INFLUENCE OF WETWOOD ON PULSED-CURRENT RESISTANCES IN LUMBER BEFORE AND DURING KILN-DRYING[1]

James C. Ward

Research Forest Products Technologist
Forest Products Laboratory,[2]
Madison, WI 53705

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ABSTRACT

Measurements of resistance to a pulsed electric current were lower in wetwood of aspen (*Populus tremuloides*) and white fir (*Abies concolor*) than in normal wood—i.e., sapwood and heartwood—both before and during kiln-drying. The physicochemical properties of wetwood associated with lower resistances are apparently due to invasion of the living tree by bacteria; these bacteria may concentrate excess amounts of ions as well as chemically altering the ion-binding nature of cellular surfaces in the wood. Wetwood also caused discrepancies in the estimation of fiber saturation points (FSP) from measurements of shrinkage and of pulsed-current resistances taken during kiln-drying. Fiber saturation point discrepancies between wetwood and normal wood indicate a need to develop electronic measuring devices in lumber charges, for computerized control of kiln-drying, that will compensate for wetwood.

Keywords: Wetwood, bacteria, electric resistance, kiln-drying.

INTRODUCTION

The operating efficiency of most present-day dry kilns could be improved if they were reequipped with computerized controls for remote measurement of wood moisture content (MC) by electronic methods (Hill and Munkittrick 1970; James and Boone 1982; Kordes 1980a, b). There is the possibility, though, that wetwood in lumber will cause operational errors during computerized control of kiln-drying when the MC of the charge is determined by resistance measurements with electronic probes.

An exploratory investigation was initiated at the Forest Products Laboratory (FPL) to determine how the presence of wetwood in lumber might influence measurements of resistance to a pulsed electric current during kiln-drying.

Electrical properties of wetwood

Wetwood, or sinkerheart, is an abnormal type of heartwood (Hillis 1977) that is infused with water and causes problems with the drying of lumber from certain commercially important species such as aspen, hemlock, true firs, white pines, and oaks (Ward and Pong 1980). Drying rates are retarded and boards are prone to develop one or all of a variety of defects: deep surface checks, honeycomb, ring failure, collapse, and chemical brown stain. Formation of the chemical and physical properties that predispose wetwood to drying problems can be traced to the

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enzymatic action of anaerobic bacteria that invaded and colonized the trunks of living trees (Ward and Zeikus 1980).

Previous FPL drying tests with white fir (Ward and Shedd 1981) and western hemlock (Kozlik and Ward 1981; Ward and Kozlik 1975) have found that the pulsed-current resistances of wetwood were lower than the resistances of sapwood and normal heartwood. On that basis, we proposed that measurements of pulsed-current resistances in green wood may provide a fast, accurate method for identifying and segregating wetwood boards from normal lumber on the green chain. Each board sort could then be dried separately under schedules that optimize drying times with a minimum development of defects. Measurements of pulsed-current resistances in those FPL tests were made with the Shigometer, a portable ohmmeter normally used to detect discolorations and decay in living trees and utility poles (Shigo and Shigo 1974). During an investigation of die-back in European silver fir, Bauch et al. (1975) found the Shigometer useful for distinguishing bacterial wetwood (with low resistances) from normal wood (with high resistances).

Computerized kiln-drying

Interest is widespread in methods for fully automating the kiln-drying operation as one way of offsetting the increasing costs of energy, labor, and raw materials. The drying operation consumes 60% to 70% of the total energy used in manufacturing most wood products (Comstock 1975). This suggests that operating costs can be reduced with automatic acceleration of drying conditions as soon as the wood reaches safe MC levels where risk of drying degrade is minimal.

The most frequently proposed systems for computerized control of kiln-drying are dependent upon remote measurement of wood MC by electronic probes (Kordes 1980a). Skaar (1964) believes that the use of electrical resistance measurements for detecting moisture gradients in wood offers great promise because of the tremendous change in resistance with MC, but he lists several factors that combine to prevent practical realization with direct-current meters. These include the strong temperature effect on resistance, the polarization phenomenon that causes resistance to change with time, the effect of voltage gradients on resistance, the concentration of resistance in the vicinity of the electrode due to electrode geometry, poor contact, and the accumulation of electrode deposits. Furthermore, ohmic heating and property variations in the wood itself will affect resistance measurements.

Couture and Hill (1974) developed a pulsed-current resistance-measuring meter that eliminates or minimizes the effect of most electrical phenomena that interfere with accurate resistance measurements of wood MC by direct current meters. They could not report on the possible variation in resistances of different woods at constant MC and temperature that Skaar (1964) had noted. The present investigation was initiated to determine if the differences between pulsed-current resistances of wetwood and normal wood persist during kiln-drying.

MATERIALS AND METHODS

Sample board sections from quaking aspen (*Populus tremuloides* Michx.) and California white fir [*Abies concolor* (Gord. and Glen.) Lindl.] were end-sealed and dried from green to 8% average MC in an experimental drying chamber. Representative samples of wetwood and normal wood were included in each species group. Measurements of resistance to a pulsed-electric current were taken from the core zone of each sample before and during the course of drying. Supplemental wood characteristics of MC, shrinkage, growth rate, specific gravity, ash, and fiber saturation point (FSP) were determined directly from the drying samples or from end-matched sections. The FSP of wetwood and normal wood was calculated from measurements of both shrinkage and resistance; according to Stamm (1971), these two estimations of FSP should be similar for a given sample. Scanning electron micrographs (SEM) were made from green wood of the end-matched sections for evaluating the condition of cell lumens in order to explain differences between resistances of wetwood and normal wood. A series of electrolyte solutions was also tested to provide insight into the different effects of heat on resistance of wetwood and normal wood during the early stages of drying.

Sample preparation

Aspen samples were obtained from two trees growing near Madison, Wisconsin, and white fir samples from green lumber shipped to FPL from northern California. Representative samples of sapwood and wetwood could be obtained only from the aspen, but the white fir contained normal heartwood as well as sapwood and wetwood.

For experimental drying, seven samples of aspen (four sapwood, three wetwood) and nine samples of white fir (three each of sapwood, heartwood, and wetwood) were prepared. All samples were flatsawn. White fir samples measured 1.75 inches thick, 7.7 to 8.0 inches wide, and 5.0 inches along the grain. Aspen samples measured 2 inches thick, 3.5 inches wide, and 3.0 inches along the grain.

Stainless steel needles (1/8 in. diameter) were inserted into the end grain of each wood sample to a depth of approximately 0.6 inch. These needles were used as electrodes to measure pulsed-current resistances. Three electrodes were located on one end of each sample in the core zone (Fig. 1). Two resistance measurements were made at electrode points 1–2 and 2–3.

All green samples with inserted electrodes were end-coated with a silicone rubber adhesive-sealant, and the sealant was allowed to cure at room temperature for 25 min. During this time the noncoated wood surfaces of thickness and width were wrapped in moist toweling to prevent moisture loss. Drying tests were done separately, so the aspen and white fir samples were not prepared at the same time.

Experimental drying

The samples were dried in an air-cooled temperature- and humidity-controlled cabinet from the green condition to an average MC of approximately 8%. The drying schedule from green to 8% MC is outlined in Table 1 and simulates some commercial schedules used for softwood dimension lumber. When each sample reached an estimated 8% MC, it was transferred to a drying oven and dried to 0% MC.

Pulsed-current resistance measurements

Measurements were made with the Shigometer Model No. 7950 (Northeast Electronics Corporation, Concord, N.H.). Resistance measurements were made

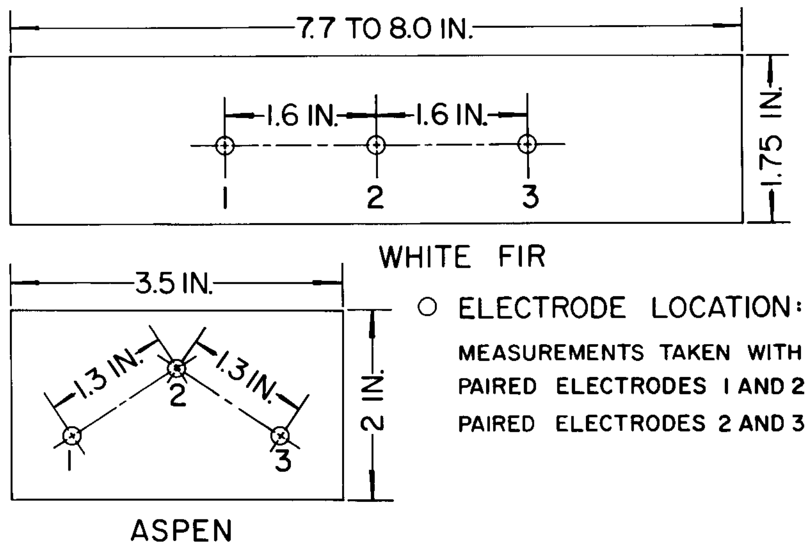

FIG. 1. End-grain view of drying samples showing location of stainless steel electrodes for measurement of resistances to a pulsed-electric current with the Shigometer.

on the green wood samples at room temperature (60–65 F) before drying. During drying, resistance measurements were made on the samples while in the temperature-humidity cabinet. Leads with alligator clips were attached to the electrodes in the samples in the cabinet and then connected to the Shigometer on the outside. Before measuring resistances, the electrodes were checked to ensure they were firmly embedded in the wood. No electrodes became loose until after the wood had dried to a condition at which resistances were greater than 500 kilohms and could no longer be measured on the Shigometer. At this stage any loose electrodes were pressed deeper into the wood and resistances checked to ensure they were greater than 500 kilohms.

Supplemental wood characteristics

Moisture loss and shrinkage.—After resistance measurements were taken, each sample was removed from the cabinet, weighed for MC determination, measured at marked points across the width and thickness, and then returned to the cabinet. No sample remained outside the drying cabinet longer than 5 min; MC was calculated on the basis of oven-dry wood weight.

TABLE 1. *Schedule used in a controlled temperatre and humidity cabinet to dry aspen and white fir samples.*

Time	Temperature		Equilibrium moisture content	Relative humidity
	Dry-bulb	Wet-bulb		
	°F		%	
h				%
0 to 24	180	170	11.1	79
24 to 48	180	165	9	70
48 to end	180	157	7	57

Two measurements of thickness and two of width were taken on each sample with a caliper having a vernier scale reading to 0.001 inch. Final measurements for shrinkage were made on heated samples immediately after oven-drying.

Growth rate and specific gravity.—Growth rate and specific gravity were measured on specimens taken from green wood sections that end-matched the drying samples. Growth rate was measured along the rays and expressed as number of growth rings per inch. Specific gravity was then determined by the water immersion method and calculated as the ratio of the oven-dry wood weight to the weight of the volume of the water displaced by the green wood volume.

Ash content.—Ten-gram sections for ash-content determinations were taken from the interior of each experimental sample after completion of the kiln-drying. The sections were ground in a Wiley mill to pass a 40-mesh screen, weighed, oven-dried, and reweighed. The ground wood samples were heated in an electric muffle furnace at 1,067 F (575 C) for at least 3 h to burn off all carbon. The residue or inorganic ash was cooled in a desiccator and weighed. Ash concentration was expressed as the percentage of the oven-dry wood weight.

Fiber saturation point.—FSP determinations are based on two methods described by Stamm (1971). One method measures changes in volumetric shrinkage-MC plots and depends on an extrapolation for determining FSP. The other involves determining a transition point due to changes in electrical conductivity during drying. FSP is the point at which shrinkage begins because the cell lumens no longer contain free water and any further water removal must be from within the cell walls, thus causing a decrease in cell volume. Electrical conductivity decreases when free water no longer exists in the cell lumen, so FSP is indicated by an abrupt increase in electrical resistance.

In this study transverse shrinkage (combined tangential and radial shrinkage) rather than total volumetric shrinkage values was used to determine FSP. Because of the end-grain sealant with electrodes, it was not convenient or practical to measure longitudinal shrinkage during the course of drying. However, transverse or cross-sectional shrinkage is a very close approximation of total volumetric shrinkage because longitudinal shrinkage from green to oven-dry dimensions is only 0.1% to 0.2% (U.S. Forest Products Laboratory 1974).

Transverse shrinkage was plotted over MC from green to oven-dry dimensions for each sample. Each shrinkage-MC plot was examined to determine the MC point at which subsequent shrinkage to 0% MC was linear. A regression equation for this straight-line relation was calculated by using combined data for each sample group of species and wood type. A regression line was plotted and extrapolated to zero shrinkage where the MC at intersection was considered the FSP value.

Two separate determinations were made of FSP from resistance measurements. One estimate was made at the MC level or point at which resistance measurements increased abruptly during the final stages of drying. The other estimate of FSP was based on an extrapolation of resistance—MC plots taken from data between (and including) the point of abrupt increase in resistance measurements and the last point at which resistances could be read before exceeding the maximum value of 500 kilohms on the meter scale. A regression equation was calculated from these data. A linear regression line was plotted and extrapolated to a point at which resistance measurements had remained somewhat constant during the mid-

TABLE 2. *Average drying times to 8% MC for $^{5}/_{4}$-inch aspen and $^{7}/_{4}$-inch white fir.*

Species and wood type	Drying time
	h
Quaking aspen	
Sapwood	182
Wetwood	257
White fir	
Sapwood	127
Heartwood	79
Wetwood	182

dle stages of drying. The MC at the point of intersection was compared with the other two estimates of FSP.

Electrolyte solution tests

A series of electrolyte solutions of varying concentrations of sodium chloride in distilled water was measured with the Shigometer at temperatures of 65 F and

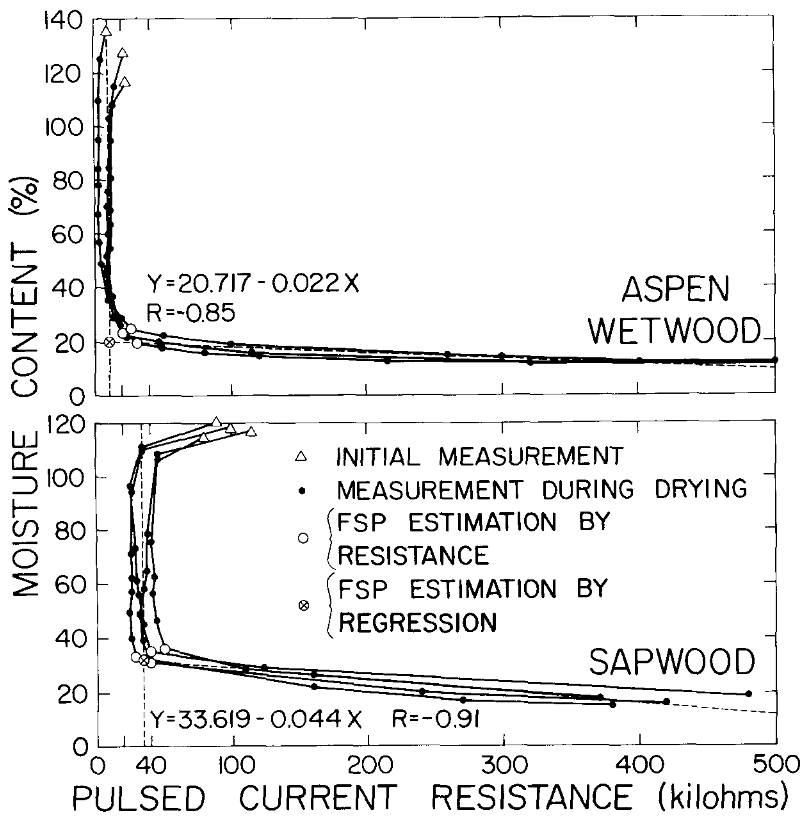

FIG. 2. Relation between moisture content (average of entire sample) and resistance to a pulsed-electric current (sample core) for quaking aspen sapwood and wetwood during kiln-drying.

180 F to test the influence of temperature increase on the lowering of resistances similar to reduction of resistances in heated green wood. Above FSP the temperature dependence of conductivity in wood should approach that of dilute ionic aqueous solutions (Langwig 1971); both sodium and chloride ions are prevalent and naturally occurring charge carriers in wood (Langwig and Meyer 1973).

Scanning electron microscopy

Green wood specimens, 0.1 by 0.4 by 0.4 inches, were cut from the board sections that end-matched the drying samples. These sections were fixed for 4 h in 2% buffered glutaraldehyde and then dehydrated through increasing concentrations of ethanol for a total of 48 h. Final solvent removal exchanged ethanol for liquid carbon dioxide followed by gaseous diffusion of carbon dioxide. The dried specimens were mounted on specimen holders, vacuum coated with approximately 100–200 Å of gold, and examined with a Cambridge Stereoscan Electron microscope at 20 kV.

RESULTS

Wetwood of both aspen and white fir took much longer to dry than did normal wood (Table 2). Changes in pulsed-current resistances throughout the course of drying are shown in Fig. 2 for sapwood and wetwood of aspen and in Fig. 3 for sapwood, wetwood, and normal heartwood of white fir. Shrinkage of the cross-section area (thickness × width) of these samples during the course of drying is shown in Fig. 4 for aspen and Fig. 5 for white fir. When comparing these figures, one must remember that shrinkage and changes in MC are based on measurements of the entire sample while pulsed-current resistances are measured from electrodes in the core of the sample.

Resistances to a pulsed electric current

At the start of drying, measurements of pulsed-current resistances in the wetwood of aspen (Fig. 2) and white fir (Fig. 3) were one-fourth to one-eighth the resistance measurements in normal wood. After the start of drying when the wood was being heated to a kiln temperature of 180 F, there was a decided drop in the resistance values of all samples.

The lowering of resistance measurements with the heating of green wood was greater for normal wood (i.e., sapwood and heartwood) than for wetwood. These reductions of resistances were compared after 2 h of drying (Table 3). The lowest resistance values measured were not compared because they occurred at widely different hours of drying for various samples. With aspen the lowest resistances were measured for sapwood at 19 to 34 kilohms after 6 to 40 h, and for wetwood at 3 to 8 kilohms after 18 to 54 h. Lowest resistance values for white fir were measured in all samples after 4 to 6 h of drying. They ranged from 14 to 15 kilohms for sapwood, 7 to 8 kilohms for heartwood, and 2 to 3 kilohms for wetwood.

For most samples in Figs. 2 and 3, the changes in pulsed-current resistances above 50% MC were small and erratic while below 50% MC there was a consistent and changing rate of increase in resistances with moisture loss. Abrupt increases in resistance measurements occurred at moisture levels of 30% to 35% for normal wood and at lower levels of 20% to 25% for wetwood (Figs. 2 and 3).

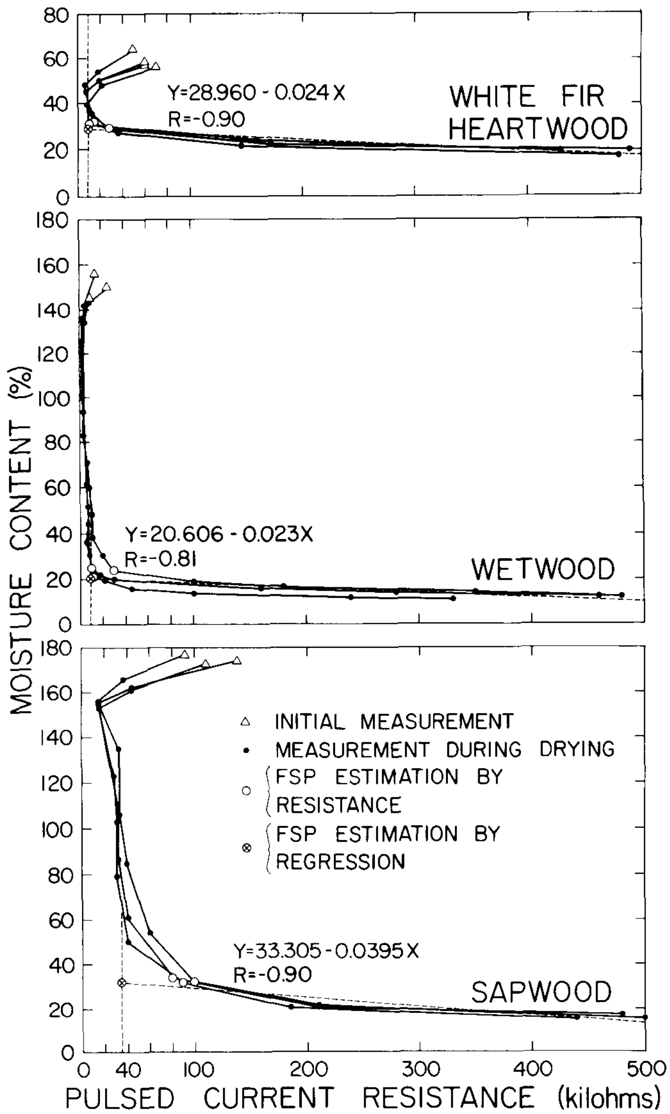

FIG. 3. Relation between moisture content (average of entire sample) and resistance to a pulsed-electric current (sample core) for white fir sapwood, wetwood, and heartwood during kiln-drying.

Pulsed-current resistances were successfully measured throughout the course of drying until the MC of the samples averaged less than 20%. Below 20% MC the resistance readings soon exceeded the maximum meter scale of 500 kilohms, but solid contact could still be maintained between wood and electrodes. Final resistances could be read at lower average MC's in wetwood than in normal wood. The last possible measurements of resistance were made in aspen wetwood at 11% to 12% MC and in white fir wetwood at 10.5% to 12% MC. Final resistance measurements in normal wood were made at 15% to 18.5% MC for aspen sapwood, 15% to 17% MC for white fir sapwood, and 17% to 19% MC for white fir

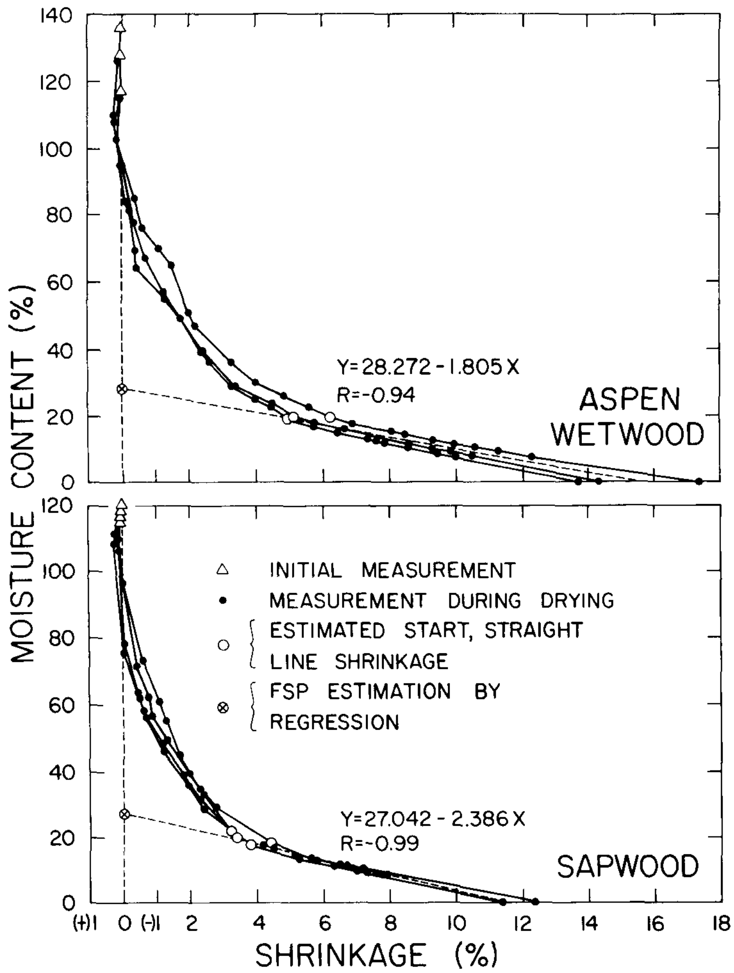

FIG. 4. Relation between moisture content and shrinkage (transverse area from green dimensions) for quaking aspen sapwood and wetwood during kiln-drying.

heartwood. Electrodes did not become loose in the end grain until the wood had dried to below 10% average MC. At final MC levels of 6% to 9%, resistance readings could not be taken with the Shigometer even with small needle electrodes driven into intact wood.

Dimensional changes during drying

Although wood MC was lowered during the initial stage of drying, the cross section of each sample increased or swelled (Figs. 4 and 5). This can be attributed to thermal expansion of wood and to hygrothermal recovery. Hygrothermal recovery refers to a tangential expansion and radial contraction of green wood when heated for the first time over an extended period. In contrast to thermal expansion of wood, hygrothermal recovery is not reversed during cooling and will not occur again with repeated heating (Kubler 1973).

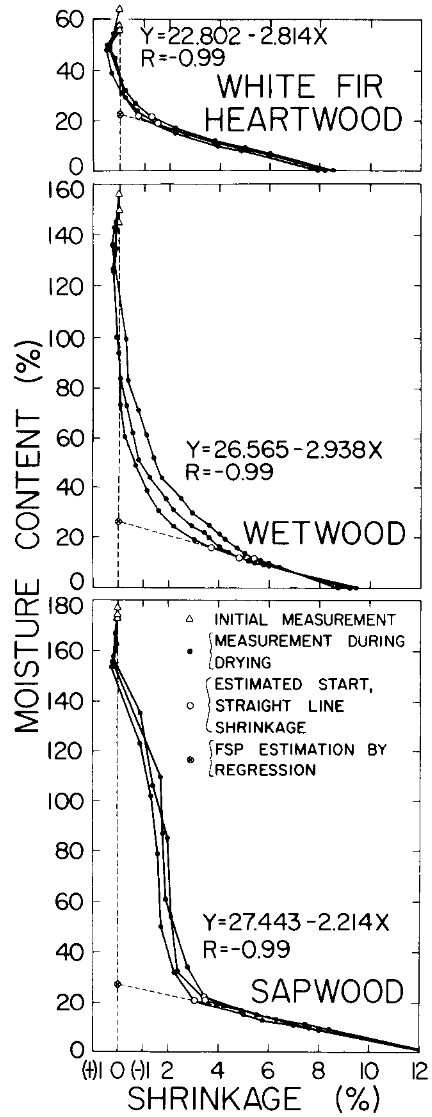

FIG. 5. Relation between moisture content and shrinkage (transverse area from green dimensions) for white fir sapwood, wetwood, and heartwood during kiln-drying.

After a short period of initial drying, all samples began to shrink below the initial green dimensions, and this shrinkage gradually increased throughout the intermediate stage of drying. Shrinkage was curvilinear for normal wood of both species until an MC of approximately 20% was reached; then shrinkage was essentially linear. Shrinkage of wetwood was essentially curvilinear throughout drying with a less distinct transition to linear shrinkage at 20% MC. The transition to linear shrinkage for aspen wetwood (Fig. 4B) could be reasonably approximated at 20% MC. For white fir wetwood (Fig. 5B), there appears to be a distinct transition to linear shrinkage at 16% to 11% MC.

TABLE 3. *Effect of heating on measurements of resistance to a pulsed electric current in the core of aspen and white fir samples*[a] *containing either normal wood or wetwood.*

Species and wood type	Number of samples	Green wood at room temperature (65 F) Average moisture content	Green wood at room temperature (65 F) Average resistance	Heated wood[b] after 2 hours drying time Average moisture content	Heated wood[b] after 2 hours drying time Average resistance	Difference between resistance values
		%	*kilohm*	%	*kilohm*	*kilohm*
Quaking aspen						
Sapwood	4	117	96	109	40	56
Wetwood	3	127	19	116	11	8
White fir						
Sapwood	3	175	113	163	41	72
Heartwood	3	59	60	51	20	40
Wetwood	3	150	13	140	5	8

[a] Sample thickness and width: Aspen, 2 by 3½ inches; white fir, 1¾ by 7.7–8.0 inches.
[b] Heated from room temperature under kiln conditions of 180 F dry-bulb and 170 F wet-bulb temperature (79% RH).

Other characteristics

Shrinkage, specific gravity, and growth rate.—Average values for total shrinkage (green to 0% MC), SG, and growth rate are listed in Table 4. Shrinkage of sapwood from aspen and white fir was comparable while aspen wetwood shrank more than sapwood. Shrinkage of white fir wetwood was comparable to shrinkage of white fir heartwood, which had the least shrinkage of all samples. Within each species wetwood SG was greater than sapwood SG; white fir heartwood had the lowest SG.

Growth rates partially explain the differences in SG and shrinkage among wood types. Wider growth rings in aspen wetwood contain greater volumes of dense, heavier latewood fibers than the slower growing sapwood. The higher SG of aspen wetwood is probably responsible for its greater shrinkage. In white fir the slower growing sapwood contains a greater proportion of thick-walled latewood tracheids than does faster growing heartwood, resulting in a greater SG and greater shrinkage for sapwood. White fir wetwood has a higher SG than sapwood but a low shrinkage

TABLE 4. *Total shrinkage, specific gravity, and growth rate of normal wood and wetwood from aspen and white fir, averaged for specimen types.*

Species and wood type	Shrinkage, green to 0% MC[a]	Specific gravity (green)	Growth rate
	%		*Ring/in.*
Quaking aspen			
Sapwood	11.5	0.416	12
Wetwood	15.0	0.442	9
White fir			
Sapwood	12.6	0.371	18
Heartwood	8.2	0.326	10
Wetwood	9.0	0.414	17

[a] Shrinkage measurements taken at end of oven-drying on heated oven-dry samples. After oven-dry samples had cooled for 45 min, additional shrinkage averaged 0.19% for aspen samples and 0.14% for white fir.

TABLE 5. *Comparison of fiber saturation point estimations from shrinkage (transverse area) measurements and from pulsed-current resistance measurements with the Shigometer.*

Species and wood type	Shrinkage measurement FSP[a]	Resistance measurement FSP: Direct estimation FSP[b]	Direct estimation Difference[c]	Regression line estimation FSP[d]	Regression line estimation Difference[c]
	% MC	% MC		% MC	
Quaking aspen					
Sapwood	27	34	+7	32	+5
Wetwood	28	22	−6	20	−8
White fir					
Sapwood	27	33	+6	32	+5
Heartwood	23	31	+8	29	+6
Wetwood	27	23	−4	20	−7

[a] Estimated from extrapolation of regression lines to zero shrinkage. See Figs. 4 and 5.
[b] Average of resistance values at point where abrupt rises in resistance measurements begin. See Figs. 2 and 3.
[c] Difference between shrinkage estimation of FSP and resistance estimation. Resistance FSP greater (+) or less (−) than shrinkage FSP.
[d] Estimated from extrapolation of regression lines to point of minimal resistance measurements during intermediate stages of drying. See Figs. 2 and 3.

comparable to heartwood. Low shrinkage of white fir wetwood may be due to excess extractives that provide a bulking effect similar to the effect of extractives for reducing shrinkage in wetwood of western hemlock (Kozlik and Ward 1981; Kozlik et al. 1972).

Fiber saturation point estimations.—FSP values (Table 5) ranged from 20% to 34% MC and varied by wood type and measurement technique. Sapwood and heartwood comparisons show that FSP values estimated from shrinkage measurements were lower than FSP estimations from resistance measurements. Conversely, estimations of wetwood FSP from shrinkage measurements were higher than FSP estimations from resistance measurements. For most woods the FSP is reached at approximately 30% MC (U.S. Forest Products Laboratory 1974), but variations greater than FSP values determined in this study have been reported (Ahlgren et al. 1972; Feist and Tarkow 1967; Stamm 1971; Stone and Scallan 1967; Tarkow and Feist 1969).

Ash concentrations.—Wetwood of both species had higher concentrations of inorganic ash than did sapwood (Table 6). Ash concentrations in white fir heartwood were between those of sapwood and wetwood.

DISCUSSION

Electrical resistances in green wood

Ash concentration has more influence than MC on differences between resistances of wetwood and normal wood in green condition (Table 6). The greatest differences in resistance measurements are between sapwood and wetwood, yet both have similarly high MC. Wetwood with the lowest resistances has greater concentrations of ash than sapwood with the highest resistances. White fir heartwood with low MC and intermediate resistance values had ash concentrations between those of sapwood and wetwood. These data suggest that the higher con-

TABLE 6. *Comparison of pulsed-current resistances for green wood of quaking aspen and white fir with moisture content and ash content.*

Species and wood type	Number of samples	Pulsed-current resistance[a]	Green MC[a]	Ash content (oven-dry wood weight)[b]	
				Mean	Range
		kilohm		%	
Quaking aspen					
Sapwood	4	96	117	0.27	0.25–0.30
Wetwood	3	19	127	0.77	0.67–0.91
White fir					
Sapwood	3	113	175	0.36	0.29–0.44
Heartwood	3	60	59	0.72	0.44–0.85
Wetwood	3	13	150	1.17	0.86–1.41

[a] Mean values taken on green wood before drying. Range of average values can be observed in Figs. 2 and 3.
[b] From analysis of samples after completion of drying tests.

centrations of inorganic ash in wetwood are indicative of greater numbers of soluble ions that decrease the resistance.

The relationship between high ash concentrations and lower electrical resistances is based on the theory that electrical conduction in wood is ionic (Brown et al. 1963).

A distinction must be made between naturally occurring ions in wood and ions introduced after wood formation. With Neutron Activation Analysis, Langwig and Meyer (1973) found that both positive and negative monovalent ions migrated readily in wood under the influence of a direct current electric field, identifying them as charge carriers. These mobile ions were identified as sodium (Na^+), potassium (K^+), chloride (Cl^-), and bromide (Br^-) and occurred naturally in wood. Naturally occurring polyvalent ions such as manganese (Mn^{++}) were immobile, suggesting that they exist in wood as chelates or other complexes that do not ionize readily. They also report that polyvalent copper ions artificially introduced into wood can exist as free ions and carry an electric charge. This corresponds to James' (1980) findings that wood treated with inorganic salts has lower resistances than untreated wood at the same MC.

Bacteria are probably responsible for the increased accumulation of ions in wetwood. Berchtold et al. (1980) considered large concentrations of Ca, K, and Mg in silver fir wetwood to be a tree response to bacterial attack. Another possible explanation is that wetwood bacteria adsorb and immobilize ions from the sap stream. The surfaces of bacterial cells are anionic and attract and bind many metal ion species (Beveridge and Koval 1981). In discolored and decayed wood, fungi have been associated with an increase in ash concentration and a corresponding decrease in resistances to a pulsed-electric current (Piirto and Wilcox 1978; Shortle 1982; Tattar et al. 1972). Fungi are rarely found in wetwood (Bauch et al. 1975; Berchtold et al. 1980; Ward and Zeikus 1980), so bacteria are presumably an indirect cause of the low resistances.

Scanning electron micrographs of aspen vessels and white fir tracheids show differences between normal wood (Fig. 6) and wetwood (Fig. 7) that help to explain variations in resistance. Cell lumina in the sapwood of aspen (Fig. 6A) and white fir (Fig. 6B) are clean and free of bacteria and related "slime" coatings that occur

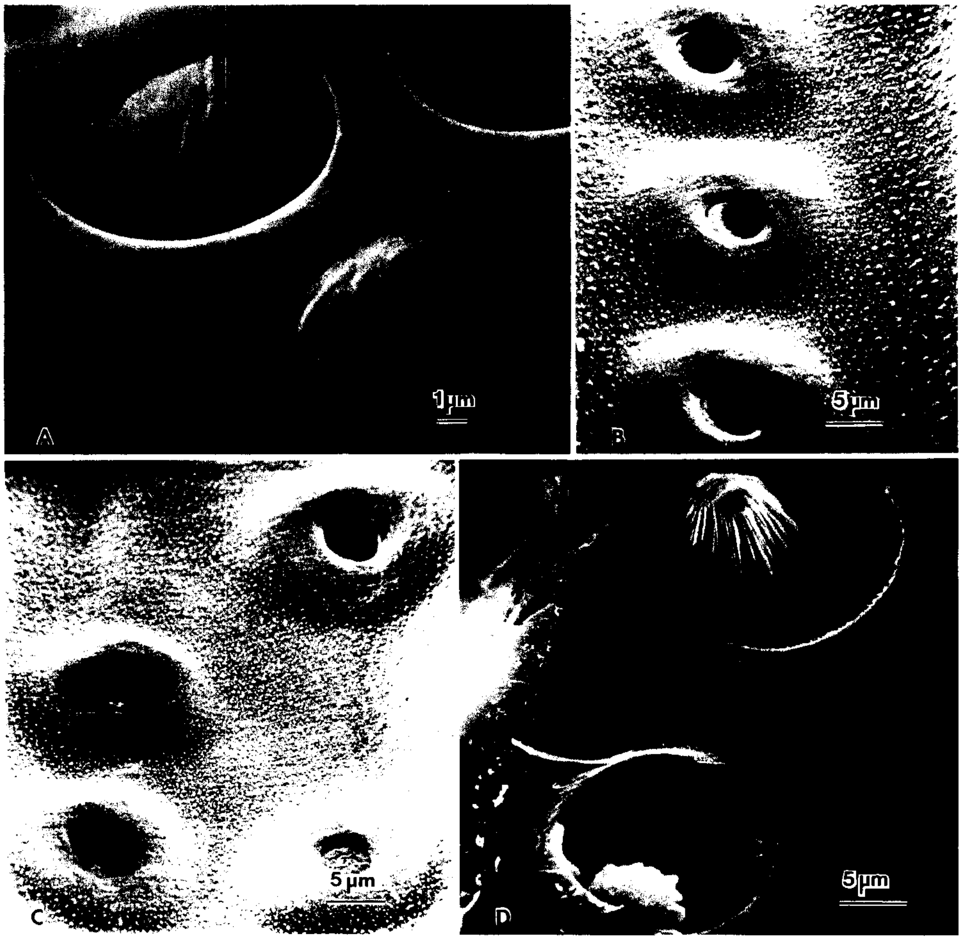

FIG. 6. Scanning electron micrographs of normal wood from quaking aspen and white fir. A. Aspen sapwood: Vessel to ray pit membranes. B. White fir sapwood: Tracheid showing bordered pits and warty layer on lumen wall. C. White fir heartwood: Tracheid showing bordered pits and warty layer on lumen wall. D. White fir heartwood: Bordered pits with aspirated tori and crystalline deposits.

in wetwood of both aspen (Figs. 7A, B) and white fir (Figs. 7C, D). White fir heartwood is free of bacteria (Fig. 6C), but some tracheids contain crystalline deposits (Fig. 6D) that may cause a lowering of resistance values. Resistances of white fir heartwood can be higher or lower than sapwood, but are rarely as low as wetwood (Ward and Shedd 1981).

Resistance changes during kiln-drying

The pulsed-current resistances in green lumber soon change once kiln-drying starts, but the essential differences between wetwood and normal wood persist throughout drying. Resistances decrease in the early stage of drying, then increase at varying rates during the middle and final stages.

Early drying stage.—Temperature increase had a pronounced effect on lowering

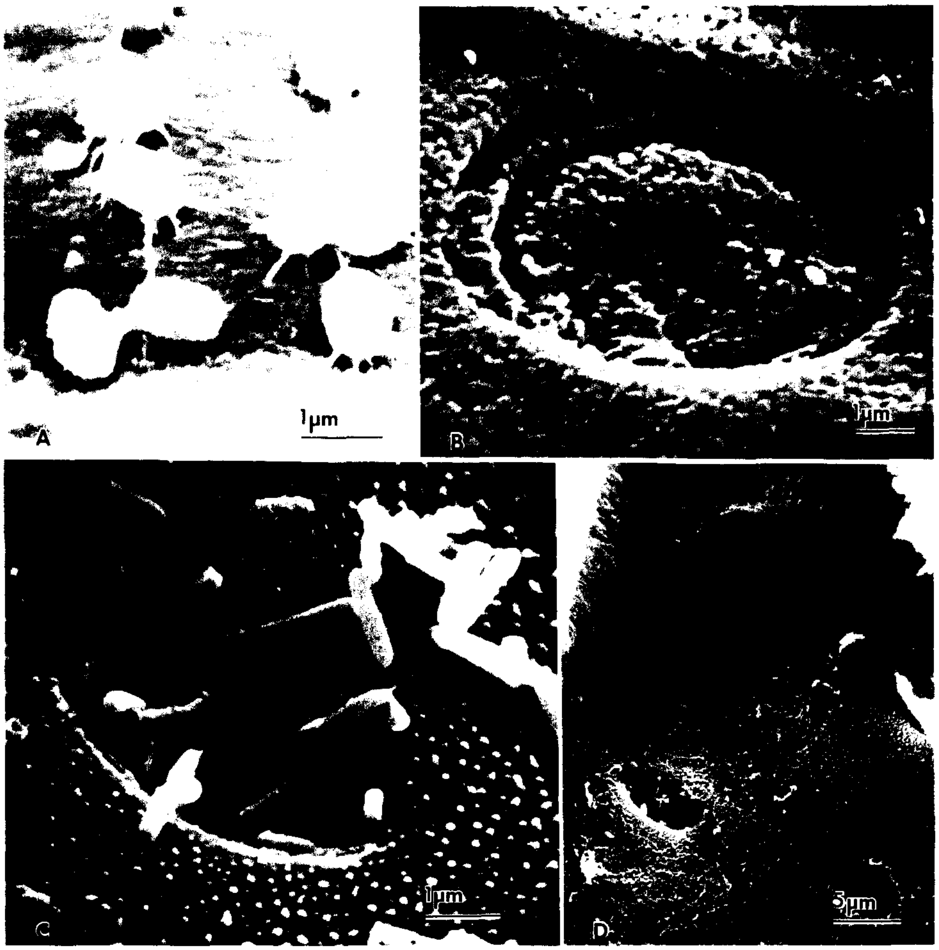

FIG. 7. Scanning electron micrographs of wetwood from quaking aspen and white fir. A. Aspen wetwood: Bacteria on surface of vessel lumen. B. Aspen wetwood: Ray pit membrane and vessel lumen coated with bacterial "slime." C. White fir wetwood: Bacteria on surface of tracheid lumen and aspirated torus of bordered pit. D. White fir wetwood: Bacterial "slime" and extraneous material on lumen wall of tracheid.

resistance measurements, but differences of ash concentration in wetwood and normal wood influenced the degree of reduction. Langwig's (1971) contention that, above FSP, the temperature dependence of conduction in wood should approach that of a dilute aqueous solution appears to be supported by a comparison of data in Tables 3 and 7. When heated, green sapwood with the lowest ash concentrations had a greater decrease in resistance measurements than did wetwood with the highest ash (Table 3). The resistance of electrolyte solutions decreased with heating from room temperature to 180 F (Table 7). These decreases in resistance values varied with solute concentration and are comparable to what would occur in the wood samples of this study.

Middle and final drying stages.—As drying progressed, resistances in the heated wood increased, but the rate of increase differed between wetwood and normal

TABLE 7. *Effect of increased temperature on measurements with the Shigometer of pulsed-current resistances in an electrolyte solution.*[a]

Molarity	Resistance reading[b] 65 F	180 F	Difference
Mole solute/liter solution		*kilohm*	
3.9×10^{-5}	200	110	90
5.66×10^{-5}	140	50	90
6.52×10^{-5}	125	65	60
2.95×10^{-4}	28	13	15
6.24×10^{-4}	15	7	8

[a] NaCl solute in distilled H_2O.
[b] Measured with needle electrodes (hardened steel: 0.05 in. diameter by 0.7 in. long) spaced 0.5 inch apart. Applied voltage = 145 mV.

wood. Changes in the rate of increasing resistance occurred at different MC levels for wetwood and normal wood. A possible explanation might include consideration of an interaction of several factors: drying temperature, moisture gradient variations within and among boards, and different physicochemical properties of wetwood and normal wood.

The elevated temperatures (180 F) used in this study reduced resistances in wood to the point at which measurements could be made at lower MC levels than would be possible with air-dried stock at room temperatures. Calculations can be made from Davidson's (1958) data to show that when Douglas-fir at 19% MC is heated from room temperatures (55–75 F) to 140 F, electrical resistance decreases from about 4 megohms to less than 4 kilohms. When the heated Douglas-fir is dried to 15% MC, resistance increases to over 1 megohm. This indicates that Shigometer measurements could only have been made on heated wood with 19% or higher MC, but it is possible to measure pulsed-current resistances in wood at lower MC levels. Couture and Hill (1974) used a pulsed-current meter capable of measuring resistances in red oak at 6% to 7% MC when the wood is heated above 110 F. For dry wood, 22% to 6% MC, Couture and Hill's meter sensitivity ranged from 10 megohms at 1 V to 100 megohms at 10 V with a pulse width of 0.04 second and a repetition rate of 2.5 Hz. Kuroda and Tsutsumi (1981) demonstrated with sugi (*Cryptomeria japonica*) in the MC range of 3% to 14% that electrical conductivity increases (therefore resistivity decreases) with increases in frequency of the current and increases in MC and temperature of the wood.

The moisture gradient influence on resistance measurements depends upon progression of drying, whereby the outside shell of the board dries below FSP during the early stages of drying while the inner core remains above FSP until the later stages. Wetwood often contains soluble extractives that migrate from the core outward to the surface during kiln-drying and precipitate as incrustations in the dry surface of the boards (Lin and Lancaster 1973). These incrustations retard the loss of moisture during drying so that wetwood boards have steeper moisture gradients, or wetter cores, than faster drying normal boards. During the final stages of kiln-drying, it is not unusual for wetwood boards to have internal pockets of trapped water (Ward and Pong 1980). Because of the steeper moisture gradient, it is possible to measure electrical resistances in the core of wetwood boards at a lower average MC than is possible with normal boards having a more shallow moisture gradient with dryer cores.

In normal wood boards, too, of course, the MC of the core is higher than the shell. This partly explains why resistances could be measured with the Shigometer in white fir sapwood at 15%–18% MC (Fig. 3A), while Piirto and Wilcox (1978) found that in white fir sapwood at 29%–30% MC resistances exceeded the maximum scale on the meter. They used small samples in which average MC approximated core MC. The other part of the explanation is that their resistance measurements were made at room temperature, whereas measurements in this study were made in wood heated to 180 F.

The physicochemical properties of wetwood may also contribute to lower meter readings and greater persistence of measurable resistances in boards during the middle and final stages of kiln-drying. Chemical extractives and cell-wall matrices in wetwood may be so altered by bacteria that they are less able to adsorb and immobilize charge-carrying ions as the wood dries below FSP. Kuroda and Tsutsumi (1981, 1982) suggest that the response of wood to an electric field can be related to attractive forces between adsorbed ions and wood substances. Also, the excess ash in wetwood may increase its hygroscopicity, thus reducing resistances similar to the effect that James (1980) observed with moisture meter measurements of wood treated with inorganic salts.

The possible influence of physicochemical properties on differences between resistances of wetwood and normal wood could be determined by comparing activation energies of electrical conduction in wetwood and normal wood. Activation energy can be related to wood MC by Langwig's (1971) method, which employed NAA to identify which trace elements in wood were charge carriers and which were immobile.

Activation energy is the energy required to dissociate current-carrying ions in wood. It will increase exponentially with decreasing MC and can vary by species and wood type (Brown et al. 1963; Davidson 1958; Langwig 1971; Lin 1965). Lin (1965) postulated that the number of charge carriers in wood is the major factor affecting electrical conduction below 20% MC, whereas mobility of ions becomes more important above 20% MC.

FSP considerations and electronic kiln controls

Comparison of FSP values (Table 5) indicates an interaction of factors related to shrinkage and pulsed-current resistances during kiln-drying that differ between wetwood and normal wood. This suggests that the presence of wetwood in lumber should be considered when developing electronic systems to measure MC for computerized control of kiln-drying.

As determined from resistance measurements, FSP values for wetwood samples were 8%–12% lower than FSP values for normal wood. FSP values determined from shrinkage measurements varied by 0%–4% between wetwood and normal wood. This points out that fundamental differences between the electrical properties of wetwood and normal wood exist during kiln-drying from the green condition, and these differences do not necessarily parallel shrinkage properties. Stamm (1971) observed that FSP values determined by electrical conductivity measurements can be comparable to those determined by shrinking and swelling measurements. Stamm's comparison did not always stand up here in this study because of elevated temperature effects on resistance measurements.

Stamm (1971) also observed that FSP determined from shrinkage of green lumber during kiln-drying differs from FSP in the same piece after being soaked and redried. He termed the first set of determinations as "apparent FSP" because they were influenced by collapse, which was relieved with soaking and which did not influence the second set of determinations from redrying. The influence of collapse (or compression set) is evident in the shrinkage curves for most samples in this study (Figs. 4, 5). Below 30% MC the increase in shrinkage from the green condition is ill defined and not as sharp as the increase in resistance measurements (Figs. 2, 3).

For computerized control of kiln-drying, these interacting factors can be coordinated and resolved with a dual set of electronic measuring devices that will detect continuous changes in both MC and shrinkage of board samples. An integrated measuring system for MC and shrinkage does not yet exist, but individual components have been developed (Brunner 1981).

Results from this study suggest that electronic measurement of moisture loss must consider the differences between moisture gradients of wetwood and normal wood during kiln-drying. For electronic measurements of moisture gradients to be consistent, Skaar (1964) believes it is necessary to obtain empirical relationships between the resistivity in the three grain directions and the resistance obtained with various electrode combinations.

CONCLUSIONS

Resistance measurements of wetwood, sapwood, and heartwood will vary within a species both before and during kiln-drying, because of three conditions: MC, ash concentration, and temperature. Wetwood in green lumber of aspen and white fir has lower resistance to a pulsed electric current than normal sapwood and heartwood because of higher ash. During kiln-drying, measurements of pulsed-current resistances drop with heating of the lumber, but wetwood boards still have resistance measurements that are lower than those of normal boards even though moisture contents are equal. This means that the presence of wetwood in lumber must be considered when pulsed-current resistances are used for remote measurement of moisture loss for computerized control of kiln-drying. Unless proper precautions are observed in drying mixed-wood charges, resistance measurements from wetwood boards will tend to overestimate MC for the kiln charge, while resistances in normal wood boards will underestimate MC.

Additional research is needed to resolve the problem of remote measurement of MC in lumber species with wetwood. For problem species such as aspen, true fir, and hemlock, investigators must consider the interacting influences of drying temperatures, changing moisture levels in wood, and the different physicochemical properties of wetwood and normal wood when advocating the use of pulsed-current resistance measurements for monitoring kiln controls. There will be a distinct and dynamic variation between pulsed-current resistances of wetwood and normal wood throughout most of the kiln-drying operation.

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Del Shedd, Quality Control Supervisor, Roseburg Lumber Co., Anderson, Calif., selected the white fir board samples.

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