21.5	22.1	....	....	....	13.7	21.7	22.0	
	6	1	7.9	17.6	17.8	7.6	17.7	18.2	7.7	18.3	18.6	....	....	....	7.8	18.6	18.5	
		2	7.8	17.9	18.1	7.5	17.8	18.4	7.7	18.2	18.5	....	....	....	7.9	18.1	18.6	
G		1		0.368			0.375			0.397			....			0.377		
		2		0.372			0.412			0.404			....			0.374		
4	19	1	20.9	32.0	32.6	20.7	30.3	30.7	20.1	30.9	32.1	....	....	....	20.9	32.9	33.9	
		2	20.8	33.4	34.5	20.5	30.5	31.4	....	....	....	....	....	....	20.9	33.9	35.5	
	12	1	13.6	20.5	20.8	13.2	20.9	21.9	13.1	21.0	22.2	....	....	....	13.6	21.3	22.0	
		2	13.2	21.3	21.9	13.6	22.1	22.6	....	....	....	....	....	....	13.5	21.9	22.0	
	6	1	7.9	17.3	17.5	7.7	18.1	18.5	7.5	18.1	18.8	....	....	....	7.9	17.7	18.1	
		2	7.7	17.9	18.0	7.6	18.1	18.1	....	....	....	....	....	....	7.9	18.3	18.5	
G		1		0.354			0.387			0.390			....			0.358		
		2		0.387			0.395			....			....			0.367		

(Continue next page)

Appendix V. Continued.

Ht.	N MC (%)	Repl.	Lodgepole pine 2 — Moisture content measurements: 1 OD	1 MT-R	1 MT-T	2 OD	2 MT-R	2 MT-T	3 OD	3 MT-R	3 MT-T	4 OD	4 MT-R	4 MT-T	5 OD	5 MT-R	5 MT-T
1	19	1	20.0	33.6	34.2	19.7	31.6	32.4	19.8	30.2	32.2	19.4	29.6	30.1	20.1	31.6	32.8
		2	20.4	33.4	34.9	20.2	32.5	34.0	19.6	30.7	31.7	....	....	....	20.4	33.7	34.1
	12	1	13.8	22.5	23.1	13.5	21.8	22.6	13.6	21.9	22.3	13.4	21.9	21.7	14.0	22.3	22.3
		2	13.8	22.5	22.9	13.7	22.2	22.7	13.5	22.1	22.3	....	....	....	13.8	23.4	23.6
	6	1	7.8	18.1	18.3	7.5	18.3	18.6	7.5	17.7	18.3	7.7	18.0	18.5	7.7	17.5	17.6
		2	7.7	17.6	17.9	7.6	18.4	18.5	7.6	18.0	18.5	....	....	....	7.8	18.4	18.7
G		1		0.396			0.395			0.384			0.413			0.353	
		2		0.376			0.389			0.403			....			0.365	
2	19	1	20.4	32.3	32.4	19.2	29.9	31.0	20.3	29.3	30.1	....	....	....	20.1	31.9	33.2
		2	20.6	32.0	33,1	20.4	31.2	31.4	....	....	....	....	....	....	20.2	32.7	34.2
	12	1	13.2	21.4	22.0	12.8	21.5	22.1	14.0	21.1	21.6	....	....	....	13.5	22.7	23.2
		2	14.0	21.8	22.2	13.9	21.9	21.9	....	....	....	....	....	....	13.8	22.7	23.2
	6	1	7.6	17.8	18.1	7.7	17.8	18.2	7.7	17.5	17.9	....	....	....	7.5	18.0	18.5
		2	7.7	18.1	18.2	7.6	18.1	18.3	....	....	....	....	....	....	7.6	18.5	18.8
G		1		0.366			0.404			0.376			....			0.363	
		2		0.369			0.368			....			....			0.372	
3	19	1	20.6	31.6	33.2	20.3	30.2	31.1	20.0	30.7	32.2	....	....	....	20.1	32.7	33.8
		2	21.1	32.0	33.2	20.7	31.8	33.0	....	....	....	....	....	....	20.1	33.7	34.2
	12	1	13.5	22.0	22.8	13.1	21.4	22.0	13.3	21.8	22.2	....	....	....	13.2	22.7	22.3
		2	13.6	22.3	23.5	13.3	21.8	22.5	....	....	....	....	....	....	13.4	23.5	23.5
	6	1	7.8	18.5	18.5	7.7	18.1	18.6	7.8	18.2	18.5	....	....	....	7.8	18.2	18.2
		2	7.8	18.4	19.0	7.8	18.4	19.0	....	....	....	....	....	....	7.7	18.5	18.9
G		1		0.384			0.369			0.418			....			0.360	
		2		0.386			0.396			....			....			0.375	
4	19	1	21.2	36.5	37.0	20.8	31.5	32.7	19.8	30.3	31.4	....	....	....	20.6	32.2	32.4
		2	20.6	33.8	33.8	20.6	30.7	32.2	....	....	....	....	....	....	20.5	31.8	32.3
	12	1	13.7	23.1	23.5	13.5	21.8	21.5	13.3	21.9	22.9	....	....	....	13.8	22.4	22.7
		2	19.9	23.8	23.8	13.9	22.2	23.0	....	....	....	....	....	....	13.5	23.0	23.0
	6	1	7.9	19.3	19.6	7.7	18.0	18.1	7.8	18.1	18.2	....	....	....	7.8	18.0	17.8
		2	8.0	18.9	18.9	8.0	18.2	.8.5	....	....	....	....	....	....	8.0	18.4	18.4
G		1		0.418			0.371			0.381			....			0.358	
		2		0.407			0.371			....			....			0.367	
5	19	1	20.1	33.5	34.9	....	....	....	....	....	....	....	....	....	20.3	32.5	33.0
		2	20.5	32.7	32.6	....	....	....	....	....	....	....	....	....	20.5	33.2	33.5
	12	1	13.5	23.4	22.9	....	....	....	....	....	....	....	....	....	13.4	23.0	23.1
		2	13.2	23.0	23.1	....	....	....	....	....	....	....	....	....	13.3	22.8	23.1
	6	1	7.8	18.4	18.7	....	....	....	....	....	....	....	....	....	7.9	18.5	18.7
		2	7.9	19.019.2		....	....	....	....	....	....	....	....	....	8.0	18.4	18.9
G		1		0.386			....			....			....			0.365	
		2		0.405			....			....			....			0.364	

(Continue next page)

Appendix V. Continued.

Ht.	N MC (%)	Repl.	1 OD	1 MT-R	1 MT-T	2 OD	2 MT-R	2 MT-T	3 OD	3 MT-R	3 MT-T	4 OD	4 MT-R	4 MT-T	5 OD	5 MT-R	5 MT-T
			Lodgepole pine 3 — Moisture content measurements														
1	19	1	21.5	35.8	36.9	21.2	34.8	36.4	21.2	34,9	35.2	20.7	33.6	33.7	21.0	38.0	38.9
		2	20.5	34.9	35.5	20.4	34.4	35.0	20.0	32.8	34.0	....	....	....	20.3	37.5	38.2
	12	1	13.9	25.1	25.5	13.7	25.5	25.3	13.6	25.8	26.1	13.4	25.8	26.2	13.7	26.9	27.2
		2	13.6	25.1	25.0	13.4	24.7	25.1	13.2	24.8	25.1	....	....	....	13.7	25.9	26.0
	6	1	7.9	20.1	20.4	7.7	21.0	20.9	7.6	21.4	21.2	7.6	21.4	21.7	7.8	21.4	21.3
		2	7.6	20.0	20.3	7.5	20.0	20.2	7.4	20.3	20.5	....	....	....	7.8	20.0	20.3
G		1		0.441			0.454			0.469			0.479			0.447	
		2		0.438			0.434			0.442			....			0.411	
2	19	1	20.6	32.2	33.8	20.0	30.4	31.8	20.3	32.5	33.6	....	....	....	20.3	34.0	34.7
		2	20.4	32.5	34.2	20.2	30.5	32.7	....	....	....	....	....	....	20.1	33.5	32.8
	12	1	13.2	24.7	25.6	13.5	24.4	24.9	13.6	25.4	26.2	....	....	....	13.7	25.7	26.0
		2	13.7	25.2	25.6	13.6	25.0	25.1	....	....	....	....	....	....	13.7	25.0	25.3
	6	1	7.9	18.7	19.2	7.5	19.8	19.9	7.6	20.5	20.8	....	....	....	7.7	20.5	20.2
		2	7.7	19.6	20.0	7.7	20.3	20.3	....	....	....	....	....	....	7.7	19.1	19.2
G		1		0.426			0.430			0.451			....			0.436	
		2		0.399			0.425			....			....			0.402	
3	19	1	21.3	34.8	36.4	21.2	32.9	34.1	21.2	32.3	32.5	....	....	....	20.8	33.7	34.2
		2	21.4	36.3	38.4	20.7	32.9	33.8	....	....	....	....	....	....	20.5	33.2	33.6
	12	1	13.9	24.2	24.7	13.8	24.4	24.6	13.7	26.3	26.2	....	....	....	13.7	25.0	25.4
		2	14.1	25.4	25.3	13.7	25.4	25.9	....	....	....	....	....	....	13.9	24.7	24.8
	6	1	7.9	19.2	19.5	7.9	19.6	19.9	7.2	20.6	20.7	....	....	....	7.7	20.7	20.6
		2	8.0	20.4	20.6	7.8	20.7	20.7	....	....	....	....	....	....	7.9	19.1	19.2
G		1		0.404			0.407			0.429			....			0.412	
		2		0.417			0.430			....			....			0.395	
4	19	1	21.0	34.1	35.0	20.3	32.3	33.3	....	....	....	....	....	....	20.5	35.0	36.0
		2	20.9	33.5	34.6	20.4	31.9	33.3	....	....	....	....	....	....	20.7	33.7	34.1
	12	1	13.9	24.7	25.4	13.7	25.3	25.7	....	....	....	....	....	....	13.8	25.0	24.9
		2	13.7	24.0	23.8	13.5	23 7	24.8	....	....	....	....	....	....	13.9	24.2	24.3
	6	1	7.9	19.6	19.7	7.8	20.4	20.4	....	....	....	....	....	....	7.8	19.6	19.6
		2	7.7	19.7	19.6	7.7	20.0	20.2	....	....	....	....	....	....	8.0	20.2	20.3
G		1		0.397			0.428			....			....			0.412	
		2		0.402			0.417			....			....			0.384	
5	19	1	21.4	36.5	37.2	20.0	32.1	34.6	....	....	....	....	....	....	20.3	34.4	35.3
		2	20.4	32.3	33.1	....	....	....	....	....	....	....	....	....	21.1	36.1	36.4
	12	1	14.1	25.6	25.8	13.2	24.5	24.6	....	....	....	....	....	....	13.5	25.4	25.8
		2	13.9	25.0	25.1	....	....	....	....	....	....	....	....	....	13.3	24.5	24.2
	6	1	8.1	21.1	20.8	7.6	20.8	21.0	....	....	....	....	....	....	7.8	20.4	20.8
		2	8.0	20.4	20.5	....	....	....	....	....	....	....	....	....	7.8	20.0	20.0
G		1		0.426			0.450			....			....			0.426	
		2		0.412			....			....			....			0.422	

(Continue next page)

Appendix V. Continued.

Ht.	N MC (%)	Repl.	Lodgepole pine 4 — Moisture content measurements 1			2			3			4			5		
			OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T
1	19	1	20.4	38.3	38.5	19.7	34.4	35.7	19.3	33.0	34.0	19.4	33.6	34.0	20.9	36.5	37.0
		2	20.7	38.7	39.1	20.3	37.1	38.7	19.3	33.6	34.0	....	....	....	20.5	36.0	36.5
	12	1	13.6	25.1	25.6	12.9	24.4	24.5	12.7	24.3	24.2	13.0	24.4	24.7	13.9	25.2	25.9
		2	13.2	24.6	24.8	12.9	23.6	23.8	12.6	22.9	23.5	....	....	....	13.5	23.8	24.0
	6	1	7.7	19.7	20.3	7.4	19.7	20.2	7.3	20.0	20.0	7.6	20.6	20.6	7.8	20.8	21.2
		2	7.5	20.3	20.4	7.2	20.2	20.3	7.1	19.9	20.0	....	....	....	7.7	20.2	20.3
G		1		0.432			0.428			0.435			0.453			0.405	
		2		0.428			0.431			0.432			....			0.378	
2	19	1	20.1	33.6	35.0	19.5	32.9	34.0	19.1	32.5	33.5	....	....	....	20.9	36.0	37.1
		2	20.8	35.3	36.8	20.1	33.7	34.6	19.6	32.7	33.6	....	....	....	20.5	35.3	36.2
	12	1	13.0	22.0	22.7	12.7	22.8	23.3	12.6	23.1	23.9	....	....	....	13.9	24.4	24.5
		2	13.5	23.1	23.4	13.1	23.0	23.4	12.9	22.6	22.7	....	....	....	13.6	24.0	24.0
	6	1	7.5	18.7	19.3	7.3	19.5	19.7	7.2	19.9	20.6	....	....	....	8.0	20.2	20.3
		2	7.7	18.7	19.0	7.5	19.0	19.3	7.5	18.4	18.7	....	....	....	7.8	19.0	19.0
G		1		0.401			0.425			0.443			....			0.392	
		2		0.397			0.419			0.416			....			0.381	
3	19	1	20.6	36.7	37.2	20.3	34.2	35.3	19.4	32.8	33.2	....	....	....	20.5	35.1	36.2
		2	20.3	34.0	36.4	19.6	31.9	33.2	....	....	....	....	....	....	20.4	35.0	36.1
	12	1	13.6	23.5	24.3	13.6	23.6	24.3	12.9	24.3	23.7	....	....	....	13.7	24.7	24.6
		2	13.4	22.6	23.5	12.9	22.8	23.2	....	....	....	....	....	....	13.5	23.8	24.1
	6	1	7.8	19.5	19.9	8.0	20.5	20.7	7.4	20.3	20.5	....	....	....	7.8	19.7	19.5
		2	7.7	18.4	18.8	7.5	18.9	19.2	....	....	....	....	....	....	7.7	18.8	18.9
G		1		0.426			0.444			0.444			....			0.399	
		2		0.396			0.415			....			....			0.371	
4	19	1	20.8	33.5	34.4	20.4	33.9	34.4	....	....	....	....	....	....	20.9	34.6	34.9
		2	20.9	34.0	35.3	19.6	31.5	32.6	....	....	....	....	....	....	19.6	32.1	33.0
	12	1	13.6	24.0	24.4	13.3	24.0	24.3	....	....	....	....	....	....	13.9	25.1	24.9
		2	13.8	23.5	23.4	12.9	22.9	23.5	....	....	....	....	....	....	13.8	24.4	24.4
	6	1	8.0	19.4	19.5	7.4	19.2	19.3	....	....	....	....	....	....	7.8	19.2	19.2
		2	7.8	18.0	18.2	7.4	17.9	18.3	....	....	....	....	....	....	7.5	18.7	18.7
G		1		0.420			0.430			....			....			0.390	
		2		0.396			0.410			....			....			0.385	
5	19	1	20.6	35.8	36.5	19.9	34.4	35.6	....	....	....	....	....	....	20.8	38.8	39.5
		2	20.3	38.0	39.6	....	....	....	....	....	....	....	....	....	20.5	38.0	37.5
	12	1	13.8	24.2	24.6	13.3	24.2	23.9	....	....	....	....	....	....	14.0	25.9	25.8
		2	13.1	24.6	25.0	....	....	....	....	....	....	....	....	....	13.7	25.1	25.1
	6	1	7.8	19.2	19.2	7.5	19.1	19.0	....	....	....	....	....	....	7.9	19.8	19.3
		2	7.7	19.9	20.2	....	....	....	....	....	....	....	....	....	7.8	19.3	19.3
G		1		0.421			0.422			....			....			0.398	
		2		0.457			....			....			....			0.386	

(Continue next page)

Appendix V. Continued.

Ht.	N MC (%)	Repl.	1 OD	1 MT-R	1 MT-T	2 OD	2 MT-R	2 MT-T	3 OD	3 MT-R	3 MT-T	4 OD	4 MT-R	4 MT-T	5 OD	5 MT-R	5 MT-T
			Lodgepole pine compression wood — Moisture content measurements														
1																	
Compression wood																	
	19	1	20.7	38.6	38.0	20.1	38.0	39.3	20.5	36.7	37.6	20.5	36.6	36.9	21.4	39.3	39.6
	12	1	13.9	27.8	29.3	13.3	25.5	25.9	14.0	29.1	29.1	13.9	29.0	29.7	14.5	29.8	29.7
	6	1	8.0	22.6	23.2	7.9	25.1	25.0	8.2	24.0	24.0	8.2	24.3	24.3	8.5	25.1	24.8
G				0.508			0.584			0.540			0.541			0.525	
Opposite wood																	
	19	1	20.5	35.0	35.6	19.9	32.7	34.0	....	....	....	....	....	....	20.3	33.9	35.0
	12	1	13.6	24.8	25.3	13.3	25.5	25.9	....	....	....	....	....	....	13.6	27.5	27.8
	6	1	7.7	19.6	19.6	7.6	20.8	21.3	....	....	....	....	....	....	8.2	22.5	23.0
G				0.444			0.462			....			....			0.498	

(Continuenext page)

Appendix V. Continued.

			White spruce															
			Moisture content measurements															
Ht.	N MC (%)	Repl.	1			2			3			4			5			
			OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	
1	19	1	21.0	29.2	29.9	20.4	25.7	27.7	20.0	24.9	26.7	20.8	27.3	27.3	20.6	31.3	33.2	
		2	21.2	29.3	30.2	20.6	26.6	27.9	20.7	25.7	27.4	20.6	25.4	26.9	20.2	29.2	30.5	
	12	1	14.0	19.7	20.1	13.8	19.0	19.6	13.8	19.7	20.8	14.3	19.8	20.2	13.7	21.0	21.4	
		2	14.0	19.7	19.7	13.8	18.8	19.6	13.9	19.2	19.5	13.8	19.7	20.2	14.0	21.6	22.1	
	6	1	8.0	16.1	16.3	7.8	16.2	16.2	7.8	16.0	16.5	8.3	16.5	17.1	7.9	17.5	17.7	
		2	8.1	16.8	16.9	8.0	15.8	16.0	8.0	16.1	16.4	7.9	16.3	16.4	8.0	17.2	17.2	
G		1		0.334			0.302			0.305			0.329			0.334		
		2		0.331			0.298			0.301			0.310			0.325		
2	19	1	20.7	28.7	29.8	20.6	26.3	28.5	20.6	26.5	27.4	20.5	27.6	29.3	20.6	31.5	32.2	
		2	20.5	27.3	28.0	20.7	26.8	27.5	20.5	27.0	28.3	....	....	....	20.7	30.0	31.2	
	12	1	13.8	19.1	19.4	13.8	19.2	19.6	13.7	18.6	20.0	13.6	19.5	19.9	13.6	21.6	21.2	
		2	14.0	19.5	19.6	13.8	18.6	18.9	13.7	20.1	21.1	....	....	....	13.8	20.9	21.4	
	6	1	8.0	16.0	16.0	8.0	15.8	16.0	7.9	16.2	16.7	7.8	16.6	17.0	7.8	17.4	17.5	
		2	8.0	16.3	16.5	8.1	16.0	16.4	7.9	16.6	17.4	....	....	....	8.0	17.1	17.1	
G		1		0.309			0.310			0.315			0.327			0.340		
		2		0.302			0.303			0.320			....			0.328		
3	19	1	20.2	27.4	29.0	20.4	26.0	26.9	20.2	25.4	27.1	....	....	....	20.3	29.1	31.0	
		2	21.0	27.5	29.3	21.1	28.9	28.9	21.1	27.3	28.6	....	....	....	21.2	31.7	32.0	
	12	1	14.1	20.0	20.8	13.9	19.6	20.3	13.9	20.2	20.7	....	....	....	13.9	21.2	21.6	
		2	14.0	19.4	20.2	13.9	19.8	20.2	13.8	20.0	20.0	....	....	....	13.9	21.0	21.6	
	6	1	8.0	16.4	17.1	7.9	16.3	16.7	8.0	16.8	17.1	....	....	....	8.0	17.4	17.6	
		2	8.0	16.2	16.7	8.0	16.5	16.8	7.8	16.7	16.8	....	....	....	8.0	17.4	17.6	
G		1		0.325			0.317			0.326			....			0.338		
		2		0.311			0.313			0.320			....			0.335		
4	19	1	21.5	32.0	31.9	21.1	29.2	30.0	20.8	28.8	30.0	....	....	....	20.5	32.2	32.0	
		2	21.0	31.2	32.0	21.5	30.9	31.2	21.0	29.4	30.2	....	....	....	21.0	31.3	31.9	
	12	1	14.1	20.5	21.5	13.9	20.2	21.3	13.8	20.2	20.9	....	....	....	13.8	21.2	22.1	
		2	14.2	21.2	21.5	13.8	19.9	20.2	13.7	19.6	20.4	....	....	....	13.7	21.2	21.4	
	6	1	8.1	17.3	17.1	7.9	17.0	17.3	8.0	17.5	17.6	....	....	....	8.0	18.1	18.0	
		2	8.1	17.0	17.6	7.9	17.4	17.7	7.9	16.9	17.0	....	....	....	8.0	17.7	18.2	
G		1		0.356			0.333			0.336			....			0.355		
		2		0.355			0.333			0.334			....			0.341		
5	19	1	20.7	29.8	30.5	20.4	27.8	29.4	....	....	....	....	....	....	20.7	31.0	32.4	
		2	20.9	29.5	30.6	20.7	28.1	29.9	....	....	....	....	....	....	20.8	32.3	35.0	
	12	1	14.0	21.8	22.8	13.8	31.0	21.2	....	....	....	....	....	....	14.1	22.9	23.0	
		2	14.0	20.9	21.4	13.8	21.0	21.0	....	....	....	....	....	....	13.8	21.8	22.3	
	6	1	8.1	17.8	18.0	8.0	17.0	17.3	....	....	....	....	....	....	8.2	18.2	18.4	
		2	8.1	17.4	17.5	8.0	17.3	17.4	....	....	....	....	....	....	8.1	18.0	18.2	
G		1		0.347			0.332			....			....			0.364		
		2		0.341			0.333			....			.....			0.350		

(Continue next page)

Appendix V. Continued.

Ht.	N MC (%)	Repl.	Douglas-fir: Moisture content measurements 1			2			3			4			5		
			OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T
1	19	1	20.9	29.0	29.8	20.7	29.1	29.3	20.2	29.8	30.8	19.9	29.5	29.8	21.6	41.3	43.5
		2	21.3	29.5	30.9	20.4	29.8	30.0	20.3	29.4	29.9	....	....	....	21.2	35.6	38.3
	12	1	13.4	24.0	23.1	13.2	24.4	25.5	13.1	25.7	25.9	13.0	25.6	26.3	12.8	29.2	29.2
		2	13.6	24.0	24.9	13.0	24.5	25.1	13.1	25.9	26.0	....	....	....	13.9	28.7	28.9
	6	1	7.9	21.9	22.2	7.7	22.3	22.5	7.6	23.6	23.6	7.6	24.7	24.8	8.0	25.8	26.0
		2	8.1	21.1	21.8	7.7	22.0	22.3	7.7	23.1	23.4	....	....	....	8.0	24.7	25.7
G		1		0.442			0.447			0.483			0.507			0.513	
		2		0.434			0.458			0.478			....			0.503	
2	19	1	21.1	28.1	28.4	20.9	29.4	30.6	20.7	29.3	30.0	....	....	....	21.3	35.8	38.4
		2	21.6	30.1	31.8	20.5	28.5	28.8	20.1	27.8	28.5	....	....	....	20.7	36.0	35.8
	12	1	13.6	23.4	23.8	13.1	24.3	24.3	13.2	24.9	25.4	....	....	....	13.5	27.4	26.8
		2	13.4	23.1	22.8	13.2	23.0	23.4	13.0	23.7	24.1	....	....	....	13.4	26.3	25.8
	6	1	8.0	20.9	21.2	7.6	21.6	21.7	7.5	22.4	22.5	....	....	....	7.7	24.0	23.5
		2	7.8	20.5	20.8	7.8	20.9	21.1	7.7	22.3	22.4	....	....	....	7.9	23.6	23.8
G		1		0.414			0.430			0.456			....			0.477	
		2		0.406			0.425			0.448			....			0.473	
3	19	1	20.5	29.4	20.3	20.0	26.4	27.4	....	....	....	....	....	....	20.4	32.0	33.3
		2	20.4	26.4	27.5	20.3	28.8	27.9	....	....	....	....	....	....	20.6	33.9	34.7
	12	1	13.5	22.8	23.8	13.2	24.0	23.1	....	....	....	....	....	....	13.5	26.2	25.8
		2	13.5	23.1	23.5	13.2	24.2	24.2	....	....	....	....	....	....	13.7	26.7	26.7
	6	1	7.8	20.3	20.7	7.7	21.7	21.7	....	....	....	....	....	....	7.9	22.9	22.9
		2	7.8	20.0	20.5	7.7	21.1	21.3	....	....	....	....	....	....	7.7	22.6	22.4
G		1		0.405			0.432			....			....			0.455	
		2		0.403			0.434			....			....			0.458	
4	19	1	20.7	27.5	29.3	20.4	27.9	27.9	20.3	26.6	26.8	....	....	....	20.8	33.4	24.5
		2	20.6	26.8	27.6	20.3	27.2	26.9	....	....	....	....	....	....	19.9	32.4	33.6
	12	1	14.0	23.7	24.5	13.7	24.2	24.7	13.7	23.7	24.0	....	....	....	14.0	26.7	26.7
		2	13.6	23.0	23.4	13.5	23.6	23.8	....	....	....	....	....	....	13.8	25.2	25.1
	6	1	7.9	20.9	21.1	7.8	21.5	22.0	7.8	21.5	21.7	....	....	....	8.0	22.8	23.1
		2	7.8	20.6	21.0	7.7	21.0	21.5	....	....	....	....	....	....	7.9	22.1	22.8
G		1		0.425			0.429			0.430			....			0.448	
		2		0.423			0.424			....			....			0.432	
5	19	1	20.0	27.7	28.7	20.1	28.6	28.9	....	....	....	....	....	....	20.4	33.5	33.5
		2	20.6	28.3	29.7	19.7	27.5	27.0	....	....	....	....	....	....	21.0	33.3	34.1
	12	1	13.4	24.6	24.9	13.3	25.2	25.2	....	....	....	....	....	....	13.7	25.9	26.4
		2	13.6	24.8	25.4	13.1	24.7	25.6	....	....	....	....	....	....	13.4	25.2	25.7
	6	1	7.8	21.7	22.1	7.7	21.9	22.0	....	....	....	....	....	....	7.9	22.3	22.3
		2	7.9	21.3	22.2	7.8	21.4	21.9	....	....	....	....	....	....	8.0	21.8	21.8
G		1		0.442			0.442			....			....			0.440	
		2		0.439			0.437			....			....			0.425	

(Continue next page)

Appendix V. Continued.

Ht.	N MC (%)	Repl.	Subalpine fir — Moisture content measurements: 1			2			3			4			5		
			OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T	OD	MT-R	MT-T
1	19	1	20.7	39.0	39.5	20.0	31.8	33.4	20.0	31.2	31.3	....	....	....	20.5	21.5	32.8
		2	20.8	35.0	35.5	20.2	30.2	30.6	20.2	27.8	29.7	....	....	....	20.3	28.9	30.4
	12	1	13.4	24.6	24.8	13.0	24.1	24.4	13.1	24.0	24.1	....	....	....	13.4	23.5	24.2
		2	12.8	22.0	22.7	13.3	23.7	24.2	13.4	23.0	23.6	....	....	....	13.6	24.2	24.6
	6	1	7.6	19.0	19.2	7.3	19.7	20.4	7.3	19.5	19.8	....	....	....	7.6	19.8	19.7
		2	7.7	16.9	18.9	7.5	19.4	19.8	7.5	19.9	19.8	....	....	....	7.7	19.6	19.9
G		1		0.416			0.430			0.428			....			0.406	
		2		0.414			0.413			0.404			....			0.406	
2	19	1	20.5	33.8	34.6	20.2	31.2	31.4	20.1	30.4	30.8	....	....	....	20.4	30.4	30.8
		2	20.3	31.3	32.4	20.3	30.4	34.6	....	....	....	....	....	....	20.2	29.6	30.1
	12	1	13.2	31.8	23.7	13.2	22.4	22.6	13.3	22.9	23.4	....	....	....	13.6	24.1	24.3
		2	13.0	21.7	23.0	13.3	22.2	22.6	....	....	....	....	....	....	13.5	23.8	24.1
	6	1	7.5	16.6	17.3	7.5	17.8	18.3	7.5	18.0	18.3	....	....	....	7.8	19.5	19.4
		2	7.3	16.7	17.4	7.7	18.6	18.3	....	....	....	....	....	....	7.6	18.6	18.4
G		1		0.360			0.388			0.377			....			0.408	
		2		0.375			0.380			....			....			0.403	
3	19	1	19.9	34.5	36.0	19.6	31.4	31.8	....	....	....	....	....	....	19.8	29.7	30.1
		2	20.0	34.3	34.7	19.5	29.8	30.6	....	....	....	....	....	....	19.6	30.5	29.7
	12	1	13.3	23.5	23.8	13.2	23.6	23.7	....	....	....	....	....	....	13.3	22.9	23.2
		2	13.1	22.4	22.6	13.0	21.9	22.4	....	....	....	....	....	....	13.1	22.5	23.0
	6	1	7.7	17.5	17.7	7.5	18.5	18.5	....	....	....	....	....	....	7.5	17.8	18.0
		2	7.6	17.1	17.4	7.4	18.3	17.9	....	....	....	....	....	....	7.5	18.5	18.6
G		1		0.385			0.385			....			....			0.378	
		2		0.367			0.373			....			....			0.383	
4	19	1	20.0	33.8	33.9	19.6	32.0	32.2	....	....	....	....	....	....	19.4	27.8	28.6
		2	20.4	33.2	33.7	....	....	....	....	....	....	....	....	....	20.0	28.9	29.3
	12	1	13.7	23.7	24.1	13.4	23.5	23.6	....	....	....	....	....	....	13.3	22.4	22.4
		2	13.5	22.8	23.6	....	....	....	....	....	....	....	....	....	13.4	22.0	22.2
	6	1	7.7	17.2	17.3	7.5	17.1	17.6	....	....	....	....	....	....	7.6	17.4	17.0
		2	7.9	17.0	17.4	....	....	....	....	....	....	....	....	....	7.7	17.5	17.7
G		1		0.379			0.383			....			....			0.368	
		2		0.364			....			....			....			0.363	
5	19	1	20.5	34.5	34.9	....	....	....	....	....	....	....	....	....	20.4	30.0	30.4
		2	20.6	34.2	34.8	....	....	....	....	....	....	....	....	....	20.6	28.9	29.7
	12	1	13.4	24.0	24.2	....	....	....	....	....	....	....	....	....	13.3	21.7	22.3
		2	13.5	23.9	24.4	....	....	....	....	....	....	....	....	....	13.4	20.9	21.6
	6	1	7.7	17.0	18.1	....	....	....	....	....	....	....	....	....	7.5	16.7	17.4
		2	7.7	16.8	18.0	....	....	....	....	....	....	....	....	....	7.5	16.6	17.0
G		1		0.368			....			....			....			0.353	
		2		0.363			....			....			....			0.342	

(End)