PROPERTIES OF PLANTATION GROWN RED PINE RELATED TO ITS UTILIZATION

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Cover background figure, photomicrograph of fibril angle in plantation-grown red pine

Dedicated

to

Professor Gregory Baker

Forest Research

University of Maine

1935-1968

Professor Emeritus

1968-Present

PREFACE

In addition to the authors, a number of persons have participated directly in the research described in this report. The initial work leading to this series of investigations was begun by Professor Gregory Baker, with a number of studies devoted to specific gravity in the plantations that are the subject of this research. Since becoming Professor Emeritus, Professor Baker has continued to contribute actively to this work.

Investigations conducted by several graduate students at the School of Forest Resources in the completion of the requirements for the Master of Science Degree provided a basis for this report: Richard S. Shumway, of the Eastman Kodak Company (physical and mechanical properties); Michael J. Morin, of the Packaging Corporation of America (pulping characteristics); and Raymond R. McOrmond, of the Western Electric Company (kiln drying studies).

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PROPERTIES OF PLANTATION GROWN RED PINE RELATED TO ITS UTILIZATION

BACKGROUND OF THE STUDY

Plantation-Grown Red Pine

Because of its rapid growth rate, good form and relative freedom from the danger of serious insect and disease injury, red pine (*Pinus resinosa* Ait.) has often been advocated as a species for commercial planting throughout its natural range. Within the past half century many plantations have been established in the Northeast, the Lake States and Canada. In the Lake States, red pine has been planted more extensively than any other species, and in the future these plantations may well be the greatest sources of merchantable timber in that region (39). Red pine has been a specifically recommended plantation species in central New England, where many plantations have been successfully established on a wide variety of sites with a minimum amount of cultural work (53). In 1971 it was conservatively estimated that more than 15,000 acres of red pine plantations had been established in Maine alone (36).

The nation is constantly faced with an increasing need for raw material and, more specifically, for wood fiber. The paper and paperboard market alone in the United States is expected to increase from 52.3 million tons in 1966 to 102 million tons by 1985 (23). During the latter year, an estimated 120 million cords of pulpwood will be harvested. If such demands on our forest resources are to be met, efficient and economical use of existing resources is imperative. For more effective utilization of those species which are potentially important as a commercial resource, their wood and pulp properties require further investigation. This species, variously termed red, Norway or hard pine, is definitely of interest as such a future raw material for the wood conversion industry. The early plantations have or will soon contain trees of sufficient size to be harvested for small sawlogs, pulpwood, piling and even veneer bolts.

Investigations have indicated that some of the basic properties of the wood from plantation-grown red pine may be considerably at variance with those of wood from naturally-grown material (28, 33, 42, 46). It might well be possible therefore, that the inherent characteristics of plantation-grown red pine would also affect wood pulping and drying procedures differently than the naturally-grown material. For example, the core of juvenile wood, which is prominent in plantation-grown material and known to cause distinct variations in its mechanical properties, is also known to react to kiln drying procedures differently than comparable wood from naturally-grown material.

Since little has been published regarding the nature and interrelationship of the characteristics of the wood produced in middle-age plantation-grown red pine that might directly influence its utilization, this series of investigations was undertaken.

Purpose and Scope of the Study

Previous research (9, 10, 11) devoted to plantation-grown red pine in the same forest area, together with the reported results of work with the species in other regions, provided a conceptual basis for this investigation. It was evident that, in regard to the utilization of this material, its strength and physical properties as well as their possible interrelationship would be of particular interest, as would more specific information than that available regarding its drying and pulping characteristics. It should be noted, however, that the actual conduct of the various phases of the investigation was not only sequential in nature, but spanned several years and included a number of staff members in addition to the authors. The specific objectives and scope of each portion of the study were, therefore, actually defined as the research was undertaken, but are presented together here in the interests of clarity.

The first phase of the study was conducted to evaluate the static bending and compression parallel to the grain properties evident within and among material from 19 plantation-grown red pine trees, and to determine what effect position in the tree, latewood percentage, fibril angle, specific gravity and rate of growth might have on these mechanical properties.

The second phase of the study was conducted concurrently with the first to determine what effect position in the tree and specific gravity might have on the characteristics of red pine Kraft pulp. Physical strength tests and yield determinations were made using pulped material from selected positions along the bole of the same sample trees evaluated in the first phase of the investigation.

The third investigation was conducted to evaluate the effect of three dry kiln schedules, representing a wide range of conventional kiln temperatures, on the visual grade characteristics and on the static bending, compression parallel to the grain, shear parallel to the grain and toughness strength properties of plantation-grown red pine. Material was again selected so as to reflect the effect of tree position in its response to experimental treatment.

Review of the Literature

The utilization of a tree species for a particular wood product is commonly influenced by one or more of the inherent physical characteristics of its wood. Extensive investigations, therefore, have been conducted to determine what tree growth characteristics might influence wood characteristics, and to evaluate wood properties in terms of some wood quality parameter. Of all the various wood property indices available, specific gravity is one of the most commonly used criteria of wood quality. It is of particular interest to the forest manager and scientist, since it may be employed without complete destruction of the growing tree.

Results from many studies conducted to determine the variation in the specific gravity of wood in coniferous trees tend to indicate definite patterns. Jayne (27) found that the specific gravity of bolewood increased from the pith to the cambium in 36-year-old red pine plantation trees in New Hampshire. Paul (44) found a similar pattern in a 43-year-old red pine plantation in Wisconsin. He reported that the increase in specific gravity with age was greatest in the lower portion of the tree bole, indicating that the wood formed near the ground was characteristically more mature wood, while that formed at greater heights was characteristically juvenile wood.

Wood formed in that portion of the bole below the living branches is frequently referred to as stem-formed wood, while that formed in that portion of the bole bearing living branches is designated as crown-formed wood. Such stem-formed wood in plantation-grown red pine reportedly has significantly higher specific gravity than crown-formed wood (18). Brunden (15) reported that the stem-formed wood from natural stands of red pine has both significantly higher specific gravity and longer fibers than crown-formed wood. A definite logitudinal pattern of specific gravity variation is also evident in red pine. Wahlgren *et al.* (58) found that, for naturally-grown red pine in Maine, specific gravity of the bolewood decreased with increasing height above ground. A similar pattern of specific gravity variation in 36-year-old plantation-grown red pine was observed by Jayne (27), Cooper (18) and Maeglin (39). In a wood density study of 25-year-old plantation-grown red pine, Baker (9) found that the specific gravity variation also followed this pattern in trees with merchantable heights greater than 28 feet. For trees with merchantable heights less than 28 feet, however, an initial decrease, followed by an increase in specific gravity of the bolewood was observed with increasing height.

The effect of site and spacing of trees upon the specific gravity of bolewood in plantation-grown red pine has also been investigated. Baker and Shottafer (10) examined the effect of spacing on the specific gravity in a 25-year-old red pine plantation and concluded that for two- and ten-foot spacings, the two-foot spacing resulted in a continuous decrease in the specific gravity of the bolewood from breast height to a four-inch top. The reverse was observed in the ten-foot spacing. A lower form class and a greater live-crown ratio in the ten-foot spacing were believed to be responsible for the reversal in the specific gravity pattern. In contrast, Jayne (27) evaluated the effects of site and spacing on the specific gravity of plantation-grown red pine, and concluded that four-foot, six-foot and eight-foot spacings appeared to have little influence on specific gravity. Environment, however, as reflected by site, was thought to have a definite effect on specific gravity

Specific gravity variations within a tree stem have been found to be closely correlated with variations in the percentage of latewood present. Pillow (47) found that specific gravity was linearly correlated with percentage of latewood in 14- to 37-year-old plantation-grown red pine. Zahner *et al.* (65) studied earlywood and latewood formation in 20-year-old red pine grown under both irrigation conditions and simulated drought, and found that the lower and upper bole of the irrigated trees produced 100 percent and 50 percent, respectively, more wood than drought trees; however, in both treatments latewood percentages at comparable positions in the tree bole were equal. A later seasonal initiation of latewood tracheids in the irrigated trees was advanced as the reason an equal proportion of latewood was formed. Hall (21) found that latewood area increased down the stem as the weight of foliage above a given point increased.

The results of a number of investigations of various wood characteristics and their effects upon the strength properties of plantation-grown red pine have been reported. Olson *et al.* (42) evaluated the strength properties of red pine trees at two height levels and observed significant differences for the values of stress at the proportional limit (FSPL), modulus of rupture (MOR) and modulus of elasticity (MOE) in static bending. Although specific gravity was correlated with the strength properties, no direct correlation between growth rate and strength was evident. Kramer (33), however, using sub-standard size samples from 25- to 44-year-old plantations, found rate of growth to be better correlated than specific gravity with strength in static bending and compression, parallel to the grain. Site, variation between individual trees and radial location of the sample within the tree all affected the mechanical properties of samples, but north or south orientation of the samples within the tree had no apparent significant effect. A definite relationship between fibril angle and both MOR and MOE was also observed.

Pillow (47) found that although maximum crushing strength increased directly with specific gravity, it also varied in samples having similar specific gravity, indicating that other factors do affect strength. Perem (45) reported that although there was no difference between the average maximum crushing strength (MCS) and modulus of rupture of air-dried normal wood and compression wood in red pine, the normal wood did correlate better with specific gravity than the compression wood. Perkins and Walz (46) evaluated the comparative strength of plantation-grown red pine from two locations in Indiana and somewhat older forest-grown material from Wisconsin. While a number of strength properties and physical characteristics were reported, no attempt was made to evaluate the relationship between them, and only the butt logs of the trees were used. Both full size (2 x 4) and laboratory size strength samples were included in this study, and the strength values determined were somewhat below those generally accepted for the species. Again, the high proportion of juvenile wood present in the material was thought to have significantly affected the test results.

The literature suggests that although the wood properties of plantation-grown red pine have been intensively investigated, previous growth-strength evaluations have been restricted to young plantations. Particularly, little effort has been made to evaluate the growth-strength properties of middle-age plantation-grown red pine with respect to the original position of the wood in the tree.

In the pulp industry, specific gravity is often used as an index for estimating potential pulp yield from a given volume of wood. Extensive studies have found that specific gravity is directly related to fiber density, which in turn may be correlated with the ratio of cell wall thickness to diameter (13). Increases in fiber density will usually result in greater pulp yield per unit volume of wood, and therefore from an economic standpoint it is advantageous to purchase wood of high specific gravity, all other factors being equal.

Relatively little has been published on the pulping of red pine. An early report by Wells and Rue (62) stated that red pine reduced fairly easily by the sulfite process, with yields of 45 to 55 percent for strong pulps and 40 to 45 percent for bleachable pulps. Residual pitch in the sulfite pulp seemed to cause a bleaching problem, and it was concluded that red pine might have limited use as a sulfite pulpwood species; however, the problem was evidently not encountered when producing sulfate pulps. Studeny and Libby (56) conducted a pulping study on 23- and 46-year-old red pine plantation thinnings, using a calcium-base sulfite process. Pitch problems, as described by Wells and Rue, were not evident in pulps from the 23-year-old trees, but were encountered in pulps from the 46-year-old thinnings. This led to the conclusion that the pitch difficulty was obviated with young, less resinous trees and a pulp of good quality could still be produced. In the older, more resinous trees, the penetration of acid cooking liquors was limited and resulted in pulps of higher resin content. Where pulps with high physical strength characteristics were not required, the use of dolomite-base liquors in the sulfite process alleviated the pitch problem.

The Forest Products Laboratory at Madison, Wisconsin (26) has conducted a study of Michigan wood species in which 20-year-old plantation-grown red pine thinnings and 40-year-old naturally-grown stock were cooked by the Kraft process and tested. The yield and physical strength characteristics were similar for both types, and compared with other softwood species tested. An investigation by Jones and Weisel (29) of a single 84-year-old red pine tree obtained from the University of Maine Forest produced ammonium-bisulfite pulps with about 45 percent yield and good strength properties.

In all the investigations cited no effort was made to separate pulp properties with respect to the original position of the wood in the tree or to its specific gravity. Studies conducted on other species, however, have reported higher yields for the butt portion of the tree as compared to the top (30). Several investigators working with the southern hard pines have found that sheet density, burst factor and breaking length were directly related to both height in the tree above ground and specific gravity, while tear factor appeared to be inversely related (12, 19, 25, 37, 60).

Visual defects in lumber decrease both its value and serviceability, and the greatest percentage of degrade associated with the conventional drying process is attributed to warp (32). There is often an increase in the incidence of warp noted in a commercial species as old-growth stands are depleted and second-growth material is introduced, since second growth material generally has a smaller diameter and therefore greater susceptibility to this defect. Wood located near the pith is characterized by several wide growth rings of relatively low density material. In drying, this juvenile core may tend to exert greater tension stress than normal wood; if this juvenile wood predominates on one side or face of a board, there will be an increased tendency for warp to occur. Twist has been found to be the major type of warp occuring in lumber cut from such second growth material. Wickstein and Rice (61), in a study of plantation-grown red pine, found that twist accounted for one-half to two-thirds of all the warp defect present.

Proper drying conditions usually vary with wood species; however, if an acceptable dry kiln schedule is used for a species, there should be no significant change in the physical strength characteristics of the wood as compared to air-dried material. Since kiln drying offers better control of drying conditions than air-drying, less degrade can, in fact, normally be expected. The strength of wood may be affected by high temperatures, however, depending on the duration of exposure and the moisture content of the wood (2). Panshin and de Zeeuw (43) mention that there is a loss of strength when wood is heated above 150°F for any appreciable time. High temperatures may cause permanent changes in the chemical nature of the wood that reduce its hygroscopicity, with an accompanying reduction in the strength properties. This strength loss occurs in kiln drying principally before the wood falls below the fiber saturation point (FSP) (54).

MacLean (38) noted a permanent loss of static bending strength with various heat treatments up to 230°F for exposure time periods of varying lengths. Work to maximum load (WML) was affected the most, followed in turn by MOR, FSPL and MOE. Salmon(49) reported that temperatures above 212°F affect Douglas fir in regard to MOR, followed by MOE, FSPL and MCS. Kozlik (34) investigated the effects on Douglas fir and western hemlock of drying both at constant equilibrium moisture content (EMC) and constant temperatures of 90°F to 230°F. Of the strength characteristics evaluated, toughness in Douglas fir was affected the most, with a progressive reduction of 12 to 15 percent as temperature intervals increased. Other strength properties also reduced were tangential shear strength and MOR, but no definite conclusions could be drawn from the FSPL and MOE data.

Alexander and Archer (1) conducted a study involving five constant temperature kiln schedules, together with varied conditions of EMC. They stated that temperature levels of 160°F decreased strength so as to make western hemlock unsuitable for aircraft use, but that this reduction would not be critical in other types of construction. Kozlik (35) used constant temperatures of 70°F to 230°F with increasing wet bulb depressions to study the bending strength of 2 x 6 inch Douglas fir and western hemlock lumber. Here it was concluded that MOR was affected most, and MOE was affected least. Graham (20) found that timbers of Douglas fir treated at a constant temperature of 202°F lost 15 percent of their strength. He evaluated the static bending and toughness characteristics of the timbers and found that they were lower in regard to work values than comparable air-dried pieces. He also reported a pronounced reduction in the toughness value level with an increase in temperature. It was concluded from a study of the effect of seasoning methods on the strength of plantation-grown red pine poles that there are no large differences between steam-conditioned poles and Boultonized poles (7).

A number of investigations, therefore, have described the effects of temperature and various dry kiln conditions on the properties of several species of wood. Plantation-grown red pine, however, has not been extensively studied and its response to high temperature and specific dry kiln conditions is neither established or fully understood.

CONDUCT OF THE STUDY

Source of the Material

During this sequence of investigations, material was obtained from two specific areas in the University of Maine Forest that had been under management by the staff of the School of Forest Resources for a number of years.

The Sewall Plantation was established in 1920 on a burned area, with 2-1 transplants of unknown progeny planted at six-foot spacing. A one-tenth acre permanent growth plot was established in 1946; the first thinning of the area, conducted in 1948, reduced the basal area from 148 square feet per acre to 102 square feet per acre. A second thinning, conducted in 1954, further reduced the basal area from 151 square feet per acre to 94 square feet per acre. Following a third thinning in 1967, the plot basal area was reduced from 174 square feet per acre to approximately 103 square feet per acre. The land, which had been devoted to agriculture prior to the burn in 1918, has been described as a Whitman Stony loam soil with some areas of gravelly loam.

The second area from which the test material was selected, designated by the School of Forest Resources as S1 61B, was established in 1936 with 2-1 transplants of unknown progeny, planted at a six-by six-foot spacing on a Biddeford Silt loam soil. The plantation was divided by a gravel road, and in 1961 was partitioned off into ten one-tenth acre plots. Seven of these plots were located south of the road and three were located to the north. The same year a thinning treatment was conducted on nine of the plots, involving six on the south side of the road and three on the north. The basal area was reduced from 165 square feet per acre to 116 square feet per acre, and 185 trees were pruned to a height of 17 feet. A second thinning in 1969 of the same nine plots subsequently reduced the basal area from 173 square feet per acre to 127 square feet per acre.

Selection of Experimental Material

Sixteen well-formed dominant and codominant potential crop trees and three overtopped, smaller-sized trees were selected for removal from the growth plot located on the Sewall Plantation. Each tree was removed to improve the growth conditions of the residual stand, not primarily to provide experimental material for this study. The north side of each selected tree was marked, the tree felled and standard mensurational data were recorded. A summary of the pertinent data for the 19 trees used in this investigation is presented in Table 1. The material obtained from these trees was utilized in the evaluation of strength properties, physical properties and pulping characteristics.

Eighteen well formed, dominant and codominant trees in the nine and ten inch diameter classes were selected from the S1 61B area for removal from the plantation in a thinning operation. The material from these trees was used in the study of the effects of kiln drying on the incidence of material defects and strength properties. The mensurational data were recorded, but were not considered applicable to the planned conduct of this phase of the investigation.

The trees from the Sewall Plantation were sectioned into bolts 4.2 feet long up to a 4-inch top, and 0.2 foot disks were removed from the top

Table 1
Summary of Mensurational Data for Plantation-Grown Red Pine Trees Selected for Investigation of Physical and Pulping Characteristics

	Physical Properties Evaluation (16 trees)		Pulping Properties Evaluation (19 trees)	
	Average	Range	Average	Range
Diameter, breast height (in.)	9.5	7.2 - 11.0	9.2	6.1 - 11.0
Total length (ft.)	61.4	59.2 - 63.4	60.4	54.0 - 63.4
Merchantable length (ft.)	45.4	42.0 - 46.2	43.3	29.4 - 46.2
Merchantable volume (cu. ft.)	11.2	4.3 - 15.4	10.9	3.9 - 15.4
Length to Live crown (ft.)	32.3	26.9 - 36.0	30.6	23.6 - 36.0

Note: Trees used in the physical property study are the same trees used in the pulping study with the three smallest trees deleted.

of each bolt for specific gravity determinations. The specific gravity of the disks was calculated by the method developed by Henrichs (24), and for the pulping study the specific gravity of the bolts was assumed to be the average of the disk specific gravity at each end of the bolt. Individual tree bolts were numbered consecutively from the base to the top of the tree, and the tree number and north side were marked on each bolt. Bolt numbers two, five and eight from each tree were then selected for the evaluation of physical and mechanical properties, so that a representative sample from the butt, middle and upper portion of each tree was obtained. Since the eighth bolt from each of the three smaller trees was too small to yield a series of two or more wood samples, these trees were subsequently eliminated from this phase of the investigation. Bolts numbered one, six and nine of each tree were selected for the pulping study, with suitable material available from all 19 trees. Again, samples were obtained from the bottom, middle, and top portion of each tree. The pulp bolts were debarked by hand, taken to a sawmill and quartered, and one quarter from each bolt then randomly selected for chipping. The bolts designated two, five and eight were also transported to the sawmill, where a nominal 2½ inch thick flitch was sawn from the center of each bolt parallel to the pith on the north-south axis. Each flitch was appropriately marked with tree and bolt number, peeled and carefully piled under cover for air seasoning to approximately 12 percent moisture content. To reduce or prevent end checking, the ends of each flitch were coated with a thick application of commercial end sealer.

Each tree from the S1 61B plantation was sectioned into six 4-foot bolts, the bolts transported to the sawmill, and sawn into nominal size 2 x 4 pieces by the "Forest Products Laboratory Improved Method" as defined by Hallock (22). Each piece measured 2 inches by 4 inches in cross section and 4 feet in length. These 2 x 4 samples were numbered so that core (C) and peripheral (P) material could be identified. Six 2 x 4's designated as core material and six from peripheral material were randomly selected from each tree for the drying study. For each of three planned dry kiln treatments two samples were randomly selected from the array of both the core and the peripheral material, so that each dry kiln treatment sample group consisted of 72 of the 2 x 4 drying samples. Each treatment group was then tight piled and kept under cover in a frozen condition until the drying operations could be implemented.

Evaluation of Physical and Mechanical Properties

Preparation of test material. Because of the small tree diameter involved, it was necessary to follow the procedures described by American Society for Testing and Materials (ASTM) standard D143-52, for secondary-sized specimens (6) in order to obtain a strength evaluation series from each flitch. Each flitch was accurately resawn on a table saw to yield a series of square sticks from the north and the south radius. To produce specimens with a minimum of cross grain, the cuts were made parallel to the bark on each side and the wedge-shaped center piece discarded. Each stick was surfaced to a nominal 1 inch square cross section, and one static bending specimen and one compression parallel to the grain specimen 16 inches and 5 inches in length, respectively, were taken from each stick. Each specimen was marked with the appropriate tree number, bolt designation, north-south orientation and radial position. Within each flitch the radial positions were numbered from one to three centripetally.

One static bending and one compression specimen were selected for testing from each pair of specimens, a pair consisting of two adjacent specimens equidistant from the pith. All specimens with obvious defects such as knots, checks and pronounced compression wood were discarded before testing.

To reduce the moisture gradient and insure conditioning to a nominal 12 percent equilibrium moisture content, the specimens were stored in a controlled environment of 68 ± 2°F and 65 ± 1 percent relative humidity for a minimum period of one month prior to testing.

Experimental procedures. Since red pine is utilized as dimension stock and piling, the effect that position of the wood in the tree has upon bending and compressive strength was of particular interest, and static bending and compression parallel to the grain tests had been selected. Both strength tests were performed on an Instron universal testing machine equipped with a chart recorder. The samples were tested at random, and all procedures were conducted in a controlled environment of 68 ± 2°F and 65 ± 1 percent relative humidity, which produced a nominal 12 percent equilibrium moisture content.

ASTM standard D143-52, Secondary Methods (6) were tested as a guide for both strength tests. Deflections were recorded only until the proportional limit had been exceeded, and the loading then continued until a maximum value had been attained. All necessary data to describe the type of failure were recorded. The calculated strength values of the specimens, which ranged in moisture content from 10.9 to 12.4 percent, were subsequently adjusted to 12 percent moisture content.

Static bending tests were conducted using center-point loading to determine the stiffness and mechanical strength properties of the material, which included fiber stress at proportional limit, modulus of rupture, modulus of elasticity and work to the proportional limit (WPL). Prior to testing, the cross section of each specimen was measured to the nearest 0.001 inch with a calibrated dial micrometer. A 14-inch span length was employed with all specimens. Both deflections were measured to the nearest 0.01 inch as continuous load was applied at the rate of 0.05 inches per minute to the pith side tangential surface of the specimen. Immediately after testing, a specimen one inch in length was sawn from the specimen as close as possible to the point of failure for moisture content and specific gravity determinations.

Compression strength tests were conducted to determine the compressive fiber stress at the proportional limit, maximum crushing strength and modulus of elasticity. Prior to testing, a section one inch in length was sawn from one end of each specimen for moisture content and specific gravity determinations. The actual cross sectional dimensions were measured to the nearest 0.001 inch. A Baldwin strain follower, used to record sample deformation to the nearest 0.0001 inch over a 2 inch gage length, was attached along the central axis and in the approximate center of the specimen. The only deviation from the ASTM standard was that a continuous loading rate of 0.0025 inches per inch of specimen (0.01 inches per minute) was used, rather than the stipulated 0.003 inches per inch of specimen length (0.012 inches per minute), due to the drive characteristics of the test machine.

In addition to the effect of position in the tree, it had been decided to evaluate certain relationships among the mechanical properties determined for material and various physical factors which might influence these properties. Based upon the review of the literature, four such factors had been selected: latewood percent, fibril angle, specific gravity and rate of growth.

Percentage of latewood was determined from a sample approximately ⅓ inch in length, sawn from each static bending specimen near the point of failure and adjacent to the moisture content block. These samples were soaked in water for approximately 12 hours, split along the central radial axis, and the end grain surface adjacent to the central radial plane smoothed with a razor blade. A differential stain for earlywood, consisting of a solution of 0.015 grams of malachite green and 0.015 grams of methylene blue in 25 milliliters of 20 percent alcohol, was applied to the smooth surface with a brush to accentuate the boundary between earlywood and latewood. Cumulative measurments of the latewood and earlywood widths were recorded to the nearest 0.01 millimeter across the entire radial line using a DeRowen dendrochronograph. Although latewood percentage is commonly determined by microscopic methods, review of two previous studies (51, 63) indicated that, with proper sample preparation and the application of a differential stain, accurate results could be obtained by macroscopic techniques. Macroscopic determination of the percentage of latewood was, therefore, employed in this investigation.

Fibril angle alignment was determined from a stratified sample consisting of 150 specimens taken from fifty strong, fifty average and fifty weak static bending specimens. Specimen strength criteria were based on the MOR values corrected to 12 percent moisture content. Microscopic slides were prepared from the ⅓ inch samples selected for latewood determinations. Each sample was appropriately marked, soaked in water, aspirated approximately 12 hours and dehydrated through 30 and 50 percent ethanol. Two to four radial sections, 13 microns thick, were prepared from each sample with a sliding microtome. The wood samples were continuously saturated with 50 percent ethanol during the sectioning procedure. The most satisfactory section from each sample was placed on a microscope slide, secured with a fine mesh screen, dehydrated and then stained with safranin. Slides were permanently mounted in Permount mounting media.

Fibril angle was measured within the central S_2 layer of the secondary cell wall, since the S_2 region constitutes the bulk of the wall. The orientation of the microfibrils in the S_2 layer is the dominant orientation in the cell wall, and this layer presumably controls the physical strength of the wood, to a great extent. Since bordered pit apertures are parallel to the fibrils in the secondary cell wall, the alignment of these apertures was selected for measurement (8). Fibril orientation within the earlywood zone was obtained by measuring the alignment of the flattened bordered pit apertures between the longitudinal and ray tracheids. Within the latewood zone, fibril orientation was determined by measuring the alignment of the half-bordered pits between the longitudinal tracheids and ray parenchyma cells. A Zeiss photomicroscope with a polarized light source was utilized to measure the deviation of the bordered and half-bordered pit apertures from the longitudinal axis of the tracheids. Pit aperture alignments were measured at 400 power magnification with an eye piece goniometer, and recorded to the nearest degree from the vertical.

Fibril angle measurements were made on materials from every annual ring in each of the specimens, with six measurements taken within each ring. Within the earlywood zone a measurement was made in the first-formed tracheid, in a tracheid representing the middle of the earlywood and in a tracheid within the earlywood portion of the transition zone. Within the latewood zone a measurement was made in a tracheid located in the latewood portion of the transition zone, in a tracheid in the middle of the latewood zone and in the next-to-the-last tracheid in the latewood. (The next-to-last tracheid in the latewood was selected rather than the last tracheid, as the latter is often markedly compressed, thereby obscuring the pit aperture alignment.) A total of 6,822 observations was made. The average fibril angle for each sample was computed by obtaining the mean latewood fibril angle and the mean earlywood fibril angle for each sample, and weighting each by the average sample latewood percentage and earlywood percentage, respectively. A detailed description of the procedures employed in these determinations of fibril angle has been reported by Shumway *et al.* (50).

All specific gravity determinations were based on samples from which the resin had not been extracted. Specific gravity was determined for each static bending and compression parallel to the grain specimen, using the one inch long sample previously prepared for moisture content determination. Specific gravity, based on oven-dry weight and oven-dry volume, was obtained by the immersion method. Rate of growth, as indicated by the number of annual rings per radial inch, was determined from both static bending and compression specimens. All measurements were taken while the specimens were conditioned at approximately 12 percent moisture content.

Evaluation of Wood Pulping Characteristics

Preparation of experimental material. The bolt quarters selected for pulping were chipped on a Carthage laboratory chipper with knife settings adjusted to produce 5/8 -to 3/16 -inch chips. The material from position one bolts in all the trees was chipped together and then screened for sizes of 5/8 and 3/16 inch. This procedure was repeated for the wood from each bole position. Chips from the butt bolts were designated as type A, those from bolts six as type B and those from bolts nine as type C. A fourth type, D, was composed of an equal-weight mixture of chip types A, B and C.

Determination of pulp yield. Cooking of the various chip types was conducted in small digesters made from 1¼ inch (ID) 316 stainless steel pipe. The use of larger digesters was impractical, due to the large number of cooks made. Details of the digesters, temperature recording instrumentation and the heating equipment employed were as described by Brown (14). By using this equipment, eight digester cooks could be made at one time. Several preliminary cooks at different conditions were made to determine those conditions which would yield a Kappa number of about 30, intermediate between bleachable and strong pulps. As a result of these pilot cooks, the following conditions were selected for the pulping yield study:

Active Alkali: 18 percent as Na_2O
Sulfidity: 27 percent as Na_2O
Liquor-to-wood ratio: 5.3:1 (milliliters per oven-dry grams wood).
Liquor concentration: 60 grams per liter as Na_2O
Maximum temperature: 338°F
Time at maximum temperature: 2 hours

The digesters were charged with 16.0 grams of 3/16 inch oven-dry chips and the proper amounts of liquor and water. Two digesters were loaded with each type of chips and the procedure was repeated once, thus obtaining four individual cooks for each chip type. The method used in preparing the pulp for yield and Kappa number determinations followed that prescribed by Brown (14). Briefly, this consists of washing the chips, disintegrating them with a Waring blender, and forming pulp pads with a Buchner funnel.

After the pulp pad from each digester reached moisture content equilibrium under TAPPI standard conditions of temperature and humidity (57), it was weighed and a sample was removed to determine moisture content. Screening of the pulp was not considered necessary, since it had been well cooked and thoroughly disintegrated with the Waring blender. Yields based on both weight and volume of wood charged to the digester were calculated in the analysis. A Kappa number test was also made on each pulp, in accordance with TAPPI method T236 m-60 (57). Variation in the Kappa number test was estimated by testing four samples taken from a single digester cook, and found to be well within acceptable limits.

Determination of pulp properties. The cooks to prepare material for the evaluation of pulp properties were conducted under the following conditions:

Wood charged: 1,000 grams (oven-dry)
Chip size: ⅜ inch
Active Alkali: 25 percent as Na_2O
Sulfidity: 21 percent as Na_20
Liquor-to-wood ratio: 7.5:1 (milliliters per oven-dry grams wood)
Maximum temperature: 338°F
Time at maximum temperature: 1½ hours

A three pound oven-dry wood capacity laboratory stainless steel digester, indirectly heated by steam, was used for all cooks. Four cooks were made, one for each pulp type, with identical procedures used for all cooks. The pulp produced by each cook was screened immediately after cooking on a Bird vibratory screen, with openings 0.008 to 0.010 inches wide. This was followed by dewatering the pulp to approximately 20 percent consistency and storing it in polyethylene bags until strength evaluations were made. A Kappa number test was made on each pulp to obtain an approximate measure of the extent of delignification.

The pulp was beaten in accordance with TAPPI method T200 ts-66 (57) for a period of two hours, to obtain Canadian Standard Freeness (CSF) values ranging from 715 ml to 240 ml. Samples were extracted from the laboratory beater at the following time intervals: 0, 45, 75, 90, 100, 110 and 120 minutes. These were stored in air tight containers until headsheets could be made. Sheetmaking, couching, pressing and drying procedures were performed in accordance with TAPPI method

T205 m-58 (57), and the sheets allowed to condition at 50 percent relative humidity and 72°F nominal before testing. Each set of headsheets was tested for basis weight, caliper, bulk, density, bursting strength, tensile strength and tearing strength. Tappi method T220 m-60 (57) was the basis for all strength tests and related calculations.

Evaluation of Wood Drying Characteristics

Experimental dry kiln procedures. For the conduct of this phase of the study a Moore Cabinet dry kiln was used (Figure 1). The three kiln schedules that were selected as representing low, medium and high kiln temperatures are described in Tables 2, 3 and 4. Procedures as outlined in the Dry Kiln Operators Manual (48) for kiln operation, moisture content sampling, equalizing and conditioning were employed. Equilibrium moisture content equivalent was recorded on a time chart as the wet and dry bulb temperature. A single tier of stock was added to the top of each kiln charge to simulate center kiln conditions in an actual test package.

Determination of drying effects on material degrade. Prior to drying, the 2 x 4's were dressed to a uniform thickness of 1¾ inches and measured for warp to the nearest 1/16 of an inch. Warp was measured as twist, cup, crook and bow by the degree of deviation from a flat plane, using a steel taper gauge. Each piece was also graded by a qualified lum-

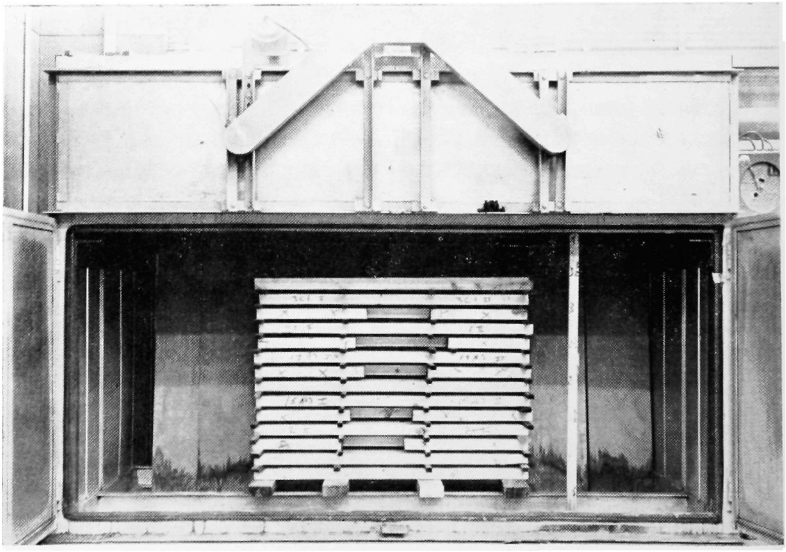

Figure 1. Experimental Dry Kiln Charge of Plantation-Grown Red Pine.

Table 2
Experimental Low Temperature Dry Kiln Schedule
for Plantation-Grown Red Pine[1]

Time Interval (hours)	Temperature Dry Bulb (°F)	Temperature Wet Bulb (°F)	Wet Bulb Depression (°F)	Relative Humidity (percent)	Equilibrium Moisture Content (percent)
9	100	100	0	100	100.0
24	100	90	10	68	11.8
24	105	90	15	55	9.4
48	110	95	15	57	9.5
26	110	90	20	46	7.7
22 (Equalize)	110	96	14	60	10.0
10 (Condition)	110	104	6	81	15.0

[1] Developed through personal correspondence with James E. Catterick, Moore Dry Kiln Company, Jacksonville, Florida. (16).

Table 3
Experimental Medium Temperature Dry Kiln Schedule
for Plantation-Grown Red Pine[1]

Moisture Content Initial (percent)	Moisture Content Terminal (percent)	Temperature Dry Bulb (°F)	Temperature Wet Bulb (°F)	Wet Bulb Depression (°F)	Relative Humidity (percent)	Equilibrium Moisture Content (percent)
Green	35	150	145	5	87	15.4
35	30	150	143	7	82	13.7
30	25	160	149	11	75	11.0
25	20	160	145	15	67	9.4
20	12	170	150	20	60	7.8
Equalize	12	170	157	13	72	9.9
Condition	12	170	165	5	89	15.0

[1] Schedule T11-B3, Rasmussen (48).

Table 4
Experimental High Temperature Dry Kiln Schedule
for Plantation-Grown Red Pine[1]

Moisture Content Initial (percent)	Moisture Content Terminal (percent)	Temperature Dry Bulb (°F)	Temperature Wet Bulb (°F)	Wet Bulb Depression (°F)	Relative Humidity (percent)	Equilibrium Moisture Content (percent)
Green	35	180	175	5	89	14.5
35	30	180	173	7	85	12.9
30	25	190	179	11	78	10.5
25	20	190	175	15	71	8.9
20	15	200	180	20	64	7.2
15	12	200	150	50	30	3.3
Equalize	12	200	188	12	77	10.0
Condition	12	200	196	4	92	15.0

[1] Schedule T14-B3, Rasmussen (48).

ber grader according to the rules of the Northeastern Lumber Manufacturers Association (4) and the warp limitations described by the Southern Pine Inspection Bureau (3).

Following the kiln drying operation each 2 x 4 was again measured for warp to the nearest 1/16 of an inch using a steel taper gauge. Each piece was regraded and its moisture content determined with a resistance type moisture meter. A stress sample was cut from each piece and tested for the presence or absence of drying stresses. A stress grade, as described by the New England Kiln Drying Association (5), was assigned to the sample.

Determination of drying effects on strength properties. Since the 2 x 4's had been dressed to a 1¾-inch thickness, it was necessary to follow the procedures described by ASTM D143-52, Secondary Methods (6). Every piece was resawn to yield one each of the following specimens: static bending, compression parallel to the grain, shear parallel to the grain and toughness. The shear samples deviated from the ASTM size specification in regard to depth dimension. A depth of 1⅝ inch was used, since the 2 x 4's had been previously dressed below the specified 2-inch depth. To reduce any possible moisture gradient within the material and to ensure conditioning to 12 percent EMC the specimens were stored in a controlled environment of 68 $\pm$ 2°F and 65 $\pm$ 1 percent relative humidity for a minimum period of one month prior to evaluation.

The static bending, compression parallel to the grain and shear parallel to the grain tests required were performed on an Instron universal testing machine, in a controlled environment of 68 $\pm$ 2°F and 65 $\pm$ 1 percent relative humidity. Toughness tests were performed on a Baldwin toughness tester at ambient laboratory conditions of 72°F and 43 percent relative humidity, with the specimens removed from the controlled environment and tested within 30 minutes.

The static bending tests were conducted to determine fiber stress at the proportional limit, modulus of rupture and modulus of elasticity. The specimens were tested using center point loading over a 14-inch span, with beam deflections measured to the nearest 0.01 inch until the proportional limit was exceeded. Continuous loading at a machine rate of 0.05 inches per minute was applied to the tangential surface of the specimen nearest the pith. A moisture content sample was cut from each specimen shortly after failure occurred.

The compression parallel to the grain tests were conducted to determine fiber stress at the proportional limit, maximum crushing strength and modulus of elasticity. The specimens were tested using a 4-inch length, as prescribed by ASTM D143-52, Secondary Methods. A Baldwin strain follower with a 2-inch span length was mounted across the center 2 inches of the specimen and deflections measured to the nearest 0.0001 inch until the proportional limit of the specimen was exceeded. The compression parallel to the grain test varied from ASTM standards in regard to the rate of loading. Due to the drive system characteristics of the Instron universal testing machine, continuous loading at a machine rate of 0.01 inches per minute was used rather than the 0.012 inches per minute loading rate specified by ASTM. A moisture content sample was cut from each specimen shortly after failure occurred.

The shear parallel to the grain test was conducted in order to determine maximum shearing strength (MSS) and total breaking load in shear (TBLS). The specimens were loaded over a shear area of approximately 4 square inches in a conventional shear testing fixture, as described in ASTM D143-52. Those specimens in which failure at the base of the specimen extended back into the supporting surface region were not used in determining MSS (stress). They were, however, included when determining TBLS (load). The shear parallel to the grain test varied from the ASTM standard in the rate of loading employed. Again, due to the drive characteristics of the Instron testing machine loading at a machine speed of 0.02 inches per minute was used rather than the 0.024 inches per minute loading rate specified.

Toughness tests were performed on a Baldwin pendulum impact testing machine, using specimens 0.79 by 0.79 inches in cross section and 11 inches long. A span length of 10 inches was used, a slight deviation from the ASTM standard D143-52 which specifies a 9.47 inch (24 cm) span. The load was applied to the tangential surface nearest the bark whenever possible, but in some instances, where the specimen had to be cut from the 2 x 4 in such a way as to produce angled growth ring orientation in the sample, the load was applied at an angle oblique to the tangential plane.

Specific gravity and growth rate determinations were made from each strength test specimen in order to have some measure of the physical characteristics of the specimens. Every 2 x 4 provided specimens for the four different strength tests; therefore, there were four specific gravity and growth rate determinations made from each of the original 2 x 4 drying samples. Specific gravity was determined using the samples already prepared for moisture content evaluation in connection with the strength tests. The measurements were made on samples from which the resin had not been extracted, and the values, obtained by the immersion method, were based on oven dry weight and volume. Growth rate was determined by counting the growth rings per inch in each test specimen prior to the strength testing procedures.

Analytical Procedures Employed

Standard formulas for determining mechanical properties were used as presented by Wangaard (59). Other formulas are identified as appropriate in the description of the various procedures employed in the investigation. Conventional statistical techniques, as described by Steel and Torie (55) and Snedecor and Cochran (52), were utilized in the analysis of the results. The values for the various material properties were computed and the analyses were performed by an IBM System 360 Model 30 computer using both original and prepared programs.

DISCUSSION AND ANALYSIS OF RESULTS

Results of Mechanical Properties Evaluation

A summary of the mean, standard deviation and range of the mechanical property values for all 16 trees studied appears in Table 5. Table 6 presents the average mechanical property values of all 16 trees, based on the two outermost radial positions within the tree for each of the tree height levels investigated; Table 7 summarizes the average mechanical property values for each individual tree based on the two outermost radial positions. An examination of the data indicated that it would not be feasible to subject all the data to statistical analysis, since the distribution of the test specimens among trees, height levels and radial positions was not uniform. To maintain statistical balance the mechanical property values that were determined for specimens originally located in radial position 3 (adjacent to the pith) were discarded from the

Table 5

Summary of the Mechanical Strength Values Determined for Wood of Plantation-Grown Red Pine[1]

Mechanical Property	Mean	Standard Deviation	Range	Coeff. of V. (percent)
Static Bending				
Fiber stress at P.L. (psi)	3,535	588	2,360 - 5,361	17
Modulus of rupture (psi)	9,676	1,393	7,143 - 13,420	14
Modulus of elasticity (1,000 psi)	1,414	317	626 - 2,280	22
Work to P.L. (in. lb./cu. in.)	0.51	0.13	0.21 - 1.03	22
Compression Parallel to the Grain				
Fiber stress at P.L. (psi)	3,651	785	1,801 - 5,452	21
Maximum crushing strength (psi)	5,210	853	3,246 - 7,446	16
Modulus of elasticity (1,000 psi)	1,455	346	585 - 2,344	24

[1] Based on sixteen, forty-eight year old trees obtained from a uniform site; 221 samples obtained from up to three radial positions at three height levels.

Table 6
Average Mechanical Strength Property Values of Wood From Various Tree Positions in Plantation-Grown Red Pine[1]

Mechanical Property	Butt Level		Mid Level		Upper Level	
	Pos. 1	Pos. 2	Pos. 1	Pos. 2	Pos. 1	Pos. 2
tic Bending						
Fiber stress at P.L. (psi)	3,964	3,428	3,765	3,616	3,635	3,412
Modulus of rupture (psi)	11,914	9,270	10,985	9,220	9,483	8,698
Modulus of elasticity (1,000 psi)	1,868	1,291	1,722	1,393	1,388	1,212
Work to P.L. (in. lb./cu. in.)	0.47	0.52	0.47	0.53	0.54	0.54
mpression Parallel to the Grain						
Fiber stress at P.L. (psi)	4,608	3,237	4,400	3,435	3,786	3,259
Maximum crushing strength (psi)	6,446	4,861	5,989	4,947	5,266	4,711
Modulus of elasticity (1,000 psi)	1,920	1,312	1,793	1,392	1,492	1,257

osition 1 adjacent to the bark, position 2 adjacent to position 1 on the pith side.

strength property analysis. Because of the relatively small diameters of the trees included in this study, a complete evaluation of the effect of radial position on strength properties was therefore not possible, despite the use of the ASTM secondary sized samples.

Table 6, which summarizes the mechanical property values for radial positions 1 (adjacent the bark) and 2 (nearer the pith) at each height level, indicates that at any selected height level the mechanical property values for the FSPL in compression, MOR, MOE and MCS exhibit an evident reduction with decreasing radial distance from the pith. Kramer (33) reported a similar relationship for static bending properties of red pine wood obtained only at breast height, but concluded that this effect was not due to position alone, but also from the influence of specific gravity, rings per inch and fibril orientation. The static bending FSPL exhibited a similar but less pronounced trend, but flexure FSPL values are considerably more subjective than MOR data. The proportional limit values in compression were more sharply defined and are, therefore, somewhat more precise than those in static bending, where the deviation of the stress-strain diagram from a straight line was more gradual.

Analyses of variance, employing a split-split plot design (Table 8), indicated that the strength differences between FSPL, MOR, MOE and MCS of wood produced in radial position 1 and comparable wood produced in radial position 2 were highly significant. Likewise, but in an inverse relationship, WPL was also significantly affected by radial position within the tree. Duncan's new multiple range test was employed to determine which radial positions in respect to height were significantly different for each strength property. Although the observed differences between the strength properties of radial positions 1 and 2 diminish with

Table 7

Average Mechanical Strength Property Values of Wood from Two Radial Tree Positions in Sixteen Plantation-Grown Red Pine[1]

Tree No.	Static Bending: Fiber Stress at P.L. (psi)	Static Bending: Modulus of Rupture (psi)	Static Bending: Modulus of Elasticity (1,000 psi)	Static Bending: Work to P.L. (in. lb./cu. in.)	Compression Parallel to the Grain: Fiber Stress at P.L. (psi)	Compression Parallel to the Grain: Max. Crushing Strength (psi)	Compression Parallel to the Grain: Modulus of Elasticity (1,000 psi)
1	3,370	9,836	1,455	0.44	3,468	5,348	1,452
2	3,724	9,481	1,487	0.53	3,670	5,390	1,553
3	3,743	10,300	1,575	0.52	3,753	5,535	1,584
4	3,638	9,587	1,461	0.51	3,387	5,133	1,479
5	3,579	10,093	1,516	0.49	3,970	5,745	1,633
6	3,204	9,629	1,448	0.41	3,931	5,311	1,552
7	3,362	9,965	1,426	0.46	3,710	5,099	1,367
8	3,427	9,585	1,450	0.46	3,736	5,219	1,525
9	3,389	9,244	1,356	0.49	3,557	4,968	1,380
10	3,780	10,069	1,523	0.53	4,076	5,360	1,613
11	3,729	10,024	1,466	0.54	3,966	5,526	1,608
12	3,696	10,445	1,531	0.51	3,949	5,536	1,507
13	3,485	9,672	1,428	0.48	3,737	5,268	1,495
14	3,996	10,464	1,521	0.60	3,898	5,592	1,573
15	3,857	10,186	1,504	0.57	4,109	5,635	1,585
16	4,210	10,278	1,514	0.66	3,638	5,264	1,534

[1] Based on twelve samples per tree obtained from the two outermost radial positions at heights of 6, 19 and 35 feet in the tree.

each successive height level up the tree, the results indicated that the effect of radial position is significant at all the height levels investigated. Main factor analysis by heights confirmed the results of Duncan's test.

The effect of height in the tree on the mechanical properties tested was neither as pronounced nor as consistent as was the effect associated with the radial position within the stem. The analyses of variance (Table 8) indicated that significant differences in the MOR, MOE, FSPL in compression and MCS values were related to height level in the tree. A Duncan's multiple range test was employed to determine which levels for each strength property were significantly different. The results are summarized in Table 9. Although the MOR and MCS were significantly different at all height levels, the values for flexural and compressive MOE and compressive FSPL at the butt and mid levels were significantly different from the respective values at the upper level. Table 6 illustrates that all the mechanical property values which were determined for radial position 1 except WPL exhibited some progressive reduction with corresponding height increases in the tree. This pattern is probably associated with the decrease in specific gravity and rings per inch, and possibly the increase in fibril angle, observed with corresponding height increases in the tree (Table 12). In contrast, Table 6 indicates that the effect of

Table 8

Results of Analyses of Variance of Data from Strength Tests of Plantation-Grown Red Pine

		Level of Significance (percent)						
		Static Bending				Compression Parallel to Grain		
urce of ariation	df	Fiber Stress at P.L.	Modulus of Rupture	Modulus of Elasticity	Work to P.L.	Fiber Stress at P.L.	Maximum Crushing Strength	Modulus of Elasticity
plications	15	99	99	N.S.	95	N.S.	N.S.	N.S.
ientation	1	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
ror	15	—	—	—	—	—	—	—
ight	2	N.S.	99	99	N.S.	99	99	99
X H	2	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
ror	60	—	—	—	—	—	—	—
dial Position	1	99	99	99	95	99	99	99
X R	1	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
X R	2	95	99	99	N.S.	99	99	99
X H X R	2	N.S.	N.S.	N.S.	N.S.	95	N.S.	N.S.
ror	90	—	—	—	—	—	—	—
tal	191	—	—	—	—	—	—	—

te: N.S. denotes no significant differences at the 95 percent level of significance.

Table 9

Duncan's New Multiple Range Test of Strength Property Values of Wood from Three Tree Height Levels

Strength Property	Height Position Butt	Middle	Upper
Static Bending			
Fiber stress at P.L. (psi)	3,696	3,691	3,524
Modulus of rupture (psi)	10,592	10,103	9,091
Modulus of elasticity (1,000 psi)	1,580	1,557	1,300
Work to P.L. (in. lb./cu. in.)	0.50	0.50	0.54
Compression Parallel to the Grain			
Fiber stress at P.L. (psi)	3,923	3,918	3,522
Maximum crushing strength (psi)	5,654	5,468	4,989
Modulus of elasticity (1,000 psi)	1,616	1,592	1,374

Note: No significant difference at the 95 percent level between mean values underscored by a common line.

height in the tree is apparently not consistent for the similar strength values determined for radial position 2. The FSPL, MOE and MCS values exhibited an initial increase from the butt to the mid level, followed by a reduction in the strength values from the mid level to the upper level. The MOR value, however, exhibited only a minor decrease from the butt to the mid level, followed by a reduction from mid height to the upper level. Lower strength could be expected in the upper level, since this bolt was in the vicinity of the base of the crown and undoubtedly contained the larger proportion of crown-formed wood, which is characterized by shorter fibers and lower specific gravity (15).

Since the observed differences in latewood percentage, fibril angle and specific gravity between positions 1 and 2 diminish with increased height in the tree (Table 12), much of the difference in response to radial position at the various height levels may undoubtedly be attributed to the physical characteristics of the wood itself. Such differences are evident in Table 8 as the highly significant interactions for the mechanical properties of MOR, MOE, compressive FSPL and MCS, and as the significant interaction for flexural FSPL.

Although north or south orientation of the specimen in the tree has no discernible influence on any of the mechanical characteristics, the significant second order interaction in Table 8 between north-south orientation, height and radial position for compressive FSPL implies that the difference in response of FSPL to radial positions at the various height levels is also influenced by the side of the tree from which the wood is obtained. No confirmed explanation for this phenomenon is currently available.

Tables 5 and 7 illustrate that some of the strength property values under consideration vary considerably among the 16 trees that were evaluated. The analyses of variance confirmed that these differences are highly significant for the mechanical properties of flexural FSPL and MOR, and are significant for WPL. Significant variation in mechanical properties among the trees was not expected, since the influence of site and tree age were controlled and should not have appreciably affected the strength of the material. Heredity may have contributed to this variation, but since the trees that were evaluated in this study were of unknown progeny, analysis of this factor must remain beyond the scope of the study.

Determination of Physical and Mechanical Properties

Table 10 summarizes the mean, standard deviation, and range of values of the latewood percentage, ring fibril angle, specific gravity and growth rate of the wood from all 16 trees studied. Table 11 presents the average physical values of radial positions 1 and 2 for each individual tree. Table 12 summarizes the average physical values of all trees based on the two outermost radial positions within the tree for each of the three height levels.

Table 10

Summary of the Average Physical Characteristic Values for Wood from Plantation-Grown Red Pine[1]

Physical Characteristic	Mean	Standard Deviation	Range
Latewood Percent[2]	16.75	6.42	6.65–34.58
Ring Fibril Angle (deg.)[3]	36.5	3.6	27.8–47.0
Growth Rate (rpi)[4]	8.2	2.3	4.5–14.0
Specific Gravity[4,5]	0.401	0.035	0.347–0.516

[1] Based on sixteen, forty-eight year old red pine trees.
[2] Based on 1,760 observations.
[3] Based on 6,822 observations.
[4] Based on 221 samples.
[5] Based on oven-dry weight and volume.

Table 11

Average Physical Characteristic Values for Wood from Two Radial Positions in Sixteen Plantation-Grown Red Pine Trees[1]

Tree No.	Latewood Percent	Ring Fibril Angle (deg.)	Growth Rate (rpi)	Specific Gravity
1	17.01	34.6	9.2	0.403
2	16.68	35.8	8.3	0.397
3	18.57	34.7	8.8	0.414
4	18.01	36.3	8.0	0.399
5	17.74	35.3	8.8	0.419
6	18.36	37.0	8.6	0.392
7	16.60	38.1	7.8	0.398
8	20.87	34.9	7.8	0.406
9	18.31	35.8	8.1	0.390
10	10.01	34.8	8.2	0.412
11	17.94	34.1	8.8	0.408
12	19.22	35.5	9.0	0.419
13	17.48	35.4	8.5	0.389
14	17.62	36.4	8.1	0.422
15	16.78	33.9	9.2	0.408
16	18.11	34.7	10.0	0.409

[1] Based on values obtained from height levels of six, nineteen and thirty-three feet. Specific gravity based on oven-dry weight and volume.

Table 12

Average Physical Characteristic Values for Wood From Various Positions in Plantation-Grown Red Pine Trees[1]

Physical Property	Butt Level		Mid Level		Upper Level	
	Pos. 1	Pos. 2	Pos. 1	Pos. 2	Pos. 1	Pos. 2
Latewood Percent	27.63	16.83	21.82	14.06	15.21	13.50
Fibril Angle (deg.)	32.4	37.0	34.0	36.9	37.1	38.6
Specific Gravity	0.465	0.388	0.424	0.378	0.396	0.375
Growth Rate (rpi)	11.5	10.0	10.3	7.9	6.9	5.4

[1] Position 1 adjacent to the bark, position 2 adjacent to position 1 on the pith side. Specific gravity based on oven-dry weight and volume.

The Relationship of Physical and Mechanical Properties

A series of three separate stepwise multiple regression analyses was performed between the mechanical strength properties under consideration and the following independent variables: latewood percentage, fibril angle, specific gravity, growth rate, radial position and height level in the tree. The choice of the independent variables was made primarily on an empirical basis; previous investigations had shown that the mechanical properties involved are related in varying degrees to each individual independent variable included. The analyses were performed by computer, employing prepared correlation and stepwise regression analysis programs.

The initial multiple regression analysis was performed on all of the static bending strength property values of FSPL, MOR, MOE and WPL, and all of the independent variables mentioned above except fibril angle. Since fibril angle was obtained from a stratified sample consisting of only 150 of the static bending specimens, it was necessary to employ a second separate multiple regression analysis between the individual flexure strength properties discussed and each of the independant variables. A third multiple regression analysis was performed between the individual compression parallel to the grain strength properties of FSPL, MCS and MOE and the independent variables, but excluding the fibril angle and latewood percentage factors. The coefficient of multiple determination (R^2) of the regressions between the static bending strength properties and wood physical characteristics, and the regression coefficient sign for the first and second multiple stepwise regressions are summarized in Tables 13 and 14, respectively. The correlation coefficients are shown in Tables 15 and 16.

As illustrated in Table 13, although radial position alone accounted for 23 percent of the variation in FSPL, approximately 71 percent of the observed variation remained unexplained after the addition of three highly significant independent variables: specific gravity, rings per inch and height in the tree. An insignificant decrease in the residual sums of squares was observed when latewood percentage was added as a third independent variable. With latewood percentage held constant, however, a significant reduction in the residual sums of squares was obtained when rings per inch and height in the tree were included as a fourth and fifth independent variable, respectively. Since latewood percentage was apparently directly related to both specific gravity and rings per inch (Table 15), the contribution of latewood percentage to the variability of FSPL was probably masked. Although the results of the second multiple regression indicated that fibril angle alone accounted for 33 percent of the variation of FSPL, the addition of specific gravity, late-

Table 13

Relationship of Static Bending Strength Values to Statistically Significant Independent Variables[1]

Strength Property	Number of Variables	Regression Coefficient Signs of the Independent Variables: Specific Gravity	Radial Position	Rings/ Inch	Height in Tree	Percent Latewood	R^2
Fiber Stress at P.L.	1						0.23
	2	+	–				0.26
	3	+	–			N.S.	0.26
	4	+	–	+		–	0.28
	5	+	–	+	+	–	0.29
Modulus of Rupture	1	+					0.79
	2	+	–				0.82
	3	+	–	+			0.84
Modulus of Elasticity	1	+					0.68
	2	+	–				0.75
	3	+		+			0.77
	4	+	–	+	+		0.78
	5	+	–	+	+	+	0.78
Work to P.L.	1					–	0.03
	2		–			–	0.05

[1] Significant at the 99 percent level; N.S. denotes non-significance.

wood percentage and radial position increased the total R^2 to only 40 percent. It is quite possible that the magnitude of the variability in the FSPL strength values themselves may be responsible for the unaccounted variation.

A much larger percentage of the variation in both the MOR and the MOE was accounted for by the variables considered. An R^2 of 0.79 for the relationship between MOR and specific gravity was obtained in the first regression. With the effect of specific gravity held constant the addition of radial position and rings per inch, both also highly significant, increased the total R^2. The second regression again indicated that specific gravity was the strongest factor affecting the MOR. The five-variable relationship accounted for 88 percent of the variation in the MOR. The first regression indicated that specific gravity alone accounted for 68 percent of the variablity observed in MOE; fibril angle alone, however, accounted for 77 percent of the MOE variation in the second regression analysis. This would support Meylan and Probine (41) and others who conclude that the elastic properties of the wood cell are closely related

Table 14

Relationship of Static Bending Strength to Statistically Significant Independent Variables[1]

		Regression Coefficient Signs of the Independent Variables						
Strength Property	Number of Variables	Fibril Angle	Specific Gravity	Radial Position	Rings/Inch	Percent Latewood	Height in Tree	R^2
Fiber Stress at P.L.	1	–						0.33
	2	–	+					0.36
	3	–	+			–		0.38
	4	–	+	–		–		0.40
Modulus of Rupture	1		+					0.82
	2	–	+					0.86
	3	–	+	–				0.88
	4	–	+	–	+			0.88
	5	–	+	–	+	–		0.88
Modulus of Elasticity	1	–						0.77
	2	–	+					0.83
	3	–	+	–				0.85
	4	–	+	–	+			0.86
	5	–	+	–	+		+	0.86
Work to P.L.	1					–		0.03
	2		+			–		0.06

[1] Significant at the 99 percent level.

Table 15

Correlation Coefficients for Static Bending Sample Physical and Mechanical Strength Values

	Radial[1] Position	Height in Tree	Latewood Percent	Rings Inch	Specific Gravity	Work to P.L.	Modulus of Elasticity	Modulus of Rupture	Fiber Stress at P.L.
Fiber Stress at P.L.	-0.478	0.036	0.390	0.376	0.445	0.734	0.585	0.561	1.000
Modulus of Rupture	-0.731	-0.234	0.811	0.723	0.890	-0.076	0.928	1.000	
Modulus of Elasticity	-0.748	-0.126	0.802	0.694	0.822	-0.111	1.000		
Work to P.L.	0.039	0.129	-0.180	0.105	-0.125	1.000			
Specific Gravity	-0.669	-0.337	0.874	0.726	1.000				
Rings/ Inch	-0.448	-0.578	0.756	1.000					
Latewood Percent	-0.699	-0.325	1.000						
Height in Tree	-0.222	1.000							
Radial Position	1.000								

[1] Distance from the bark.

Table 16

Correlation Coefficients for Static Bending Sample Physical and Mechanical Values

	Fibril Angle	Radial Position[1]	Height in tree	Latewood Percent	Rings/ Inch	Specific Gravity	Work to P.L.	Modulus of Elasticity	Modulus of Rupture	Fiber Stress at P.L.
Fiber at P.L.	-0.574	-0.538	-0.029	0.484	0.484	0.550	0.674	0.659	0.648	1.000
Modulus of Rupture	-0.833	-0.784	-0.260	0.860	0.794	0.905	-0.905	-0.052	1.000	
Modulus of Elasticity	-0.879	-0.802	-0.144	0.845	0.767	0.832	-0.098	1.000		
Work to P.L.	-0.099	-0.076	0.082	-0.163	-0.100	-0.070	1.000			
Specific Gravity	-0.767	-0.719	-0.388	0.913	0.793	1.000				
Rings/ Inch	-0.746	-0.585	-0.536	0.804	1.000					
Latewood Percent	-0.827	-0.761	-0.331	1.000						
Height in Tree	0.137	-0.178	1.000							
Radial Position	0.760	1.000								
Fibril Angle	1.000									

[1] Distance from the bark.

to the microfibril angle in the S_2 layer. The addition of specific gravity, radial position, rings per inch and height, respectively, as significant independent variables accounted for 86 percent of the variability in the MOE.

Although the presence of mild forms of compression wood was observed in a few individual growth increments in the test material, no effort was made to eliminate it since, like high resin content, it was considered a valid portion of the error variation in the analysis. Possibly the R^2 estimate would have improved if the resin had been extracted prior to determining specific gravity. In like manner, the presence of mild compression wood tends to lower the specific strength of wood. An improved R^2 value may also have resulted if the test samples containing mild compression wood had been eliminated, since the modified S_2 layer of the compression wood cell wall exhibits a much greater fibrillar angle than normal wood. Although specific gravity and latewood percentage proved significant in the analysis of WPL, a negligible proportion of the variability in WPL was accounted for by these variables. The difficulty in precisely determining the proportional limit may have contributed to the rather poor R^2 estimate. Table 16 illustrates that fibril angle has a strong negative relationship to latewood percentage, specific gravity and rings per inch. Rings per inch is also significantly correlated with both specific gravity and latewood percentage. These relationships suggest that possibly an initial dense establishment in red pine plantations should be considered, followed by timely thinnings after crown closure has been achieved to maintain a desirable rate of growth.

The third stepwise multiple regression analysis performed between compressive FSPL, MCS, MOE and the independent variables indicated that specific gravity alone is the most important contributing variable. Table 17 reveals that 55, 73 and 65 percent of the variability in the FSPL, MCS and MOE, respectively, is accounted for by specific gravity. The R^2 is significantly increased when radial position is added as a second variable. The addition of rings per inch and tree height, although highly significant in themselves, increased the total R^2 only an additional one to four percent. It is also possible that the effect of rings per inch would have accounted for more of the variability in both the flexure and compression strength properties if the radial position variable were omitted from the regression, since Tables 15, 16 and 18 indicate a correlation between radial position and rings per inch.

Results of Wood Pulping Investigation

Analysis of pulp yield study. Table 19 shows the total yield results, based on the oven-dry weight of wood, obtained from each pulping sample for each tree position, together with the Kappa number and residual lignin of these samples. An examination of yield data revealed no notable difference between the chip types, and this was statistically verified by standard analysis of variance procedures. Since these yields were based on the oven-dry weight of wood cooked, the effect of specific gravity was masked. Different values were obtained, however, when yield was calculated on the basis of the volume of wood cooked. Table 20 indicates the total weight of chips cooked for each tree position, as well as the yield in grams obtained for these positions. Table 20 also presents yields based on oven-dry weight of wood converted to yield based on an equal volume of wood cooked for each chip type. Figure 2 illustrates the effect of specific gravity and position in the tree on pulp yield. In working with the southern pines, Cole *et al.* (17) found that differences in yield were directly proportional to differences in specific gravity, and that these differences could be directly related to yield per acre. Chip types A, B and D exhibited higher specific gravities than type C, as well as higher yield results, in agreement with Cole's observation that yield is directly related to specific gravity. An analysis of variance also revealed no significant differences among cooks from a chip type, suggesting that variations due to cooking were essentially random. Brown's (14) assessment of the

Table 17

Relationship of Compression Parallel to the Grain Strength Values and Significant Independent Variables[1]

Strength Property	Number of Variables	Regression Coefficient Signs of the Independent Variables: Specific Gravity	Radial Position	Rings/ Inch	Height in Tree	R^2
Fiber	1	+				0.55
Stress	2	+	–			0.64
at P.L.	3	+	–		+	0.64
	4	+	–	+	+	0.66
Maximum	1	+				0.73
Crushing	2	+				0.79
	3	+	–	+		0.79
	4	+	–	+	+	0.80
Modulus of	1	+				0.65
Elasticity	2	+	–			0.74
	3	+	–	+		0.76
	4	+	–	+	+	0.78

[1] Significant at the 99 percent level.

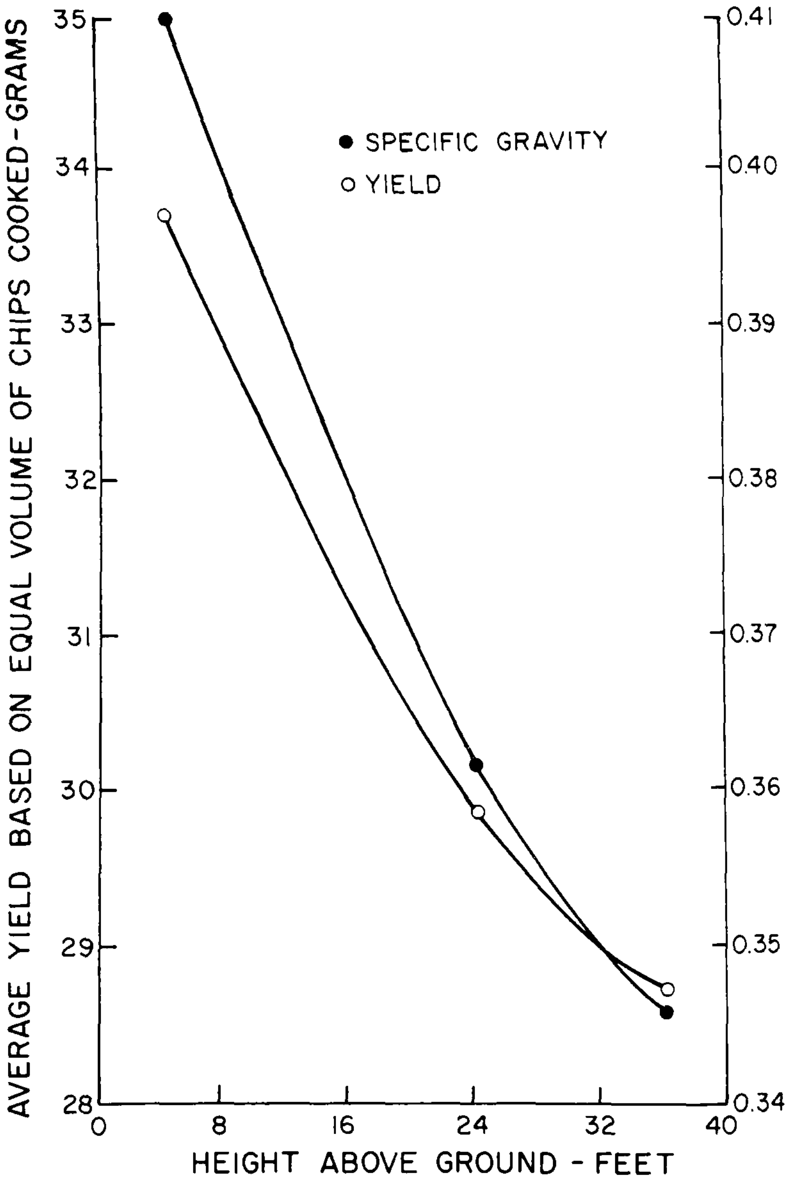

Figure 2. The Relationship of Pulp Yield and Specific Gravity to Height in Plantation-Grown Red Pine.

Table 18

Correlation Coefficients for Compression Parallel to the Grain Physical and Mechanical Strength Values

	Radial Position	Height in Tree	Rings/ Inch	Specific Gravity	Modulus of Elasticity	Maximum Crushing Strength	Fiber Stress at P.L.
Fiber Stress at P.L.	–0.716	–0.016	0.549	0.743	0.901	0.927	1.000
Maximum Crushing Strength	–0.747	–0.115	0.642	0.857	0.939	1.000	
Modulus of Elasticity	–0.770	–0.061	0.648	0.806	1.000		
Specific Gravity	–0.674	–0.338	0.702	1.000			
Rings/ Inch	–0.479	–0.567	1.000				
Height in Tree	–0.222	1.000					
Radial Position	1.000						

Table 19

Yield, Kappa Number and Residual Lignin Values of Various Cooks of Experimental Red Pine Pulp

Pulp Type	Cook	Yield (percent)	Kappa Number	Residual Lignin (percent)
A	1	44.2	29.0	4.4
	2	44.3	34.1	5.1
	3	44.0	30.5	4.6
	4	44.5	34.4	5.2
	Average	44.4	32.0	4.8
B	1	45.1	30.8	4.6
	2	45.1	29.2	4.4
	3	43.9	27.1	4.1
	4	44.7	26.1	3.9
	Average	44.7	28.3	4.2
C	1	45.1	31.0	4.6
	2	45.6	31.7	4.8
	3	44.8	24.3	3.6
	4	44.2	25.0	3.8
	Average	44.9	28.0	4.2
D	1	44.1	24.8	3.7
	2	45.1	26.7	4.0
	3	44.5	24.7	3.7
	4	44.3	27.2	4.1
	Average	44.5	25.8	3.9

Table 20

Average Yield Results for Experimental Red Pine Pulp Based on Weight and Volume of Wood Cooked

Pulp Type	Average Specific Gravity	Total Weight Chips Cooked (grams)	Volume of Chips Cooked (c.c. cent.)	Average Yield (grams)	Average Yield Weight Base (percent)	Average Yield 185 c.c. Base (grams)
A	0.41	64.0	156	28.4	44.4	33.7
B	0.36	64.0	177	28.6	44.7	29.9
C	0.35	64.0	185	28.7	44.9	28.7
D	0.37	64.0	172	28.5	44.5	30.6

Note: Average Yield based on chip volume = Average Yield (gm.) x 185/Vol. chips cooked.

cooking equipment employed in this investigation stated that, operating in the 45 percent yield range, cooks could be expected to vary ± 0.05 percent, and the yield results for the individual pulp types followed this anticipated variability.

Pulp purity, as measured by the Kappa number, is reported for each cook in Table 19. A Duncan's test was conducted to determine if significant differences in the Kappa numbers of one pulp type versus another existed. Although types A and D were the only ones that differed significantly, a possible trend of increased pulp purity with increasing tree height is suggested by the mean values. Since there is an indication that the lignin and extractive contents are slightly higher in the butt portion of the tree (13), inadequate penetration of the liquor or insufficient cooking time might result in lowered pulp purity for that section. As to why type D pulp had a higher purity value than the others, two explanations are possible. The first is that when a composite of all tree positions is cooked, liquor penetration into the chips is perhaps more even, and a higher purity pulp is obtained. The second possibility is that no real difference exists, and that those observed were caused by random variation. Barefoot *et al.* (12), in conducting pulping studies on loblolly pine found that composite material made up of core and peripheral wood resulted in improved pulp purity, but no reason for this difference was offered. Four Kappa tests were conducted on one pulp sample, Type D Cook 3, to confirm the accuracy of the test. Examination of the results indicated that the test exhibited good reproducibility, with a coefficient of variation of 4.2 percent.

Determination of pulp properties. Table 21 presents the yield, Kappa number and residual lignin determinations made on the pulp prepared for strength property evaluation. Figures 3 and 4 illustrate the effect that beating time had on the burst factor and breaking length properties of

Table 21

Yield, Kappa Number and Lignin Content of Experiment Red Pine Pulp Used in Strength Evaluation Study

Pulp Type	Yield (percent)	Kappa Number	Lignin Content (percent)
A	44.7	36.1	5.4
B	45.8	34.4	5.2
C	46.2	34.4	5.2
D	46.9	33.0	5.0

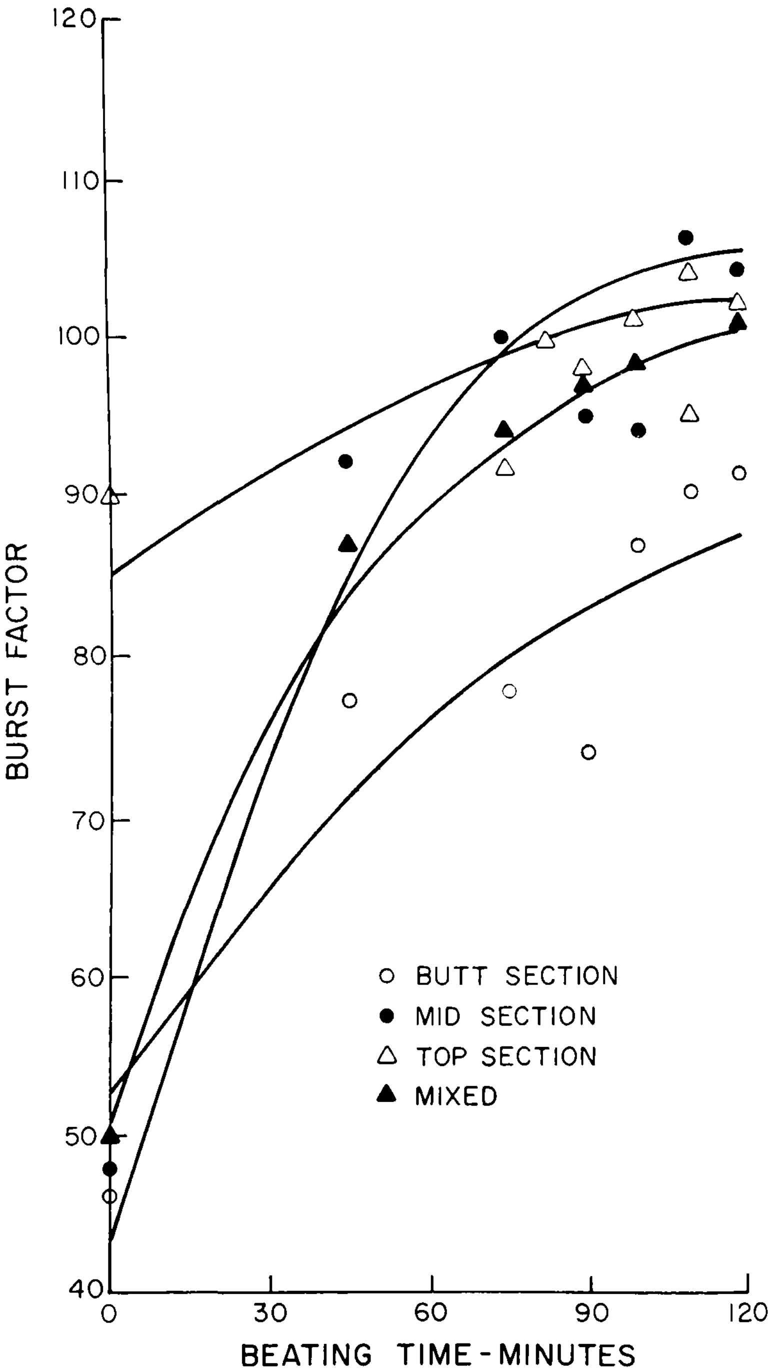

Figure 3. The Relationship of Burst Factor to Beating Time for Experimental Pulps from Plantation-Grown Red Pine

each pulp type. For all pulp types, the curves established followed the typical pattern of developing strength with increasing beating time. Examination of these curves also indicates that stronger pulps were obtained as the height above ground increased. Evaluation of the results by analysis of variance, employing a subplot design, indicated significant differences in beating time and pulp type, or position in the tree, and a significant interaction between these main factors. Tables 23 and 24 provide a summary of these analyses. The average strength values used in constructing the curves appear in Table 22, and the physical properties of the pulp types in Table 25.

Duncan's new multiple range test was employed to determine which beating times, for each pulp type, were significantly different. The results

Table 22

Average Strength Values for Experimental Red Pine Pulp

Pulp Type	Beating Time (min.)	Burst Factor	Breaking Length (100 m)	Tear Factor
	0	47	91	197
	45	77	99	144
	75	78	108	140
A	90	74	101	131
	100	87	103	134
	110	90	105	136
	120	91	107	132
	0	48	75	229
	45	92	124	134
	75	100	131	131
B	90	95	130	124
	100	94	105	125
	110	106	114	141
	120	104	128	132
	0	90	123	123
	75	92	132	116
	83	100	130	115
C	90	98	131	121
	100	101	129	119
	110	104	129	116
	120	102	112	116
	0	50	80	179
	45	87	119	129
	75	94	125	116
D	90	97	127	124
	100	98	131	116
	110	95	127	115
	120	101	124	108

Note: Average values based on $n=5$ for breaking length, burst factor and tear factor.

of this analysis are also summarized in Tables 23 and 24. Generally, little additional strength developed after 75 minutes of beating, and in the case of breaking length, strength evidently decreased after 90 minutes. This indicates that 75 to 90 minutes of beating would suffice for this pulp to reach maximum strength. Comparison of the four pulp types, representing the different tree heights, at various beating times was not attempted statistically because of the complex interactions evident in Figures 3 and 4.

The higher burst factors and breaking lengths obtained as tree height increased may well result from the effect of fiber morphology on the mechanism of beating and fiber bonding. Since specific gravity may be directly correlated with cell wall thickness and fiber flexibility, those sheet properties dependent on strong fiber-to-fiber bonds will tend to exhibit higher strength values as height above ground increases. Such is the case for burst factor and breaking length results. Analysis of variance has also indicated that a significant interaction existed between beating time and position in the tree, but this was expected, since the

Table 23

Analysis of Variance and Duncan's New Multiple Range Test of Average Burst Factor Values for Experimental Red Pine Pulp

Source Variation	df	Sum of Squares	Mean Square	F Value	Percent Level of Significance
Beat. Time	5	23,033	4,606	209.36	94
Tree Position	3	6,033	2,011	91.41	99
B X T	15	5,393	360	16.36	99
Error	96	2,087	22	—	—
Total	119	36,546	307	—	—

Duncan's Test of Burst Factor Values

Pulp Type	Beating Time (minutes) 0	90	75	100	110	120
A	47	74	78	87	90	91
B	48	94	95	100	104	106
C	90	92	98	101	102	104
D	50	94	95	97	98	101

Note: No significant difference between values underscored by a common line (95 percent level).

Table 24

Analysis of Variance and Duncan's New Multiple Range Test of Average Breaking Length Values for Experimental Red Pine Pulp

Source Variation	df	Sum of Squares	Mean Square	F Value	Percent Level of Significance
Beat. Time	5	13,496	2,649	55.00	99
Tree Position	3	8,842	2,947	60.14	99
B X T	15	10,075	672	13.71	99
Error	96	4,726	49	—	—
Total	119	37,112	312	—	—

Duncan's Test of Burst Factor Values

Pulp Type	Beating Time (minutes) 0	90	100	110	120	75
A	91	101	103	105	107	108
B	75	105	114	128	130	131
C	112	123	129	129	131	132
D	80	125	124	127	127	131

Note: No significant difference between values underscored by a common line (95 percent level).

specific response to beating was different and disproportionate for each pulp type.

Freeness, a reflection of energy expended in beating the pulp, indicated that all the pulps needed approximately the same degree of beating to achieve similar freeness levels (Figure 5). The tear strength values obtained in the course of the investigation followed the expected inverse relationship with beating time. Figure 6 graphically illustrates this. Higher values were obtained from the butt portion, as expected, since stronger fibers tend to be found in the lower part of the stem. Sheet density is considered a measure of fiber plasticity and is presumed to be directly related to it. It is calculated as the inverse of bulk, which is the volume of pulp per unit weight. Figures 7 and 8 describe the relationship of density and bulk to beating time for each pulp type. As might be expected, density exhibits a direct relationship to burst factor and breaking length. Density increases with both beating time and height above ground. Since specific gravity decreased with increasing height above ground, the fibers formed in the top portion of the stem of sample trees

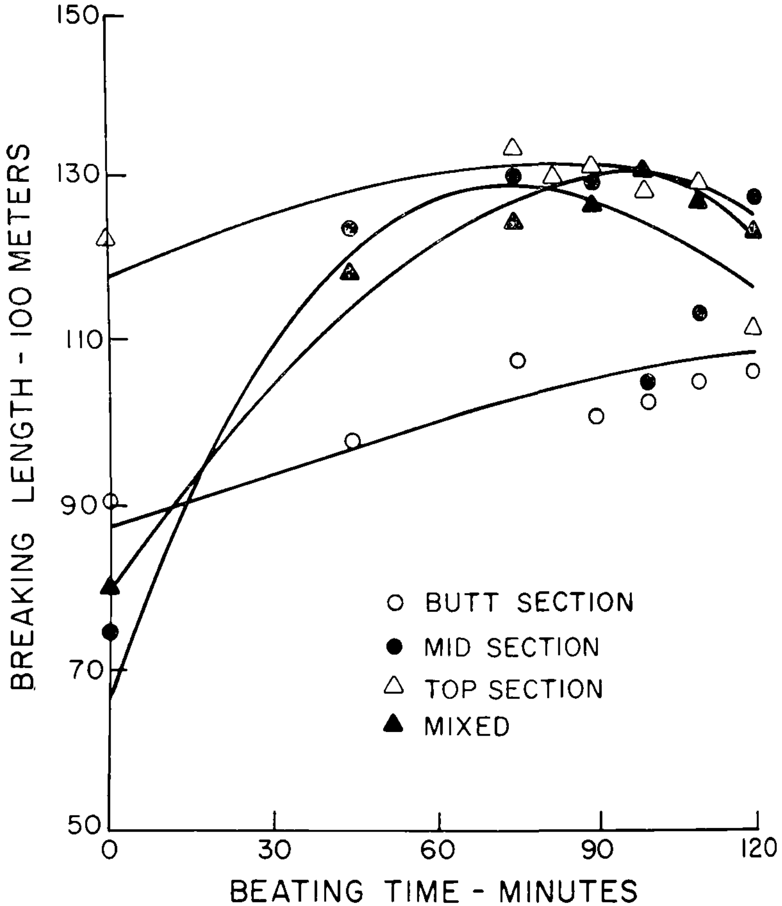

Figure 4. The Relationship of Breaking Length to Beating Time for Experimental Pulps from Plantation-Grown Red Pine.

may well have had thinner cell walls and therefore greater plasticity, resulting in higher density values. Because of its inherent relationship to density, bulk responded exactly opposite to density. Freeness and tearing strength values were further examined by analysis of variance techniques, revealing significant differences for both the main factors, beating time and pulp type. Further analysis was not attempted in either instance, due to the very significant and complex (cross-over) interactions evident in both analyses.

Table 25

Various Physical Characteristics of the Experimental Red Pine Pulp

Pulp Type	Beating Time (min.)	Freeness CSF (ml.)	Basis Weight (g.s.m.)	Bulk (cc/g)	Density (g/cc)
A	0	715	59.93	1.95	0.513
	45	640	62.38	1.55	0.646
	75	510	61.98	1.48	0.678
	90	430	60.24	1.52	0.659
	100	360	59.32	1.46	0.687
	110	300	60.42	1.43	0.700
	120	240	61.43	1.41	0.711
B	0	715	64.55	1.89	0.529
	45	640	64.34	1.50	0.668
	75	520	64.70	1.45	0.688
	90	425	62.76	1.46	0.686
	100	360	65.81	1.43	0.700
	110	300	65.50	1.40	0.716
	120	240	63.28	1.40	0.712
C	0	690	64.35	1.46	0.685
	75	495	66.52	1.38	0.727
	83	450	62.74	1.42	0.706
	90	405	64.81	1.41	0.709
	100	350	63.09	1.37	0.730
	110	290	62.15	1.40	0.719
	120	240	61.93	1.39	0.717
D	0	715	61.78	1.89	0.529
	45	640	62.05	1.52	0.660
	75	535	62.85	1.46	0.687
	90	460	59.44	1.45	0.688
	100	410	60.20	1.44	0.697
	110	360	58.99	1.42	0.704
	120	290	62.51	1.38	0.724

Analysis of Wood Drying Characteristics

Effect of kiln drying schedules on material grades. In the drying of the plantation-grown red pine it became apparent that it was not feasible to follow every step of the schedules suggested by Rasmussen (48). In the high temperature schedule several steps involving dry and wet bulb adjustment were omitted, since the drying rate was developed in such a way that these steps would have had a duration of only two to four hours. The actual wet and dry bulb settings followed are shown in Figure 9. The medium temperature schedule was altered from the planned procedure in that a period of equalizing occurred prior to the fiber saturation point, due to a malfunction in which the internal kiln fans were not in operation. It was concluded, however, that this did not affect the results

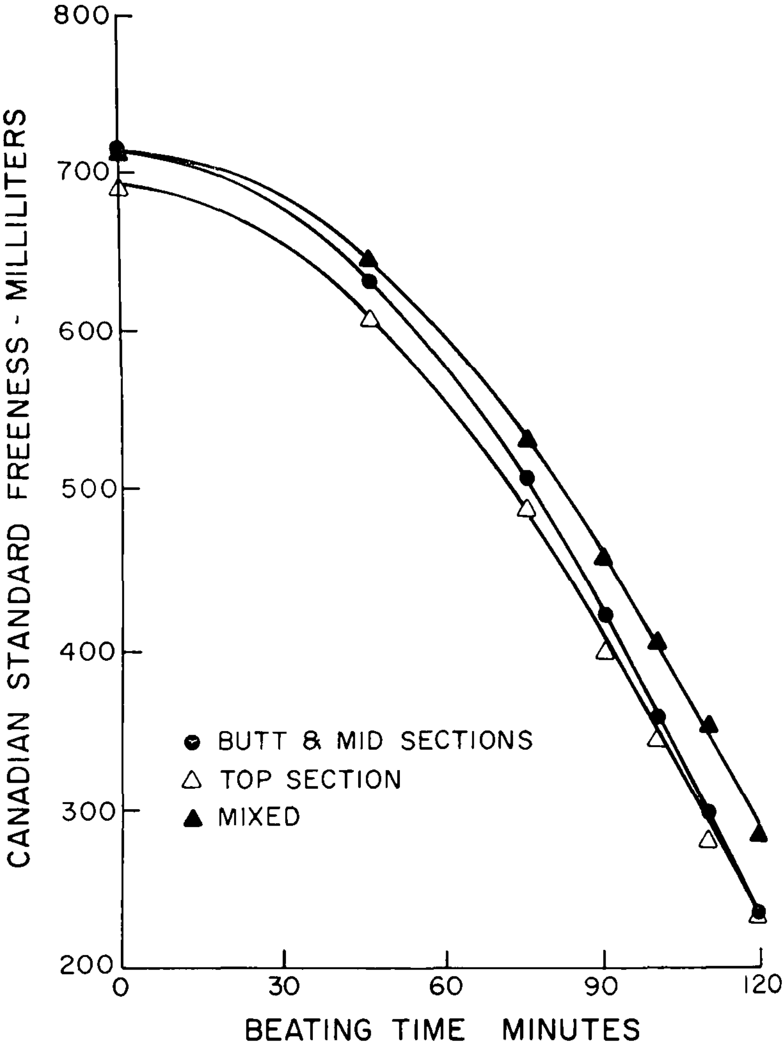

Figure 5. The Relationship of Freeness to Beating Time for Experimental Pulps from Plantation-Grown Red Pine.

but did, in fact, only serve to equalize the moisture content of the wood above the FSP. The low temperature schedule, which is structured as a time-based schedule, was not altered from the originally proposed procedure.

The low temperature schedule required the shortest period of time to dry the material. As shown in Table 26, the low temperature schedule

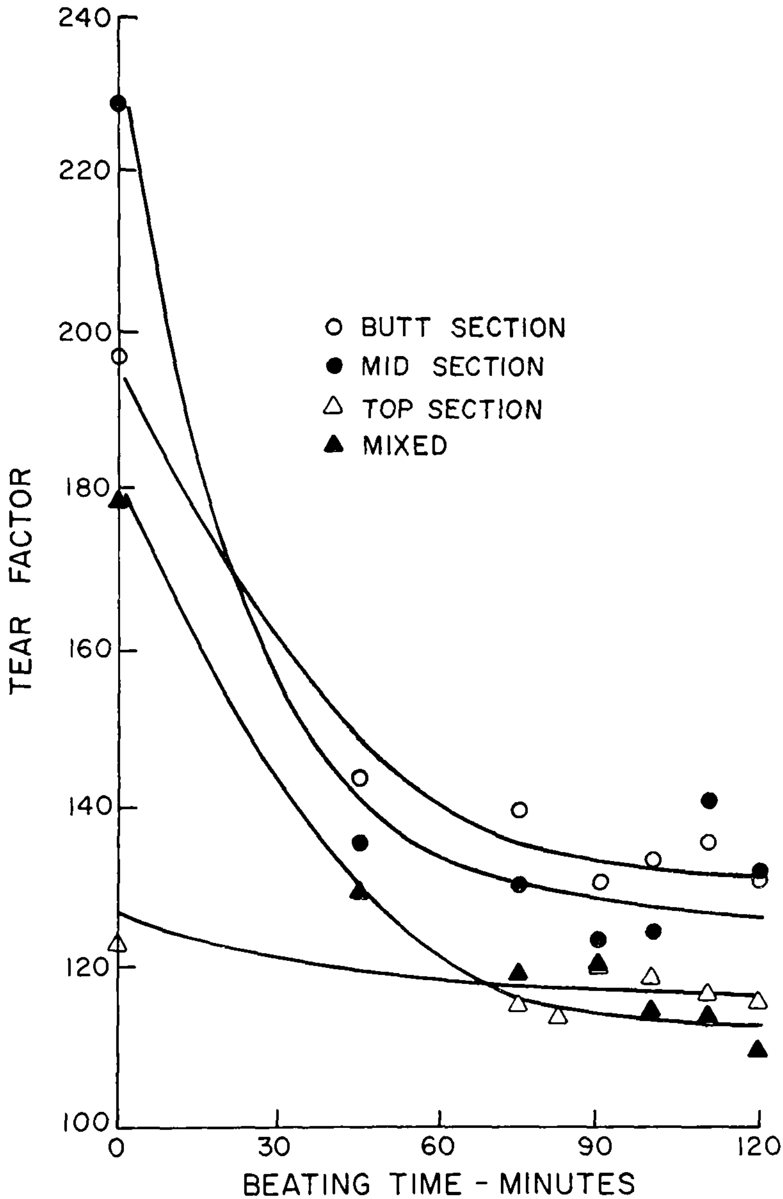

Figure 6. The Relationship of Tear Factor to Beating Time for Experimental Pulps from Plantation-Grown Red Pine.

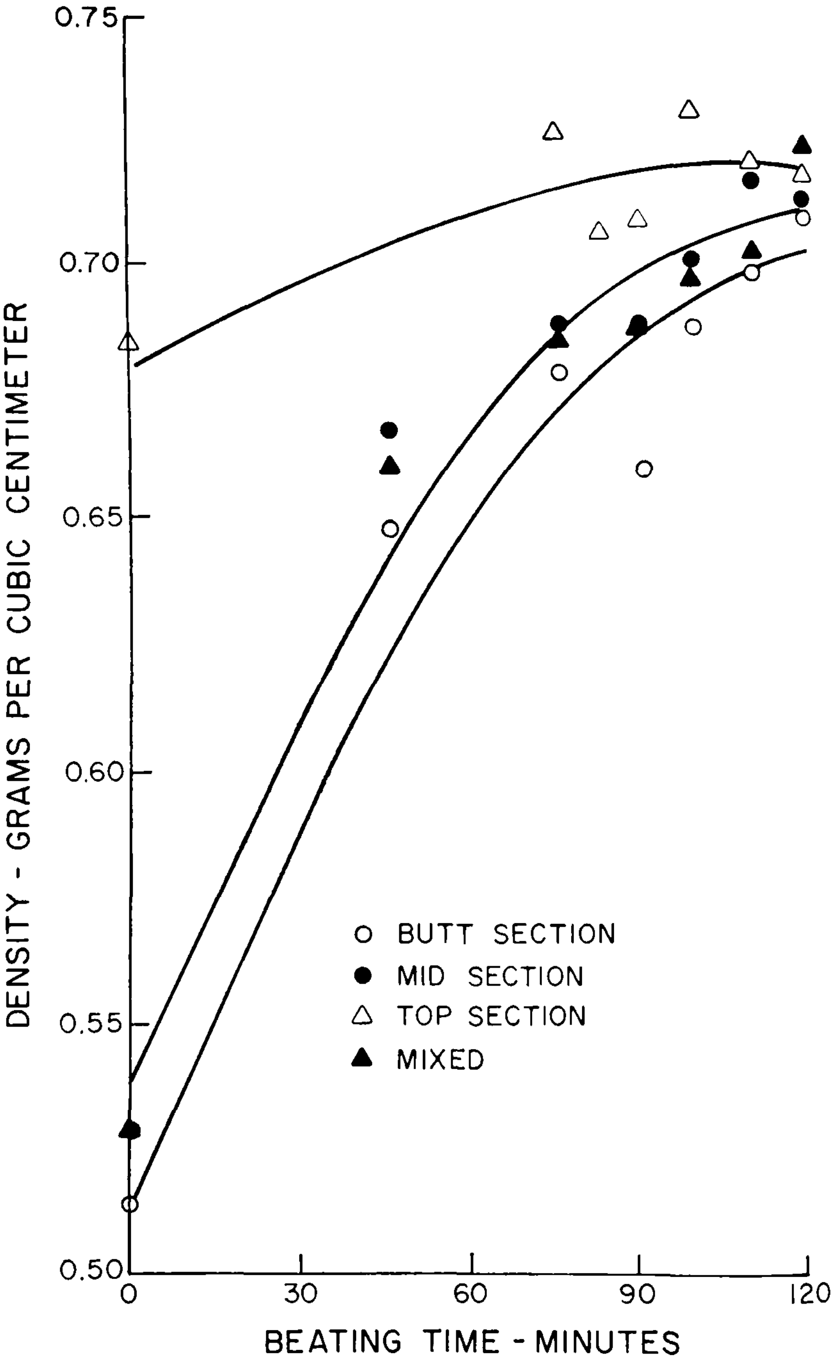

Figure 7. The Relationship of Sheet Density to Beating Time for Experimental Pulps from Plantation-Grown Red Pine

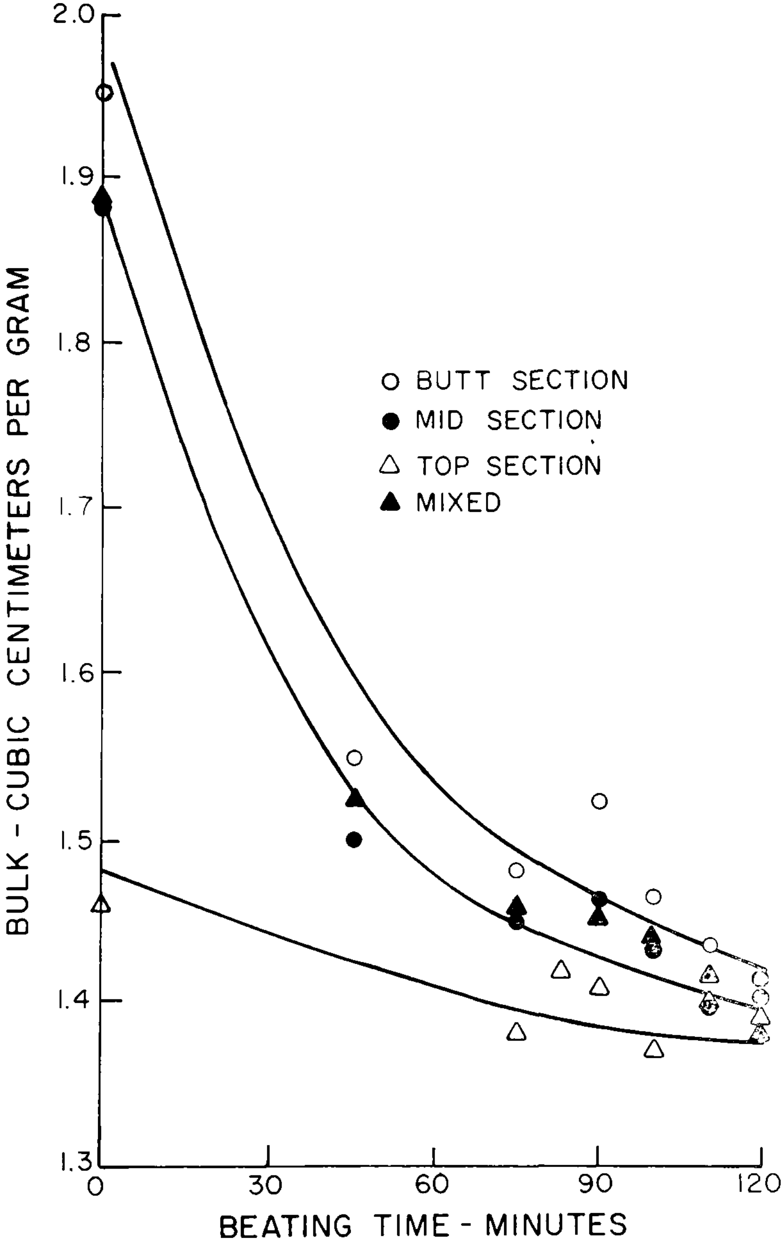

Figure 8. The Relationship of Bulk to Beating Time for Experimental Pulps from Plantation-Grown Red Pine.

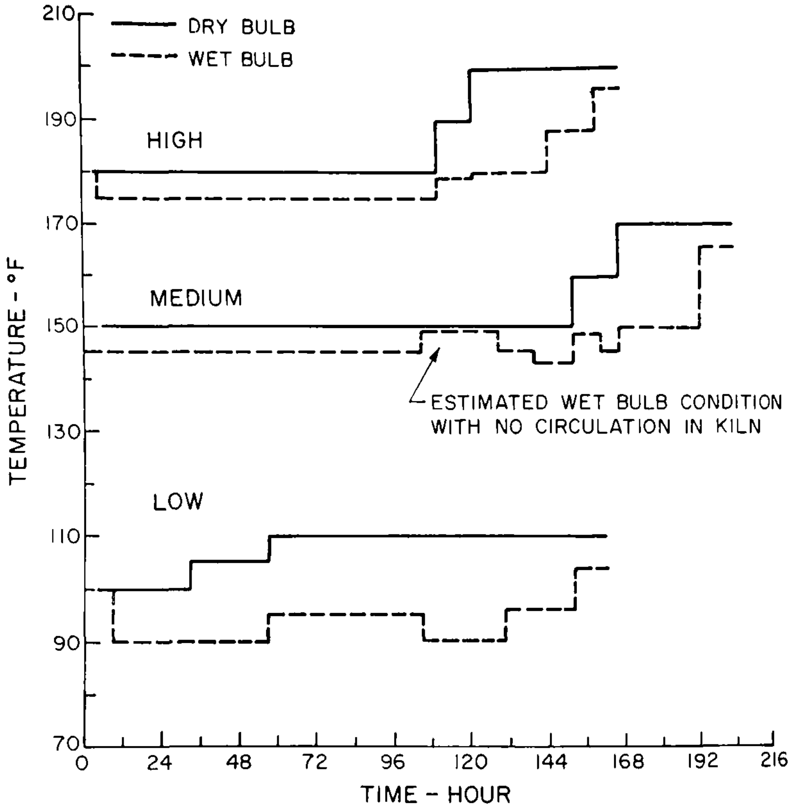

Figure 9. Experimental Dry Kiln Schedules as Completed in Drying Plantation-grown Red Pine Samples.

dried the lumber in 163 hours, while the medium and high temperature schedules required 193 and 168 hours, respectively. In addition, the low temperature schedule exhibited the lowest percentage of degrade with 74 percent, while the medium and high schedules yielded 85 percent and 76 percent, respectively. The rates of drying evident in Table 26 indicate that the low temperature schedule dried the red pine to the fiber saturation point (FSP) in about 73 hours. This is notably shorter than the other schedules, when compared to 107 hours for the high temperature schedule and 113 hours for the medium temperature. (Note: for the latter schedule the actual time to FSP is 137 hours minus the inadvertant 24 hours of equalizing). It is also evident, however, that the drying rate decreased perceptibly after the FSP was reached. It is possible that at this stage the low bulb temperature level was relatively inefficient in moving the residual water still within the cell walls; it required actually less effective time to dry the wood from an average 140 percent to 27 percent moisture content than it did to dry the wood from 27 percent to a nominal 12 percent moisture content.

Table 26

Summary of the Results of Experimental Kiln Schedules and Resulting Sample Degrade

chedule	Dry Bulb Temperature range (°F)	Moisture Content Range[1] Initial (percent)	Moisture Content Range[1] Final (percent)	Time of Schedule: Effective Time to F.S.P.[2] (hours)	Time of Schedule: Elapsed Time to F.S.P. (hours)	Time of Schedule: Total (hours)	Amount of Degrade (percent)
ow	100-110	49-192	13.6	73	73	163	74
ledium	150-170	51-197	11.8	113	137	193	85
ligh	180-200	56-183	10.2	107	107	168	76

Based on oven weight.
F.S.P. (fiber saturation point) of red pine is presumed 27 percent moisture content.

Before the drying treatment procedure was initiated, there was, in general, an equal distribution of grades within the three kiln treatment groups. The highest, or stud grade, accounted for 190 of the 216 sample 2 x 4's, or 88 percent of the total material. The remaining 12 percent consisted of samples exhibiting slight degrade due either to crook or to some natural defect such as knots, wane or bark pockets. The distribution of defects in the sample material before drying, by grade is summarized in the following schedule.

Defect	Kiln Schedule	Grade: stud	Grade: No. 1	Grade: No. 2	Total
Natural	Low	65	0	5	70
	Medium	66	0	5	71
	High	59	0	7	66
	Total	190	0	17	207
Crook	Low	—	2	0	2
	Medium	—	1	0	1
	High	—	6	0	6
	Total	—	9	0	9

Upon completion of the drying procedures, only 35 of the initial 190 were still classified as stud grade (Table 27). After drying, only nine 2 x 4's still had natural defects as the predominant defect. These, together with the 35 stud grade samples, comprised the 20 percent, or 44 pieces, that retained their original grade following drying.

Of the 35 samples that remained in the original stud grade, it should be noted that all but three were classified as coming from the peripheral region of the tree. This would support the view that older, larger diameter second growth red pine material will tend to dry with less seasoning degrade. The final results after drying showed that twist in some degree was predominant in 135 of the 216, or 62.5 percent of the samples. Table 27 also shows a notably greater occurrence of twist in the lower dimension grades No. 3 and No. 4; and of the 135 sample 2 x 4's in which twist was noted, 70 percent were those designated as core material. This supports Hallock's (22) contention that whenever possible, waste in the log should be planned into the pith area and not in the slabs when sawing. The incidence of cup appeared very slight and accounted for the degrade of only four 2 x 4's graded as No. 3 or No. 4 dimension. The low temperature schedule had no assignable degrade due to cupping, while the medium temperature and high temperature schedules had degrade in only four samples. Since only these four samples reflected degrade due to cup defect, no technological significance seems evident. Crook had accounted for some reduction in grade prior to drying; but in some instances, the crook effect was probably masked by twist defect following drying as the predominant type of warp accounting for degrade. Crook accounted for the degrade of 16 of the 2 x 4's, but there was no apparent difference attributable to either kiln temperature or tree position factors. Bow was responsible for the degrade of 17 of the 2 x 4 samples, mostly in the No. 1 and No. 2 dimension grades.

The average amount of warp in the samples follows very closely the distribution of degrade ascribed to warp. The mean value for twist is almost twice as high as any other type of warp, and the amount of twist in the core position approaches three times the twist in the peripheral position, as shown in Table 28. It was found that this difference in tree position was statistically significant at the 99 percent level (Table 29), but the effect of kiln temperature on twist was found to be insignificant.

Kiln temperature apparently had no significant effect on the amount of bow, while the effect of tree position was significant at the 99 percent level (Table 29). There was a greater amount of bow in material from the peripheral region of the tree. This may well be due to the presence of the compression wood that was found to be common in the larger or butt logs of the trees. Since compression wood is known to exhibit a much

Table 27

Summary of Grade Distribution in Samples of Red Pine Following Drying by Three Experimental Kiln Schedules

		Grade										
		Stud Grade		No. 1		No. 2		No. 3		No. 4		Total
	Kiln	*Position*[1]		*Position*		*Position*		*Position*		*Position*		*Samples*
Defect	Schedule	C	P	C	P	C	P	C	P	C	P	Degrade
Natural[2]	Low	1	14	0	0	1	2	0	0	0	0	3
	Medium	0	7	0	0	1	2	0	0	0	0	3
	High	2	11	0	0	2	1	0	0	0	0	3
Twist	Low	–		0	5	9	3	15	3	7	0	42
	Medium	–		0	1	6	5	12	5	13	1	43
	High	–		0	4	5	7	8	6	19	1	50
Cup	Low	–		0	0	0	0	0	0	0	0	0
	Medium	–		0	0	0	0	1	1	1	0	3
	High	–		0	0	0	0	0	1	0	0	1
Crook	Low	–		0	2	1	1	0	0	0	1	5
	Medium	–		1	4	0	0	1	1	1	0	8
	High	–		1	0	0	1	0	1	0	0	3
Bow	Low	–		1	3	0	2	0	1	0	0	7
	Medium	–		0	1	0	4	0	2	0	1	8
	High	–		0	1	0	0	0	1	0	0	2

[1] Tree position C indicates core and tree position P indicates peripheral.

[2] Includes defects such as knots, wane and bark pockets.

Table 28

Average Drying Defect Values of Red Pine Samples from Two Tree Positions Dried Using Three Commercial Kiln Schedule Treatments

Drying Defect	Low Temp.		Medium Temp.		High Temp.		All Samples
	Pos. C[1]	Pos. P[1]	Pos. C	Pos. P	Pos. C	Pos. P	
Twist (in.)	.33	.13	.37	.16	.41	.18	.26
Cup (in.)	.02	.02	.04	.03	.02	.03	.02
Crook (in.)	.11	.11	.12	.13	.11	.11	.11
Bow (in.)	.09	.15	.10	.24	.08	.16	.14
Stress[2]	1.11	1.22	1.25	1.47	1.03	1.00	1.18

[1] Tree position C indicates core, P indicates peripheral.

[2] Units indicate presence of stress at 2.00 and absence of stress at 1.00 (5)

Table 29

Results of Analysis of Variance of Data from Defect Evaluation Following Drying of Plantation-Grown Red Pine

Source of Variation	d.f.	Level of Significance (Percent)				
		Twist Defect	Cup Defect	Crook Defect	Bow Defect	Drying Stress
Replications	17	N.S.	N.S.	99	N.S.	N.S.
Kiln Schedule	2	N.S.	99	N.S.	N.S.	99
Error	34	—	—	—	—	—
Radial Position	1	99	N.S.	N.S.	99	95
K X R	2	N.S.	99	N.S.	N.S.	N.S.
Error	51	—	—	—	—	—
Sub Sampling	108	—	—	—	—	—
Total	215	—	—	—	—	—

Note: N.S. denotes no significant difference at the 95 percent level of significance.

greater degree of longitudinal shrinkage than normal wood, its presence in a board causes it to have a greater tendency to bow. It should be noted, however, that due to the inherent variability in woody tissue along the grain, the absolute results of a study involving evaluation of material distortion are sensitive to sample geometry.

A summary of the evaluation of the residual stresses after conditioning is shown on Table 28. This test involved a conventional driving stress sample with two prongs, and was evaluated on a stress-no stress basis (5). There was a slight difference evident due to tree position, in that there was a greater incidence of stress in the peripheral material that might be readily attributed to compression wood or growth stresses in the outer portion of the tree. Kiln temperature level affected the incidence of drying stress, with a significant difference at the 99 percent level, as shown by the results of analysis of variance, Table 29. A conventional Duncan's new multiple range test confirmed that the results of all the kiln temperature schedules were significantly different, and that the medium temperature schedule exhibited the greatest degree of drying stress. In retrospect, the relationship of warp defect to location in the experimental kiln charge might have been of some interest, but this factor had not been included in the scope of the experimental procedure.

Effect of kiln drying schedules on strength properties. Static bending, compression parallel to the grain and toughness tests were performed on a total of 216 specimens. There were 213 tested in shear parallel to the grain; and although there were three missing specimens at the time of testing, these were later adjusted for by arithmetic balancing in the analysis of variance. Of the 213 that were tested in shear, 89 specimens failed within the prescribed limits of ASTM specifications and were used to determine MSS. The other 124 specimens exhibited failure occurring at the base of the specimen which extended back onto the supporting surface. These specimens were, however, included when determining strength in terms of TBLS. It has been shown that failure in shear is caused primarily by cleavage stresses, which reflect both tensile stresses and a bending moment, caused by a tendency to rotation of the specimen in the test fixture (64). Table 30 summarizes the average mechanical property values for the two tree positions, for each of the three dry kiln schedules.

The individual values for FSPL, MOR and MOE in static bending and MOE, FSPL and MCS in compression parallel to the grain were adjusted to 12 percent moisture content. It was concluded that the values of MSS for each kiln temperature treatment would not be appreciably altered by the moisture content adjustment, so rather than adjusting the individual values, the mean MSS value presented in Table 30 was adjusted to 12 percent moisture content for purposes of general comparison. No adjustment was made in the toughness values for moisture content, as it is thought to have little effect. The mean growth rate exhibited by the material was 5.1 rings per inch (rpi), with a standard deviation of 1.4 and a range of 2.5 to 11.0 rpi. The mean specific gravity of the test material was 0.358, with a standard deviation of 0.023 and a range of 0.310, to 0.490, measured as oven-dry weight and volume.

An analysis of variance indicated that there was no significant effect on flexural FSPL, MOR or MOE due to either kiln temperature or tree position (Table 31). Although not statistically significant, FSPL did show an increase with an increase in kiln temperature, and both MOR and MOE also showed a very slight increase with an increase in kiln temperature. This might only indicate, however, a randomness in the FSPL values that was due to a lack of precision in determining the departure from linear elasticity. The proportional limit observed later in compression appeared to be more sharply defined, and therefore, may be more precise than the proportional limit found in static bending.

Compressive FSPL was affected by kiln temperature at the 99 percent level of significance. Duncan's new multiple range test indicated that the FSPL values of the low temperature schedule material were lower than those from the medium or high temperature schedule samples. The magnitude of the differences involved would raise some question of technological significance, however. This is a similar trend to that exhibited by the FSPL in flexure, but the effect evidently becomes signifi-

Table 30

Average Mechanical Strength Property Values of Red Pine Wood from Two Positions in the Tree Dried by Three Experimental Dry Kiln Schedules

Mechanical Property of Plantation-Grown Red Pine	Low Temp. Pos. C[1]	Low Temp. Pos. P[1]	Medium Temp. Pos. C	Medium Temp. Pos. P	High Temp. Pos. C	High Temp. Pos. P
Static Bending						
Fiber stress at P.L. (psi)	3,380	3,153	3,450	3,233	3,616	3,575
Modulus of rupture (psi)	7,169	7,172	7,150	7,210	7,133	7,423
Modulus of elasticity (1,000 psi)	857	800	848	807	822	861
Compression Parallel to the Grain						
Fiber stress at P.L. (psi)	2,088	2,296	2,525	2,483	2,600	2,757
Maximum crushing strength (psi)	3,766	3,987	4,045	4,040	4,040	4,131
Modulus of elasticity (1,000 psi)	962	1,088	988	1,008	969	1,058
Shear Parallel to the Grain						
Maximum shearing strength (psi)	1,043	1,075	965	993	928	986
Total shearing strength (lbs.)	4,364	4,486	3,982	4,155	3,997	4,125
Toughness						
Toughness (in. lbs.)	115	147	94	128	99	118

[1] Tree position C indicates core, P indicates peripheral.

cant in the compressive loading mode. As noted above, the proportional limit found in compression was more sharply defined, and therefore may be more precise that the proportional limit found in static bending. MCS and MOE apparently were not significantly affected by kiln temperature level. The medium temperature exhibited a lower average value in both cases, but the low and high temperature schedules yielded only a slightly higher value. The effect of radial tree position on the physical properties in compression was found to be non-significant. It was noted, however, that there was some slight increase in average strength values in the peripheral position over the core position in FSPL, MCS and MOE (Table 30).

Shear strength parallel to the grain was found to be significantly affected by kiln temperature level. There was a reduction in MSS (psi) and TBLS (lbs.) evidenced by both the medium and high temperature schedule material. A Duncan's new multiple range test indicated that the TBLS value from the low temperature schedule samples was significantly different from both the medium and high temperature schedule material. Table 32 shows there is also significant difference at the 95 percent level in TBLS related to tree position. The peripheral material apparently exhibited a real increase in shearing strength over the core material.

Of those strength properties studied, toughness seemed most affected by dry kiln temperature factors, with the low temperature schedule material found to be considerably stronger. A reduction of 15 percent and 17 percent was found that was apparently due to the medium and high temperature schedules, respectively. Analysis of variance revealed that this difference was significant at the 99 percent level (Table 31). A Duncan's multiple range test confirmed that the low temperature schedule was significantly different from both the medium and high temperature schedules. It should be noted that Kozlik (34) also found that, of the strength properties he studied, toughness was most affected by temperature level. He also observed reductions in strength up to 15 percent with increases in temperature.

There appeared to be an even greater difference in toughness values between peripheral and core material than was evident among dry kiln temperature levels. The core material was about 21 percent weaker in toughness than the peripheral material, as shown in Table 30. The weakness of core or juvenile material in toughness is probably due to its wide growth rings and lower density, both of which tend to encourage failure under shock or impact loads.

Table 31

Results of Analyses of Variance of Strength Tests Following Drying of Plantation-Grown Red Pine

		Level of Significance (percent)						
		Static Bending			Compression Parallel to Grain			
Source of Variation	d.f.	Fiber Stress at P.L.	Modulus of Rupture	Modulus of Elasticity	Fiber Stress at P.L.	Maximum Crushing Strength	Modulus of Elasticity	Toughness value
Replications	17	N.S.	N.S.	95	N.S.	99	99	N.S.
Kiln Schedule	2	N.S.	N.S.	N.S.	99	N.S.	N.S.	99
Error	34	—	—	—	—	—	—	—
Radial Position	1	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	99
K X R	2	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.
Error	51	—	—	—	—	—	—	—
Subsampling	108	—	—	—	—	—	—	—
Total	215	—	—	—	—	—	—	—

Note: N.S. denotes no significant difference at the 95 percent level of significance.

Table 32

Results of Analyses of Variance of Shear Test Data Following Drying of Plantation-Grown Red Pine

	Maximum Shearing Strength		Total Breaking Load	
Source of Variation	Degrees of Freedom	Level of Significance (percent)	Degrees of Freedom	Level of Significance (percent)
Replications	—	—	17	N.S.
Kiln Schedule	2	99	2	99
Error	86	—	34	—
Radial Position	—	—	1	95
K X R	—	—	2	N.S.
Error	—	—	51	—
Subsampling	—	—	105	—
Total	88	—	212	—

IN CONCLUSION

Summary of the Results of the Investigation

Table 33 presents a comparative review of physical and mechanical values for middle-age plantation-grown red pine, as determined in this investigation, with similar values for the immature plantation-grown red pine evaluated by Kramer (33), Perkins and Walz (46) and Olson *et al.* (42), and studies of more mature naturally-grown red pine, such as those reported by Markwardt and Wilson (40). Although the values determined in this study appear lower than those determined for old-growth red pine, middle-age plantation-grown material would seem of substantially better quality than young plantation-grown wood, possibly since it undoubtedly contains a smaller proportion of juvenile wood.

Although considerable variation was found in the first phase of the investigation between trees from the same site, variability of the flexural and compressive mechanical properties within the individual trees studied appears substantially greater than the variation between trees. The importance of the effect of tree age, as reflected by radial position, on the mechanical properties of red pine is evident. At all the tree height levels considered, the static bending and compressive strength characteristics of the wood adjacent to the bark were substantially greater than wood found closer to the pith. It is interesting to note that the MOR and MOE of the wood adjacent to the bark in the first 16 foot log, formed at approximately 40 years of age, was about 19 percent and 25 percent greater, respectively, than comparable wood produced closer to the pith at about 28 years old. The MCS of wood adjacent to the bark was about 22 percent greater than wood produced closer to the pith.

The influence of height in the tree on the mechanical properties evaluated appeared neither as pronounced nor as consistent as the effects of radial position within the stem. Although the average strength characteristics of the material generally tended to decrease with increasing height in the tree, this was not typical of wood produced closer to the pith. Wood produced at an older age and adjacent to the bark exhibited a gradual decrease in strength properties with increased height in the tree, while wood closer to the pith generally exhibited an initial increase in strength from the butt to mid level, with subsequent reduction from the mid-level to the upper level. The physical characteristics of the wood also showed similar patterns of within-tree variation. Specific gravity appeared to account for approximately 82 percent of the variability in the MOR value and 73 percent of the variability in MCS. The high resin content observed in the wood, however, may have masked the total actual variation that could be attributed to specific gravity. The fibrillar orientation of the secondary cell wall alone evidently accounted for approximately 77 percent of the variation observed in MOE. Much less of the variation in the fiber stress values was accounted for, but again these values are in general more variable. The plantation in this study was somewhat older than others that have been the subject of similar research, and for the most part the material exhibited strength values somewhat higher than the younger material included in Table 33. In contrast, MOR and FSPL in flexure and FSPL in compression parallel to the grain were, to some extent, lower than the values reported in other studies of naturally-grown material.

MOE values in flexure appeared considerably higher than those determined by other investigations of plantation type red pine. This may possibly be attributed to growth rate, since Kramer (33) found that the rings per inch characteristics have a highly significant effect on the MOE, as well as a significant effect on the MOR in red pine. The average growth rate found in this study was 8.2 rpi, as compared to growth rates of 6.6, 6.9 and 5.1 rpi for similar plantation-grown stock shown in Table 33. However, the influence of juvenile core material could possibly have also caused a reduction in the MOE values reported in these studies.

FSPL in flexure, MCS and MSS all appear within the range reported by other studies, but the toughness appears somewhat high for this material when compared to the other plantations, particularly since the value is an average known to reflect some reduction due to drying methods. The Wood Handbook (2) reports the toughness of red pine

Table 33

Summary of Comparative Physical and Mechanical Strength Values from Various Investigations of Natural and Plantation-Grown Red Pine[1]

	Present Study	Kramer (33)	Olson, *et al.* (42)	Perkins, Walz (46)	Kennedy (31)	Markwardt, Wilson (40)
Origin of Material	Maine plantation	Connecticut plantations	Connecticut plantations	Greencastle, Ind. Plant.	Canadian range	Wisconsin old-growth
Age	48	31.4	40	33	unknown	unknown
Growth rate (rpi)	8.2	6.6	6.9	5.1	17	22
Specific gravity	0.40	0.36	0.36	0.43	0.42	0.51
Static Bending						
FSPL[1] (psi)	3,535	4,477	unknown	unknown	5,890	9,400
MOR (psi)	9,676	7,975	7,954	7,755	10,110	12,500
MOE (1,000 psi)	1,414	1,070	1,016	1,386	1,370	1,800
Compression Parallel to the Grain						
FSPL (psi)	3,651	unknown	unknown	2,266	3,410	5,330
MCS (psi)	5,210	3,680	unknown	4,726	5,390	7,340
MOE (1,000 psi)	1,455	unknown	unknown	771	1,360	unknown
Maximum Shearing Strength (psi)	595	unknown	unknown	526*	1,088	1,230
Toughness (in. lbs.)	117*	80	unknown	93	unknown	unknown

[1] FSPL-fiber stress at P.L.; MOR-modulus of rupture; MOE-modulus of elasticity; MSC-maximum crushing strength. Shear and toughness values taken from drying study. EMC 12 percent, except as marked (*).

as 80 inch pounds for radially applied loads and 150 inch pounds for tangentially applied loads. The toughness specimens for this study, however, were tested using the tangential loading mode for 62 percent of the total specimen array, with the remaining specimens being tested with the load applied half way between the radial and tangential plane. This would tend to highly qualify any comparison of results, and so this value, as well as that for shearing strength, are included for purposes of general comparison only.

The results of the pulping study indicated that the yield level varied directly with both specific gravity, and height above ground. While some differences in pulp purity were noted, the real technological significance of these differences, in terms of a commercial pulping process, is open to question. The pulp appeared to gain strength, in terms of burst test and breaking length values as height above ground and beating time increased. Optimum beating times would appear to be in the 70 to 90 minute range, however, with little gain and perhaps even some loss in strength with longer beating periods. Little absolute difference was noted between the freeness of the pulp types at various beating times, although statistically significant differences were detected in analysis. Again, while these differences may be real, their magnitudes may mean little in a full scale pulping operation. Tearing strength decreased and sheet density increased with the height above ground, which would tend to follow the conjecture that the lower portion of the tree contains stronger fibers, and the upper portions more flexible fibers. The greater bursting strength and breaking length values evident with increasing tree height also imply that flexible fibers and increased fiber bonding may be associated with lower specific gravity values. The general trend of the results would confirm that, with proper control of material input and processing factors, a satisfactory pulp may be expected from plantation-grown red pine.

The results of the drying study indicate that the low temperature kiln schedule employed required the shortest period of time to dry 2 x 4 red pine samples, 4 feet in length, to 12 percent moisture content. When the time required to dry the material to FSP is considered, the low temperature schedule was able to dry the wood considerably faster than either the high or medium temperature schedules in this stage of the drying process. Kiln temperature appeared to have little or no significant effect on either the magnitude or incidence of warp. Warp, however, was significantly affected by radial tree position. Twist, which accounted for 79 percent of all degrade, was affected by tree position at the 99 percent level of statistical significance. Core material with a high proportion of juvenile wood was associated with two-thirds of all the twist defect.

Severe bow was present in some peripheral material where compression wood was present, but in the final analysis, twist caused most of the degrade, followed by bow, crook and cup defects. Of all the strength properties evaluated, toughness was most affected by the kiln temperatures employed. Both toughness and shear parallel to the grain strength values appeared to be appreciably reduced with an increase in kiln temperature. FSPL in compression values increased significantly statistically with an increase in temperature, but the effect was adjudged to be of questionable technological significance. Strength in flexure, however, did not appear to be significantly affected by kiln temperature. In almost all instances, the peripheral material exhibited higher strength values. In retrospect, examination of the strength properties related to all three kiln schedules strongly suggests that the kiln dried material did not develop the strength characteristics evidenced by the air dry material tested in the initial phase of the investigation. Differences in basic material strength, however, remain undetermined, so that a question remains as to whether or not *all* the kiln schedules reduced the material strength. The presence of an air dried control sample group would have been most helpful, had the appropriate material been available and the magnitude of the potential differences anticipated. The operational possibility of developing a combination low-high temperature schedule to shorten the total time required in the dry kiln should not be overlooked. The higher temperatures could be used as soon as the fiber saturation point was reached, and the subsequent time to 12 percent moisture content could possibly be reduced by as much as 30 hours.

In considering the more comprehensive implications of the entire investigation, the influence of juvenile core material on the characteristics of plantation-grown red pine appears as the most consistent factor. This may be recognized as a function of radial distance from the pith at a given tree height, or height in the tree itself, but the effect remains pervasive in regard to properties of the wood. It becomes obvious that the possible presence of juvenile wood is a dominant constraint in considering some potential aspects of the utilization of plantation-grown material. The strength properties of the material can evidently be drastically affected by the behavior of core wood, and this would be a significant factor in developing reliable stress grades for red pine lumber. The influence of juvenile material on the strength of red pine plywood could also be a serious problem, as well as any potential effect related to structural balance in a laminar composite. Juvenile wood certainly could constitute a potential source of difficulty in the kiln drying of plantation-grown red pine if it were present in any significant amount. The most serious effect of juvenile core on the pulping of the material, however, would appear to be the somewhat reduced yields associated with the lower specific gravity of the wood, and some loss of tear resistance.

In regard to the cultivation of red pine plantations, some consideration by the forest manager and scientist of the possible utilization of the material would certainly seem justified. While such criteria as total fiber production and increased growth in individual trees would seem no less important, in some instances techniques which would encourage the suppression of juvenile tissue development would appear to be of real potential value.

Conclusions

The following conclusions are based on the results of the investigations, consistent with their limitations and objectives:

1. The flexural and compressive mechanical properties of middle-age plantation-grown red pine appear substantially improved over the corresponding properties of younger plantation-grown red pine. The wood produced adjacent to the bark exhibited considerably more desirable mechanical properties than wood closer to the pith. The wood adjacent to the bark exhibited a progressive decrease in all flexural and compressive mechanical properties with increasing height, but wood closer to the pith exhibited an initial increase in mechanical strength from the butt level to the mid level followed by a decrease from mid level to the upper level in the tree.
2. Individual plantation-grown red pine trees grown on a uniform site and of the same age can exhibit considerable variation in the mechanical properties of fiber stress at the proportional limit and modulus of rupture. These differences may possibly be related to indeterminate hereditary factors. Orientation within the tree (north or south) did not appear to affect the flexural and compression parallel to the grain mechanical properties.
3. Specific gravity accounted for most of the variation in modulus of rupture and maximum crushing strength, while fibrillar orientation within the secondary cell wall appeared to contribute most to the variation in fiber stress at the proportional limit and modulus of elasticity in static bending.
4. The pulp yield, in terms of fiber weight, from the butt portion of plantation-grown red pine was greater than that of the top portion of the stem, when based on equal volumes of material cooked. Pulp of higher purity was apparently obtained from the

entire stem portion of the tree, in comparison to material limited to the butt portion of the tree only.

5. Pulp burst factor, breaking length and density values tend to increase with increasing distance above the ground, while values for tear factor and bulk tend to decrease with increasing distance from the ground.
6. The pulps tested were difficult to beat but developed their strength within 90 minutes of beating and then remained relatively unaffected with prolonged beating and decreasing freeness. Therefore, beating times in excess of 90 minutes do not appear justified.
7. A low temperature kiln drying schedule appears to be the most advantageous for plantation-grown red pine, on the basis of those incorporated in this investigation.
8. The kiln temperature levels employed in this study had little or no significant effect on the degree of warp for the size material used in the investigation. Twist was the predominant type of warp causing degrade in the plantation-grown red pine evaluated. The juvenile core appears to be a major cause of twist.
9. The strength of plantation-grown red pine in respect to toughness and shear parallel to the grain was reduced with an increase in kiln temperature. Strength, in compression parallel to the grain, was evidently affected little by kiln temperature. The strength of plantation-grown red pine in static bending was not significantly affected by the kiln temperature employed in the investigation.

Recommendations for Further Research

1. Additional studies of this type should be conducted with individual trees of known progeny to determine the variation that is associated with genetic composition.
2. Anatomical investigations should be conducted to determine the specific influence tree age has on earlywood and latewood fibril orientation.
3. Latewood percentage determination might be omitted from similar studies (except when it is necessary to weight earlywood and latewood fibril angle values), since it appears related to strength properties only through its association with specific gravity.
4. Additional research should be considered with chip combinations from all tree height positions to ascertain specifically why

higher purity pulp was obtained from chips collectively taken from all tree height positions.

5. Anatomical and chemical study of the wood as it varies within and between trees might explain further the differences in pulp strength obtained among height positions in the tree.
6. Additional drying research should be conducted to investigate the effect of a combined low-high temperature schedule on plantation-grown red pine.
7. The effect of a high temperature schedule, above 212°F, on plantation-grown red pine should be evaluated.

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