Shrinkage Characteristics of Lodgepole Pine

by

Janice Kathryn Wiedenbeck

Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Master of Science
in
Forestry and Forest Products

APPROVED:

Christen Skaar, Chairperson

Frederick A. Kamke

Fred M. Lamb

March, 1988
Blacksburg, Virginia

Shrinkage Characteristics of Lodgepole Pine

by

Janice Kathryn Wiedenbeck

Christen Skaar, Chairperson

Forestry and Forest Products

(ABSTRACT)

This study examined shrinkage and related characteristics of two North American varieties of lodgepole pine: *Pinus contorta* var. *latifolia* and *Pinus contorta* var. *murrayana*, sampled at 10% of tree height.

For var. *murrayana*, size was the only factor that had a significant effect on specific gravity; specific gravity decreased with increasing tree diameter. For var. *latifolia*, latitude was the only factor that had a significant effect on specific gravity; in general, specific gravity increased with increasing latitude.

Conversely, specific gravity had a significant effect on radial shrinkage, the radial shrinkage-tangential shrinkage ratio, and volumetric shrinkage for both varieties.

The analysis of variance procedure indicated that the factors size, latitude, and elevation had no effect on the shrinkage of var. *latifolia*. However, for var. *murrayana*, radial shrinkage was affected by both tree size and latitude. Tangential shrinkage was also affected by latitude (increasing with increasing latitude).

Linear correlations between radial shrinkage and growth rate, longitudinal shrinkage and distance from the pith (a negative relationship), and specific gravity and growth rate were highly significant for both varieties. For var. *latifolia*, the linear association between specific gravity and heartwood percent was also significant.

For var. *murrayana,* no difference in shrinkage or specific gravity was detected between the heartwood and sapwood. For var. *latifolia,* heartwood shrank less radially and had a lower specific gravity than sapwood.

A comparison of the two varieties at their common latitudes indicated that *murrayana* trees have both higher specific gravity and shrinkage than do *latifolia* trees of the same size.

Acknowledgements

Many thanks go out to my advisor , my dear friend and roommate , and my father.

Table of Contents

List of Illustrations

List of Tables

Introduction

This study examines the shrinkage characteristics of lodgepole pine (*Pinus contorta* Dougl. ex Loud.). It is part of a decade-long research program, commissioned by the U.S. Forest Service, that is designed to provide information that will lead to improved utilization of the species in the 21st century.

Two commercially important varieties of the species are included in this study: *Pinus contorta* var. *latifolia* Engelm., and *Pinus contorta* var. *murrayana* [Grev. & Balf] Engelm.. Lodgepole pine is a western species whose potential for utilization has, to date, been largely untapped. It has an estimated total growing stock in North America of 68.6 billion cubic feet (1.943 billion m^3; Summitt amd Sliker 1980, as cited by Taylor 1982). The Lodgepole Pine Type (USDA 1965) occupies approximately 22% of all western Canadian forested land area (Koch 1987) and 10% of all commercial forest land area in the Pacific Coast and Rocky Mountain regions of the United States. There are only three timber types west of the Mississippi River in the United States that occupy more forest land area (Koch 1987).

Virtually all wood properties, shrinkage included, vary in magnitude when tested along different spatial planes with respect to the tree stem. The anisotropic shrinkage of wood can lead to a wide variety of drying defects: splitting, checking, cupping, bowing, crooking, honeycombing, casehardening, and the loosening of knots can all be attributed to this wood trait.

Knowing the approximate average degree of shrinkage of the gross wood in each of the primary planes should improve the grade and volume recovery of primary and secondary manufacturing operations. Green target sizes and finishing machine settings can be optimally determined when this information is utilized. Understanding between-species and within-species shrinkage variation can also be very helpful when making raw material procurement and end product decisions.

Koch (1987) reported that over 4,000 publications make-up the existing body of literature on lodgepole pine. The bulk of the shrinkage-related lodgepole pine research documented in the literature was performed on lumber from a single geographic source.

This research effort was designed to detect differences in radial, tangential, and longitudinal shrinkage as related to latitude, elevation, and diameter class origin. Certain relationships between shrinkage and individual tree parameters (specific gravity, growth rate, and radial location of specimen), were also explored. The test material was systematically collected from throughout the range of lodgepole pine in North America.

It is expected that the results of this research will:

1. Fill in existing gaps in the scientific characterization of lodgepole pine.
2. Furnish information that will aid in source selection for tree improvement programs (Taylor 1982).
3. Provide industry personnel with knowledge that can be used to improve procurement, processing and product decisions.

Purpose and Objectives

The purpose of this study was to measure radial, tangential, and longitudinal shrinkages (from the water-soaked to the oven-dried condition), identify variations in these measured shrinkage values, and then analyze these variations. The analysis focused on establishing the relationship between linear shrinkage and each of four tree parameters: variety, latitude, elevation, and diameter.

The following five objectives guided this research effort:

1. Make precise linear shrinkage and specific gravity measurements.
2. Analyze the variation in shrinkage as related to variety, latitude, elevation, and tree diameter.
3. Extend the analysis to include consideration of the effects of specific gravity, growth rate, tissue type (heartwood vs. sapwood), and radial position of sample, on shrinkage.
4. Factor out the effect of specific gravity to establish which parameters directly affect shrinkage.
5. Validate the study results by comparing them with the results of related research efforts.

Review of Literature

The Shrinkage - Moisture Content Relationship

Most physical properties of wood are affected by changes in moisture content. Because wood is a hygroscopic material, changes in the relative humidity and temperature of the environment lead to changes in the moisture content of wood. Dimensional instability is associated with the addition and removal of water from the wood cell walls. Water expands the microfibrillar lattice of the cell walls in proportion to the amount which has been added (Panshin and deZeeuw 1970). Shrinkage of wood occurs when water bound within the cell walls is withdrawn. This occurs after all of the water in the cell lumina has been removed. The moisture content at which the cell lumina are empty and the cell walls are still completely saturated is termed the fiber saturation point (fsp.).

Under normal conditions (in the absence of collapse), the volumetric shrinkage of wood is proportional to the weight of the water that is lost below the fiber saturation point. Shrinkage is expressed as the percentage change in linear (or cubic) dimension relative to the fully swollen condition:

$$\text{SHRINKAGE (\%)} = \frac{\text{change in dimension from swollen size}}{\text{swollen dimension}} \times 100$$

Shrinkage occurs when wood is dried initially from the green condition and when wood loses moisture due to cyclic shifts in environmental conditions (Skaar 1972).

Above fiber saturation point a form of shrinkage known as collapse may sometimes occur (Hart 1984). Tiemann (1951) proposed that collapse occurs when relatively impermeable cell cavities, filled with water, begin to dry: the removal of the water pulls the cell walls into the lumina. Hart's (1984) results suggest that the impermeability that can lead to collapse is found in two types of cells: cells which from the outset are impermeable due to the presence of impermeable parenchyma, and cells that are rendered impermeable after extractives build-up and plug pit pores.

A straight-line relationship exists between volumetric, tangential, and radial shrinkage and moisture content between approximately 18 and 6 percent moisture content (Panshin and deZeeuw 1970). At moisture contents outside this range the relationship is curvilinear. At the lower moisture contents the curve is concave downward and at the higher moisture contents it assumes a concave upward form.

The longitudinal shrinkage - moisture content relationship is inconsistent. Koehler (1946) recorded negative longitudinal shrinkage values for normal wood dried from the green condition to 12 percent moisture content. He concluded that longitudinal shrinkage from fiber saturation point (fsp.) to 12 percent moisture content is equal to approximately one-half the total longitudinal shrinkage from fsp. to the oven-dried state. Espenas (1974), in a study conducted on three softwood species, found that most of the longitudinal shrinkage occurred below 12 percent moisture content. Foulger's (1966) longitudinal shrinkage measurements on eastern white pine (*Pinus strobus* L.) yielded similar results: one-third of the samples expanded when dried from fsp. to the air-dried state, and the average longitudinal shrinkage from the green to the air-dried state was 0.06 ± 0.19

percent while the average shrinkage from the green condition to 0 percent moisture content was 0.18 ± 0.13 percent.

Shrinkage Theory

The anisotropic shrinkage of wood has been extensively researched. It is widely accepted that the ratio of volumetric, tangential, radial, and longitudinal shrinkage for normal mature wood is approximately equal to **3.0:2.0:1.0:.05**. The Wood Handbook (1987) values for the volumetric, tangential, and radial shrinkages of lodgepole pine (*Pinus contorta* Dougl. ex Loud) are:

$$s_v = 11.1\%$$

$$s_t = 6.7\%$$

$$s_r = 4.3\%$$

The ratio of these three shrinkage values, **2.6:1.6:1.0**, indicates the degree of transverse shrinkage anisotropy in lodgepole pine.

The mechanisms which control the magnitude of shrinkage in each of the primary planes of wood are not clearly understood. Numerous theories have been forwarded to explain the tranverse shrinkage anisotropy of wood. Some of these theories focus on differences at the cellular level, while others focus on differences between tissue types.

Longitudinal Shrinkage Theory

Normal wood shrinks less than 0.4% along the grain when dried from the green condition to 0% moisture content. Radial and tangential shrinkage of normal wood is ten to thirty times greater than longitudinal shrinkage. The angle of the cellulose microfibrils relative to the long axes of the wood fibers (tracheids) and gross wood is the most important determinant of longitudinal shrinkage.

Understanding the means by which water is adsorbed and desorbed by wood clarifies the relationship between microfibril angle (mfa) and shrinkage. The cellulose molecules in the cell walls are composed of both crystalline and amorphous sections. In the regions of crystallinity in which the individual cellulose strands are aligned approximately parallel to one another. The orientation of these microfibrils varies within the different layers of the cell wall. In the dominant S_2 layer of normal wood the mfa varies from 5° to 25° (Hann 1969).

X-ray diffraction studies have revealed that water is adsorbed in the non-crystalline regions of the microfibrils and on the crystallite surfaces (Hermans 1949 as cited by Boutelje 1973). As water is removed in drying, the fibrils are drawn together. The result is that the microfibrils tend to shrink predominantly in the direction perpendicular to their length-wise orientation.

The reinforced matrix model of Barber and Meylan (1964) is cited repeatedly in the literature (Boyd 1977; Koch 1972; Skaar 1972). Meylan (1968), in work done on *Pinus Jeffreyi* Grev. and Balf., produced results that support the model of Barber and Meylan. These research efforts established a curvilinear relationship between longitudinal and tangential shrinkage and the mean mfa in the S_2 layer of the cell wall. At an mfa between 20° and 30°, longitudinal shrinkage reached its minimum value. At an angle slightly greater than 45°, the longitudinal and tangential shrinkage curves intersect; at higher mfa's, shrinkage along the grain is larger than shrinkage across the grain. The crystalline microfibrils, which have a high elastic modulus, act to restrain shrinking in the direction parallel to their long axes (Barber 1968, Skaar 1972). The ratio of the effective elastic modulus of the microfibrils to the sheer modulus of the matrix (which varies with moisture content) was shown to have an effect on the magnitude of shrinkage (Barber 1968).

Anisotropic Transverse-Shrinkage Theories

The differential shrinkage of wood in the transverse plane has been the subject of much research and discussion. Several theories have been proposed to explain transverse shrinkage anisotropy. There is fairly widespread agreement that not one, but several of these theories are valid; the different mechanisms act in combination to create the 2:1 ratio of tangential to radial shrinkage. Two of the more comprehensive summaries of the various transverse-shrinkage theories are contained in Pentoney (1953) and Skaar (1972).

The ray restraint theory holds that the ray cells, whose long axes lie in the radial direction, have a moderating effect on the shrinkage of the gross wood. Measurements on isolated ray tissue yield radial shrinkage values ranging from 0.2 to 3.8 percent (McIntosh 1955; Schniewind 1959; Skaar 1972). Ray tissue exhibits not only low radial shrinkage, but also high radial stiffness (Schniewind 1959). In combination these two properties allow the rays to exert a restraining influence on the radial shrinkage of the prosenchyma tissue. The degree to which the rays contribute to the transverse-shrinkage anisotropy of the gross wood is compounded by the increase in tangential shrinkage expected as a result of Poisson's effects (Schniewind 1959; Skaar 1972). Rays exercise no significant restraining effect on the tangential movement of the gross wood; the tangential shrinkage of isolated ray tissue approximates that of summerwood (McIntosh 1955).

A few research efforts have yielded results which seemingly contradict the ray restraint theory. Pentoney (1953) cites the work of Ritter (1939) in which basswood rays were found to have a crystalline orientation very nearly parallel to the crystalline orientation found in the prosenchma cells. Skaar (1972) discusses this discrepancy and cites a similar study conducted on *Cryptomeria japonica* which revealed a crystalline orientation in the ray tissue parallel with the ray cell axes (Harada and Waldrop 1960). Boutelje (1973) cites the research results of Nakato (1958) in which the ratio of tangential to radial shrinkage was the same in tissue containing rays as it was in ray-free tissue. Fountain and Guernsey (1956) reported a negative relationship between ray volume and radial shrinkage between species. Ray tissue and ray-free tissue shrinkage values were not included in this study, nor were the results statistically analyzed.

The earlywood-latewood interaction theory proposes that the alternating bands of relatively low shrinkage earlywood and relatively high shrinkage latewood interact differently in the radial direction than do they in the tangential direction insofar as aggregate shrinkage is concerned. Tangential shrinkage of the gross wood is strongly influenced by the high potential for shrinkage of the latewood bands. The parallel bands of earlywood are much weaker than the neighboring bands of latewood, thus they are forced to shrink with the latewood in the tangential direction. In the radial direction the net shrinkage across an annual ring is approximately equal to the weighted mean radial shrinkages of the individual earlywood and latewood components which occur in series (Boutelje 1973; Hale 1957; Pentoney 1953; Skaar 1972).

In studies conducted on Doulas-fir (*Pseudotsuga mensiezii* [Mirb.] Franco) Pentoney (1953) concluded that the earlywood-latewood theory largely accounted for the differences in transverse shrinkage. He also derived a mathematical model for predicting the shrinkage of gross wood in both transverse directions based on: the shrinkage of isolated earlywood and latewood tissue, the relative earlywood and latewood volumes, and the ratio of the elastic modulus of the latewood to the elastic modulus of the earlywood.

The fibril angle variation theory accounts for transverse-shrinkage anisotropy based on observed differences in the mfa of radial and tangential walls (Frey-Wyssling 1940). Frey-Wyssling recorded radial wall mfa's that were as much as 15° greater than tangential wall mfa's. The maximum tangential shrinkage to radial shrinkage ratio (T/R) which a 15° difference in mfa's would explain is 1.11 (Pentoney 1953). Since the actual T/R for most species is closer to 2, it must be concluded that the variation in fibril angle is not the major cause of transverse-shrinkage anisotropy.

A variation on the fibril angle theory includes consideration of the localized effect of pits on fibril angle (Ritter and Mitchell 1952). The radial walls of conifer tracheids contain numerous pits while pitting on the tangential walls is scarce. The average mfa near the pits is higher because the microfibrils tend to deflect around them. Pentoney (1953) calculated the T/R ratio that would result if the radial wall was entirely covered by pits (mean radial wall mfa = 45°). In even this most extreme case the T/R ratio is only 1.42.

Frey-Wyssling (1940) proposed a second theory to explain differential transverse shrinkage which focused on the middle lamella. His theory states that all of the difference between tangential and radial shrinkage can be attributed to differences in the number of layers of middle lamella in the two directions. Frey-Wyssling's research on larch (1940) showed there to be more cross-walls in the tangential direction than in the radial direction. Quirk (1984) in a study he conducted on Douglas-fir, found the number of cross walls per unit length to be higher in the radial direction for latewood but higher in the tangential direction for earlywood. Frey-Wyssling's theory hinged on his belief that middle lamella tissue exhibits a high degree of shrinkage. He calculated a T/R ratio based on his model of approximately 2.

Kelsey (1963) predicted that the compound middle lamella serves as a deterrent to transverse shrinkage. Lignin, the major chemical constituent of the middle lamella, has a lower sorptive capacity than cellulose and is very rigid. In the radial direction the middle lamella is both thicker (Frey-Wyssling 1940) and higher in lignin content than in the tangential direction.

Ellwood and Wilcox (1962) suggested that differences in the degree to which the wood cell lumina shrink in the tangential and radial planes might account for some of the transverse-shrinkage anisotropy. From their work with old-growth redwood (*Sequoia sempervirens* [D. Don] Endl.) heartwood they concluded that the lumina shrink more tangentially than radially. Quirk's studies of Douglas-fir yielded different results: earlywood cell lumina expanded when dried while latewood lumina shrank. Conversely, Boutelje (1973) found that in Swedish pine (*Pinus silvestris*) the earlywood cell lumina shrank and the latewood lumina expanded. Skaar (1972) observed that the behavior of the lumina seems to be species dependent. In the absence of collapse it is fair to assume that the change in the size of the lumina is not significant, especially for gross wood (earlywood and latewood combined; Boutelje 1973; Skaar 1972).

Factors Affecting Shrinkage

Specific Gravity

Volumetric and radial shrinkage increase with increasing specific gravity (Boutelje 1973; Choong 1969b; Foulger 1966; Kelsey 1956; Yao 1968; Yao 1972). Markwardt and Wilson's (1935) data when plotted by Stamm and Loughborough (1942) showed a linear relationship in which the ratio of volumetric shrinkage percentage to specific gravity for fifty-two softwood species equaled 26. Kelsey (1956) found that 57 percent of the between-species variation in volumetric shrinkage for 131 Australian and Pacific Island species could be accounted for by differences in basic density. By comparison, Yao (1968), in research he conducted on loblolly pine (*Pinus taeda* L.), found that only 11 percent of the between-tree variation in volumetric shrinkage could be explained by variations in specific gravity. In the same study Yao's analysis of the relationship between specific gravity and within-tree variations in volumetric shrinkage yielded an R^2 value of 0.828.

The correlation coefficient for the relationship between specific gravity and volumetric shrinkage is lower for the corewood ($R^2 = 0.20$) than for the maturewood ($R^2 = 0.72$) for four southern pine species (Choong 1969b). For mixed wood (corewood and maturewood combined), an intermediate correlation coefficient was found ($R^2 = 0.37$). Further studies by Choong (1969a) led him to the conclusion that the presence of extractives is responsible, at least in part, for the lower correlation between shrinkage and specific gravity in the corewood. Water-soluble extractives reduce shrinkage (a discussion of this may be found later in this chapter) while water-insoluble extractives increase specific gravity.

The relationship between specific gravity and tangential shrinkage is weak (Choong 1969a; Salamon and Kozak 1968; Yao 1968). Choong's (1969a) studies of four southern yellow pine species led him to conclude that most of the variation in volumetric shinkage due to specific gravity was due to the strong correlation between radial shrinkage and specific gravity ($R^2 = 0.62$).

A straight-line relationship between the ratio of radial shrinkage and tangential shrinkage (R/T) and specific gravity has been described (Choong 1969a; Choong 1969b; Yao 1968). Choong (1969b) found that the R/T ratio for southern pine increased linearly from 0.50 to 0.97 when plotted against specific gravity. Yao's (1968) analysis indicated that radial shrinkage exceeds tangential shrinkage at high specific gravities (>0.72). The fact that latewood tends to shrink more radially than tangentially while in earlywood the reverse is true seems to validate Yao's findings.

Longitudinal shrinkage tends to decrease with increasing specific gravity within a given species (Foulger 1966; USDA 1960; Yao 1968). This relationship accounted for only 1 percent of the between-tree variation in longitudinal shrinkage in loblolly pine but it explained 26 percent of the within-tree variation (Yao 1968). The effect of juvenile wood (which had a high fibril angle) on this relationship was noted by Foulger (1966), who studied this relationship in eastern white pine. The relationship was non-existent when the entire cross-section of the tree was included in the analysis but exclusion of the twelve rings nearest the pith yielded a correlation coefficient of -0.08. Koehler (1938) found that rapidly grown southern pine wood (less than 2 rings per inch) had very low specific gravity and very high longitudinal shrinkage (≃2%; 17 times greater than normal).

Shrinkage and specific gravity seem to be strongly correlated within-trees, less strongly associated between-trees (Yao 1968), and inconsistently related between-species (Boutelje 1973; Kelsey 1956; USDA 1960). The relationship is due in large part to structural differences; thick-walled cells tend to have a higher proportion of S_2 layer than do thin-walled cells (Hale 1957). The microfibril orientation of the S_2 layer thus has a stronger influence on the shrinkage properties of thick-walled cells. The amount of wood substance has less of an influence on shrinkage than does cell structure (USDA 1960).

Koch (1972) presented one form of a commonly cited relationship:

$$\text{Volumetric Shrinkage Percentage} = (\text{M.C at Fiber Saturation}) \times (\text{Specific Gravity})$$

This relationship is relatively accurate providing the cell cavities do not change significantly is size during drying (Choong 1969b; Ellwood and Wilcox 1962; Yao 1972).

Kelsey (1956) detailed the significance of the volumetric shrinkage intersection point (the moisture content which corresponds with zero shrinkage as determined by extending the linear portion of the shrinkage-moisture content curve). She concluded that the shrinkage intersection point calculated from measurements made in the green condition, at 12 percent moisture content, and in the oven-dried state, is too high. A better method of determining the shrinkage intersection point is to base it on measurements taken from green, 12 percent, and 5 percent moisture contents.

Since shrinkage is related to specific gravity, factors that affect specific gravity can also be expected to affect shrinkage. Significant relationships exist between specific gravity and each of the following tree parameters:

1. Relative percentages of earlywood and latewood,
2. Tree height (Koch 1986; Paul et al. 1959; Taylor 1982; Yao 1972),
3. Growth rate (rings per inch; Koehler 1938; Paul et al. 1959),
4. Horizontal position in stem (Taylor 1982),

5. Water-insoluble extractive content (Choong 1969a).

Earlywood vs. Latewood

Within a given annual ring latewood (also known as summerwood) tissue shrinks more radially and tangentially but less longitudinally than earlywood (also known as springwood) tissue (Boutelje 1973; Ellwood and Wilcox 1962; Erickson 1955; Koch 1972; Quirk 1984; Schniewind 1959; USDA 1960; Yao 1968). Shrinkage potential differences between earlywood and latewood may be attributed to a combination of factors. The three most commonly cited sources of variation are: the higher specific gravity of latewood, the higher lignin content of earlywood (Boutelje 1973; Quirk 1984), and the higher microfibril angle of the S_2 layer in the earlywood of softwoods (20° to 25° vs. 4° to 8° in latewood; USDA 1960).

Much of the shrinkage variation can be accounted for by differences in the specific gravity of the two tissues. Erickson's (1955) summary of all existing data on Douglas-fir revealed a ratio of latewood specific gravity (green volume basis) to earlywood specific gravity of 2.4. The results of his own research on Douglas-fir indicated that in nearly all cases tangential shrinkage is lowest in the cell layers in the first part of the springwood, increases throughout the springwood and transition zone, and reaches a maximum in the middle of the summerwood. Boutelje (1973) calculated higher maximum volume shrinkage in Swedish pine latewood cell walls (30%) than in earlywood cell walls (27%). He also recorded differences in the fiber saturation point for the two tissue types: latewood fsp. averaged 14.1 percent moisture content while earlywood averaged only 13.4 percent.

Extractive Content

Extractives have an effect on shrinkage beyond that described earlier in the discussion of collapse. The research efforts of Nearn (1955), Salamon and Kozak (1968), and Stamm (1971) all indicate that extractives have a bulking affect on the cell wall which reduces the amount of water that can be adsorbed. As a result, fiber saturation point, radial shrinkage, and tangential shrinkage are all lowered. The effect of total extractive content on the shrinkage of Douglas-fir was found to be more significant than the effect of specific gravity (Salamon and Kozak 1968). Spalt (1979) summarized published information on a wide variety of species and concluded that woods with a high extractive content show reduced shrinkage at room temperature but may shrink more than normal during high-temperature kiln drying . Demaree and Erickson's (1976) results agreed with Spalt's; redwood cell walls became plasticized during high-temperature drying which led to increased shrinkage and collapse.

Heartwood vs. Sapwood

Most shrinkage differences that exist between heartwood and sapwood are attributable to variations in other factors that affect shrinkage. Shrinkage differences caused by differences in extractive content, horizontal variation in specific gravity, the presence of juvenile wood, growth rate and the proportion of earlywood vs. latewood, may be misinterpreted as being due solely to differences in heartwood-sapwood tissue type.

Generally speaking, heartwood shrinks less in the transverse plane than does sapwood. Most of the difference is due to the higher extractive content associated with the heartwood (Choong 1969b, Paul et al. 1959; Salamon and Kozak 1968). Paul et al., in studies performed on noble fir (*Abies procera* Rehd.), found the radial shrinkage of mixed heartwood and sapwood samples to be higher than either isolated heartwood or sapwood radial shrinkage. Longitudinal shrinkage differences between heartwood and sapwood are complicated by the profound affect of juvenile wood. Excessive longitudinal shrinkage frequently occurs close to the pith in the innermost heartwood (Cockrell 1943; Foulger 1966; USDA 1960). Outside this inner zone (which extends to the 10th ring in eastern white pine) longitudinal shrinkage is relatively constant (Foulger 1966).

Juvenile Wood

The effect of juvenile wood on longitudinal shrinkage has been the subject of much research. Juvenile wood, that wood located near the pith which is significantly different in its structure and properties than normal maturewood, tends to shrink excessively in the direction parallel to the grain (Cockrell 1943; Foulger 1966; Paul 1957; USDA 1960). In plantation-grown stock it is often associated with the wide growth rings near the pith while in suppressed trees no correlation with growth rate exists (Panshin and deZeeuw 1970). Meylan (1968) and Paul (1957) measured relatively large fibril angles in corewood samples of high longitudinal shrinkage.

The amount of juvenile wood surrounding the pith seems to vary considerably from species to species. The transition from juvenile wood may be either gradual or abrupt (Panshin and deZeeuw 1970). Cockrell (1938) recorded excessive longitudinal shrinkage (greater than 0.30 percent) in ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) in a zone that measured 3 to 6 inches in width at stump height and 1 inch in width higher in the tree. Paul (1957) found that the 2 to 3 inches nearest the pith had the highest average longitudinal shrinkage as well as the greatest variation in longitudinal shrinkage. He noted an abrupt transition between the juvenile and mature wood zones in ponderosa pine.

Growth Rate

Varied research results have been published concerning the effect of growth rate on longitudinal shrinkage. The influence of growth rate can sometimes be hard to distinguish from the effect of juvenile wood. As noted previously, the juvenile zone surrounding the pith in plantation-grown trees often is a region of fast growth (wide rings; fewer rings per inch of radius).

Koehler (1938) concluded that southern pine specimens having less than 3½ rings per inch tend to shrink in length in excess of 0.25 percent. Paul (1957) charted longitudinal shrinkage and average ring width versus distance from the pith for ponderosa pine. His graph showed that longitudinal shrinkage decreased closer to the pith than did average ring width. Cockrell (1943), Foulger (1966), and Yao (1968) in studies conducted on ponderosa pine, eastern white pine, and loblolly pine respectively, agreed that shrinkage is independent of growth rate.

Radial Position

The relationship which exists between radial position and shrinkage is not a cause-and-effect association. Radial variation in shrinkage is dependent on variations in extractive content, wood structure (juvenile wood), and specific gravity. Transverse shrinkage is lowest near the pith, increases sharpely outside the juvenile wood zone, then increases only slightly or remains steady throughout the sapwood (Choong 1969a; Cockrell 1943). The pattern of longitudinal shrinkage across the cross-sectional radius is exactly opposite the transverse shrinkage pattern (Koch 1972; Paul 1957).

Tracheid Length

Transverse shrinkage is positively related to tracheid length. Conversely, longitudinal shrinkage decreases with increasing tracheid length (Yao 1968). These relationships are predicted by the fact that the microfibril angle of the S_2 is negatively correlated with tracheid length (Panshin and deZeeuw 1970).

Lodgepole Pine Structure and Properties

Specific Gravity

The Wood Handbook (USDA 1987) lists an average specific gravity for lodgepole pine grown in the U.S. of 0.38 (green volume basis). The figure listed for Canadian stock is 0.40. Koch (1987) reported a statistically significant correlation between latitude and specific gravity. Taylor et al. (1982) failed to discover any relationship between specific gravity and latitude in a 60-tree sample of lodgepole pine in Canada.

A significant finding of Koch's research was that specific gravity decreased with increasing tree diameter. No correlation between elevation and specific gravity was found by either Koch or Taylor et al. Both research efforts reported a highly significant negative linear relationship between specific gravity and tree height.

Taylor et al's research into the variation of specific gravity with radial position showed that the relationship was dependent on sampling height. At breast-height specific gravity decreased slightly in the 10-ring zone surrounding the pith, then it increased from the corewood boundary reaching a maximum between rings 30 and 50. From this point outward there was a slight decrease in specific gravity. For samples taken from 7 meters and higher in the tree there was a constant reduction in specific gravity from the pith out to the bark.

Latifolia vs. Murrayana

Koch (1987) reported higher average specific gravity values for var. *murrayana* than for var. *latifolia.* He compared samples from common latitudes and relatively similar elevations.

Extractive Content

The Wood Handbook (USDA 1987) classifies lodgepole pine heartwood as being only slightly resistant to decay. Decay resistance is a funtion of several factors. Two of the more important of these factors are kind and quantity of extractives.

Pettersen (1984) detailed the results of solubility tests conducted on thirty-six North American softwood species. Lodgepole pine ranked 20th in total solubility (the sum of hot water and ethanol/benzene solubilities). Since hot water extracts inorganic salts and low molecular weight polysaccharides and ethanol/ benzene extracts most of the fats, resins, oils, sterols, terpenes, and inorganic materials insoluble in hot water, Pettersen's results provide a very good estimate of the extractive content of lodgepole pine relative to other softwood species.

Tracheid Length

Taylor et al. (1982) did not detect any relationship between latitude and tracheid length. However they did find that tracheid length was related to elevation; tracheid length decreased with increasing elevation. The variation in tracheid length with radial position was quite similar throughout the height of the tree with the exception of the highest sampling point. Tracheid length generally increased from the pith before reaching a maximum between rings 45 and 55 from which point it decreased slightly out to the bark.

Pathological Factors

Piirto et al. (1974) studied the effects of dwarf mistletoe (*Arceuthobium americanum* Nutt. ex. Engelm.) on certain physical properties of lodgepole pine. A 1964 survey by Gill and Hawksworth revealed that one-third to one-half of the commercial lodgepole pine in the Rocky Mountain states was affected by dwarf mistletoe.

Infected lodgepole pine wood was 10 percent higher in specific gravity than wood from non-infected trees (Piirto et al. 1974). The same study found infected wood to have a higher extractive content (3x), higher longitudinal shrinkage, shorter tracheid length (0.7x), and larger microfibril angle (2x) than wood from trees not infected by dwarf mistletoe.

Material and Methods

Material

Species Occurrence

The species of interest in this study, lodgepole pine, *Pinus contorta* Dougl. ex Loud., is made up of four varieties. Only two of these varieties, *Pinus contorta* var. *latifolia* Engelm. and *Pinus contorta* var. *murrayana* [Grev. & Balf.] Engelm., are included in the exhaustive U.S. Forest Service study of the species (Koch 1985), of which this research is a part. The other two varieties, *Pinus contorta* var. *contorta* and *Pinus contorta* var. *bolanderi*, collectively known as shore pine, are much more limited in their occurrence.

Lodgepole pine can be found as far north as southeastern Alaska and the Yukon Territory of Canada (latitude = 64° N.) and as far south as Baja California (latitude = 31° N). The eastern extreme of its occurrence is in the Black Hills of South Dakota (USDA 1965). The inland varieties (var. *latifolia* and var.*murrayana*) occur at elevations between 1,500 and 11,500 feet. *Pinus contorta* var. *latifolia* grows in the Rockies while *Pinus conotorta* var. *murrayana* is native to the Cascade, Blue and Sierra-Nevada moutain ranges (Harlow et al. 1979). An intolerant species, it may occur in either pure, even-aged stands or in mixed stands with ponderosa pine, Douglas-fir, western white pine and other minor species (Harlow et al. 1979; USDA 1965).

Lodgepole pine is a major timber species in the "Canadian Life Zone" (USDA 1965). Volume estimates of the lodgepole pine resource in North America indicate the total growing stock is approximately 68.6 billion cubic feet (1.943 billion m^3), 66% of which is located in Canada (Taylor et al. 1982). In the United States the volume of lodgepole pine timber is estimated to be 5.9 billion cubic feet (Koch 1987).

The Lodgepole Pine Type (Type 218 in the U.S. Forest Service classification system; USDA 1965) occupies 20 million hectares (49.4 million acres) in Canada which is equal to approximately 22% of all western Canadian forested land area (Koch 1987). In the United States approximately 10% of Pacific Coast and Rocky Mountain commercial forest land area (5.25 million hectares or 12.9 million acres) is covered by the Lodgepole Pine Type.

Tree Selection

Samples for this research effort were collected from natural, unthinned stands of lodgepole pine. Collection zones for var. *latifolia* were located between 40 and 60 degrees north latitude at 2.5 degree intervals. Five of these latitudinal collection zones were located in Canada (50°, 52.5°, 55°, 57.5°, and 60° N.). At each of the nine latitudes, nine typical stands were identified. There was a 10° variation in the longitudinal origin of these nine stands per latitude. The stands were ranked according to their elevation. These relative rankings were used to segregate the stands into three elevational categories: high, medium, and low (three stands per elevation). In general, the elevation of the "middle-elevation" stands decreased with increasing latitude; for var. *latifolia* the greatest variation in the elevations of the sample population occurred at intermediate latitudes. From each of these nine stands three representative trees were selected, one per diameter class (diameter classifications were 3, 6, and 9 inches at d.b.h.). Every effort was made to select only trees that were free of insects and diseases (Koch 1987). This sampling scheme yielded a total of 243 *latifolia* trees: 9 latitudes x 9 stands per latitude (3 stands per each of 3 elevations) x 3 diameters per stand.

Murrayana trees were sampled at four latitudes in the United States (37.5°, 40°, 42.5°, and 45° N.). Sampling was performed on mid-elevation stands only. The same three diameter classes sampled for var. *latifolia* were sampled for var. *murrayana* . Var. *murrayana* trees were sampled at only one longitude per latitude. The total number of *murrayana* trees sampled in this investigation was 36: 4 latitudes x 3 stands per latitude (1 elevation with 3 replications) x 3 diameters per stand. Little's (1971) range map of lodgepole pine, presented by Koch (1987) with this studies' sampling points and lines superimposed, is displayed in Figure 1.

The experimental design detailed in the preceding paragraphs focuses on var. *latifolia* (87% of the 279 trees sampled). This percentage reflects the fact that var. *latifolia* is considerably more widespread in North America than is var. *murrayana.* No attempt was made to adjust sampling intensity so as to reflect the relative volume distribution of lodgepole pine in the various latitude, elevation and diameter classes. Because no such adjustments were made, the "average" shrinkage values obtained in this research effort cannot be considered to be true species' averages.

Sample Preparation

The material used in this study was cut from the trunks of the selected trees at a height corresponding to 10% of the total tree height (Hofmann 1986). It was received at Virginia Tech in the form of 6 inch long roundwood sections. Each section was endcoated by the U.S. Forest Service prior to shipment to retard moisture movement. The var. *latifolia* samples were not labelled as to

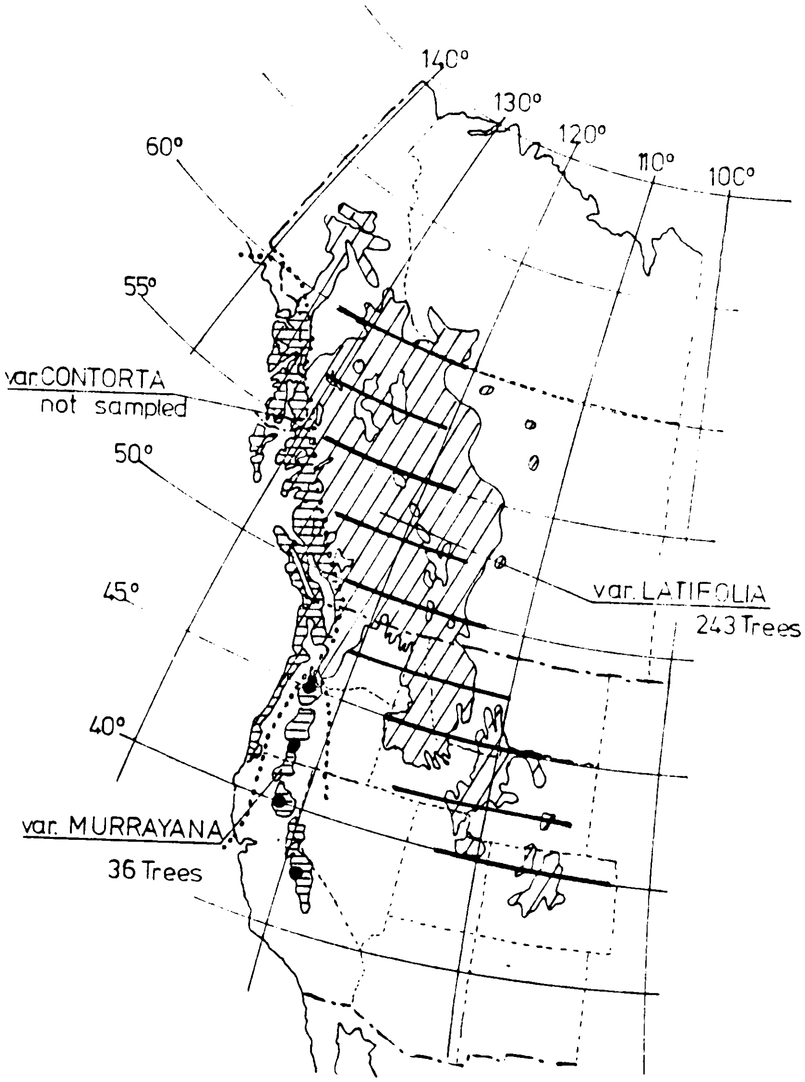

Figure 1. Little's Range Map With Sampling Points Superimposed (Koch 1987)

their longitudinal origin. Permeability tests conducted on samples cut from these same sections in 1986 removed the protective coating from one end of each section. The sections were stored indoors at Virginia Tech in an non-air conditioned, heated room in the corrugated containers in which they had been shipped.

The transverse shrinkage specimens were cut from cross-sectional discs which ranged in thickness from 0.4 to 0.8 in. Kass (1965) proposed that the optimum length along the grain for radial and tangential shrinkage specimens is two times the tracheid length (lodgepole pine tracheid length = .12 in.; Taylor et al. 1982). Samples of this length would allow for the majority of the cells' lumina to be exposed, minimizing the magnitude of the moisture gradients that arise as a result of non-uniform drying. The disc thickness was somewhat greater than the optimum thickness (.24 in.) due to machine limitations.

Pie-shaped pieces extending from the pith to the outermost edge of the wood were cut from sections of the discs that were free of compression wood and knots. These samples were used for combination (sapwood and heartwood) radial shrinkage measurements and for tangential shrinkage measurements of the sapwood. The pieces were sanded to create flat, square measurement surfaces at each of four measurement points. The radial measurement points were located near the pith (at a point 1 to 2 annual rings in from the pith; 0.14 inches from the pith on average), and at a position on the outer edge of the wood. Thus, the size of these samples in the radial direction was just slightly less than the tree's radius. The tangential measurement points were located on either side of the pie-shaped piece, near its periphery, in the most recently formed sapwood (Figure 2). The sample sizes in the tangential direction were approximately 1, 1.5, and 2 inches for the 3, 6, and 9 inch diameter trees, respectively. The samples were carefully selected so as to avoid knot tissue and compression wood. The isolation of the samples was totally random with regards to the cardinal orientation of the tree.

In addition to the transverse shrinkage samples described in the preceding paragraph, samples were cut from all of the medium-elevation, 9-inch roundwood sections for use in a study of isolated

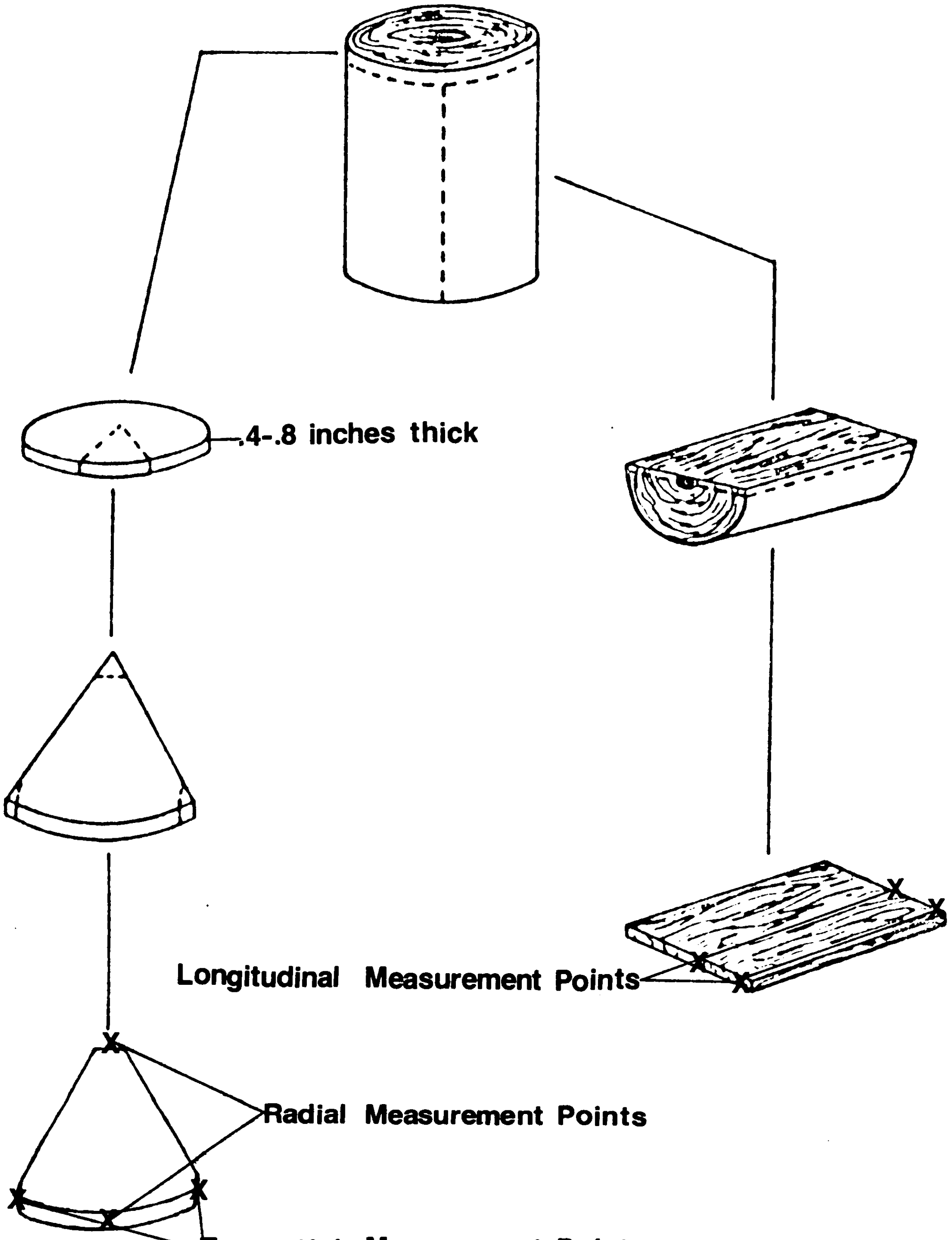

Figure 2. Shrinkage Measurement Points

heartwood and sapwood shrinkages. The boundary between the heartwood and sapwood was located based on color variation. Pie-shaped pieces were again cut. The bandsaw was then used to separate the heartwood and sapwood. This created samples that were triangular in shape, in the case of the heartwood sections, and shaped like the outer one-third of a piece of pie, in the case of the sapwood sections. The tangential measurement points on the sapwood samples were located in the most recently formed sapwood. Likewise, the tangential measurement points for the heartwood were located in the most recently formed heartwood, very near the heartwood-sapwood boundary. Radial shrinkage measurements for the heartwood included the entire heartwood radius save for the 0.14 inches that were sanded off next to the pith. Radial shrinkage for the sapwood was calculated based on the difference between the radial shrinkage of the combined heartwood-sapwood samples and the heartwood only samples; the relative percentage of heartwood and sapwood in the combined sample was accounted for in the calculation.

Longitudinal shrinkage measurements were made on quarter-sawn samples that averaged approximately 4 inches along the grain. The samples included the pith and cut across the entire diameter of the tree. They were sawn as thin as possible so as to minimize the stresses which occur as a result of uneven drying. Their average thickness was on the order of 0.125 inches. Two longitudinal shrinkage measurements, one .25 inches rom the pith (hereafter referred to as the corewood measurement), and the other .25 inches from the outer wood surface (designated hereafter as the maturewood measurement), were made on the 3 and 6 inch diameter specimens. In addition to the corewood and maturewood measurements a third shrinkage measurement, located approximately 2.25 inches from the pith (midway between the other two), was made on the 9 inch specimens. Measurements were taken only on straight-grained, knot-free material. The cardinal orientation of the samples was unknown.

In total, 1326 shrinkage values were obtained in this research effort. The measurement design is summarized in Table 1.

Table 1. Shrinkage Measurement Scheme

	Number of Measurements Taken					
	Variety *Latifolia*			Variety *Murrayana*		
Measurement	3″	6″	9″	3″	6″	9″
Radial (combined heartwood-sapwood)	81	81	81	12	12	12
Radial (heartwood)			27[1]			12
Tangential (sapwood)	81	81	108[2]	12	12	24[2]
Tangential (heartwood)			27[1]			12
Longitudinal (.25″ from pith)	81	81	81	12	12	12
Longitudinal (.25″ inside bark)	81	81	81	12	12	12
Longitudinal (2.25″ from pith)			81			12

1 - Only specimens from middle elevation trees were included in measurement.

2 - Tangential sapwood measurements were taken on both the pie-shaped samples and the heartwood-sapwood separation samples.

Methods

Measurement Instruments and Accuracy

The shrinkage samples were measured with a stand mounted dial-guage to the nearest 0.001 inch (Figure 3). The accuracy of the measurements varied by sample and measurement direction, but in no case did the accuracy fall below ±0.125%. Measurement precision, determined by taking repeat measurements on 20% of the samples, averaged ±0.0015 inches. Sample weights were determined to the nearest .01 grams. For the 3-inch samples this represented an accuracy of approximately ±0.3%. For the larger (and heavier) samples the accuracy met or exceeded the level set forth in the ASTM Standard Methods D 143-52 (1972) Designation for small, clear specimens of timber: ±0.2%.

Experimental Procedure

The samples were measured and weighed prior to being immersed in water. Schniewind and Kersavage (1962) concluded that the rate of resoaking did not significantly affect "residual" shrinkage (shrinkage of previously air-dried specimens). After soaking for a period of about one week they were reweighed. These weights were compared with the air-dried weights (from which oven-dried estimates had been calculated) to insure that a moisture content of at least 35% had been reached. The green volume of each of the transverse shrinkage specimens was measured using the water immersion method (ASTM 1972; Smith 1961).

After the swollen dimensions were determined the samples were placed for two days in a closed chamber to maintain high humidity conditions in order to minimize checking (Fountain and

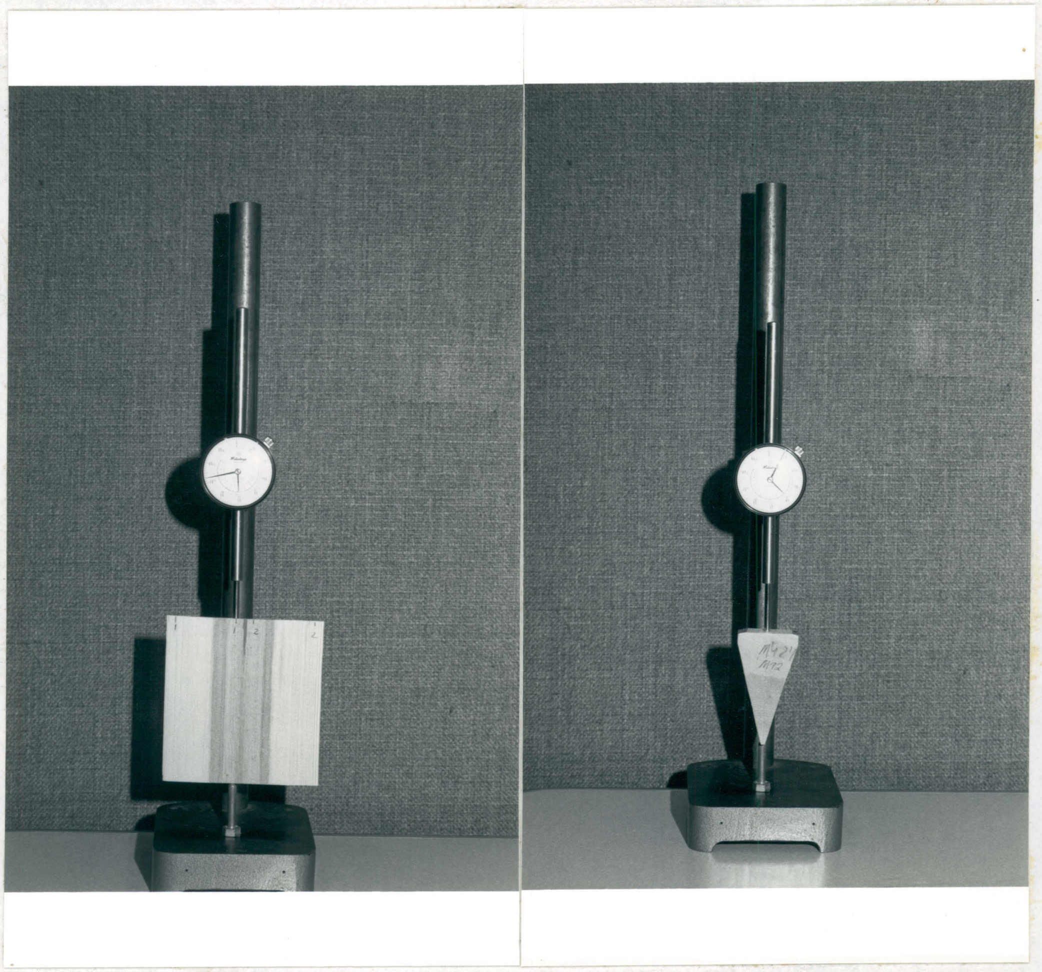

Figure 3. Dial Guage Used For Shrinkage Measurements

Guernsey 1956). The open-piled samples were then exposed to room conditions as per ASTM Standard D 143-52 (1972) until they reached approximately 12% moisture content. They were then put in the oven (longitudinal samples were stacked and stickered) and dried at 103° ± 2° C. (ASTM 1972). The oven-dried condition was reached in 15 to 20 hours (depending on the number and type of samples in the batch).

Each oven-dried sample was weighed within seconds of being removed from the hot oven. After being weighed the samples were placed in plastic bags. The bags, in turn, were placed in a desiccator until the samples cooled to room temperature. The final linear measurements were taken on the cooled specimens. Kelsey and Kingston (1953) proposed this procedure after their research indicated that thermal expansion has a significant effect on the oven-dry measurements.

Secondary Data Collection

The oven-dried samples were used to collect the following data:

1. Central angle of transverse (pie-shaped) samples,
2. Heartwood-sapwood percentages,
3. Growth rate (rings per inch),
4. Location of longitudinal shrinkage measurement points (rings from pith),

Knowledge of the central angle on the transverse samples and the amount of wood sanded off in forming the radial measurement faces provided the information necessary to correct the tangential shrinkage measurements for growth ring curvature. Kelsey and Kingston (1953) derived the applicable correction equation:

$$t = \frac{TL}{R\theta} - \frac{rL}{R\theta} + r$$

where:

t = true tangential shrinkage (%)

r = true radial shrinkage (%)

T = measured tangential shrinkage (%)

L = tangential dimension at moisture content M_0

R = radius of curvature of growth rings at moisture content M_0

θ = the "central angle"

Analysis Framework

The sampling design set forth by P. Koch, the chief investigator and administrator of this decade-long lodgepole pine research program, was intended to establish the following relationships (as stated by Koch, 1987):

> Tree data will primarily be correlated with diameter at breast height outside bark (d.b.h.), and with elevational, latitudinal, and longitudinal zones. Also, within-tree variation in properties with height and radial position will be determined. Properties of variety *latifolia* and those of *murrayana* will be compared for trees in latitudinal zones common to both varieties.

In this particular study the longitudinal origin of the samples was not differentiated. Likewise, within-tree variation in shrinkage with tree height was not explored (the research material all came from approximately 10% of tree height). However, within-tree variation in shrinkage with growth rate, tissue type (heartwood vs. sapwood), radial position, and specific gravity, were investigated.

Specific gravity was computed on the oven-dry weight, green volume basis. Linear shrinkages were computed as the percentage dimensional change from the fully swollen condition. Volumetric shrinkage figures were derived for each of the 279 trees using Skaar's (1972) simplification of Greenhill's (1936) equation:

$$S_V \simeq S_R + S_T - 0.01 S_R S_T$$

Since the longitudinal shrinkage measurements were made on different samples than were the transverse measurements S_L was not included in the calculation of volumetric shrinkage used in the analysis of variance procedure. S_L was included in the calculation that is reflected in the summary statistics.

The statistical procedure used in testing var. *latifolia* for differences in shrinkage as affected by variations in latitude, elevation, and diameter was a three-factor, random effects model ANOVA. The three factors were considered to be random because the intent of the analysis was to make generalizations based on the results.

For var. *murrayana* the statistical test used was a two-factor, random effects model ANOVA; elevation was not a factor in this analysis.

In testing for differences in shrinkage between the two varieties, a three-factor, mixed effects model ANOVA was used. The fixed factor in this case was the variety. The random factors were latitude (the three common latitudes - 40°, 42.5°, and 45° - represented three levels for this factor), and diameter.

Table 2 lists all of the factors and interactions together with their associated degrees of freedom, for each of the three ANOVAS. The test statistics used were found in Zar (1984). Their validity was checked using expected mean squares.

Simple regression analysis provided information on the functional dependency of shrinkage on specific gravity. Heartwood-sapwood shrinkage differences were tested for using a two-sample t-test. Scatter plots and multiple correlation analyses were used to explain the relationships between shrinkage and growth rate and radial position. Analysis of covariance and partial correlation analysis were used to distinguish the degree of influence and association between shrinkage and various other independent variables (factors) by controlling the effects of specific gravity (Boutelje 1973; Schroeder 1972; Yao 1972).

Table 2. ANOVA Layout

A. Variety *Latifolia*

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

C. *Latifolia-Murrayana* Comparison

Source	*df*
VAR	1
LAT	2
DIA	2
VAR x LAT	2
VAR x DIA	2
LAT x DIA	4
VAR x LAT x DIA	4
ERROR (between tree)	36

B. Variety *Murrayana*

Source	*df*
LAT	3
DIA	2
LAT x DIA	6
ERROR (between tree)	24

Results and Discussion

In this chapter, the experimental results will be discussed in the following order:

1. Var. *murrayana* results,
2. Var. *latifolia* results,
3. Heartwood - sapwood comparison results.
4. *Latifolia* - *murrayana* comparison results,

Within each of these sub-sections, the summary statistics are presented first, followed by the analysis of variance (or t-test) test results. Multiple comparison tests and linear associations are included in the var. *murrayana* and var. *latifolia* presentations.

All of the shrinkage values given are based on the change in dimension from the fully swollen to the oven-dried condition. Specific gravity was calculated using the oven-dried weight and fully swollen volume of the samples. Throughout the results presentation the following naming conventions will be used:

- S_{LC} or the longitudinal shrinkage of the corewood, refers to the longitudinal shrinkage measurement that was taken 0.25″ from the pith.

- S_{LM} or the longitudinal shrinkage of the maturewood, refers to the longitudinal shrinkage measurement that was taken 0.25″ inside the bark.
- S_{V1} refers to the volumetric shrinkage figure calculated using the equation that includes longitudinal shrinkage: $S_{V1} = S_{LM} + S_R + S_T - (0.01)(S_R)(S_T)$
- S_{V2} refers to the volumetric shrinkage figure calculated using the equation that neglects longitudinal shrinkage: $S_{V2} = S_R + S_T - (0.01)(S_R)(S_T)$

S_{LM} , rather than S_{LC}, was used in the calculation of S_{V1} in order to avoid the inordinately high longitudinal shrinkages which might be expected in the core region due to the presence of juvenile wood.

The tangential shrinkage of the sapwood and the radial shrinkage of the mixed wood (combined heartwood and sapwood) were used in the calculation of volumetric shrinkage. Obtaining "combined" heartwood and sapwood tangential shrinkage measurements would have required taking two separate measurements on each sample. This was done on a small subset of samples (27, 9-inch *latifolia* samples and 12, 9-inch *murrayana* samples). The results, which are presented in a subsequent section of this chapter, indicate that no difference exists between the sapwood and heartwood mean tangential shrinkage values, thus, it is not statistically incorrect to use the sapwood figure in these calculations and tests.

Variety Murrayana

Var. Murrayana Summary Statistics

Table 3 presents the summary statistics for var. *murrayana.* Four longitudinal-maturewood shrinkage observations and thirteen longitudinal-corewood observations were missing. Slightly more than one-half of the missing observations were 3″ and 6″ samples which bowed and crooked severely in the drying process such that the oven-dry measurements reflected the presence of the drying defect rather than the actual degree of shortening in the longitudinal direction. The other observations which are missing are cases in which knots were present on both sides of the pith such that no clear wood section could be isolated for the measurement.

The average volumetric (S_{vl}) and radial shrinkages for the thirty-six *murrayana* specimens were 12.531% and 4.845%, respecitively. The average tangential shrinkage was 7.801%; this is the corrected value which includes the growth ring curvature adjustment. The uncorrected average tangential shrinkage value was 7.693%. These values are approximately thirteen percent greater than the values given in the Wood Handbook (1987) for lodgepole pine. The volumetric, tangential, and radial shrinkage ratio, **2.6:1.6:1.0** is the same as that cited in the Wood Handbook. It is unclear if the Wood Handbook values are for a given variety of lodgepole pine or if they are averages for the entire species.

The average specific gravity measured for var. *murrayana* in this study was 0.419. This value is somewhat lower than the value cited by Koch (1987); he reported an average value of 0.451 for *murrayana* trees from 40.0°, 42.5°, and 45.0° N. latitudes. Koch's specific gravity value was based on measurements made on stemwood samples from several different tree heights.

Table 3. Variety Murrayana: Summary Statistics

	Summary Statistics			
Measurement[1]	Sample Size	Mean (%)	Std. Dev.	Coeff. of Var.
S_R (mixed wood)	36	4.845	0.905	18.7
S_T (sapwood)	36	7.801	1.070	13.7
S_R/S_T	36	0.629	0.126	20.0
S_{LC}	23	1.109	1.298	117.0
S_{LM}	32	0.243	0.303	125.2
S_{V1}	32	12.531	1.388	11.1
S_{V2}	36	12.266	1.462	11.9
G	36	0.419	0.054	12.9

1 - S_R = radial shrinkage; S_T = tangential shrinkage; S_{LC} = longitudinal, corewood shrinkage; S_{LM} = longitudinal, maturewood shrinkage; S_{V1} = volumetric shrinkage (including longitudinal shrinkage component); S_{V2} = volumetric shrinkage (does not include longitudinal shrinkage component); G = specific gravity.

The coefficients of variation for each of the measurements are relatively similar with the exception of the two longitudinal measurements. The variation in the longitudinal-corewood values might be attributed to the presence of juvenile wood (Cockrell 1943; Foulger 1966; Paul 1957; USDA 1960). This assumption cannot be substantiated however, since no effort was made to identify and isolate the juvenile wood in this study. Much of the variation is probably due to measurement error. While the precision of the measurements was the same regardless of measurement direction, a .0015″ error in the measurement of the longitudinal dimension would cause the shrinkage value to be 15 to 25 percent inaccurate. The same .0015″ measurement error made in the radial direction would yield a value that would be only 2 to 4 percent inaccurate.

Var. Murrayana Analysis of Variance and Covariance

Table 4 presents the results of the analysis of variance and covariance tests that were performed on the *murrayana* data. The analysis of variance tests indicated that latitude has a significant effect ($0.01<P<0.05$) on S_R ,S_T ,S_{LC} , and S_{V2}. Additionally, size has a highly significant ($P<0.01$) effect on S_R , and the interaction between size and latitude has a highly significant effect on S_{LM}.

The results of the analysis of variance test conducted with specific gravity as the dependent variable indicate that size (tree diameter) has a significant effect on specific gravity but latitude is not a significant factor. A similar variation of lodgepole pine specific gravity with size was found by Koch (1987). Taylor et al.'s (1982) research into the sources of variation of lodgepole pine specific gravity failed to show any relationship between specific gravity and latitude while Koch's study did note a significant specific gravity - latitude relationship.

In the analysis of covariance procedure specific gravity was included as an independent variable in the model. In this analysis the variation in shrinkage associated with specific gravity is eliminated thus providing a more precise estimate of the degree of influence of each of the other factors of in-

Table 4. Variety Murrayana: Analysis of Variance and Covariance

Analysis of Variance and Covariance

F-Values[1] [2]

	S_R		S_T		S_{LC}	
Source	Var.	Cov.	Var.	Cov.	Var.	Cov.
(G)	—	10.75 **	—	0.29 NS	—	0.14 NS
SIZE	11.96 **	N/A[3]	1.57 NS	N/A	0.32 NS	0.33 NS
LAT	4.61 *	3.65 NS	5.24 *	4.45 NS	5.71 *	5.14 NS
SIZE X LAT	0.50 NS	0.17 NS	1.23 NS	1.22 NS	0.93 NS	0.85 NS

F-Values

	S_{LM}		S_{V2}		G
Source	Var.	Cov.	Var.	Cov.	Var.
G	—	11.32 **	—	12.43 **	—
SIZE	2.05 NS	N/A	1.52 NS	N/A	13.97 **
LAT	1.05 NS	0.95 NS	6.82 *	4.51 NS	3.69 NS
SIZE X LAT	21.42 **	29.29**	1.04 NS	0.86 NS	0.72 NS

1 - ** = significant at the 0.01 level; * = significant at the 0.05 level; NS = not significant.

2 - S_R = radial shrinkage; S_T = tangential shrinkage; S_{LC} = longitudinal, corewood shrinkage; S_{LM} = longitudinal, maturewood shrinkage; S_{V2} = volumetric shrinkage (does not include the longitudinal shrinkage component); G = specific gravity.

3 - The analysis of covariance cannot be used to make adjustments for the effect of specific gravity in studying the size factor because specific gravity varies significantly with size.

terest. The analysis of covariance also indicates whether the influence of the covariate (specific gravity) has a significant effect on the variation of the dependent variable (shrinkage). In the cases of radial, longitudinal-maturewood, and volumetric shrinkages, differences in specific gravity have a highly significant effect on the shrinkage values. These results agree with those of Boutelje (1973), Choong (1969b), Foulger (1966), and Yao (1968, 1972).

The analysis of covariance revealed that specific gravity does not have a significant influence on tangential and longitudinal-corewood shrinkage. A lack of significance between tangential shrinkage and specific gravity was previously reported by Choong (1969a), Salamon and Kozak (1968), and Yao (1968).

When the variation due to specific gravity is isolated by means of covariance analysis, the mean shrinkage differences previously associated with different latitudes disappear, i.e. much of the apparent influence of latitude on shrinkage (radial, tangential, longitudinal-corewood, and volumetric) is due to variations in specific gravity. The variation in specific gravity might be due to chance or due a significant association between specific gravity and latitude. The results of the analysis of variance test, cited earlier, indicated that latitude does not have a significant effect on specific gravity. The P-value (the probability that the difference between the specific gravity means could be due strictly to chance) associated with that analysis of variance result was 0.08...just slightly above the 0.05 significance level used in these tests. In the analysis of covariance specific gravity variations were controlled so that the effects of size and latitude on shrinkage would not be masked. Since the effect of latitude on each of four shrinkage properties was significant before adjustment but not after, and the P-value obtained in the analysis of variance test was quite low, the best interpretation seems to be that latitudinal variations in specific gravity probably do exist.

The influence of the interaction between size (diameter) and latitude on the longitudinal shrinkage of the maturewood remained highly significant in the analysis of covariance. Thus, one can conclude that the effect of size on longitudinal-maturewood shrinkage varies from latitude to latitude.

The analysis of covariance cannot be used to distinguish whether size influences radial shrinkage independent of specific gravity because specific gravity is itself strongly influenced by size. The slope of the linear relationship between radial shrinkage and specific gravity is quite different for the 3″, 6″, and 9″ trees. Since covariance solutions are based on group adjustments employing the overall mean, applying these adjustments yields inaccurate results when there is this kind of interaction between the covariate (specific gravity) and the class variable (size; Kleinbaum and Kupper 1978).

Var. Murrayana Multiple Comparisons

The results of the multiple comparison tests performed on those factors which were found to be significant in the analysis of variance procedure are contained in Table 5. Duncan's multiple range test was used to separate the means for S_R, S_T, S_{V2} , and G. The Tukey-Kramer method was used for mean separation in the case of S_{LC} which had 13 missing observations.

The letter A is assigned to the groups which have the highest non-significantly different (P<0.05) means. Similarly, the letter B is assigned to the levels of a factor which have means that are intermediate in magnitude, etc. This assignment scheme makes it easy to look at the multiple comparison output and spot trends.

The analysis of variance procedure indicated that mean radial shrinkage and mean specific gravity are both affected by tree diameter at d.b.h. A comparison of the group means indicates that both radial shrinkage percent and specific gravity tend to decrease with increasing tree diameter. The difference between the mean radial shrinkages recorded for the 3″ and 6″ trees was not large enough to be detected by the Duncan test at the 0.05 level of significance. The mean radial shrinkage for the 9″ population was found to be significantly different from the other two means.

Table 5. Variety Murrayana: Analysis of Significant Factors

Multiple Comparisons[1] [2]

	S_R		G	
Size	Mean(%)	Grp	Mean	Grp
3″	5.239	A	0.458	A
6″	5.091	A	0.421	B
9″	4.206	B	0.379	C

	S_R		S_T		S_{LC}		S_{V2}	
Lat	Mean(%)	Grp	Mean(%)	Grp	Mean(%)	Grp	Mean(%)	Grp
37.5°	4.291	B	7.033	C	1.542	A,B,C	11.020	C
40.0°	5.080	A,B	7.940	A,B	2.414	A,B	12.617	A,B
42.5°	4.821	A,B	7.498	B,C	0.291	A,C	11.954	B,C
45.0°	5.190	A	8.735	A	0.623	A,C	13.474	A

1 - Duncan's multiple range test was used for the comparison of means for S_R, S_T, S_{V2}, and G. The Tukey-Kramer method was used for S_{LC} since it had an unbalanced data set.

2 - Means with the same letter are not significantly different at the 0.05 level.

The Duncan test, performed at the 0.05 level, determined that the mean specific gravities for each of the three diameter groups were significantly different from one another. The 3″ trees in the sample had an average specific gravity of 0.458, the 6″ trees averaged 0.421 and the 9″ trees had a mean specific gravity of 0.379. These results agree with those reported by Koch (1987) for var. *latifolia*: "The most important finding of this research is that stemwood specific gravity of *latifolia* trees ... decreased with increasing d.b.h."

Radial shrinkage, tangential shrinkage, longitudinal-corewood shrinkage, and volumetric shrinkage (S_{V1}) were all found to be affected by latitude as indicated by the analysis of variance test performed at the 0.05 level of significance. The multiple comparison test results indicate that only radial shrinkage varies consistently with latitude. Mean radial shrinkage increases with increasing latitude.

Var. Murrayana Linear Associations

Significant linear relationships between various tree parameters and several different shrinkage properties are listed in Table 6. Of the eight specific gravity-shrinkage regression equations investigated, four were found to be highly significant (S_R, $S_{R/T}$, S_{V1}, and S_{V2}).

The significance of the relationship between specific gravity and radial shrinkage has already been discussed (in the paragraphs which address the analysis of covariance results). Fifty-seven percent of the variation in radial shrinkage is explained by its linear association with specific gravity. A graph of the relationship between S_{V1} and G is presented in Figure 4; thirty-nine percent of the variation in volumetric shrinkage is accounted for by this regression expression.

The straight-line relationship between S_R/S_T and G has been noted by others (Choong 1969a; Choong 1969b; Yao 1968). Yao (1968) determined that radial shrinkage exceeds tangential shrinkage at high specific gravities (>0.72). The regression equation arrived at in this study for lodgepole pine predicts that S_R would exceed S_T at specific gravities greater than 0.66. The

Table 6. Variety Murrayana: Linear Associations

Regression Equations[1]

Shrinkage Property	Regression Equation	R^2
Radial (mixed wood)	$S_R = 12.525G - 0.407$	.5672
Tangential (sapwood)	—— NS ——	—
Radial/Tangential	$S_{R/T} = 1.539G - 0.016$	.4420
Longitudinal (corewood)	—— NS ——	—
Longitudinal (maturewood)	—— NS ——	—
Long. Total (core + mature)	—— NS ——	—
Volumetric (incl. S_L)	$S_{V1} = 17.897G + 5.195$	.3887
Volumetric (excl. S_L)	$S_{V2} = 12.603G + 6.981$	.2201

Correlations[2] [3]

Variables	Simple Correlation Coefficients	Partial[4] Correlation Coefficients
S_R X Rings Per Inch	.6099 (**)	.0825 (NS)
$S_{R/T}$ X Rings Per Inch	.6573 (**)	.1801 (NS)
$S_{L(maturewood)}$ X Rings From Pith	-.3754 (*)	—
G X Rings Per Inch	.6113 (**)	—

1 - All of the regression equations given are highly significant ($P<0.01$).

2 - The format of this part of the table was borrowed from Yao (Table 2; 1972).

3 - ** = significant at the 0.01 level, * = significant at the 0.05 level, NS = not significant.

4 - The partial correlation coefficient measures the degree of linear association between the given variables after controlling for the effects of specific gravity.

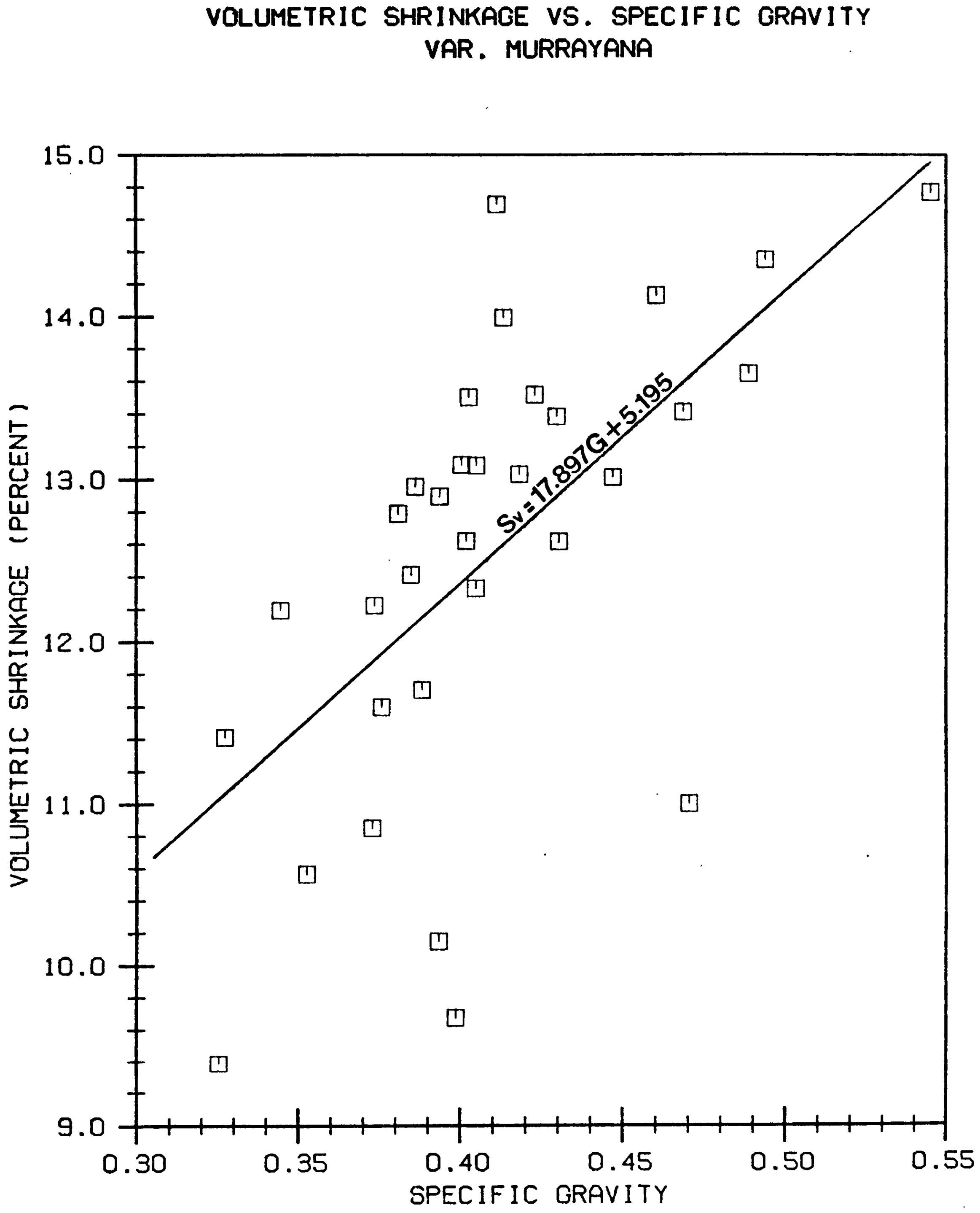

Figure 4. Volumetric Shrinkage Vs. Specific Gravity For Var. Murrayana

scatterplot of S_R/S_T vs. G with the line-of-best-fit drawn through the 36 points is given in Figure 5.

Linear correlations involving the tree parameters growth rate, heartwood percentage, and radial position of measurement (rings from pith), were investigated. Radial shrinkage and the radial shrinkage/tangential shrinkage ratio were both found to be significantly correlated with growth rate (as measured by rings per inch). A highly significant straight-line relationship between specific gravity and growth rate rate was also discovered. Paul et al. (1959) noted a similar correlation between growth rate and specific gravity in a study they conducted on noble fir.

Because the correlation between growth rate and specific gravity is highly significant as are the linear regressions between S_R and G and $S_{R/T}$ and G, a partial correlation analysis was conducted. This type of analysis is designed to assess the degree of correlation between two variables after controlling for the effects of a third variable; in this case the third variable was specific gravity. The partial correlations between radial shrinkage and growth rate and $S_{R/T}$ and growth rate both were found to be non-significant.

The linear association between longitudinal-maturewood shrinkage and rings from pith is significant at the 0.05 level. A test of the degree of correlation between longitudinal-maturewood shrinkage and growth rate proved to be non-significant. No significant correlations were found between longitudinal-corewood shrinkage and either rings from pith or growth rate. These results are very similar to those of Cockrell (1943; ponderosa pine). In Figure 6 longitudinal-maturewood and longitudinal-corewood shrinkages are graphed together on the Y-axis and rings from pith is graphed on the X-axis. Figure 7 is similar to Figure 6 except that only 9″ diameter trees are included; also, an additional longitudinal shrinkage measurement taken at a distance of 2.25″ from the pith is included. Both linear and quadratic least-squares regression curves are drawn in on both figures. These two plots show the effect on longitudinal shrinkage of radial variations in extractive content, specific gravity, tracheid length, and wood structure (eg. juvenile wood vs. normal wood).

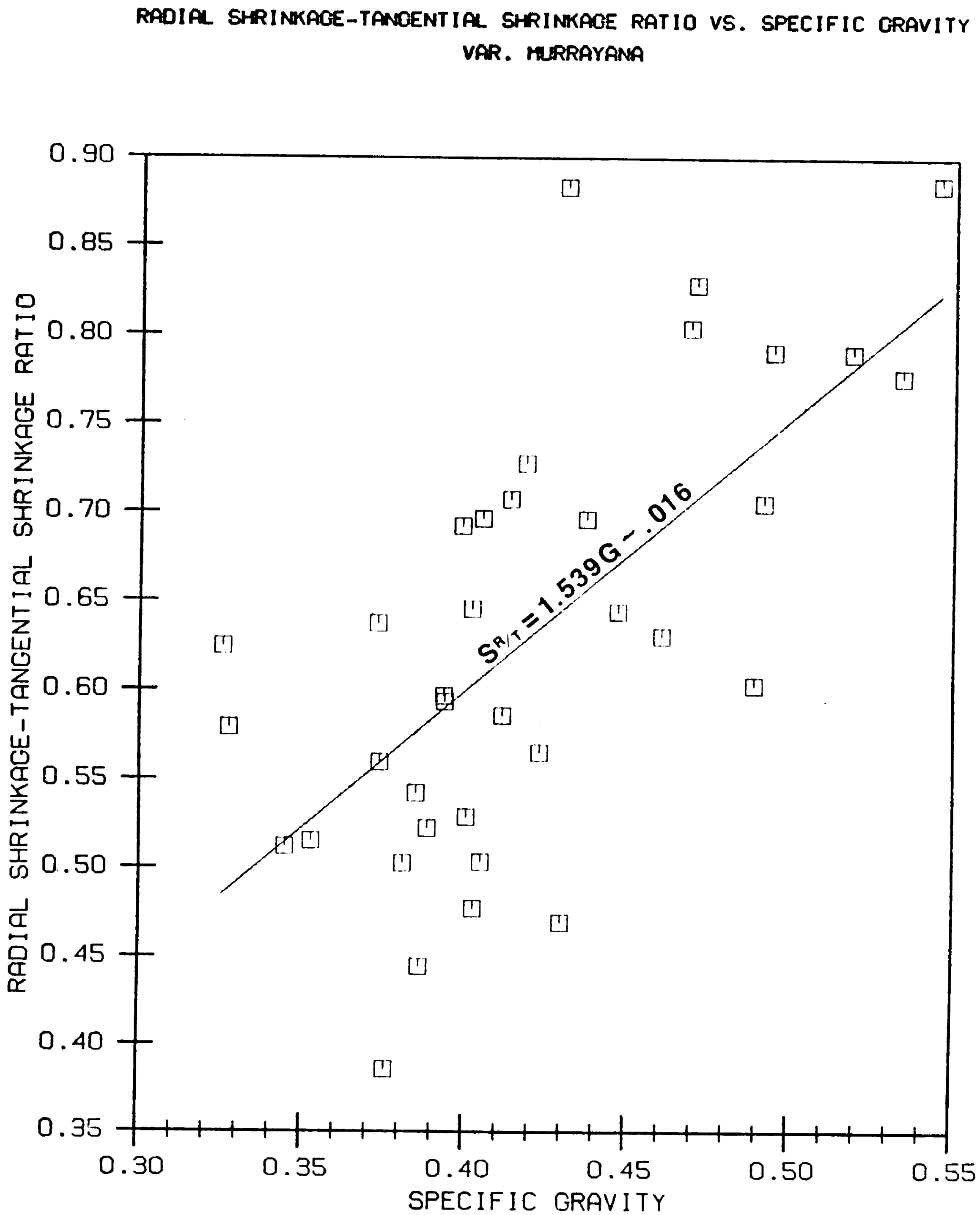

Figure 5. The Radial Shrinkage-Tangential Shrinkage Ratio Vs. Specific Gravity For Var. Murrayana

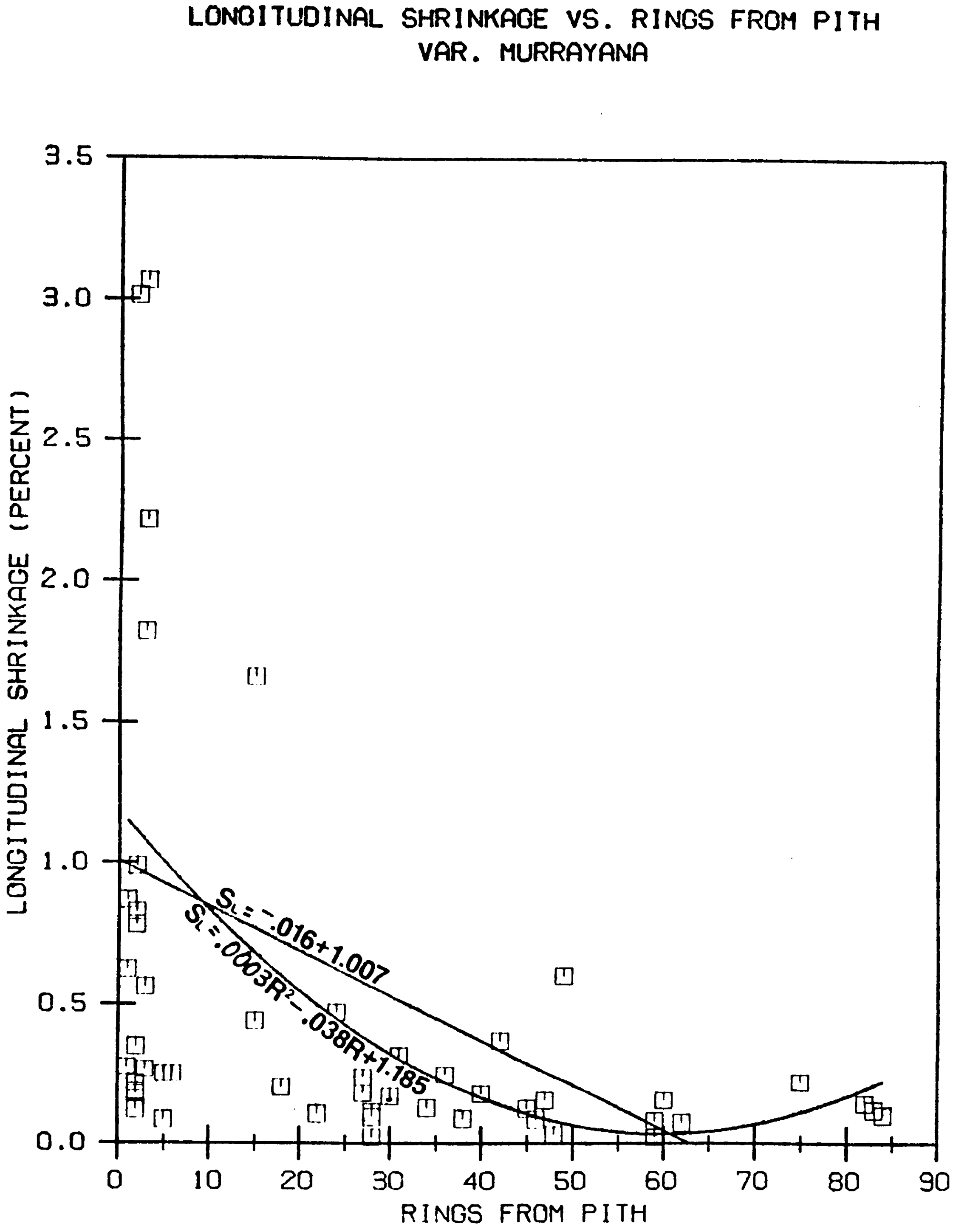

Figure 6. Longitudinal Shrinkage Vs. Rings From Pith For Var. Murrayana

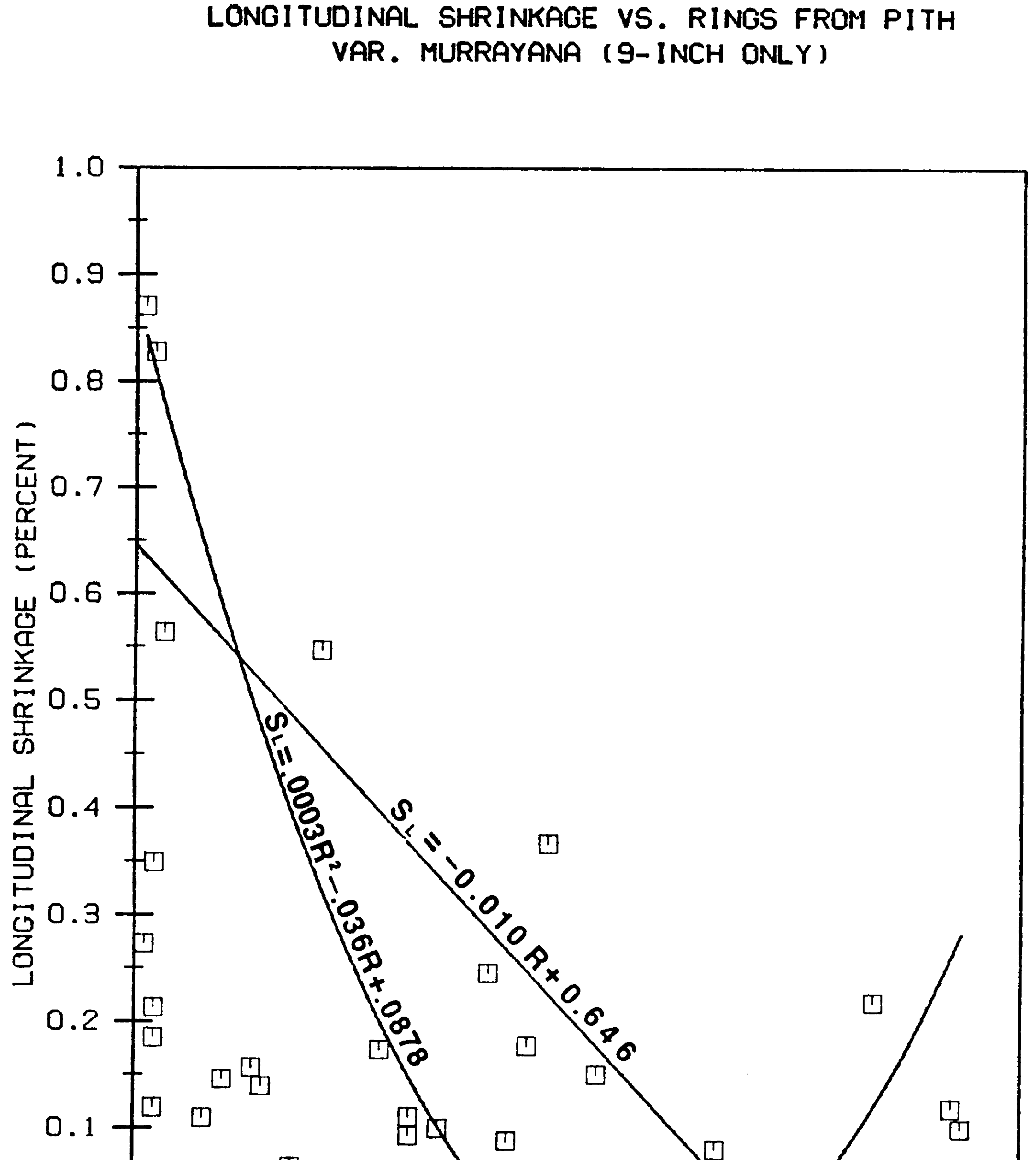

Figure 7. Longitudinal Shrinkage Vs. Rings From Pith For Var. Murrayana (9-inch Trees Only)

Var. Murrayana Fiber Saturation Point Determination

The moisture content at fiber saturation point for var. *murrayana* was calculated based on the commonly cited relationship that equates volumetric shrinkage with the product of specific gravity and fiber saturation point-moisture content. Using the average values for S_{Vl} and G listed in Table 3, a fiber saturation point-moisture content of 29.9% was calculated. This value is approximately 4 percent higher than the average value for fifty-two softwood species calculated by Stamm and Loughborough (1942).

Shrinkage intersection points were calculated based on measurements made in the fully-swollen condition, at 12% m.c., and in the oven-dried state. Moisture contents of 44.5%, 38.1% and 41.7% were calculated for the radial, tangential, and volumetric shrinkage intersection points, respectively. Kelsey (1956) predicted that shrinkage intersection points based on only one measurement from the linear portion of the shrinkage-moisture content curve would tend to be too high due to the curvalinearity of the relationship at its extremes. Her results, based on tests performed on six species (including only one softwood species), indicated that the intersection point- moisture content arrived at based on shrinkage from green to 12% and 0% would be between 1% and 2% too high. Some of the error in the shrinkage intersection point measurements might be attributed to the fact that it is quite likely the samples underwent some drying prior to their arrival at Virginia Tech; previously dried samples have been shown to have different shrinkage tendencies upon redrying (Schniewind and Kersavage 1962; Skaar 1972). Much of the discrepancy in the *murrayana* shrinkage intersection point values is probably due to the fact that since the "12% m.c." shrinkage and weight measurements were not the central focus of this research, not as much care was taken in this portion of the experimental procedure.

Variety Latifolia

Var. Latifolia Summary Statistics

Table 7 presents the summary statistics for var. *latifolia.* For each of the properties measured, a complete sample with no missing data points would consist of 243 observations. One tree section was missing altogether, which accounts for the missing specific gravity observation. Three radial shrinkage measurements could not be completed due to severe checking which occurred during the drying process. Since the equation which was used to make ring angle adjustments for tangential shrinkage included radial shrinkage, the same three tangential shrinkage measurements are missing. Of the remaining, unaccounted for, longitudinal-maturewood shrinkage observations, four were not measured due to the presence of knots on both sides of the pith which made it impossible to isolate a clear wood section for the measurement, the other two missing observations were 3″ samples which warped severely during drying. About one-half of the missing longitudinal-corewood observations were 3″ and 6″ samples which bowed and crooked severely during drying such that the oven-dry measurements reflected the presence of the drying defect rather than the actual degree of longitudinal shrinkage.

The average volumetric (S_{V1}) and radial shrinkages for var. *latifolia* are 12.101% and 4.674%, respectively. The average tangential shrinkage is 7.638%; this is the corrected value which includes the growth ring curvature adjustment. The mean uncorrected tangential shrinkage is 7.517%. The radial and volumetric shrinkage values are approximately nine percent greater than the values listed in the Wood Handbook (1987). The mean tangential shrinkage value recorded in this study is fourteen percent greater than the value given in the Wood Handbook (6.7%). As was the case for var. *murrayana*, the ratio of volumetric, tangential, and radial shrinkage for var. *latifolia* is **2.6:1.6:1.0**; this is the same ratio that is cited in the Wood Handbook.

Table 7. Variety Latifolia: Summary Statistics

	Summary Statistics			
Measurement[1]	Sample Size	Mean (%)	Std. Dev.	Coeff. of Var.
S_R (mixed wood)	239	4.674	0.693	14.8
S_T (sapwood)	239	7.638	0.892	11.7
S_R/S_T	239	0.618	0.104	16.8
S_{LC}	197	0.472	0.321	68.0
S_{LM}	233	0.145	0.103	71.0
S_{V1}	230	12.101	1.183	9.8
S_{V2}	239	11.954	1.181	9.9
G	242	0.402	0.040	10.0

1 - S_R = radial shrinkage; S_T = tangential shrinkage; S_{LC} = longitudinal, corewood shrinkage; S_{LM} = longitudinal, maturewood shrinkage; S_{V1} = volumetric shrinkage (including longitudinal shrinkage component); S_{V2} = volumetric shrinkage (does not include longitudinal shrinkage component); G = specific gravity.

The average specific gravity measured for var. *latifolia* in this study was 0.402. This value is slightly lower than the value cited by Koch (1987); he reported an average value of 0.418 for var. *latifolia.* Koch's specific gravity value was based on measurements made on stemwood samples from several different tree heights.

The coefficients of variation for each of the measurements are relatively similar with the exception of the two longitudinal measurements. The largest part of this variation is probably due to measurement error; this factor was previously discussed in the *Murrayana Summary Statistics* section of this chapter.

Var. Latifolia Analysis of Variance and Covariance

Table 8 presents the results of the analysis of variance and covariance tests that were performed on the *latifolia* data. The only shrinkage property which is significantly affected by any of the classification factors is tangential shrinkage; it is significantly influenced by the interaction between latitude and elevation. The significance of a two-way interaction is interpretted as meaning that the effect of one of the factors (latitude) on the dependent variable (tangential shrinkage) is different at different levels of the second factor (elevation).

Three test statistics could not be calculated; the complex form of the tests involving three random factors with unbalanced data sets involved subtracting the variability (mean square) associated with one factor from that associated with another in order to isolate the variability associated with a third factor. The subtraction yielded negative F-values in the analysis of the effect of size on volumetric shrinkage and the analyses (both the analysis of variance and analysis of covariance) of the relationship between size and longitudinal-corewood shrinkage. An alternative approach was taken to determine to what degree, if any, tree diameter influence these two shrinkage properties. The following results were obtained when the effect of size was analysed for subsets of the data:

Table 8. Variety Latifolia: Analysis of Variance and Covariance

Analysis of Variance and Covariance

F-Values[1] [2]

Source	S_R		S_T		S_{LC}	
	Var.	Cov.	Var.	Cov.	Var.	Cov.
(G)	—	76.16 **	—	3.87 *	—	0.22 NS
SIZE	108.98 NS	169.64 NS	24.66 NS	26.03 NS	CNC[4]	CNC
LAT	4.24 NS	N/A[3]	2.98 NS	N/A[3]	7.16 NS	N/A[3]
ELEV	1.60 NS	2.53 NS	2.95 NS	2.65 NS	4.32 NS	3.81 NS
SIZE X LAT	0.90 NS	0.76 NS	0.62 NS	0.60 NS	0.58 NS	0.57 NS
SIZE X ELEV	0.25 NS	0.30 NS	0.60 NS	0.66 NS	0.17 NS	0.19 NS
LAT X ELEV	1.22 NS	1.07 NS	2.06 *	2.07 *	1.18 NS	1.19 NS
S X L X E	1.07 NS	0.94 NS	0.79 NS	0.79 NS	1.00 NS	1.00 NS

1 - ** = significant at the 0.01 level; * = significant at the 0.01 level; NS = not significant.

2 - S_R = radial shrinkage; S_T = tangential shrinkage; S_{LC} = longitudinal, corewood shrinkage; G = specific gravity.

3 - The analysis of covariance cannot be used to make adjustments for the effect of specific gravity in studying the latitude factor because specific gravity varies significantly with latitude

4 - CNC = could not calculate; the complex form of the three factor, random effects analysis of variance yielded a negative F-value.

Table 8. Contd.

Analysis of Variance and Covariance

	F-Values				
	S_{LM}		S_{V2}		G
Source	Var.	Cov.	Var.	Cov.	Var.
G	–	0.17 NS	–	32.33 **	–
SIZE	2.38 NS	2.53 NS	CNC[4]	424.25 NS	4.50 NS
LAT	1.30 NS	N/A[3]	3.64 NS	N/A[3]	14.00 **
ELEV	0.25 NS	0.22 NS	3.24 NS	2.63 NS	1.00 NS
SIZE X LAT	0.93 NS	0.91 NS	0.73 NS	0.60 NS	1.11 NS
SIZE X ELEV	1.53 NS	1.60 NS	0.27 NS	0.40 NS	1.50 NS
LAT X ELEV	1.24 NS	1.24 NS	1.78 NS	1.88 NS	1.46 NS
S X L X E	0.85 NS	0.84 NS	0.92 NS	0.87 NS	0.90 NS

1 - ** = significant at the 0.01 level; * = significant at the 0.01 level; NS = not significant.

2 - S_{LM} = longitudinal, maturewood shrinkage; S_{V2} = volumetric shrinkage (does not include the longitudinal shrinkage component); G = specific gravity.

3 - The analysis of covariance cannot be used to make adjustments for the effect of specific gravity in studying the latitude factor because specific gravity varies significantly with latitude

4 - CNC = could not calculate; the complex form of the three factor, random effects analysis of variance yielded a negative F-value.

- Within each latitude classification neither volumetric nor longitudinal-corewood shrinkage is affected by size.
- Two out of the three altitude (elevation) classifications for both volumetric and longitudinal-corewood shrinkage were unaffected by size; the mean shrinkages for the 3, 6, and 9-inch size groupings for the subsets of data in which size was significant did not exhibit a trend ie. neither $a \leq b \leq c$ nor $c \leq b \leq a$ was true.

Although sub-set analysis is not as powerful a test as would be a test conducted on the entire data set, it does seem to indicate that size does not significantly affect either volumetric shrinkage or longitudinal-corewood shrinkage.

The results of the analysis of variance test conducted with specific gravity as the dependent variable indicate that latitude has a highly significant effect ($P<0.01$) on specific gravity, but size (tree diameter) does not. This test result is exactly opposite the result obtained in testing *murrayana*. Just as the factor latitude in the *murrayana* specific gravity analysis had a P-value (a measure of the probability that the observed difference in the dependent variable for the different levels of a given factor is due to chance alone) that was very nearly significant ($P = 0.08$), the P-value for the factor size in the *latifolia* analysis is also fairly small ($0.10<P<0.20$). Koch's study (1987) reported that var. *latifolia* specific gravity increased with increasing latitude and decreased with increasing tree diameter (d.b.h.). However Taylor et al. (1982) did not detect any association between specific gravity and latitude.

In the analysis of covariance the variation in shrinkage due to specific gravity is estimated. The *latifolia* results indicate that specific gravity has a highly significant effect on both radial and volumetric shrinkage, and a significant ($0.01<P<0.05$) effect on tangential shrinkage. Specific gravity does not have a significant effect on either longitudinal-corewood or longitudinal-maturewood shrinkage. Boutelje (1973), Choong (1969b), Foulger (1966), and Yao (1968, 1972) all concluded that the relationship between specific gravity and radial shrinkage is much stronger than the relationship between specific gravity and tangential shrinkage. The oft-cited inverse relationship between specific gravity and longitudinal shrinkage was not observed in this study. Yao's southern yellow pine research (1968) indicated that only 1 percent of the between-tree variation in longitudinal shrinkage was attributable to variations in specific gravity.

The analysis of covariance, by isolating the variation due to specific gravity, provides a more precise estimate of the degree of influence of each of the other factors of interest on shrinkage. The effect of the latitude- elevation interaction on tangential shrinkage, determined to be significant by the analysis of variance procedure, remained significant in the covariance analysis.

Var. Latifolia Multiple Comparisons

Since only two of the analysis of variance tests indicated significance and only one of the two significant results involved a main effect (the other involved an interaction), only one multiple comparison test was run. The Tukey-Kramer method was used to separate the specific gravity means for the different latitudes. The multiple comparison test results are given in Table 9.

In grouping the means, the letter A is assigned to the latitude groups which have the highest non-significantly different ($P<0.05$) mean specific gravities. The letter B is assigned to the next highest group of means, etc. This assignment scheme makes it easy to look at the multiple comparison output and spot trends (eg. direct or indirect relationships).

The specific gravity means and grouping variables both indicate that specific gravity tends to increase with increasing latitude. This result agrees with Koch's (1987) which was based on multiple specific gravity measurements per tree. The only latitude which does not conform well with this trend is 57.5° N. Figure 8 shows the scatterplot and first and second-order least-squares regression equations for the relationship between specific gravity and latitude. Both equations are highly significant; the linear equation accounts for 13% of the variation in specific gravity while the

Table 9. Variety Latifolia: Mean Separation

Multiple Comparisons[1] [2]

Size	G Mean(%)	G Grp
3″	0.415	A
6″	0.398	A
9″	0.395	A

LAT	G Mean(%)	G Grp
40.0°	0.375	D
42.5°	0.365	D
45.0°	0.387	C,D
47.5°	0.413	A,C
50.0°	0.425	A
52.5°	0.421	A
55.0°	0.429	A
57.5°	0.392	B,C,D
60.0°	0.415	A,B

1 - The Tukey-Kramer method was used in these two multiple comparison tests.

2 - Means with the same letter are not significantly different at the 0.05 level.

polynomial expression accounts for 21% of the variation. Based on the second-order equation, the maximum mean specific gravity value is expected to occur at 53.7° N. latitude.

The mean specific gravity values for each size classification are also listed in Table 9. Although size is not a significant factor, the specific gravity means illustrate a weak trend that corresponds with a significant trend noted by Koch (1987; specific gravity decreases with increasing tree diameter).

With only one exception, the mean values for rings per inch for each latitude follow the same pattern of variation as do the specific gravity means. When the mean growth rates for each size group are inspected, a significant variation is discovered: the number of rings per inch increases with decreasing tree diameter. Similarly, the relative magnitudes of the mean heartwood percentages of the various *latifolia* latitude groupings parallels the variation in specific gravity. The average heartwood percentages for the 3″, 6″, and 9″ diameter classes are 64%, 57%, and 48%, respectively. Making the assumption that the *latifolia* heartwood is higher in water-insoluble extractive content than the sapwood, and accepting the findings of various researchers (Salamon and Kozak 1968) who have shown that water-insoluble extractive content is directly related to specific gravity, it seems likely that any variation in specific gravity can be attributed, in part, to variations in the percentage of heartwood.

The assumptions of the preceeding paragraph were tested by means of partial correlation analysis. The simple correlation between specific gravity and latitude yielded an R-value of 0.36. When the effects of variations in heartwood percent on specific gravity were factored out in the partial correlation analysis, the R-value for the relationship between specific gravity and latitude dropped to 0.10 but was still highly significant. Similarly, the partial correlation between specific gravity and latitude in which the effect of rings per inch was controlled yielded a lower R-value (0.09) than did the simple correlation.

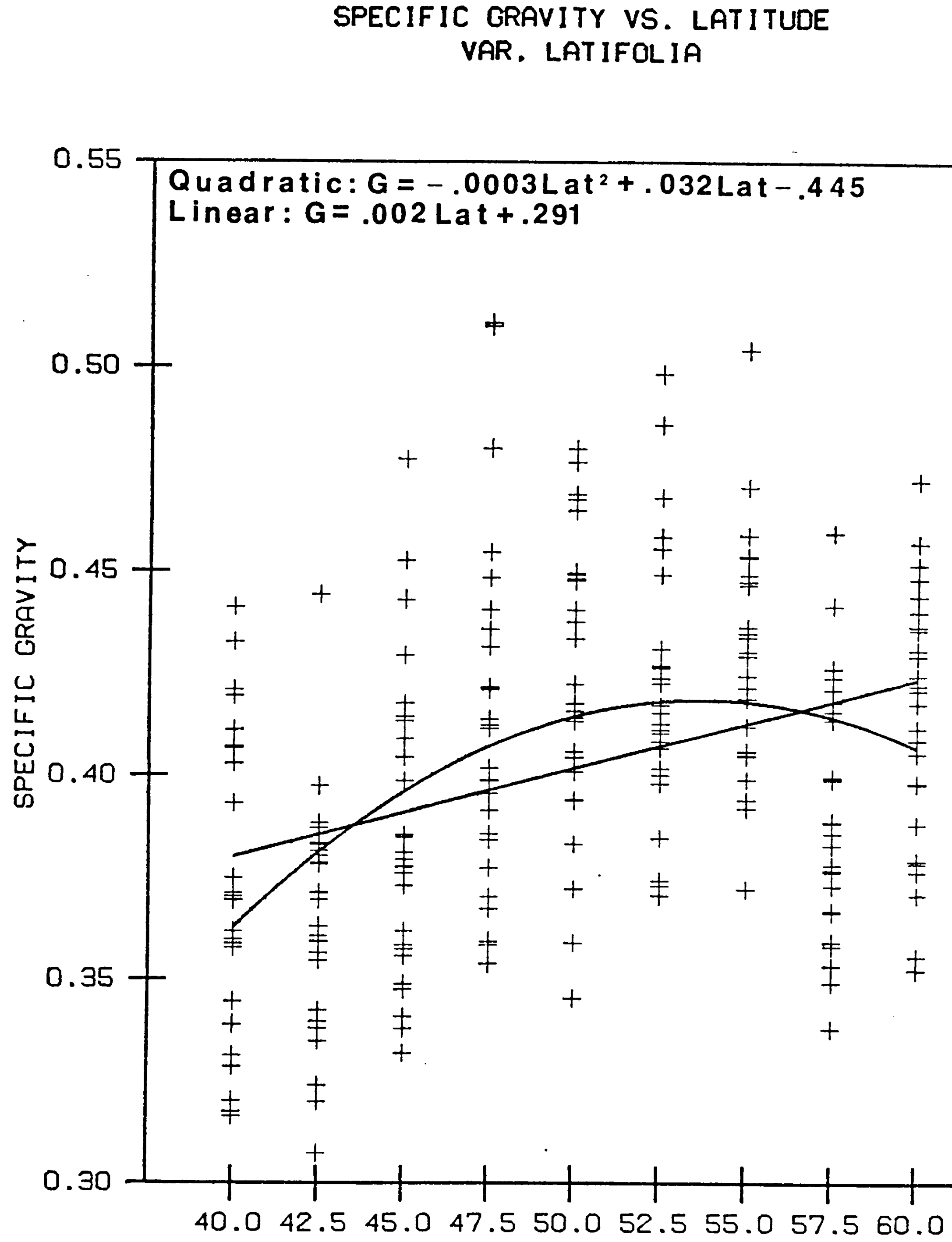

Figure 8. Specific Gravity Vs. Latitude For Var. Latifolia

Var. Latifolia Linear Associations

Table 10 lists significant linear relationships between the different shrinkage properties and various tree parameters. Of the eight specific gravity-shrinkage regression equations investigated, six were found to be highly significant (S_R , S_T , $S_{R/T}$, S_{LC} , S_{V1} , and S_{V2}).

The significance of the relationship between specific gravity and radial shrinkage has already been discussed (in the *murrayana* results and in the paragraphs which address the analysis of covariance results). Forty-seven percent of the variation in radial shrinkage is explained by its linear association with specific gravity. A graph of the relationship between S_{V1} and G is presented in Figure 9. Twenty-six percent of the variation in volumetric shrinkage is accounted for by the specific gravity regression expression.

The scatterplot of S_R/S_T versus G with the line-of-best-fit drawn through the 239 points, is given in Figure 10. The specific gravity at which $S_R = S_T$ for var. *latifolia* is 0.71. This value is extremely close to the value cited by Yao (0.72; 1968) for southern yellow pine.

Three of the specific gravity - shrinkage regression equations have very low R^2 values: for S_T vs. G the R^2-value is .0366, for S_{LC} vs. G the R^2-value is .0482, and for S_{LCM} vs. G the R^2-value is .0399. Despite the low R^2 values these regression expressions are significant at the 0.01 level....the linear correlations between these variables is significant even though the regression equation does a poor job of describing the nature of the relationships. The fact that the relationship between longitudinal-corewood shrinkage and specific gravity is significant in the regression model but not in the covariance model is possible because within the covariance model the relationship is not looked at independently, but rather in the context of the total model which is divided into groups which correspond with the different levels of each factor, while in the regression model these confounding factors are not involved.

Table 10. Variety Latifolia: Linear Associations

Regression Equations[1]

Shrinkage Property	Regression Equation	R^2
Radial (mixed wood)	$S_R = 11.952G - 0.140$	.4661
Tangential (sapwood)	$S_T = 4.310G + 5.902$	.0366
Radial/Tangential	$S_{R/T} = 1.242G + 0.118$	.2218
Longitudinal (corewood)	$S_{LC} = -1.783G + 1.189$	.0482
Longitudinal (maturewood)	—— NS ——	—
Long. Total (ave. of core and mature)	$S_{LCM} = -0.8764G + 0.656$	.0399
Volumetric (incl. S_L)	$S_{V1} = 15.442G + 5.883$	.2565
Volumetric (excl. S_L)	$S_{V2} = 15.137G + 5.856$	.2579

Correlations[2] [3]

Variables	Simple Correlation Coefficients	Partial[4] Correlation Coefficients
S_R X Rings Per Inch	.5577 (**)	.2057 (**)
S_T X Rings Per Inch	.2224 (**)	.1022 (**)
$S_{R/T}$ X Rings Per Inch	.6555 (**)	.3467 (**)
$S_{L(corewood)}$ X Rings From Pith	-.2106 (**)	—
G X Rings Per Inch	.3649 (**)	—
G X Heartwood Percent	.1710 (**)	—

1 - All of the regression equations given are highly significant ($P<0.01$).
2 - The format of this part of the table was borrowed from Yao (Table 2; 1972).
3 - ** = significant at the 0.01 level, * = significant at the 0.05 level, NS = not significant.
4 - The partial correlation coefficient measures the degree of linear association between the given variables after controlling for the effects of specific gravity.

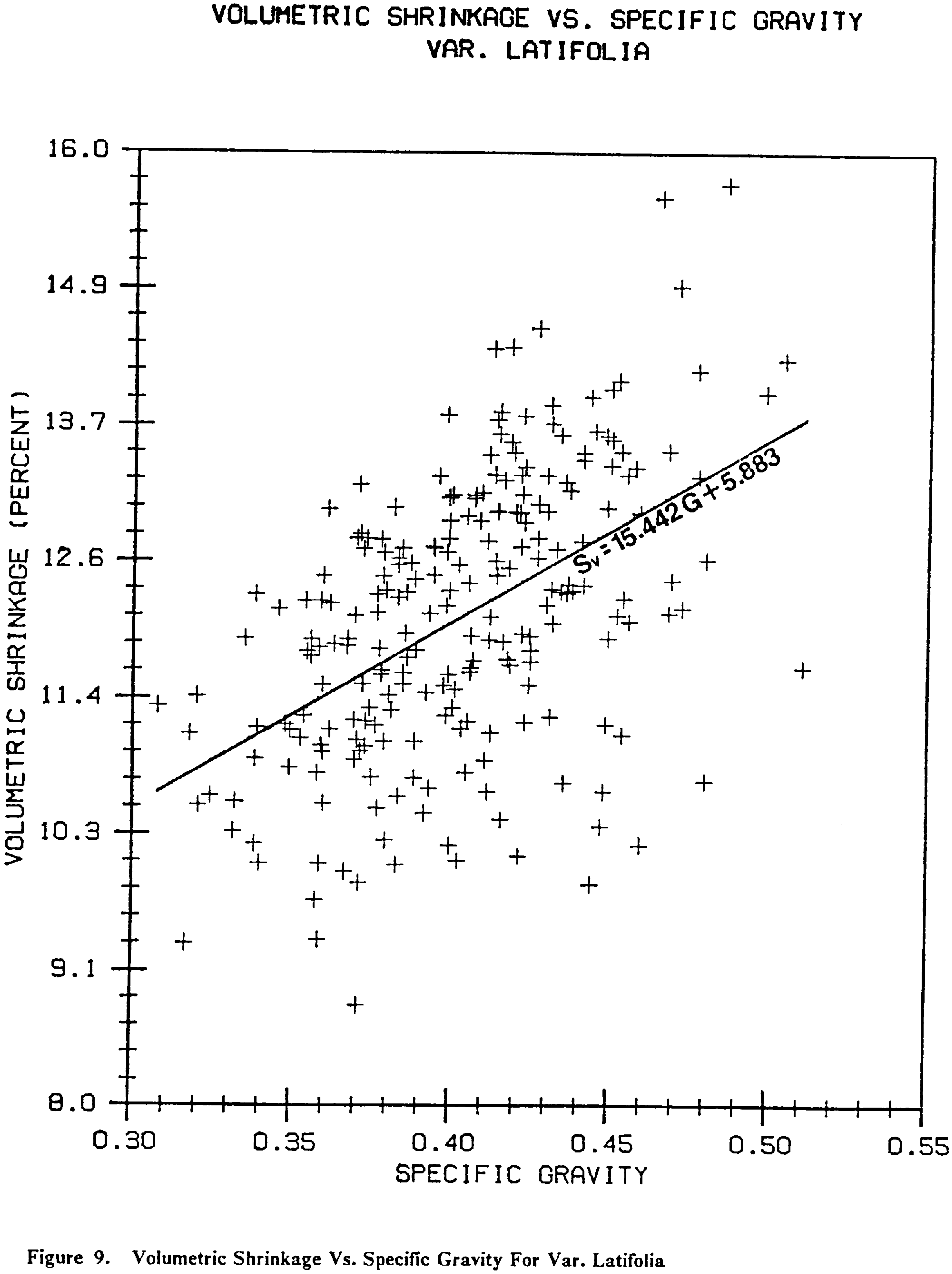

Figure 9. Volumetric Shrinkage Vs. Specific Gravity For Var. Latifolia

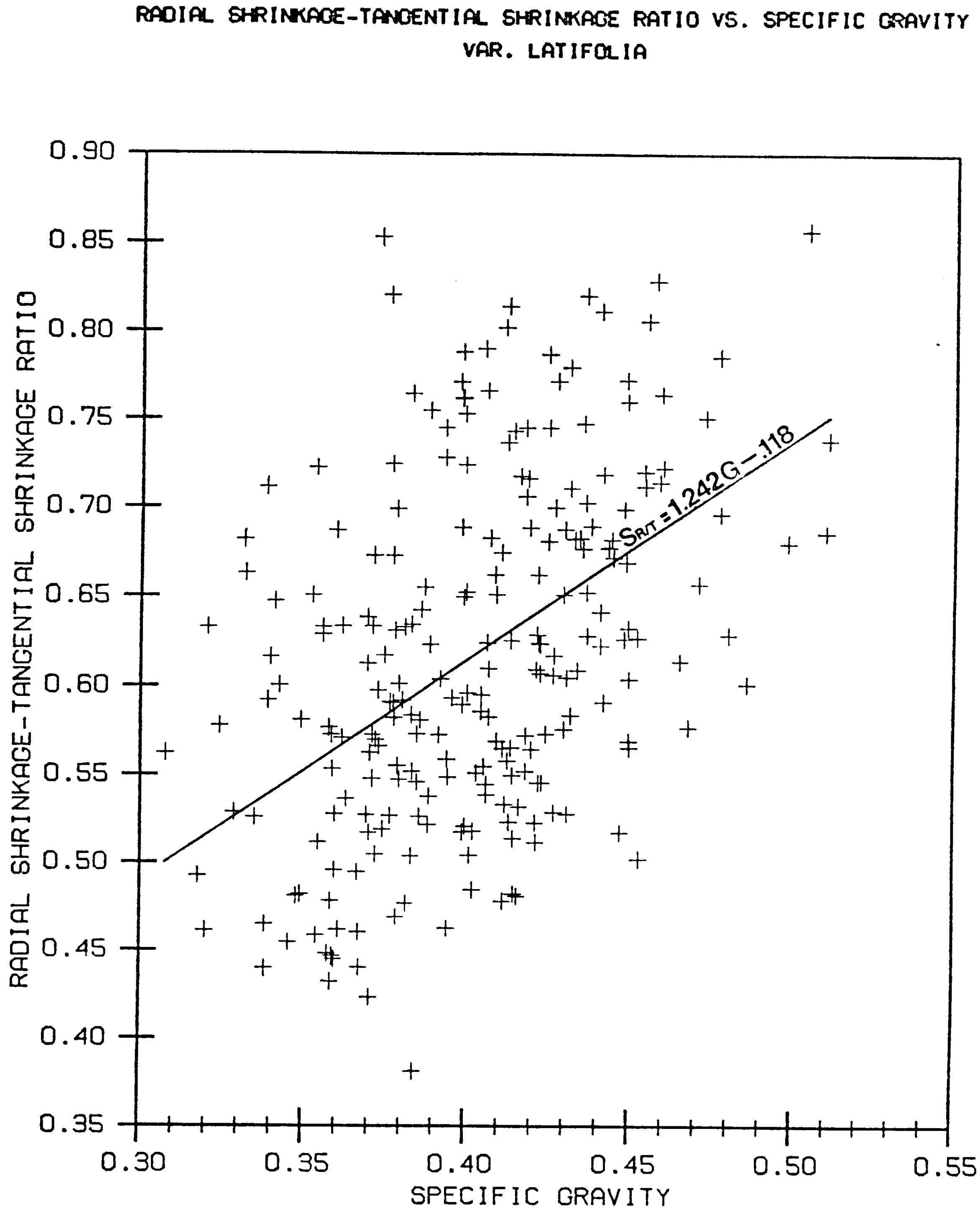

Figure 10. The Radial Shrinkage-Tangential Shrinkage Ratio Vs. Specific Gravity For Var. Latifolia

Linear correlations involving the tree parameters growth rate, heartwood percentage, and radial position of measurement (rings per inch), were also investigated. Radial shrinkage, tangential shrinkage, the radial shrinkage-tangential shrinkage ratio, and specific gravity were all found to be significantly correlated with growth rate. A partial correlation analysis was run in order to assess the degree of correlation between growth rate and shrinkage after controlling for the effects of specific gravity. Although the level of correlation dropped substantially, the three growth rate - shrinkage associations were still highly significant.

The linear association between longitudinal-corewood shrinkage and rings from pith is also significant at the 0.01 level as is the correlation between heartwood percent and specific gravity. The direct relationship between heartwood percent and specific gravity is expected since the presence of water-insoluble extractives in the heartwood is known to increase specific gravity (Choong 1969a).

In Figure 11 longitudinal-maturewood and longitudinal-corewood shrinkages are graphed together on the Y-axis and rings from pith is graphed on the X-axis. Figure 12 is similar to Figure 11 except that only 9″ diameter trees are included; also, an additional longitudinal shrinkage measurement taken at a distance of 2.25″ from the pith is included. Linear and quadratic least-squares regression curves are drawn in on both figures. These first and second-order equations which predict longitudinal shrinkage based on growth rate, provide only a slightly better estimate than do the individual corewood and maturewood mean longitudinal shrinkage values. The high longitudinal shrinkage values recorded near the pith are probably a reflection of the presence of juvenile wood. However, since no effort was made to isolate the juvenile wood this theory cannot be substantiated. The relationships shown in these two plots probably can be attributed, in part, to the effect of tracheid length on shrinkage; longitudinal shrinkage decreases with increasing tracheid length (Yao 1968). Taylor et al.'s (1982) research revealed that lodgepole pine tracheids increase in length from the pith to about ring 50 from which point they decrease slightly in length out to the bark.

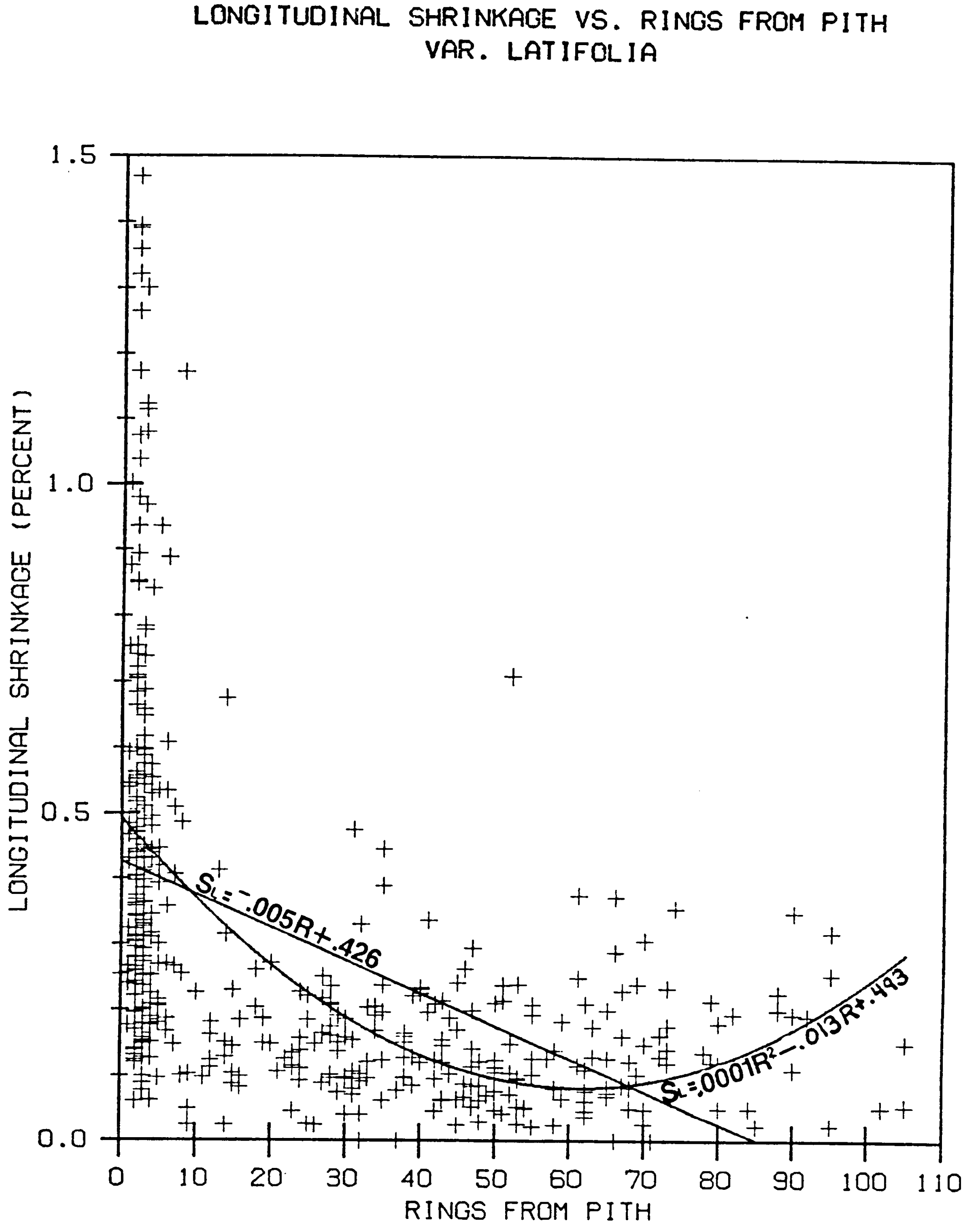

Figure 11. Longitudinal Shrinkage Vs. Rings From Pith For Var. Latifolia

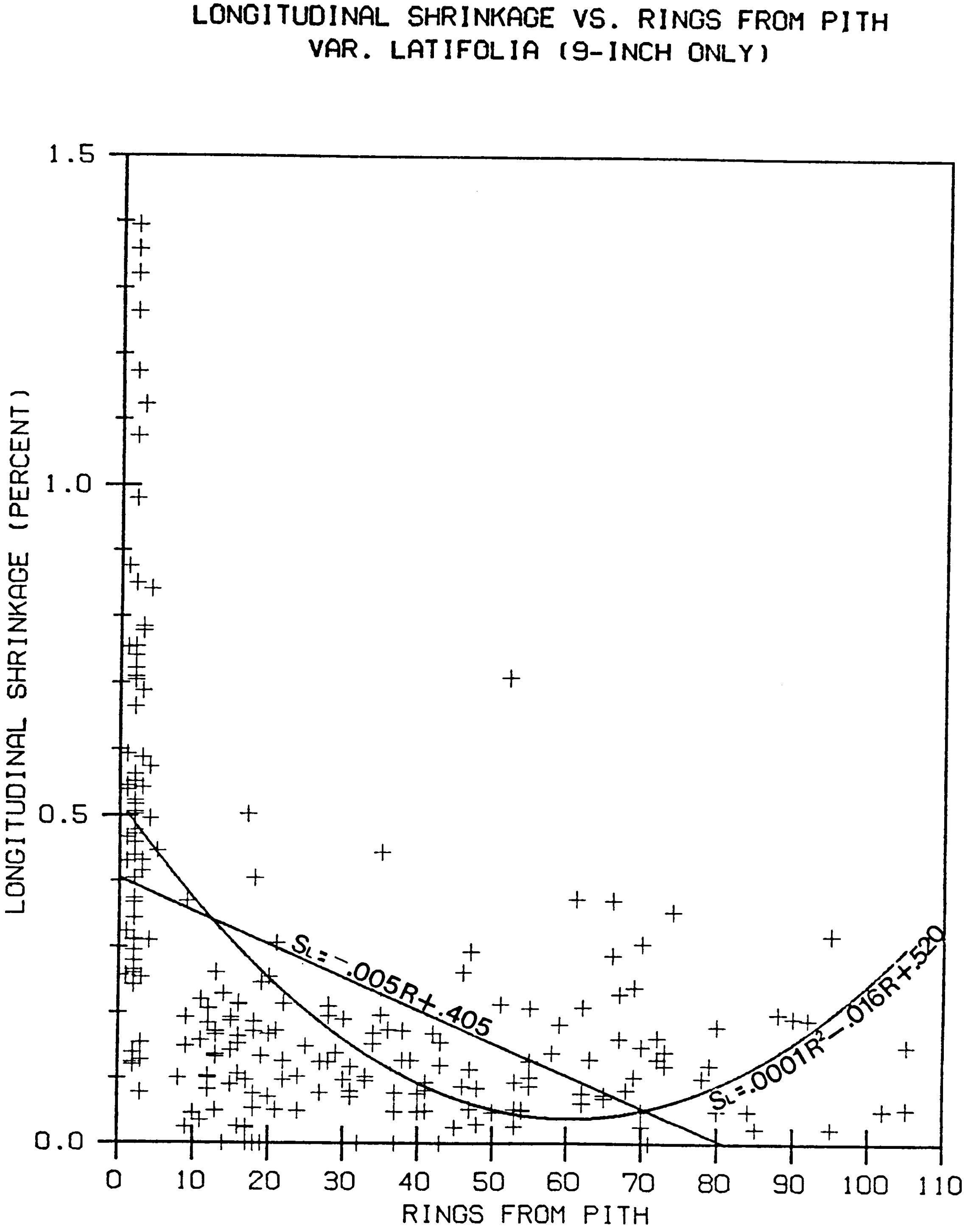

Figure 12. Longitudinal Shrinkage Vs. Rings From Pith For Var. Latifolia (9-inch Trees Only)

Var. Latifolia Fiber Saturation Point Determination

The moisture content at fiber saturation point for var. *latifolia* was calculated using the equation S_{vl} = FSP X G (Koch 1972). The fiber saturation point moisture content predicted by this equation is 30.1%.

Shrinkage intersection points were calculated based on measurements made in the fully-swollen condition, at 12% moisture content, and in the oven-dried state. Moisture contents of 38.5%, 21.4%, and 26.2% were calculated for the radial, tangential, and volumetric shrinkage intersection points, respectively. The value of the volumetric intersection point calculated in this way, is very close to the average fiber saturation point of 26% recorded for 52 softwood species by Stamm and Loughborough (1942). The large degree of variation between the three intersection points is probably an indication that there was a large amount of measurement error involved in the intersection point determination (specifically, in the "12%" moisture content measurements). This matter is discussed more completely in the last paragraph of the *murrayana* results.

Heartwood - Sapwood Comparison

The results of the paired sample t-tests were different for the two varieties, therefore the results are presented in two tables rather than one. The combined test results (*latifolia* and *murrayana* pooled together) indicated that specific gravity and radial shrinkage are significantly different for the heartwood and sapwood; the heartwood-sapwood relationship for var. *murrayana* is masked by these results since the *murrayana* sample size is small relative to the size of the *latifolia* sample (12 vs. 27).

The var. *latifolia* heartwood-sapwood comparison results are presented before the var. *murrayana* results in this section; this order was chosen so that all of the *latifolia* results would be grouped together to enhance reader comprehension.

Variety Latifolia

The *latifolia* heartwood-sapwood measurements were made on the twenty-seven middle-elevation 9-inch diameter trees (9 latitudes x 3 trees per latitude). Tangential shrinkage measurements and specific gravity measurements were obtained for both the heartwood and sapwood. Radial measurements were made only on the heartwood. The radial sapwood shrinkage figure listed in Table 11 was calculated by subtracting the product of the mean radial heartwood shrinkage and heartwood percent (decimal basis) from the average radial mixed wood shrinkage for the same 27 trees, then dividing this number by the sapwood percent (decimal basis). This calculation assumes that the radial shrinkage of the mixed wood is equal to the weighted sum of radial heartwood and radial sapwood shrinkages. However, Paul et al. (1959), in studies performed on noble fir, found the radial shrinkage of mixed heartwood and sapwood samples to be higher than either isolated heartwood of sapwood radial shrinkage. Thus, the radial sapwood shrinkage figures calculated for both *latifolia* and *murrayana* are only, at best, fair approximations of actual radial sapwood shrinkage.

The paired sample t-test results for var. *latifolia* are presented in Table 11. The difference between tangential heartwood and sapwood shrinkage proved to be non-significant at the 0.05 level. Significant specific gravity differences were detected between heartwood and sapwood; the mean specific gravity was higher for the sapwood than the heartwood (0.406 vs 0.380). Were lodgepole pine a species high in heartwood extractive content these results would be very hard to explain since the presence of water-insoluble extractives tends to increase specific gravity, but lodgepole pine with a water-insoluble extractive content of 3%, ranked 24th on a list of 36 North American softwoods

Table 11. Heartwood-Sapwood Comparison: Latifolia

Summary Statistics

Measurement	Sample Size	Mean (%)	Std. Dev.	Coeff. of Var.
Radial Shrinkage (S_R)				
-heartwood	27	4.116	0.715	17.4
-sapwood[1]	--	5.104	-----	----
-mixed wood[2]	27	4.447	0.561	12.6
Tangential Shrinkage (S_T)				
-heartwood	27	7.836	0.753	9.6
-sapwood	27	7.610	0.903	11.9
Specific Gravity (G)				
-heartwood	27	0.380	0.031	8.2
-sapwood	27	0.406	0.036	8.9

Paired Sample T-Test Results[3]

Hypothesis	T-Value	Significance
H_0: $S_{T(heartwood)} = S_{T(sapwood)}$	1.00	N.S.
H_0: $S_{R(heartwood)} = S_{R(mixedwood)}$	-2.66	$.01<P<.05$
H_0: $G_{(heartwood)} = G_{(sapwood)}$	-5.47	$P<.01$

1 - Radial sapwood shrinkage was not measured; it was calculated based on the radial shrinkage of the mixed samples and heartwood samples and the average heartwood percentage.

2 - Only mixed wood (combined heartwood and sapwood) samples from 40.0°, 42.5°, and 45.0° N. latitude are included in this comparison.

3 - Since there is pairwise correlation between the heartwood and sapwood measurements, the paired-sample t-test is more powerful than the two-sample t-test.

(Pettersen 1984). The difference between mean heartwood and sapwood specific gravity can be explained by considering the relationship between growth rate and specific gravity: a strong correlation between growth rate (rings per inch) and specific gravity was noted for var. *latifolia*; the number of rings per inch is higher for the sapwood (35.8) than the heartwood (16.2). If the number of rings per inch were the same for both the heartwood and sapwood, one might expect the specific gravity of the heartwood to be higher due to the influence of the water-insoluble extractives.

The comparison of radial heartwood shrinkage and mixed wood shrinkage also proved to be significant; mixed wood shrinkage averaged 4.447% and heartwood shrinkage averaged 4.116%. If the higher mixed wood shrinkage is in fact due to significantly higher sapwood shrinkage, then the higher average specific gravity and lower extractive content (an assumption that is supported by the observed difference in the color of the wood near the pith versus the color of the peripheral wood) of the sapwood provides a good explanation of this result. Whereas the water-insoluble extractive content affects specific gravity, the water-soluble extractive content is responsible for bulking the cell walls and causing reduced shrinkage (Choong 1969a; Demaree and Erickson 1976). The water-soluble extractive content of lodgepole pine (4%) ranked 14th on the same list of 36 North American softwoods cited previously (Pettersen 1984). Thus, one might expect that the extractive content of lodgepole pine has more of an effect on shrinkage than specific gravity (due to its relatively high water-soluble extractive content and relatively low water-insoluble extractive content). Salamon and Kozak (1968) showed that total extractive content had more of an effect on shrinkage than specific gravity for Douglas-fir.

Variety Murrayana

As was the case for var. *latifolia*, the *murrayana* heartwood-sapwood samples consisted only of middle-elevation, 9-inch diameter trees; there were only 12 specimens in the *murrayana* sample (4 latitudes x 3 trees per latitude). The equation and assumptions used in the calculation of the radial sapwood shrinkage for var. *murrayana* were the same as those employed in the *latifolia* comparison.

The paired sample t-test results for var. *murrayana* are given in Table 12. The difference between the average heartwood and sapwood values for both tangential shrinkage and specific gravity were determined to be non-significant. Similarly, the difference between the radial shrinkage of the mixed wood (heartwood and sapwood combined) and the heartwood was also found to be non-significant (at the 0.05 level).

There are several factors which might account for the different results obtained for *murrayana* and *latifolia.* Varietal differences in the extractive content of the heartwood, the horizontal variation in specific gravity, or the amount of juvenile wood, could be expected to affect the results.

Latifolia - Murrayana Comparison

Comparison Summary Statistics

The comparison of var. *latifolia* and var. *murrayana* consisted exclusively of samples from 40.0°, 42.5°, and 45.0° N. latitudes and middle elevations. Table 13 presents average shrinkage and specific gravity figures for both varieties.

For each of the seven shrinkage properties listed, var. *murrayana* has a higher average shrinkage than does var. *latifolia.* The mean volumetric shrinkage for *murrayana* is 1.15x that of *latifolia.* The average specific gravity of the 27 *murrayana* samples was 0.428; the average for the *latifolia* samples was 0.373. Koch (1987) reported slightly higher average stemwood specific gravity values for these same trees: 0.451 for *murrayana* and 0.401 for *latifolia.*

Table 12. Heartwood-Sapwood Comparison: Murrayana

Summary Statistics

Measurement	Sample Size	Mean (%)	Std. Dev.	Coeff. of Var.
Radial Shrinkage (S_R)				
-heartwood	12	4.249	0.696	16.4
-sapwood[1]	--	4.164	-----	----
-mixed wood[2]	12	4.206	0.597	14.2
Tangential Shrinkage (S_T)				
-heartwood	12	7.769	1.188	15.3
-sapwood	12	8.095	1.088	13.4
Specific Gravity (G)				
-heartwood	12	0.399	0.043	10.8
-sapwood	12	0.386	0.038	9.8

Paired Sample T-Test Results[3]

Hypothesis	T-Value	Significance
H_0: $S_{T(heartwood)} = S_{T(sapwood)}$	-1.21	N.S.
H_0: $S_{R(heartwood)} = S_{R(mixedwood)}$	0.27	N.S.
H_0: $G_{(heartwood)} = G_{(sapwood)}$	0.96	N.S.

1 - Radial sapwood shrinkage was not measured; it was calculated based on the radial shrinkage of the mixed samples and heartwood samples and the average heartwood percentage.

2 - Only mixed wood (combined heartwood and sapwood) samples from 40.0°, 4.2.5°, and 45.0° N. latitude are included in this comparison.

3 - Since there is pairwise correlation between the heartwood and sapwood measurements, the paired-sample t-test is more powerful than the two-sample t-test.

Table 13. Latifolia-Murrayana Comparison: Summary Statistics

Measurement[1]	Sample Size	Mean	Std. Dev.	Coeff. of Var.
S_R (mixed wood)				
-latifolia	27	4.257	0.760	17.8
-murrayana	27	5.030	0.891	17.7
S_T (sapwood)				
-latifolia	27	7.087	0.984	13.9
-murrayana	27	8.057	0.921	10.2
S_R/S_T				
-latifolia	27	0.607	0.114	18.8
-murrayana	27	0.632	0.129	20.4
S_{LC}				
-latifolia	20	0.468	0.215	45.9
-murrayana	20	1.044	1.321	126.5
S_{LM}				
-latifolia	25	0.173	0.144	83.2
-murrayana	25	0.203	0.325	160.1
S_{V1}				
-latifolia	25	11.159	1.275	11.4
-murrayana	25	12.832	1.238	9.6
S_{V2}				
-latifolia	27	11.040	1.348	12.2
-murrayana	27	12.682	1.236	9.7
G				
-latifolia	27	0.373	0.030	8.0
-murrayana	27	0.428	0.050	11.7

Summary Statistics spans Sample Size through Coeff. of Var.

1 - S_R = radial shrinkage; S_T = tangential shrinkage; S_{LC} = longitudinal, corewood shrinkage; S_{LM} = longitudinal, maturewood shrinkage; S_{V1} = volumetric shrinkage (includes the longitudinal shrinkage component); S_{V2} = volumetric shrinkage (does not include the longitudinal shrinkage component); G = specific gravity.

The fact that var. *murrayana* shrank more longitudinally than did var. *latifolia* (.203% vs. .173% for the maturewood) was an unexpected result; longitudinal shrinkage tends to form an inverse relationship with specific gravity (Foulger 1966; USDA 1960; Yao 1968). However, Yao (1968) found that the regression expression between longitudinal shrinkage and specific gravity accounted for very little ($\simeq 1\%$) of the between-tree variation in the longitudinal shrinkage of southern yellow pine. The relationship between longitudinal shrinkage and specific gravity is even weaker when making between-species comparisons.

Comparison T-Tests

In an effort to distinguish whether the differences between the means of the two varieties were significant, eight t-tests were conducted. Table 14 gives the hypothesis and results associated with each of these tests. The mean specific gravities of the two varieties are significantly different at the 0.01 level; this result supports the findings of Koch (1987). Additionally, significant radial, tangential, and volumetric shrinkage (both S_{V1} and S_{V2}) differences between *murrayana* and *latifolia* were detected ($P<0.01$).

The differences between the *latifolia* and *murrayana* longitudinal-maturewood and longitudinal-corewood mean shrinkage values are not significant at the 0.05 level. Similarly, the radial shrinkage/tangential shrinkage ratio is not significantly different for the two varieties.

The difference in the specific gravities of the two varieties is not explained by differences in either the average growth rate or the average heartwood percent. Based on the correlation results obtained in both the var. *latifolia* and var. *murrayana* analyses, one might expect that *murrayana's* higher mean specific gravity could be attributed to its having more rings per inch (slower growth rate) than var. *latifolia*. In fact, the opposite is true; *latifolia* has a slightly greater mean rings per inch value (28) than does *murrayana* (27). Similarly, one might expect that the variety with the higher per-

Table 14. Latifolia-Murrayana Comparison: T-Test Results

	T-Test Results	
Hypothesis	T-Value	Significance
H_0: $S_{R(latifolia)} = S_{R(murrayana)}$	-3.430	P<.01 (**)
H_0: $S_{T(latifolia)} = S_{T(murrayana)}$	-3.740	P<.01 (**)
H_0: $S_{R/T(latifolia)} = S_{R/T(murrayana)}$	-0.738	N.S.
H_0: $S_{LC(latifolia)} = S_{LC(murrayana)}$	-1.924	N.S.
H_0: $S_{LM(latifolia)} = S_{LM(murrayana)}$	-0.419	N.S.
H_0: $S_{V1(latifolia)} = S_{V1(murrayana)}$	-4.708	P<.01 (**)
H_0: $S_{V2(latifolia)} = S_{V2(murrayana)}$	-4.664	P<.01 (**)
H_0: $G_{(latifolia)} = G_{(murrayana)}$	-4.872	P<.01 (**)

1 - The calculation of S_{V1} included longitudinal shrinkage while the calculation of S_{V2} excluded the longitudinal shrinkage component.

centage of heartwood would have higher mean specific gravity and shrinkage values. This assumption also proves to be false; var. *murrayana* has significantly higher mean specific gravity and shrinkage values than var. *latifolia* but a lower percentage of heartwood (44% vs. 51%). Thus, the shrinkage and specific gravity differences between the varieties cannot be explained by any of the parameters measured in this study. Presumably they are caused by genetic differences.

Summary and Conclusions

Summary

This study examined the shrinkage variation of two North American varieties of lodgepole pine wood: *Pinus contorta* var. *latifolia* and *Pinus contorta* var. *murrayana.* The influence of various location factors (latitude and elevation of origin), and tree parameters (diameter of tree, specific gravity, growth rate, radial location of measurement and heartwood-sapwood tissue type) on radial, tangential, and longitudinal shrinkage were analyzed. Specific gravity variations were also investigated.

The results obtained in this study must be interpreted cautiously since the tree selection scheme did not necessarily reflect the volume distribution of the species.

For var. *murrayana*, size was the only factor which had a significant effect on specific gravity; specific gravity decreased with increasing tree diameter. Specific gravity, on the other hand, had an effect on radial shrinkage and volumetric shrinkage. Radial shrinkage was also significantly different for trees of different diameters and from different latitudes. Radial shrinkage was inversely related to tree diameter and directly related to latitude. Neither tangential nor longitudinal shrinkage was affected by tree diameter, but tangential shrinkage and longitudinal corewood shrinkage both varied by latitude. Tangential shrinkage tended to increase with increasing latitude. No such pattern of variation was evident for longitudinal-corewood shrinkage. For each of the shrinkage properties tested, between 45% and 65% of the variability in the measurements was explained by the model which included the factors tree size and latitude of origin. The addition of specific gravity to the radial shrinkage and volumetric shrinkage models improved their R^2-values by 5 to 10 percent.

Linear relationships between specific gravity and radial (mixed wood) shrinkage, the radial shrinkage-tangential shrinkage ratio, and volumetric shrinkage, were all found to be significant at the 0.01 level for var. *murrayana*. Linear correlations between radial shrinkage and growth rate, longitudinal shrinkage and distance from pith, and specific gravity and growth rate were also judged significant. Partial correlation analysis revealed that the relationship between radial shrinkage and growth rate was in fact an indirect relationship; their common association with specific gravity ties them together.

An estimate of var. *murrayana's* fiber saturation point was obtained by dividing average volumetric shrinkage by average specific gravity; a value of 29.9% was calculated.

For var. *latifolia*, latitude was the only factor that had a significant effect on specific gravity; in general, specific gravity increased with increasing latitude. Size, latitude, and elevation were all non-significant factors in each of the *latifolia* analysis of shrinkage variance tests.

Specific gravity has a strong influence on radial shrinkage, the radial shrinkage-tangential shrinkage ratio, and volumetric shrinkage for var. *latifolia* Analysis of variance tests and regression analysis indicated that weaker associations exist between specific gravity and tangential shrinkage ($R^2 = .0366$) and between specific gravity and longitudinal shrinkage ($R^2 = .0399$). Linear correlations between radial shrinkage and growth rate, tangential shrinkage and growth rate, longitudinal shrinkage and distance from pith (a negative relationship), specific gravity and growth rate, and specific gravity and heartwood percent were determined to be significant.

Heartwood and sapwood specific gravity and radial shrinkage were significantly different for var. *latifolia*. Heartwood tissue shrank less radially and had a lower specific gravity than the sapwood.

The fiber saturation point calculated for var. *latifolia* from the ratio of mean volumetric shrinkage and mean specific gravity was 30.1%.

The comparison of the two varieties' average specific gravities at their common latitudes indicated that var. *murrayana's* specific gravity was significantly higher (1.15x) than *latifolia's* Similarly, var. *murrayana's* volumetric shrinkage was 1.15x that of var. *latifolia.* The only shrinkage properties which were not significantly higher for *murrayana* than for *latifolia* were longitudinal-corewood shrinkage, longitudinal-maturewood shrinkage, and the radial shrinkage-tangential shrinkage ratio.

Conclusions

The following conclusions can be drawn from these research results:

1. As was shown by Koch (1987), both latitude and tree diameter have an effect on lodgepole pine specific gravity, latitude is particularly important for var. *latifolia* while diameter has more of an effect on var. *murrayana.*

2. Specific gravity has a significant effect on the radial and volumetric shrinkages of both varieties but no effect or only a very weak effect on tangential shrinkage and longitudinal shrinkage.

3. The apparent effect of location (latitude and elevation) and size factors on shrinkage variability can be attributed, in large part, to variations in specific gravity.

4. For similar size trees from common latitudes, var. *murrayana* has higher specific gravity than var. *latifolia.*

5. For similar size trees from common latitudes, var. *murrayana* has higher transverse and volumetric shrinkages than var. *latifolia.*

6. For var. *murrayana*, growth rate is negatively correlated with specific gravity.

7. For var. *latifolia*, growth rate is negatively correlated with specific gravity and heartwood percent is positively correlated with specific gravity.

Literature Cited

American Society for Testing and Materials. 1972. Standard methods of measuring specific gravity and shrinkage in volume of small clear specimens of timber. Annual Book of Standards. ASTM Standard Des. D 143-152. ASTM, Philadelphia, Pa.

Barber,N.F. 1968. A theoretical model of shrinking wood. Holzforschung 22(4):97-103 (cited by Skaar 1972).

Boutelje,J. 1973. On the relationship between structure and the shrinkage and swelling of the wood in Swedish pine (*Pinus silvestris*) and spruce (*Picea abies*). Svensk Papperstidning 76(2):78-83.

Boyd,J.D. 1977. Relationship between fibre morphology and shrinkage of wood.Wood Sci. Technol. 11:3-22.

Choong, E.T. 1969a. Effect of extractives on shrinkage and other hygroscopic properties of ten southern pine woods. Wood and Fiber 1:124-133.

Choong, E.T. 1969b. Moisture and the wood of the southern pines. Forest Prod. J. 19(2):30-36.

Choong,E.T., Manwiller,F.G. 1976. Dimensional and relative hygroscopic properties of hardwoods from southern pine sites. Wood Science 9(1):39-43.

Cockrell,R.A. 1943. Some observations on density and shrinkage of ponderosa pine wood. Amer. Soc. of Mech. Eng. Trans. 65:729-739.

Demaree,L.A. and R.W. Erickson. 1976. Temperature-dependent effect of extractive content on redwood shrinkage. Wood Science 8(4):227-233.

Ellwood,E.L. and W.W. Wilcox. 1962. The shrinkage of cell walls and cell cavities in wood microsections. Forest Prod. J. 12(5):235-242.

Erickson,H.D. 1953. Tangential shrinkage of serial sections within annual rings of Douglas-fir and western red cedar. Forest Prod. J. 5(4):241-250.

Espenas,L.D. 1974. Longitudinal shrinkage of western redcedar, western hemlock, and true fir. Forest Prod. J. 24(10):46-48.

Foulger,A.N. 1966. Longitudinal shrinkage pattern in eastern white pine stems. Forest Prod. J. 16(12):45-47.

Fountain,W.C.,Guernsey,F.W. 1956. Some variables affecting the shrinkage of western hemlock. Forest Prod. J. 6(4):148-152.

Frey-Wyssling,A. 1940. The reasons for the anisotropic shrinkage of wood. Holz als Roh-und Werkstoff 3:43-45 (cited by Skaar 1972).

Greenhill,W.L. 1936. The shrinkage of Australian timbers I.A new method of determining shrinkages and shrinkage figures for a number of Australian species. Australian CSIRO Div. of For. Prod. Tech. Paper No. 21. Melbourne (cited by Skaar 1972).

Hale,J.D. 1957. The anatomical basis of dimensional changes of wood in response to changes in moisture content. Forest Prod. J. 7(4):140-144.

Hann,R.A. 1969. Longitudinal shrinkage in seven species of wood. Research Note FPL-0203. USDA Forest Serv., Forest Prod. Lab., Madison, Wis. 13pp.

Harlow,W.M., E.S. Harrar, and F.M. White. 1979. Textbook of Dendrology. 6th ed., McGraw-Hill Book Company, New York, N.Y. pp. 109-112.

Hart,C.A. 1984. Relative humidity, EMC, and collapse shrinkage in wood. Forest Prod. J. 34(11/12):45-54.

Higgins,N.C. 1957. The equilibrium moisture content--relative humidity relationships of selected native and foreign woods. Forest Prod. J. 7(10) :371-377.

Hofmann,K. 1986. Longitudinal air permeability of lodgepole pine. M.S. Thesis, Virginia Tech Univ., Blacksburg, Vir. 89 pp.

Kass,A.J. 1965. Shrinkage stresses in externally restrained wood. Forest Prod. J. 15(6):225-232.

Kelsey,K.E. and R.S.T. Kingston. 1953. An investigation of standard methods for determining the shrinkage of wood. J. of FPRS. 3(11):49-53.

Kelsey,K.E. 1956. The Shrinkage Intersection Point--its significance and the method of its determination. Forest Prod. J. 6(10):411-417.

Kleinbaum,D.G. and L.L. Kupper. 1978. Applied Regression Analysis and Other Multivariable Methods. Wadsworth Publ. Co., Belmont, Cal. 556 pp.

Koch,P. 1972. Utilization of the Southern Pines, Volume 1. Ag. Handbook No. 420. USDA Forest Serv., Washington, D.C. pp. 289-305.

Koch,P. 1987. Gross characteristics of lodgepole pine trees in North America. General Tech. Rpt. INT-227. USDA Forest Serv., Intermountain Research Station. 311pp.

Koehler,A. 1933. Effect of heating wet wood on its subsequent dimensions. Amer. Wood Preservers Assoc. Pro. 29:376-388 (cited by Schniewind and Kersavage 1962).

Koehler,A. 1938. Rapid growth hazards usefulness of southern pine. J. of Forestry 36:17-20.

Markwardt,L.J. and T.R.C. Wilson. 1935. Strength and related properties of woods grown in the U.S. USDA Bulletin No. 479 (cited by Schroeder 1972).

Meylan,B.A. 1968. Cause of high longitudinal shrinkage in wood. Forest Prod. J. 18(4):75-78.

Nakato,K. 1958. On the cause of anisotropic shrinkage and swelling of wood. X. J. Japan Wood Res. Soc. 4(5):183-186 (cited by Boutelje 1973).

Nearn,W.T. 1955. Effect of water soluble extractives on the volumetric shrinkage and equilibrium moisture content of eleven tropical and domestic woods. Penn. State Univ. Agric. Exp. Station Bulletin No. 3. 38pp. (cited by Turc and Cutter 1984).

Panshin,A.J. and C. de Zeeuw. Textbook of Wood Technology, Vol. 1. McGraw-Hill Book Company, New York, N.Y. 705 pp.

Paul,B.H. 1957. Lengthwise shrinkage in ponderosa pine. Forest Prod. J. 7(11):408-410.

Paul,B.H., A.W. Dohr, and J.T. Drow. 1959. Some physical and mechanical properties of noble fir. Lab Report No. 2168. USDA Forest Serv., Forest Products Lab., Madison, Wis. 14 pp.

Pentoney,R.E. 1953. Mechanisms affecting tangential vs. radial shrinkage. J. of FPRS. 3(2):27-32.

Pettersen,R.C. 1984. The chemical composition of wood. In The Chemistry of Solid Wood. 1984. R.M. Rowell, ed. Am. Chem. Soc. Adv. in Chem. Series No. 207. pp. 73-81.

Piirto,D.D., D.L. Crews, and H.E. Troxell. 1974. The effects of dwarf mistletoe on the wood properties of lodgepole pine. Wood and Fiber 6(1):28-35.

Quirk,J.T. 1984. Shrinkage and related properties of Douglas-fir cell walls. Wood and Fiber 16(1):115-133.

Salamon,M. and A. Kozak. 1968. Shrinkage of sapwood and heartwood of young Douglas-fir trees. Forest Prod. J. 18(3):90-94.

Schniewind,A.P. 1959. Transverse anisotropy of wood: a function of gross anatomic structure. Forest Prod. J. 9(10):350-359.

Schniewind,A.P. and P.C. Kersavage. 1962. Influence of rate of drying and rewetting on the dimensional changes of California black oak. Forest Prod. J. 12(1):29-33.

Schroeder,J.A. 1972. Shrinking and swelling differences between hardwoods and softwoods. Wood and Fiber 4(1):20-25.

Skaar,C. 1972. Water in Wood. Syracuse Univ. Press, Syracuse, N.Y. 213 pp.

Smith,D.M. 1961. Method of determining specific gravity of small wood chips. Lab Report No. 2209. USDA Forest Serv., Forest Products Lab., Madison, Wis. 2 pp.

Spalt,A.H. 1979. Water-vapor sorption by woods of high extractive content. *In* Symposium on wood moisture content: Temperature and humidity relationships. VPI&SU, Blacksburg, Vi. (cited by Turc and Cutter 1984).

Stamm,A.J. and W.K. Loughborough. 1942. Variation in shrinking and swelling of wood. Trans Am. Soc. Mech. Engrs. 64:379-386 (cited by Schroeder 1972).

Stamm,A.J. 1971. Review of nine methods for determining the fiber saturation points of wood and wood products. Wood Science 4(2):114-127.

Taylor,F.W., E.I.C. Wang, and M.M. Micko. 1982. Differences in the wood of lodgepole pine in Alberta. Wood and Fiber 14(4):297-309.

Tiemann,H.D. 1951. Wood Technology. 3rd ed., Pitman Publishing Corp., New York, N.Y. (cited by Hart 1984).

U.S. Department of Agriculture, Forest Service. 1960. Longitudinal shrinkage of wood. Lab Report No. 1093. USDA Forest Serv., Forest Products Lab., Madison, Wi.

U.S. Department of Agriculture, Forest Service. 1965. Silvics of forest trees of the United States. Agriculture Handbook No.271. H.A. Fowells, ed. USDA Forest Serv., Div. of Timber Management Research, Washington D.C. pp. 373-383.

U.S. Department of Agriculture, Forest Service. 1987. Wood Handbook: Wood as an Engineering Material. Agriculture Handbook 72. Washington, D.C. 460 pp.

Yao,J. 1968. Shrinkage properties of second-growth southern yellow pine. Wood Sci. Technol. 3:25-39.

Yao,J. 1972. On volumetric shrinkage, specific gravity, and fiber saturation point of loblolly pine wood. Wood Science 4(3):171-177.

Zar,J.H. 1984. Biostatistical Analysis. 2nd ed., Prentice-Hall,Inc., Englewood Cliffs, N.J. 718 pp.

The two page vita has been removed from the scanned document. Page 1 of 2

The two page vita has been removed from the scanned document. Page 2 of 2