

ABSTRACT

The dielectric constant and loss tangent of white oak, Douglas-fir, and four commercial hardboards were measured at frequencies from 20 Hertz (Hz) to 50 Megahertz (MHz), moisture conditions from oven-dry to complete saturation, temperatures from -20 to +90° C., and, for the natural wood, with the electric field aligned with three principal structural orientations. The hardboard was measured with the electric field perpendicular to the faces of the board.

The behavior of all materials studied was qualitatively similar. The dielectric constant increased with increasing moisture content or temperature, and decreased with increasing frequency. Magnitudes ranged from about 2.0 for cold, dry material at high frequencies to near 1 million for warm, water-soaked wood at low frequencies (parallel to the grain).

Loss tangent showed maximum and minimum values under various conditions. The frequencies at which extremes occurred generally were higher as either moisture content or temperature increased. The loss tangent ranged from about 0.01 to about 100.

A theory based on physically plausible assumptions was developed, and provided adequate description of the observed influence of frequency on dielectric properties of wood.

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DIELECTRIC PROPERTIES OF WOOD AND HARDBOARD: VARIATION WITH TEMPERATURE, FREQUENCY, MOISTURE CONTENT, AND GRAIN ORIENTATION

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Introduction

The dielectric properties of a nonconducting material describe the interaction of the material with electric fields. The two interactions of primary interest are the absorption and storage of electric potential energy in the form of polarization within the dielectric material, and the dissipation or loss of part of this energy when the electric field is removed. The ability of a material to absorb and store energy is described quantitatively by the dielectric constant, although other terms – susceptibility, polarizability, specific inductive capacity – are used which describe the same quantity. The energy absorbed by a dielectric is most easily measured in terms of capacitance, so the dielectric constant of a material is usually defined as the ratio of the capacitance of a given capacitor with the material as the insulating medium to the capacitance of the same capacitor with vacuum (or practically, air) as the insulator.

The rate of energy loss in the dielectric is expressed commonly by the loss tangent, but other terms – dissipation factor, loss factor, and power factor – are also used to express the same process. Dissipation factor is the same as loss tangent and loss factor is the product of loss tangent and dielectric constant. If a perfect dielectric material is in a sinusoidally varying electric field, the current in the material will be a pure imaginary, being also sinusoidal and leading the field by 90° (quadrature-leading). In real dielectrics, however, the current has a component in phase with the field, which results in energy being dissipated as heat. The ratio of the in-phase to the pure imaginary or quadrature components of the current is the loss tangent. The power factor is the sine of the angle whose tangent is the loss tangent.

Polarization may take several forms (17).² Electronic polarization is the displacement of individual electrons in an atom in response to external fields. Atomic polarization is the displacement of the atomic nucleus in relation to the group of atomic electrons. Molecular polarization is the displacement of individual atoms within a molecule. These polarizations can occur in any material. In addition, crystals can be polarized by distortion of the crystal lattice; materials whose molecules are electrically unsymmetric (polar) can be polarized by alinement of their dipole moments (1); and materials that are inhomogeneous, with multiple discontinuities in electric conductance and dielectric constant, can experience interfacial polarization, which is the accumulation of charge at the discontinuities under the influence of external fields.

All polarizations require a finite time to occur, so the polarization never follows a varying electric field exactly. This is one physical contribution to energy dissipation in the dielectric. The rate at which a polarization process can vary is expressed quantitatively by the time constant, which is the time required for the polarization under zero field, or the difference between the polarization and its final value under constant field, to decrease by a factor 1/e. In general, interfacial polarizations are the slowest (longest time constants), molecular and dipole are intermediate, atomic is fast, and

¹ Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

² Italicized numbers in parentheses refer to literature cited at end of this report.

electronic fastest (17). This variation in time constant results in an influence of frequency on dielectric properties.

Interfacial and dipole polarization involve mechanisms that are thermally activated – in the former, the migration of charge carriers through structural domains, and in the latter, the general mobility of molecules. The presence of thermally activated mechanisms of polarization results in temperature influence on dielectric properties. The increase in thermal energy possessed by an average mole of active elements in the process for unit increase in temperature determines the magnitude of the influence of temperature on the process. This is related to the activation energy, which may be calculated from the observed influence of temperature on the rate of the process. The magnitude of the activation energy can be useful in identifying the thermally activated process.

The dielectric properties of wood, and their variation with frequency and temperature, are closely related to basic wood structure. Additionally, the effects on these properties of moisture content and field direction in respect to grain direction provide clues to the basic structure of Wood.

In addition to being helpful in understanding the basic structure of wood, data on its dielectric properties are essential for efficient use of wood in engineered applications where it is subjected to alternating electric fields, such as in large power transformers or in curing glue by dielectric heating.

One of the earlier studies of the dielectric properties of wood was by Skaar (16), who showed that the dielectric constant of wood increased continuously as the moisture content increased,

and decreased with increasing frequency of the applied field. His data do not show clearly recognizable trends in loss tangent. Later work (3,6) demonstrated that the loss tangent was not a simple function of moisture content, but had a complex form.

As the studies of dielectric properties became more sophisticated, other variables were considered, such as temperature (4,7-10,12,18,19), structural direction (13), and density (11,14) with the results showing that these other variables also have important influence on the dielectric behavior of wood.

A notable weakness in the literature of dielectric properties has been lack of a study that covered a wide range of all primary variables on a complete sample of material, so that interactions between the primary variables could be deduced. The study reported here attempts to ease this situation by providing dielectric data on two distinctly different species in the three principal structural directions, and over a wide range of temperature, moisture content, and frequency. The species studied were Douglas-fir (*P. menziesii*), a medium-density softwood and white oak (*Q. alba*), a moderately high-density ring porous hardwood. In selecting the two species, there was no intent to relate dielectric properties to species characteristics, but only to see if species differences are likely to be significant. Data were taken at frequencies from 20 Hz to 50 MHz, temperatures from -20 to +90° C., and moisture content from oven-dry to completely saturated.

In addition, data were obtained on four types of hardboard made from Douglas-fir or oak fibers.

Experimental Methods

Specimen Preparation

The species of wood studied here were selected to provide two sets of material with substantial differences in structure, extractive content, and mechanical properties, with no attempt to catalog data characteristic of the species. For this reason no attempt was made to secure a sample that was representative of the species; specimens of Douglas-fir were all cut from a single green flitch, 5 by 8 by 84 inches, and the oak specimens were obtained from a single freshly cut 8-foot railroad tie.

The flitch and tie were each cut into 15 blocks to provide for the three grain orientations and 5 moisture conditions, and each block yielded 8 or more individual specimens. Perfect randomization of the specimens throughout the moisture conditions would have greatly complicated specimen preparation, so inasmuch as past experience demonstrated no reason to expect that matching within a block would be substantially better than between blocks, all specimens for one grain direction and moisture condition were made from the same block. Thus, replications revealed only

within-block variability and measurement variability. The blocks were randomized within the original flitch and railroad tie however, so between-block differences would be random.

One block for each grain direction was conditioned to equilibrium in a room at 80° F. and a relative humidity of either 30, 65, 80, or 90 percent, and one block for each grain direction was soaked in distilled water. When the blocks were equilibrated, they were lathe turned to a diameter of 1.50 inches, and these 1.50-inch rods were cut into wafers approximately 0.20 inch thick using a smooth cut circular saw and a special jig to assure parallel faces on the wafers. The wafers were then returned to their respective moisture environments for final conditioning and storage. Average moisture content attained by the specimen material is tabulated in table 1.

In order to obtain reproducible data, it was necessary to eliminate variability in the electrochemical condition of the specimen surfaces. This was achieved by coating the flat surfaces of the wafer specimens with electrically conducting silver paint. In addition, in order to prevent moisture loss or regain by the specimens, aluminum foil was bonded to the silver painted surfaces using an electrically conducting contact adhesive, and the edges of the specimens were sealed by thin plastic bands stretched around the periphery of the wafers.

The hardboard types selected were a standard and a tempered board of Douglas-fir, wet-felted and wet-pressed (hardboards Nos. 1 and 2,

respectively), a tempered board of oak, dry-felted and dry-pressed (hardboard No. 3), and a tempered board of Douglas-fir, dry felted and dry-pressed (hardboard No. 4). The screen backs on the wet-pressed boards were sanded smooth for the dielectric measurements.

Specimens of hardboard were prepared in a fashion similar to the solid wood, except that individual wafers were cut from 6-inch-square pieces of moisture-equilibrated material using a 1.5 inch plug cutter. No water-soaked hardboard specimens were prepared, but a sample was equilibrated at near 100 percent relative humidity. Room temperature data were obtained on specimens from 14 different formulations of hardboard, from which four representative samples were selected to be evaluated over the complete range of temperatures covered here.

Data for "ovendry" wood and hardboard were obtained using the specimens originally conditioned and tested in equilibrium with 30 percent relative humidity. These specimens were dried in a vacuum oven at 60° C. for 30 hours after all data at 30 percent relative humidity had been obtained, and stored in desiccators between data runs.

Instrumentation

At frequencies of 1 MHz or greater, dielectric constant and loss tangent data were taken using a Boonton model 160-A Q-meter. When more moist specimens were used, the resonance voltages were

Table 1.--Moisture content of material, percent of dry weight

Relative: humidity:	Material											
	Douglas-fir			Oak			Hardboard					
	Longitudinal:Radial :Tangential:			Longitudinal:Radial :Tangential:			1	2	3	4		
	Pct.											
30	5.6	5.3	5.3	5.1	5.0	5.1	4.4	4.0	3.5	4.3		
65	11.9	11.6	11.8	12.2	12.1	12.0	8.6	8.3	8.0	8.8		
80	16.3	16.3	16.5	17.4	17.0	17.0	12.1	11.6	11.6	12.3		
90	24.3	24.5	24.0	24.9	25.1	25.4	18.2	17.0	17.8	18.9		
99	--	--	--	--	--	--	34.8	29.6	36.5	31.9		
Soak	130	130	132	112	126	144	--	--	--	--		

too small to read on the self-contained meter in the model 160-A, so these small voltages, at frequencies no greater than 10 MHz, were read using a Hewlett-Packard model 400 DR VTVM equipped with a low capacitance probe and at frequencies greater than 10 MHz using a Hewlett-Packard model 410A VTVM. Calibration of the model 400DR is inaccurate at the frequencies used here, but only linearity of the readings was required to determine resonance and the half-power points.

For frequencies of 100 kilohertz (kHz) or less, data were taken using the approximate equivalent of a General Radio model 716-C capacitance bridge: it was a modified model 716-CS1, and it differed from the 716-C in that X10 and X100 range multiplication was provided with direct reading of dissipation factor (loss tangent) at 100 Hz. The bridge was driven by a Hewlett-Packard model 200CD oscillator and balance was detected by a General Radio 1232-A tuned null detector. An external range extender for the bridge provided 0 to 11 nanofarad capacitance in 12 steps and resistance from 0 to 111.111 megohms using 5 decade switches and a linear 1000 ohm potentiometer. The range extender also could be paralleled by a series of fixed capacitors with multiple plugs that permitted stacking to build up the large external capacitances sometimes required to balance the bridge.

The specimen holder was a parallel plate capacitor with circular plates 2.0 inches in diameter (fig. 1). Spacing of the plates could be adjusted and measured by means of a screw micrometer head; spacings from 0 to 0.24 inch could be measured to 0.0002 inch. The fixed, ungrounded plate was supported by 3/4 inch of Teflon. The moveable, grounded plate was contacted electrically by a silver-to-silver spring-loaded rotating contact and was held to the micrometer spindle by a stiff ball joint that permitted the plate to conform to specimens with slightly nonparallel faces. The same specimen holder was used with both the bridge and the Q-meter. The capacitance of the empty specimen holder as a function of spacing was established by calibration against the precision variable capacitor in the capacitance bridge.

The specimen holder was enclosed in an insulated, controlled-temperature box with forced-air circulation; the temperature of the stationary plate of the specimen holder was the reference for control, and held to about $\pm 0.5^\circ$ C. The box was

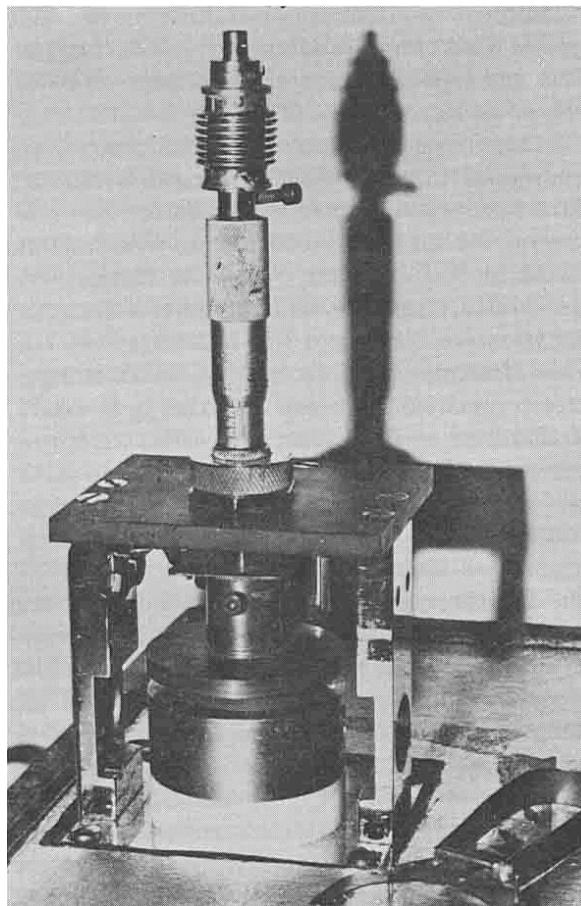


Figure 1. – Specimen holder used for all measurements reported here.

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heated electrically and cooled either by dry ice or a thermostatically controlled spray of liquid carbon dioxide. The most convenient and economical method of cooling was using an excess of dry ice and supplying heat as required to keep the specimen holder at the required temperature.

Procedures

The dielectric properties of the cellulosic materials studied here varied over such a wide range that several different measurement techniques were required.

When specimen capacitance was less than about 80 picofarads (pf), it was determined by reducing the spacing of the plates of the empty specimen holder to obtain the same capacitance as when the specimen was in the holder. For low frequency measurements on specimens of this capacitance range, using the bridge, the specimen holder was shunted with a 150 pf mica capacitor to enable the bridge to be balanced.

Specimen capacitance greater than 80 pf occurred only at the lower frequencies where the bridge was used; for these measurements specimen capacitance was determined by direct comparison with the internal standard capacitor of the bridge plus external fixed capacitors as required for balance. The constant stray capacitance of the specimen holder was subtracted during data processing.

With the bridge in use, loss tangents of the capacitor – consisting of the specimen in the specimen holder plus its shunt capacitor and connecting cable – could be read directly from the bridge settings when this loss tangent was no greater than 0.56 (at 20 Hz the upper limit was 0.112). With specimens characterized by moderately more loss, overall loss tangent was brought within these limits by using a larger shunt capacitor. All values of loss tangent were corrected for the loss of the apparatus with no specimen in place and, in the data processing, for the effect of the shunt and stray capacitance.

When the loss tangent was too great to read directly, the loss component of the specimen impedance was balanced by external resistors. Most such measurements were made using ordinary small carton potentiometers as variable resistors; the capacitance of the resistance element to ground of the type used here was 3.0 pf. The resistance required to balance the bridge was then measured using an ordinary high-quality ohmmeter. When specimens of very large capacitance were being run, the range extender described earlier was used to provide directly readable external resistance and capacitance simultaneously.

When using the Q-meter, loss tangent was determined in most cases by the width of the curve of resonance voltage against capacitance, at the half-power points. For some specimens the range of the tuning capacitor was sufficient only to read half of this width, so, for computation, the curve was assumed to be symmetric. Inductors for the Q-meter were fitted with adjustable ferrite cores to permit resonating the system with the tuning capacitor near an extreme setting, so enough range was available on the capacitor to locate one of the half-power points.

For specimens that show greatest amounts of loss, half-power points were not attainable, and the loss tangent was computed from the ratio of the resonance voltages with and without the specimen

in place. This procedure was necessary only for soaked specimens at 90° C.

All specimen material was divided into individual samples representing material (species or hardboard type), grain orientation (natural wood only), and moisture content (actually equilibrium humidity). The variables of temperature and frequency were applied over the entire range to each of these individual samples. The bulk of data was taken with just two selected specimens in each of these individual samples, although initial room temperature data (at all moisture levels except overdry) were taken using samples of five specimens each. The general procedure was to run material conditioned at a given humidity through the range of frequencies at one temperature, starting with the lowest temperature and ending with the highest.

In collecting data it was desirable to subject the specimens to extreme temperatures for the least possible time in order to minimize changes in moisture content or other properties. The procedure that best met this desire was to hold the inactive specimens at room temperature in a sealed container, and withdraw them one at a time for measurement, placing them into the specimen holder being maintained at the test temperature. Preliminary experiments using specimens with thermocouples at their center showed that in 3 minutes or less the specimens came to the temperature of the specimen holder, at least within the limits of readability of the thermocouple pyrometer. Collection of data was therefore routinely begun 3 minutes after placing the specimen into the holder. When the data were collected, the specimen was returned quickly to room temperature by placing it between two metal plates at room temperature for 3 or 4 minutes before returning it to the sealed container. Overdry specimens were treated slightly differently, in that after being tested at low temperatures they were warmed between plates at about 60° C. before being returned to the desiccator, and after high temperature tests they were simply returned to the desiccator while they were still hot.

All data were recorded directly onto computer cards using a portable keypunch. Processed data consisted of the dielectric constant and loss tangent of every specimen, plus the averages and coefficients of variation of replicated samples.

Results and Discussion

Presentation of Data

The data consisting of dielectric constant and loss tangent for various materials at various conditions are presented in tables 2 through 11. In addition, data from table 2 are plotted in figures 2 through 13. Data from other tables would plot into curves that are similar in form, indicating that the basic properties of cellulose are not strongly dependent on the source of the cellulose (species, hardboard type). Figure 14 is a plot of room temperature loss factor for longitudinal grain Douglas-fir. Loss factor, the product of loss tangent and dielectric constant, is the property most directly involved in the calibration of power-loss-type moisture meters.

General Comments

The data reported here were obtained using specimens whose electrode surfaces were sealed with an electrically conducting (silver) paint, overlaid with aluminum foil attached by an electrically conducting (silver-filled) silicone contact adhesive. Initially, however, some exploratory data were collected on bare wood specimens. Data for bare specimens at low to medium moisture content agreed well with corresponding data for encapsulated specimens, but data for more moist bare specimens were dependent on clamping pressure in the specimen holder, they were unstable with time, and were not repeatable. Data for all encapsulated specimens were insensitive to clamping pressure, did not drift excessively with time, and were generally repeatable over several months of data taking. Variability encountered using bare specimens was significant from a laboratory standpoint, but probably not of significant magnitude from a practical standpoint.

When the longitudinal grain oak specimens were being prepared, special care was taken to avoid applying excess silver paint to the specimen faces to preclude the paint filling the wood vessels and electrically "shorting" the specimens. This care was nominally rewarded in that none of the specimens were shorted several days after being painted. But surprisingly, after intervals of 2 or more weeks, some of the oak specimens at the higher moisture levels did develop shorts, even though the paint had been totally dry for many days.

Fortunately these shorts could be cleared by discharging a capacitor through the specimen; about 10 joules appeared to be an optimum

discharge energy. The electrical properties of specimens so treated were temporarily distorted, but in a few hours they were equivalent to their condition before the short occurred.

Midway through the schedule of data-taking, both of the soaked specimens of longitudinal grain Douglas-fir developed anomalously large capacitance at the low frequencies, with a simultaneous 30 percent reduction in resistance; the anomalous low frequency capacitance was between 15 and 20 μ f at room temperature. Removing and replacing the surface sealants had no effect, and it was necessary to discard and replace the specimens with new ones. The new specimens had low frequency, room temperature capacitance values somewhat less than 1 μ f in agreement with the original specimens before their deviant behavior. This event cannot now be explained, but may be due to some contaminant in the water in which the specimens were stored, or perhaps a chemical modification of the wet specimens by the carbon dioxide atmosphere from the dry ice used for cooling the test chamber.

Another incidence of anomalous behavior appeared in the oven-dry radial grain specimens of Douglas-fir; these specimens showed unrealistically large loss tangent at the lower frequencies and higher temperatures (table 3). The source of this anomaly has not been determined, but may be due to a deposit of resin that becomes highly absorptive when softened at elevated temperatures. This behavior also could be explained if a small amount of moisture were present, but it would be difficult to explain how this moisture could persist during the vacuum oven-drying and subsequent storage in a desiccator.

Accuracy and Errors

The instruments used in this study were capable of measuring the capacitance and dissipation factor of stable capacitors to a high degree of precision and accuracy, so the predominant source of error here was the inherent instability of the quantities being measured. Data taken on specimens encapsulated as described earlier were generally constant and repeatable to within plus or minus 10 percent of the mean datum, with a possible exception of some data taken at 20 Hz. At 20 Hz the bridge nulls for some specimens were quite broad and noisy, which introduced additional uncertainty of the order of 5 percent of the measured quantities. These are

“worst case” estimates of uncertainty, and the more favorable combinations of frequency and specimen parameters gave more precise data.

Temperature, frequency, and specimen dimensions could be measured with insignificant error. Further, no attempt was made to correct for the added capacitance of the tubing used to seal the edges of the specimens, because it was determined to be negligible.

Dielectric Constant

Materials with complex, electrically unsymmetric molecules usually have large dielectric constants, while those with simple, symmetric molecules have small dielectric constants (1). Heterogeneous materials whose structural elements are bounded by strong discontinuity in electrical conductance can exhibit large dielectric constants, as can certain crystals (17).

Wood is a material with complex, unsymmetric molecules and inhomogeneous structure, so might be expected to have a large dielectric constant. The data in this report confirm this expectation with the qualification that the susceptibility of wood to electric polarization depends enormously on moisture content and the rate of variation with time of the external electric field.

The present data show that extremely large susceptibility of wood to electric polarization occurs only when the external electric field is varying slowly (frequencies less than 10 kHz) and when at least moderate amounts of water are present (greater than 10 pct moisture content). These data are consistent with the findings of Hearle (2) on cellulosic fibers and Schwan (15) on biological materials. The slow response and large magnitude of these polarizations suggest that they are interfacial, that is, due to polarization at discontinuities of conductivity as described earlier (15,17). It is the opinion of the author that the most likely discontinuities to be effective here are between the amorphous and the crystalline regions of the cellulose molecules; the crystalline regions are essentially nonhygroscopic and remain nonconducting in the presence of water while the amorphous regions become rapidly more conductive as the moisture content increases. It is reasonable to assume that under the influence of the external electric field, ions would migrate through the amorphous regions and accumulate at the edges of the crystallites until the internal field from the separated ionic charges equals the applied field, or until the external field reverses. This

process would be capable of absorbing and storing considerable energy, but because the process would be retarded by impedance to the ion migration and also because there are conductance paths around the crystallites, the energy storage would be accompanied by very large energy dissipation. In fact, the large values of low frequency loss tangent reported here demonstrate that the in-phase (loss) component of the current through wood with as little as 10 percent moisture content may be 10 times greater than the leading quadrature (charging) component, and that at greater moisture levels this ratio reaches near 100. Under the latter conditions, the current leads the voltage by less than 1 degree, and the concept of capacitance in the wood seems almost fictitious. The simple fact remains, however, that to achieve this phase lead of less than 1 degree, requires the large values of dielectric constant reported here.

As the frequency increases above 10 kHz, the dielectric constant decreases to values typical of homogeneous polar solids (1), indicating that the contribution of interfacial polarization becomes insignificant, and the predominant polarization is molecular; that is, energy is absorbed in the form of induced dipole moment of the molecule, and in the form of alignment of molecules having fixed dipole moment. Moisture content is still important here, although not to the great degree observed at lower frequencies (tables 2-11). Water apparently increases the polarizability of the cellulose molecules at these higher frequencies simply by adding hygroscopically bound polar groups to the cellulose molecule, thereby increasing its fixed dipole moment and increasing the energy absorbed by the distortion of the molecules under electric stress.

The present data were obtained at discrete frequencies, but spaced closely enough that any relatively abrupt change in properties at specific frequencies would probably be recognized. The smooth decrease in dielectric constant with increasing frequency over the entire range of frequency covered, and at all combinations of other variables, demonstrates that there are no predominant processes of polarization in wood that have a characteristic time constant. This character of the dielectric constant of wood is also shown in data presented by Tsutsumi and Watanabe (18). Rather, there is a continuum of time constants with a disordered distribution, which indicates that the major centers of electric polarization occur in the amorphous (disordered) regions of the cellulose molecule. Previous data (5), included in figure 10, show that this general trend continues at least to

frequencies near 10 gigahertz (GHz). It is certain that polarization does occur in the crystalline regions as well as in the amorphous regions, but its relative contribution to the total polarization cannot be great. This portion of the total polarization could be expected to show evidence of characteristic time constants at the higher microwave frequencies.

The data presented here show that the polarizability of wood increases continuously as temperature increases, with the possible exception of water-soaked wood at some frequencies. (This exception may be due to a redistribution of moisture in the cellulose at elevated temperature, and confounded by the fact that specimens had to be replaced midway through the schedule of taking data.) Tsutsumi and Watanabe (18) also found that the dielectric constant of wood increased with temperature, with a strong interaction with frequency. This is consistent with the hypothesis that the cellulose molecules have fixed dipole moments, and that interfacial polarizations occur, at least at the lower frequencies, because both of these modes of polarization are activated by thermal energy (1, 17). By contrast, induced dipole moment is not activated thermally, as evidenced by the temperature invariance of the dielectric constant of such nonpolar compounds as teflon. The room temperature activation energy of the polarization mechanism at 20 Hz, where interfacial polarization predominates, and at 10 MHz, where molecular polarization predominates, are derived from data plotted in figures 15 and 16, respectively, and tabulated on the corresponding plots.

The apparent activation energies of polarization at 20 Hz and various moisture levels are of roughly the same magnitude as those of direct current electric conduction (4), but there are differences that indicate that the two processes are unrelated. Most notable is that the activation energy of polarization increases with increasing moisture content, at least up to fiber saturation, while that of conduction decreases with increasing moisture content. The two are nearly equal (about 12,000 cal per deg-mole) at about 16 percent moisture content.

At 10 MHz the apparent activation energy of polarization is small (about 500 cal per deg-mole) and essentially independent of moisture content up to fiber saturation (fig. 16). This magnitude is also about equal to the corresponding activation energy of polarization for oven-dry wood at 20 Hz, and probably represents the activation of polarization by orientation of polar molecules.

Thermal activation of polarization of soaked wood is small and erratic, and probably confounded with the lowering of the fiber saturation moisture content at elevated temperature; the latter would reduce the contribution of water to the polarizability of the cellulose at elevated temperature.

Loss Tangent

The loss tangent may be defined in several ways, but physically it is the ratio of the in-phase or joule current to the quadrature-leading or charging current in the dielectric. The loss tangent is related in a complicated way to the fraction of the peak stored energy dissipated as heat during a complete charge-discharge cycle. If no energy is dissipated, the loss tangent is zero, and if all of it is dissipated, there is no charging current and the loss tangent is infinite.

The data obtained here show that the loss tangent of wood and hardboard has maximum and minimum values at various frequencies depending on the temperature and moisture content. The indication of distinct relaxation times reported by Nanassy (8) for dry wood at high temperature was not seen here, but the present data are in general quantitative agreement with other work where the conditions of measurement overlap (18,19). It would be premature to assume from the present data that these extremes indicate any sort of loss mechanism with a characteristic time constant, especially in view of the data discussed earlier that indicate the lack of polarizations with characteristic time constants. It is more likely that these curves are shaped by the distribution of the continuum of polarization time constants in the disordered regions of the cellulose molecules.

Table 2.--Dielectric constant (DK) and loss tangent (tan δ) for longitudinal Douglas-fir

Relative Temperature: humidity:		Frequency, Hz															
		20		100		1 K		10 K		100 K		1 M		10 M		50 M	
		DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ
Pct.	°C.																
0	-20	4.1	0.054	3.9	0.034	3.3	0.056	3.0	0.078	2.8	0.10	2.9	0.10	2.7	0.086	2.6	0.091
	5	4.2	.047	4.0	.022	3.6	.036	3.3	.051	3.1	.078	3.2	.10	2.9	.11	2.8	.11
	25	4.3	.033	4.1	.014	3.8	.024	3.5	.038	3.4	.059	3.5	.09	3.2	.11	2.9	.14
	45	4.6	.037	4.3	.035	3.9	.021	3.7	.027	3.6	.043	3.8	.070	3.5	.11	3.2	.14
	70	5.2	.044	4.9	.036	4.4	.022	4.2	.018	4.1	.029	4.1	.054	3.8	.10	3.5	.16
	90	5.6	.13	5.3	.077	4.8	.042	4.6	.022	4.5	.020	4.3	.037	4.0	.084	3.7	.15
30	-20	6.3	.090	6.3	.061	5.8	.062	5.3	.082	4.7	.11	4.0	.14	3.4	.15	3.1	.16
	5	6.3	.11	6.0	.043	5.8	.025	5.7	.034	5.4	.061	4.9	.11	4.1	.17	3.6	.21
	25	7.1	.26	6.5	.12	6.2	.042	6.0	.029	5.7	.043	5.4	.080	4.7	.14	4.1	.19
	45	8.9	.87	7.3	.33	6.4	.095	6.1	.038	5.9	.034	5.6	.058	5.1	.11	4.6	.18
	70	13	4.1	9.3	1.6	7.5	.31	6.6	.087	6.2	.038	6.0	.047	5.6	.084	5.1	.16
	90	17	14	11.3	4.4	8.4	.73	6.8	.18	6.5	.049	5.9	.039	5.7	.081	5.1	.14
65	-20	18	1.2	13	.58	10	.20	8.8	.096	8.0	.087	7.0	.14	5.6	.20	4.6	.76
	5	43	5.8	24	2.7	13	.72	11	.21	8.8	.094	8.1	.094	6.9	.15	6.0	.31
	25	95	13	38	7.2	20	1.7	12	.52	9.0	.19	8.5	.089	7.5	.087	6.7	.19
	45	280	18	72	16	26	4.4	14	1.1	9.9	.32	8.8	.12	7.9	.098	7.2	.18
	70	1,000	.27	150	.36	32	.17	18	.32	12	.74	9.5	.26	8.1	.087	7.5	.14
	90	2,300	.34	280	.53	33	.45	18	8.1	12	1.5	9.7	.35	7.9	.13	7.3	.13
80	-20	140	8.2	59	4.5	28	1.2	16	.50	12	.22	9.6	.16	7.8	.20	6.3	.35
	5	1,100	10	220	11	51	5.6	26	1.5	16	.50	11	.25	9.2	.15	8.1	.27
	25	4,600	12	790	14	94	13	37	3.9	19	1.1	13	.40	10	.17	8.8	.23
	45	12,000	13	2,100	15	180	19	41	8.1	25	1.8	15	.62	10	.24	9.1	.25
	70	29,000	18	3,900	26	310	35	49	22	27	4.3	18	1.2	11	.36	9.3	.30
	90	34,000	28	3,700	51	280	67	54	36	23	8.9	18	1.4	11	.38	8.8	.31
90	-20	580	29	130	23	52	6.3	29	1.4	18	.53	13	.21	10	.19	8.9	.40
	5	5,200	25	923	31	94	27	42	6.2	26	1.4	16	.43	12	.18	10	.28
	25	24,000	23	3,200	35	230	44	45	21	32	3.2	19	.83	13	.28	11	.21
	45	62,000	18	8,000	27	480	44	60	34	32	6.5	21	1.3	14	.37	11	.33
	70	170,000	15	18,000	25	850	52	74	99	31	14	23	2.7	14	.62	11	.45
	90	150,000	27	19,000	32	860	70	88	68	35	32	23	3.1	14	.78	10	.54
Soaked	-20	4,700	1.1	2,000	1.4	200	3.0	35	2.5	17	.85	16	.27	14	.22	$\frac{1}{1.12}$	$\frac{1}{1.27}$
	5	220,000	35	31,000	51	1,900	89	300	61	100	17	62	.79	53	.22	$\frac{1}{1.54}$	$\frac{1}{1.42}$
	25	500,000	26	53,000	49	3,100	90	307	93	93	32	62	1.1	53	.20	$\frac{1}{1.52}$	$\frac{1}{1.30}$
	45	290,000	18	30,000	36	1,300	86	170	66	74	16	56	2.0	44	.34	$\frac{1}{1.43}$	$\frac{1}{1.42}$
	70	360,000	16	39,000	31	1,900	69	190	70	71	19	50	2.8	43	.42	$\frac{1}{1.38}$	$\frac{1}{1.3}$
	90	740,000	15	88,000	27	5,300	48	380	67	86	30	64	5.5	46	1.0	$\frac{1}{1.40}$	$\frac{1}{1.2}$

¹45 MHz.

Table 3.--dielectric constant (DK) and loss tangent ($\tan \delta$) for radial Douglas-fir

Relative Temperature: humidity:		Frequency, Hz															
		20		100		1 K		10 K		100 K		1 M		10 M		50 M	
		DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ
Pct.	°C.																
0	-20	2.6	0.063	2.6	0.038	2.4	0.060	2.2	0.059	2.2	0.059	2.2	0.059	2.1	0.055	2.1	0.062
	5	2.7	.056	2.6	.049	2.4	.030	2.3	.033	2.3	.041	2.4	.059	2.2	.090	2.2	.072
	25	2.8	.040	2.7	.025	2.4	.021	2.3	.029	2.3	.038	2.5	.041	2.3	.072	2.2	.086
	45	2.8	.23	2.7	.089	2.5	.021	2.4	.020	2.4	.026	2.6	.041	2.4	.074	2.3	.087
	70	3.9	.61	3.0	.23	2.8	.039	2.6	.015	2.6	.018	2.6	.039	2.5	.062	2.4	.10
	90	5.6	.80	3.7	.45	2.9	.10	2.8	.027	2.8	.017	2.7	.021	2.6	.050	2.6	.085
30	-20	3.8	.15	4.1	.18	3.4	.15	3.3	.10	2.9	.082	2.7	.089	2.4	.092	2.3	.096
	5	3.4	.11	3.4	.038	3.3	.018	3.2	.027	3.1	.045	3.0	.084	2.7	.11	2.5	.12
	25	3.6	.16	3.5	.065	3.4	.022	3.4	.017	3.3	.034	3.1	.055	2.9	.091	2.7	.12
	45	4.0	.63	3.7	.21	3.5	.051	3.4	.022	3.3	.020	3.2	.041	3.0	.082	2.9	.12
	70	5.4	2.1	4.4	.68	3.7	.14	3.5	.036	3.4	.022	3.4	.028	3.2	.054	3.1	.10
	90	6.0	6.8	4.9	1.7	3.8	.31	3.5	.063	3.4	.020	3.3	.030	3.1	.052	2.9	.082
65	-20	7.4	1.1	5.9	.49	4.7	.15	4.4	.074	4.1	.065	3.8	.096	3.3	.14	3.0	.18
	5	13	6.0	8.1	2.3	5.6	.50	4.8	.15	4.4	.065	4.2	.070	3.8	.11	3.5	.17
	25	20	18	12	7.2	6.9	1.7	5.8	.34	5.1	.062	4.3	.060	4.0	.044	3.7	.13
	45	46	29	17	18	9.4	3.3	6.3	.69	5.3	.14	4.5	.078	4.2	.071	4.0	.11
	70	147	47	31	44	12	11	7.9	1.9	5.8	.40	4.7	.15	4.3	.030	4.1	.086
	90	270	60	40	67	12	19	7.5	2.8	5.4	.47	4.6	.19	4.0	.076	3.9	.082
80	-20	25	10	17	2.4	9.0	.98	6.0	.35	5.2	.14	4.6	.11	4.0	.10	3.5	.23
	5	110	28	31	19	14	4.7	8.1	1.2	5.5	.37	5.2	.15	4.5	.083	4.1	.18
	25	510	33	83	38	21	14	12	3.0	7.4	.70	5.8	.22	4.9	.12	4.5	.14
	45	1,600	33	230	40	28	30	12	7.3	7.6	1.5	6.3	.41	5.0	.12	4.6	.14
	70	4,000	37	510	52	48	50	14	16	8.7	2.7	7.3	.87	5.3	.23	4.8	.16
	90	4,900	48	630	66	57	63	15	21	9.1	3.7	6.7	.93	4.9	.20	4.3	.19
90	-20	67	48	30	31	17	5.9	10	1.3	7.2	.42	6.0	.17	5.1	.11	4.4	.24
	5	760	47	130	60	23	32	14	6.0	9.0	1.2	6.7	.34	6.1	.15	4.8	.19
	25	3,800	38	480	60	40	69	16	18	12	2.7	8.0	.66	6.1	.19	5.4	.15
	45	11,000	30	1,300	51	89	73	19	36	12	5.7	8.6	1.1	6.2	.29	5.5	.19
	70	35,000	23	3,400	38	180	82	22	61	13	11	10	2.2	6.7	.48	5.6	.28
	90	57,000	23	6,500	43	330	83	33	84	14	21	11	2.8	7.0	.69	5.6	.34
Soaked	-20	4,700	1.8	1,800	1.8	200	3.2	22	4.2	11	1.2	9.6	.22	8.2	.091	7.4	.18
	5	13,000	60	2,000	92	300	66	130	15	86	2.8	46	.65	38	.18	34	.80
	25	29,000	46	3,600	77	350	79	120	23	71	4.3	47	.88	38	.18	36	.29
	45	150,000	27	17,000	48	900	96	150	60	73	12	50	1.9	36	.40	31	.63
	70	450,000	20	46,000	39	2,100	91	200	95	76	26	52	3.3	37	.66	28	1.4
	90	820,000	18	99,000	29	4,800	63	320	97	81	39	64	4.3	39	1.0	31	.78

Table 4.--Dielectric constant (DK) and loss tangent ($\tan \delta$) for tangential Douglas-fir

Relative Temperature: humidity:		Frequency, Hz															
		20		100		1 K		10 K		100 K		1 M		10 M		50 M	
		DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ
Pct.	°C.																
11	0	-20	3.0 : 0.041	2.9 : 0.026	2.6 : 0.048	2.4 : 0.052	2.4 : 0.059	2.4 : 0.065	2.3 : 0.058	2.2 : 0.062							
	5	3.1 : .055	2.9 : .044	2.7 : .035	2.5 : .034	2.5 : .045	2.6 : .060	2.5 : .073	2.4 : .075								
	25	3.2 : .022	3.0 : .0074	2.7 : .017	2.6 : .028	2.6 : .038	2.8 : .061	2.6 : .076	2.5 : .090								
	45	3.3 : .052	3.1 : .028	2.8 : .019	2.6 : .021	2.6 : .028	2.9 : .041	2.8 : .073	2.7 : .086								
	70	3.8 : .032	3.4 : .018	3.1 : .016	3.0 : .015	2.9 : .019	3.0 : .042	2.9 : .068	2.5 : .12								
	90	4.4 : .040	3.8 : .048	3.3 : .034	3.1 : .020	3.1 : .012	3.0 : .022	3.0 : .056	2.8 : .097								
	30	-20	4.2 : .050	4.3 : .17	4.0 : .13	3.7 : .090	3.4 : .085	3.1 : .098	2.8 : .11	2.7 : .10							
	5	4.0 : .12	4.0 : .041	3.9 : .016	3.8 : .025	3.7 : .045	3.5 : .086	3.2 : .11	2.9 : .12								
	25	4.3 : .16	4.2 : .068	4.1 : .025	4.0 : .020	3.9 : .033	3.7 : .057	3.4 : .093	3.2 : .13								
	45	5.0 : .49	4.4 : .18	4.2 : .048	4.0 : .022	4.0 : .022	3.8 : .042	3.6 : .080	3.4 : .12								
	70	6.2 : 1.8	5.1 : .55	4.4 : .13	4.2 : .036	4.1 : .022	4.0 : .030	3.8 : .057	3.6 : .11								
	90	6.4 : 6.5	5.8 : 1.3	4.6 : .27	4.1 : .060	4.0 : .024	3.8 : .027	3.7 : .046	3.4 : .088								
	65	-20	8.8 : .98	7.1 : .38	5.9 : .13	5.5 : .067	5.1 : .062	4.7 : .10	4.0 : .16	3.6 : .20							
	5	15 : 5.4	9.5 : 1.7	6.9 : .42	5.9 : .12	5.5 : .059	5.2 : .071	4.6 : .12	4.2 : .18								
	25	24 : 15	14 : 6.1	7.9 : 1.4	7.0 : .29	6.2 : .055	5.4 : .056	4.9 : .055	4.6 : .14								
	45	56 : 23	20 : 14	11 : 2.9	7.6 : .57	6.4 : .12	5.6 : .070	5.2 : .072	4.8 : .12								
	70	170 : 45	35 : 41	14 : 11	9.3 : 1.6	7.0 : .36	5.8 : .13	5.4 : .040	5.1 : .086								
	90	250 : 70	38 : 79	14 : 20	8.7 : 3.0	6.5 : .52	5.8 : .16	5.1 : .069	4.9 : .087								
	80	-20	28 : 9.0	19 : 3.3	11 : .83	7.5 : .30	6.5 : .13	5.7 : .12	4.8 : .12	4.2 : .25							
	5	99 : 28	34 : 17	17 : 4.1	10 : .95	7.0 : .32	6.4 : .14	5.6 : .090	5.0 : .19								
	25	410 : 35	76 : 36	23 : 13	14 : 2.5	8.8 : .60	7.2 : .22	6.0 : .11	5.5 : .14								
	45	1,300 : 32	200 : 42	30 : 27	15 : 6.0	8.4 : 1.3	7.6 : .35	6.2 : .12	5.6 : .14								
	70	3,300 : 39	400 : 56	42 : 52	17 : 14	11 : 2.1	8.7 : .69	6.5 : .19	5.8 : .16								
	90	4,800 : 44	630 : 65	59 : 63	17 : 23	11 : 3.7	8.3 : .79	6.2 : .20	5.5 : .14								
	90	-20	92 : 35	34 : 22	20 : 4.0	12 : 1.0	9.0 : .34	7.6 : .14	6.6 : .13	5.6 : .28							
	5	890 : 34	140 : 42	28 : 22	17 : 3.9	11 : .87	9.1 : .27	7.6 : .11	6.8 : .18								
	25	3,800 : 29	520 : 45	46 : 51	19 : 13	14 : 2.0	9.9 : .49	7.7 : .17	6.9 : .14								
	45	10,000 : 25	1,200 : 42	89 : 57	21 : 25	14 : 4.0	10 : .80	7.8 : .23	6.9 : .18								
	70	26,000 : 24	2,600 : 44	160 : 71	25 : 46	15 : 7.6	12 : 1.6	8.3 : .36	7.0 : .25								
	90	34,000 : 25	3,900 : 44	230 : 75	29 : 63	16 : 12	12 : 1.8	8.1 : .45	6.7 : .25								
Soaked	-20	2,100 : 3.3	550 : 3.3	99 : 3.0	19 : 2.3	12 : .50	10 : .15	8.9 : .094	7.3 : .25								
	5	24,000 : 33	3,100 : 46	440 : 35	190 : 7.5	120 : 1.6	50 : .52	43 : .17	40 : .88								
	25	30,000 : 33	3,900 : 51	370 : 55	140 : 15	86 : 2.9	49 : .60	42 : .14	40 : .28								
	45	270,000 : 13	33,000 : 24	1,300 : 46	160 : 30	80 : 6.2	47 : 1.3	38 : .26	34 : .58								
	70	610,000 : 15	70,000 : 27	3,600 : 54	250 : 55	88 : 17	50 : 2.5	37 : .50	31 : .77								
	90	1,200,000 : 11	170,000 : 20	8,600 : 43	385 : 63	86 : 26	54 : 2.9	39 : .62	34 : .58								

Table 5.--Dielectric constant (DK) and loss tangent (tan δ) for longitudinal oak

Relative Temperature: humidity: cure		Frequency, Hz															
		20		100		1 K		10 K		100 K		1 M		10 M		50 M	
		DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ
Pct.	°C.																
0	-20	3.9	0.033	3.7	0.026	3.2	0.045	2.9	0.060	2.8	0.078	2.9	0.069	2.7	0.062	2.6	0.058
	5	4.0	.045	3.7	.029	3.4	.036	3.2	.047	3.0	.062	3.2	.071	3.0	.078	2.8	.080
	25	4.1	.028	3.9	.017	3.5	.028	3.3	.041	3.1	.035	3.4	.076	3.1	.082	3.0	.090
	45	4.2	.033	4.0	.023	3.6	.022	3.4	.031	3.3	.044	3.6	.064	3.4	.091	3.1	.10
	70	4.7	.071	4.5	.020	4.1	.016	3.9	.020	3.8	.030	3.8	.054	3.6	.096	3.3	.12
	90	5.3	.084	4.9	.057	4.5	.029	4.3	.020	4.2	.023	4.0	.043	3.8	.089	3.6	.11
30	-20	6.2	.091	6.3	.14	5.4	.16	4.9	.13	4.4	.10	3.8	.11	3.4	.11	3.1	.11
	5	6.1	.20	5.6	.076	5.4	.042	5.2	.041	5.0	.065	4.5	.095	3.9	.12	3.6	.15
	25	7.3	.44	6.4	.19	5.8	.071	5.5	.044	5.3	.051	4.9	.073	4.4	.11	4.0	.15
	45	10	1.5	7.9	.60	6.4	.17	5.8	.068	5.5	.046	5.2	.063	4.8	.096	4.3	.15
	70	20	7.0	12	2.8	8.2	.63	6.6	.18	5.9	.073	5.6	.066	5.2	.090	4.8	.14
	90	26	28	16	8.8	9.2	1.9	6.9	.40	6.0	.11	5.0	.053	4.6	.085	4.2	.13
65	-20	24	1.2	17	.59	13	.23	10	.12	9.6	.090	11	.65	9.1	.22	7.6	.68
	5	85	5.1	36	2.9	18	.94	13	.28	10	.11	13	.094	11	.12	9.9	.25
	25	340	8.2	110	6.0	39	2.3	20	.72	15	.22	13	.10	12	.081	11	.18
	45	960	12	230	10	53	5.3	22	1.6	14	.50	12	.19	9.9	.090	9.1	.16
	70	4,000	17	740	20	100	16	31	5.4	17	1.3	13	.40	9.7	.15	9.4	.15
	90	11,000	18	1,500	23	170	21	23	14	11	3.9	14	.46	10	.18	9.2	.16
80	-20	260	7.7	87	4.8	35	1.7	20	.59	14	.26	12	.16	9.4	.16	7.8	.33
	5	2,100	9.8	470	9.6	80	6.2	33	2.2	19	.66	14	.26	11	.16	9.9	.27
	25	7,200	16	1,600	13	200	12	48	5.7	26	1.4	17	.48	13	.20	11	.19
	45	23,000	14	3,800	18	420	16	71	10	32	2.8	19	.79	13	.26	11	.25
	70	68,000	20	9,900	28	740	35	120	21	36	7.3	25	1.7	15	.49	11	.41
	90	130,000	16	19,000	24	1,100	38	130	35	27	17	28	1.9	15	.51	11	.42
90	-20	1,700	18	410	15	80	9.7	37	2.3	22	.66	14	.27	11	.19	9.5	.36
	5	10,000	21	2,100	21	280	18	60	8.7	32	1.9	22	.57	16	.21	11	.29
	25	43,000	18	5,800	29	680	25	100	19	40	4.8	21	1.1	14	.33	12	.20
	45	100,000	16	15,000	22	1,300	28	170	23	44	9.3	27	1.8	17	.50	14	.46
	70	270,000	15	40,000	21	2,600	36	280	39	56	18	31	3.9	19	.84	14	.58
	90	430,000	15	54,000	23	3,400	39	440	33	69	24	35	5.0	20	1.1	14	.73
Soaked	-20	6,600	1.5	3,300	1.2	540	2.4	51	3.1	27	.92	20	.18	17	.092	14	.24
	5	190,000	11	36,000	14	4,800	14	680	10	130	6.2	76	1.4	65	.26	62	.74
	25	1,600,000	9.4	230,000	14	20,000	17	2,200	15	350	12	86	2.0	66	.39	61	.56
	45	2,000,000	4.7	420,000	5.8	27,000	11	2,700	12	410	9.4	93	2.6	66	.77	59	.88
	70	3,400,000	4.8	650,000	6.1	51,000	10	4,300	14	640	11	--	--	64	1.1	55	2.4
	90	5,000,000	6.5	990,000	8.4	79,000	12	6,400	16	960	12	930	--	82	2.2	--	--

Table 6.--Dielectric constant (DK) and loss tangent (tan δ) for radial oak

Relative humidity:		Temperature:		Frequency, Hz															
				20		100		1 K		10 K		100 K		1 M		10 M		50 M	
				DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ
Pct.	°C.																		
0	-20	2.9	0.041	2.6	0.016	2.4	0.044	2.3	0.046	2.2	0.046	2.3	0.051	2.2	0.046	2.2	0.050		
	5	2.9	.063	2.7	.042	2.4	.033	2.3	.036	2.3	.040	2.4	.052	2.3	.063	2.2	.064		
	25	3.0	.037	2.8	.014	2.5	.021	2.4	.035	2.3	.045	2.5	.047	2.4	.053	2.3	.068		
	45	3.1	.038	2.8	.032	2.6	.019	2.4	.026	2.4	.036	2.6	.049	2.5	.065	2.4	.067		
	70	3.4	.034	3.1	.017	2.7	.017	2.6	.019	2.6	.027	2.7	.037	2.6	.076	2.5	.087		
	90	3.8	.12	3.4	.054	3.1	.034	2.9	.022	2.8	.021	2.7	.038	2.7	.075	2.6	.071		
30	-20	3.9	.12	3.8	.14	3.5	.10	3.3	.088	3.0	.077	2.8	.084	2.6	.079	2.5	.086		
	5	3.6	.15	3.6	.052	3.4	.029	3.4	.030	3.3	.048	3.0	.070	2.8	.095	2.7	.11		
	25	4.1	.17	3.8	.079	3.6	.038	3.6	.028	3.5	.039	3.3	.057	3.0	.085	2.8	.11		
	45	4.8	.60	4.2	.23	3.8	.072	3.6	.037	3.5	.029	3.4	.048	3.2	.072	3.0	.11		
	70	7.1	2.4	5.3	.87	4.2	.22	3.8	.070	3.6	.037	3.6	.041	3.4	.058	3.2	.097		
	90	9.7	8.1	6.4	2.1	4.5	.44	3.8	.10	3.6	.042	3.5	.036	3.3	.056	3.1	.083		
65	-20	10	1.1	8.4	.47	6.6	.22	5.6	.11	5.1	.076	4.7	.10	4.0	.15	3.5	.20		
	5	21	7.1	12	2.7	7.9	.67	6.3	.20	5.6	.085	5.2	.077	4.7	.12	4.2	.18		
	25	40	22	21	9.1	12	1.9	7.6	.48	6.5	.11	5.5	.078	5.0	.057	4.6	.14		
	45	110	31	35	20	15	5.1	8.6	1.2	6.0	.31	5.8	.12	5.2	.086	4.9	.12		
	70	480	40	81	44	21	16	12	3.1	7.4	.65	6.4	.28	5.4	.12	5.0	.10		
	90	950	52	100	71	17	33	10	4.4	6.4	.78	6.0	.32	5.1	.11	4.8	.10		
80	-20	36	16	22	5.6	12	1.3	8.1	.40	6.7	.18	5.6	.12	4.9	.11	4.2	.25		
	5	210	31	53	27	19	7.8	11	1.7	7.8	.47	6.6	.17	5.6	.098	5.2	.19		
	25	970	36	170	40	33	22	16	4.7	9.0	1.2	7.7	.33	6.2	.14	5.6	.16		
	45	3,400	31	500	42	56	37	20	11	12	2.0	8.3	.59	6.4	.19	5.8	.18		
	70	8,900	46	1,000	75	87	77	26	25	14	4.6	10	1.5	7.1	.35	6.0	.23		
	90	12,000	45	1,400	75	98	100	23	43	14	7.2	9.9	1.4	6.4	.35	5.4	.21		
90	-20	240	26	100	16	34	5.2	18	1.5	11	.58	8.0	.28	6.2	.18	5.2	.29		
	5	1,300	41	340	35	77	16	28	5.1	14	1.3	11	.48	7.4	.28	5.8	.30		
	25	6,400	34	1,100	43	190	24	49	10	23	2.5	13	.82	8.3	.35	6.6	.24		
	45	14,000	35	2,000	48	250	38	61	17	23	4.9	13	1.2	8.0	.42	6.4	.33		
	70	35,000	32	4,200	49	330	60	69	28	25	7.8	15	2.6	8.7	.65	6.6	.42		
	90	62,000	24	6,600	44	390	72	68	41	27	10	17	2.8	8.7	.78	6.4	.50		
Soaked	-20	4,400	.80	1,400	1.1	220	2.1	34	2.7	15	1.0	13	.14	11	.095	10	.23		
	5	40,000	19	6,800	20	2,300	8.1	420	5.4	110	2.6	53	.81	42	.17	40	.75		
	25	58,000	20	9,700	24	2,900	9.4	620	5.6	120	3.6	59	1.0	42	.23	39	.38		
	45	270,000	14	31,000	23	6,200	11	1,100	7.4	160	6.4	63	2.0	41	.48	36	.80		
	70	650,000	15	78,000	21	5,700	27	1,900	8.8	280	7.3	57	3.8	40	.80	31	1.3		
	90	1,200,000	11	140,000	19	8,500	28	1,600	18	340	10	72	3.8	43	1.3	33	1.2		

Table 7.--Dielectric constant (DK) and loss tangent (tan δ) for tangential oak

Relative Temperature: humidity: ture		Frequency, Hz															
		20		100		1 K		10 K		100 K		1 M		10 M		50 M	
		DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ
Pct.	°C.																
0	-20	2.6	.0061	2.5	.0024	2.2	.0047	2.2	.0046	2.1	.0037	2.1	.0044	2.0	.0043	2.0	.0045
	5	2.6	.0071	2.5	.0050	2.3	.0033	2.2	.0035	2.1	.0038	2.2	.0047	2.1	.0052	2.1	.0051
	25	2.7	.0049	2.6	.00076	2.3	.0021	2.2	.0033	2.2	.0040	2.2	.0046	2.2	.0054	2.2	.0065
	45	2.7	.0060	2.6	.0030	2.4	.0019	2.2	.0023	2.2	.0033	2.4	.0049	2.3	.0063	2.2	.0055
	70	3.0	.0048	2.7	.0021	2.5	.0017	2.4	.0018	2.3	.0029	2.4	.0040	2.3	.0075	2.3	.0077
	90	3.5	.12	3.2	.055	2.8	.0034	2.7	.0023	2.6	.0019	2.5	.0035	2.4	.0076	2.4	.0061
30	-20	4.2	.15	4.1	.15	3.5	.18	3.1	.14	2.8	.094	2.6	.076	2.5	.076	2.4	.086
	5	3.3	.16	3.2	.067	3.2	.030	3.1	.028	3.0	.042	2.8	.069	2.6	.087	2.5	.099
	25	3.6	.16	3.5	.077	3.3	.035	3.2	.029	3.2	.038	3.0	.053	2.8	.077	2.6	.10
	45	4.2	.43	3.7	.20	3.4	.068	3.3	.032	3.2	.030	3.1	.045	2.9	.065	2.8	.090
	70	6.3	1.6	4.6	.64	3.7	.18	3.4	.062	3.3	.039	3.2	.035	3.1	.053	3.0	.092
	90	7.9	4.0	5.6	1.2	3.9	.26	3.4	.076	3.2	.032	3.1	.033	2.9	.047	2.8	.082
65	-20	8.7	.96	7.4	.43	5.6	.25	4.7	.12	4.4	.075	4.4	.084	3.5	.15	3.1	.19
	5	15	6.2	9.6	2.4	6.4	.59	5.2	.18	4.7	.077	4.4	.073	4.0	.11	3.7	.18
	25	28	.19	15	8.2	9.2	1.6	6.3	.41	5.5	.081	4.6	.068	4.2	.049	4.0	.13
	45	64	.32	24	.17	11	4.0	7.1	.88	4.6	.23	4.8	.10	4.5	.077	4.2	.11
	70	200	.60	45	.48	15	.14	9.4	2.5	6.2	.54	5.3	.22	4.6	.10	4.3	.091
	90	510	.62	51	.91	13	.28	8.4	3.7	5.6	.64	5.2	.28	4.5	.11	4.2	.095
80	-20	33	.15	20	4.9	11	1.2	7.4	.36	6.2	.17	5.2	.11	4.6	.11	4.0	.24
	5	139	.34	38	.25	16	6.9	9.7	1.6	6.9	.41	6.1	.16	5.2	.091	4.8	.17
	25	550	.41	110	.41	27	.18	14	3.6	9.1	.85	6.9	.29	5.6	.11	5.2	.14
	45	1,700	.40	270	.50	35	.38	15	9.5	9.2	1.9	7.2	.51	5.8	.15	5.3	.16
	70	4,400	.52	490	.87	58	.65	21	.17	13	2.9	9.1	1.1	6.4	.27	5.4	.20
	90	6,400	.54	720	.91	82	.86	22	.28	13	4.8	8.7	1.1	5.8	.27	5.0	.18
90	-20	120	.39	44	.21	22	5.4	12	1.2	8.7	.45	7.2	.18	6.1	.13	5.2	.28
	5	690	.55	180	.42	35	.22	17	5.5	10	1.1	8.6	.35	6.9	.13	6.1	.20
	25	3,100	.47	600	.49	110	.30	26	.12	15	2.3	9.7	.62	7.3	.21	6.6	.16
	45	7,000	.49	1,100	.63	140	.48	30	.23	16	4.8	10	1.0	7.2	.29	6.3	.25
	70	17,000	.47	2,000	.75	170	.86	36	.40	17	8.6	12	2.1	7.6	.53	6.4	.30
	90	30,000	.42	3,700	.69	250	.100	41	.61	19	13	14	2.6	8.0	.67	6.5	.40
Soaked	-20	3,200	1.8	920	2.2	140	2.4	27	2.2	12	.86	11	.18	9.3	.081	8.8	.19
	5	8,200	.36	2,700	.22	1,200	5.7	290	3.5	100	1.5	51	.57	41	.14	37	.62
	25	14,000	.39	3,700	.30	1,700	7.1	450	3.7	120	2.1	57	.69	42	.20	37	.37
	45	60,000	.24	8,600	.35	2,000	.15	790	4.6	145	3.5	59	1.2	40	.34	36	.60
	70	150,000	.22	19,000	.36	2,500	.28	1,100	6.9	230	4.5	64	2.0	39	.56	32	.58
	90	300,000	.19	38,000	.32	3,500	.34	1,400	9.3	320	5.1	72	2.1	42	.66	33	.50

Table 8.--Dielectric constant (DK) and loss tangent (tan δ) for hardboard No. 1

Relative Temperature: humidity:		Frequency, Hz															
		20		100		1 K		10 K		100 K		1 M		10 M		50 M	
		DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ
Pct.	°C.																
0	-20	3.3	0.044	3.2	0.032	2.9	0.031	2.8	0.037	2.6	0.049	2.8	0.051	2.6	0.049	2.6	0.054
	5	3.4	.028	3.3	.0098	3.0	.022	2.8	.028	2.8	.037	3.0	.054	2.8	.056	2.7	.070
	25	3.5	.018	3.3	.0096	3.0	.017	2.9	.027	2.8	.034	3.1	.047	2.9	.058	2.8	.077
	45	3.6	.028	3.4	.022	3.1	.012	3.0	.017	2.9	.026	3.2	.037	3.1	.061	3.0	.074
	70	3.9	.038	3.6	.034	3.2	.018	3.0	.014	3.0	.019	3.4	.031	3.2	.063	3.1	.083
	90	4.4	.096	4.0	.061	3.7	.033	3.4	.018	3.4	.012	3.4	.026	3.3	.048	3.2	.081
30	-20	4.2	.092	4.2	.071	3.9	.064	3.7	.051	3.5	.063	3.2	.073	3.0	.065	2.9	.077
	5	4.0	.11	4.0	.013	3.9	.017	3.9	.028	3.4	.046	3.6	.063	3.2	.086	3.1	.094
	25	4.2	.060	4.1	.025	4.0	.016	4.0	.019	3.9	.031	3.7	.052	3.5	.079	3.2	.10
	45	4.6	.14	4.3	.074	4.1	.024	4.0	.015	3.7	.025	3.9	.041	3.7	.063	3.5	.096
	70	5.9	.68	4.8	.28	4.4	.077	4.2	.027	4.1	.020	4.0	.030	3.8	.059	3.7	.094
	90	7.3	1.5	5.4	.54	4.4	.13	4.2	.032	4.0	.020	5.3	.022	5.0	.035	4.8	.079
65	-20	5.6	.19	5.4	.11	4.8	.073	4.6	.053	4.3	.062	4.0	.085	3.6	.11	3.2	.13
	5	6.6	.59	5.6	.25	5.0	.076	4.8	.036	4.6	.038	4.4	.063	4.0	.096	3.7	.13
	25	9.9	1.3	6.9	.60	5.4	.19	4.9	.064	4.7	.036	4.6	.045	4.2	.059	4.0	.11
	45	18	2.8	10	1.4	6.3	.45	5.2	.13	4.9	.049	4.7	.039	4.4	.060	4.2	.10
	70	35	12	20	4.3	8.1	1.4	6.4	.33	5.5	.053	4.9	.051	4.6	.054	4.4	.087
	90	32	48	18	12	9.6	2.2	5.8	.51	5.1	.072	5.0	.065	4.6	.049	4.5	.065
80	-20	17	1.4	11	.58	7.6	.26	6.4	.19	5.5	.090	5.1	.091	4.5	.13	4.0	.18
	5	36	4.6	19	2.5	10	.79	7.1	.27	6.1	.11	5.6	.080	5.0	.10	4.6	.15
	25	57	18	34	6.4	17	1.8	9.1	.60	6.6	.18	6.0	.10	5.4	.087	5.0	.12
	45	80	46	50	14	25	3.3	10	1.3	7.0	.38	6.2	.14	5.6	.088	5.2	.11
	70	160	110	59	57	33	10	17	2.2	9.1	.71	7.0	.30	5.9	.090	5.5	.11
	90	330	110	75	95	32	22	19	4.2	8.5	1.4	7.6	.42	6.2	.15	5.7	.11
90	-20	52	8.0	30	3.6	16	1.1	10	.38	7.7	.19	6.6	.10	5.8	.095	5.1	.20
	5	140	32	73	13	27	4.3	13	1.3	8.8	.40	7.4	.16	6.5	.085	5.8	.14
	25	470	49	140	32	41	11	20	2.7	12	.77	8.4	.29	6.9	.11	6.3	.14
	45	750	86	150	82	53	24	25	5.7	13	1.6	9.1	.44	7.2	.14	6.5	.14
	70	2,200	92	300	120	69	43	34	8.5	16	2.1	11	.78	7.7	.24	6.7	.17
	90	4,500	72	580	110	75	79	32	18	18	3.5	13	1.1	8.4	.33	7.1	.22
99	-20	220	60	120	23	46	6.4	19	1.9	12	.58	8.9	.23	7.0	.094	6.6	.18
	5	1,400	150	400	110	100	44	40	12	21	2.5	12	.73	8.9	.22	8.0	.19
	25	4,100	140	960	120	170	67	52	22	25	5.0	15	1.2	9.8	.34	8.3	.18
	45	9,300	140	1,600	160	200	130	63	43	30	9.3	17	2.0	11	.50	8.9	.30
	70	28,000	100	4,000	150	340	180	73	81	34	18	19	3.2	11	.75	8.6	.44
	90	88,000	31	12,000	45	820	65	120	46	48	11	31	2.3	14	.88	9.6	.61

Table 9.--Dielectric constant (DK) and loss tangent (tan δ) for hardboard No. 2

Relative Temperature-humidity:		Frequency, Hz															
		20		100		1 K		10 K		100 K		1 M		10 M		50 M	
		DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ
Pct.	°C.																
0	-20	3.4	.062	3.3	.041	3.0	.028	2.9	.035	2.8	.049	2.9	.056	2.8	.051	2.7	.053
	5	3.5	.042	3.5	.081	3.1	.022	3.0	.029	2.9	.039	3.1	.056	2.9	.057	2.8	.067
	25	3.8	.017	3.6	.0075	3.2	.016	3.0	.026	3.0	.035	3.2	.047	3.0	.062	2.9	.078
	45	3.8	.022	3.6	.024	3.3	.013	3.1	.018	3.1	.026	3.4	.038	3.2	.061	3.1	.077
	70	4.1	.038	3.7	.037	3.4	.016	3.2	.014	3.2	.020	3.5	.032	3.3	.065	3.2	.083
	90	4.5	.084	4.1	.051	3.7	.030	3.5	.018	3.4	.013	3.6	.028	3.5	.058	3.3	.085
30	-20	4.2	.050	4.3	.066	4.0	.035	3.8	.043	3.6	.062	3.3	.075	3.1	.068	3.0	.078
	5	4.3	.089	4.2	.016	4.1	.017	4.0	.027	3.9	.043	3.6	.067	3.4	.084	3.2	.096
	25	4.4	.051	4.3	.028	4.2	.017	4.1	.018	4.0	.034	3.8	.054	3.6	.078	3.4	.094
	45	4.7	.16	4.5	.069	4.3	.023	4.2	.016	4.2	.020	4.0	.040	3.8	.067	3.5	.10
	70	5.9	.65	5.1	.26	4.6	.070	4.4	.026	4.3	.019	4.2	.031	4.0	.060	3.8	.098
	90	7.8	1.4	5.6	.53	4.7	.13	4.4	.036	4.3	.019	5.6	.025	5.2	.040	5.1	.075
65	-20	6.0	.20	5.9	.12	5.4	.079	5.1	.053	4.8	.062	4.4	.085	3.8	.11	3.5	.14
	5	8.1	.82	6.3	.37	5.5	.099	5.3	.039	5.1	.038	4.8	.063	4.4	.11	4.0	.14
	25	13	1.7	8.3	.81	6.1	.24	5.5	.070	5.3	.039	5.0	.047	4.7	.078	4.4	.11
	45	26	3.3	13	1.9	7.3	.60	5.9	.16	5.5	.053	5.2	.043	4.9	.063	4.6	.10
	70	45	13	26	4.7	10	1.7	7.2	.42	5.7	.11	5.4	.055	5.1	.059	4.9	.090
	90	55	35	24	14	13	3.0	7.0	.76	5.9	.12	6.3	.068	5.3	.054	5.1	.084
80	-20	15	1.2	10	.53	7.6	.23	6.7	.17	5.8	.10	5.2	.090	4.6	.13	4.1	.18
	5	34	3.8	18	2.1	9.6	.70	7.1	.22	6.2	.092	5.8	.073	5.3	.10	4.8	.15
	25	59	12	36	4.6	15	1.6	9.0	.48	7.3	.12	6.1	.087	5.6	.083	5.2	.12
	45	88	27	52	9.7	22	2.7	10	1.0	6.8	.31	6.3	.12	5.8	.082	5.4	.11
	70	150	86	68	36	35	7.1	16	1.9	9.0	.59	7.1	.24	6.0	.072	5.7	.10
	90	270	100	85	64	40	14	19	3.4	9.2	1.1	7.6	.37	6.3	.13	5.9	.095
90	-20	48	4.0	27	2.4	15	.70	10	.31	7.7	.18	6.7	.094	5.8	.094	5.2	.20
	5	130	16	64	6.4	24	2.3	12	.81	8.0	.29	7.4	.12	6.5	.068	6.0	.14
	25	300	34	120	17	40	6.0	18	1.7	10	.53	8.0	.20	6.9	.082	6.4	.13
	45	420	64	150	37	61	9.5	24	3.0	11	1.1	8.5	.32	7.1	.10	6.5	.12
	70	1,000	110	220	92	73	37	34	7.6	16	1.9	10	.59	7.6	.19	6.8	.14
	90	2,200	81	460	74	140	25	53	6.6	20	2.3	12	.88	8.3	.29	7.0	.17
99	-20	240	47	120	18	46	5.4	20	1.6	12	.49	9.3	.20	7.5	.10	6.9	.17
	5	1,000	120	350	75	130	22	45	6.8	19	1.9	13	.57	9.2	.20	8.2	.17
	25	3,500	100	780	87	170	39	58	11	26	3.0	14	.86	9.6	.29	8.5	.18
	45	6,100	140	920	180	190	88	77	22	34	5.3	17	1.6	11	.44	8.8	.28
	70	21,000	98	2,700	150	280	140	90	43	43	9.6	20	2.5	12	.64	8.9	.40
	90	110,000	25	13,000	40	840	59	160	28	61	7.7	27	2.8	13	.91	9.5	.53

Table 10.--Dielectric constant (DK) and loss tangent (tan δ) for hardboard No. 3

Relative Temperature: humidity:		Frequency, Hz															
		20		100		1 K		10 K		100 K		1 M		10 M		50 M	
		DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ
Pct.	°C.																
0	-20	4.0	0.032	3.7	0.036	3.4	0.032	3.2	0.042	3.0	0.053	3.2	0.050	3.0	0.045	2.9	0.040
	5	4.0	.048	3.9	.027	3.5	.035	3.2	.041	3.2	.045	3.3	.054	3.1	.052	3.0	.059
	25	4.1	.021	3.9	.026	3.5	.030	3.3	.038	3.2	.043	3.4	.048	3.2	.056	3.1	.071
	45	4.2	.034	3.8	.026	3.6	.028	3.3	.032	3.2	.038	3.6	.042	3.4	.056	3.2	.071
	70	4.5	.038	4.2	.036	3.8	.030	3.5	.029	3.4	.033	3.7	.039	3.5	.066	3.4	.077
	90	4.9	.090	4.6	.050	4.1	.037	3.8	.031	3.8	.027	3.8	.038	3.6	.055	3.5	.080
30	-20	4.7	.081	4.6	.055	4.4	.046	4.2	.050	3.9	.061	3.6	.064	3.4	.059	3.3	.064
	5	4.8	.11	4.7	.035	4.5	.029	4.4	.040	4.2	.050	3.9	.066	3.6	.072	3.4	.080
	25	5.1	.075	4.9	.062	4.7	.034	4.6	.032	4.4	.043	4.1	.059	3.8	.072	3.6	.083
	45	5.7	.17	5.2	.096	4.9	.048	4.7	.035	4.5	.035	4.4	.046	4.0	.062	3.8	.096
	70	8.5	.69	6.5	.34	5.4	.13	5.0	.057	4.8	.039	4.5	.047	4.3	.067	4.0	.092
	90	12	1.6	8.5	.72	5.9	.23	5.2	.084	4.8	.045	6.6	.040	6.2	.051	5.9	.076
65	-20	6.7	.15	6.4	.13	5.7	.088	5.3	.060	4.9	.064	4.6	.083	4.1	.096	3.8	.11
	5	8.1	.38	6.9	.20	6.1	.087	5.7	.055	5.4	.052	5.0	.069	4.6	.093	4.2	.12
	25	13	.96	8.9	.49	6.9	.20	6.1	.089	5.6	.058	5.3	.060	4.9	.076	4.6	.10
	45	28	2.7	15	1.4	8.9	.51	6.8	.19	6.0	.086	5.6	.063	5.2	.074	4.8	.10
	70	64	25	34	8.5	17	2.1	9.6	.61	7.0	.22	6.2	.10	5.5	.081	5.2	.10
	90	97	82	44	30	18	7.1	10	1.5	6.8	.40	7.2	.21	6.1	.10	5.5	.12
80	-20	17	.90	12	.42	8.9	.22	7.3	.18	6.2	.11	5.6	.091	5.0	.12	4.4	.17
	5	41	3.8	22	2.0	12	.66	8.3	.26	7.0	.12	6.3	.092	5.5	.11	5.1	.15
	25	120	12	47	6.6	21	1.9	11	.65	7.3	.25	6.9	.13	6.1	.098	5.6	.12
	45	190	39	82	17	33	4.3	14	1.4	8.8	.47	7.4	.20	6.4	.11	5.8	.13
	70	520	100	120	80	49	19	25	3.9	12	1.2	9.1	.44	6.9	.14	6.3	.15
	90	1,300	100	220	110	58	40	29	8.2	15	2.0	10	.62	7.6	.26	6.7	.15
90	-20	94	6.5	47	3.5	22	1.1	13	.46	9.4	.27	7.6	.12	6.6	.10	5.7	.21
	5	290	25	140	11	43	4.4	19	1.5	11	.52	9.1	.21	7.5	.11	6.8	.15
	25	1,400	30	440	20	95	10	34	3.4	15	1.2	11	.40	8.2	.15	7.4	.16
	45	1,000	130	330	83	120	24	44	7.0	20	2.1	12	.62	8.5	.22	7.5	.18
	70	4,200	126	580	179	130	76	55	18	26	3.9	16	1.3	9.8	.39	7.9	.26
	90	8,600	91	1,200	130	160	100	66	25	31	5.8	19	1.4	10	.50	8.4	.30
99	-20	590	63	260	31	110	8.4	31	3.5	14	1.1	11	.32	8.8	.14	7.8	.20
	5	9,100	120	1,700	130	340	69	120	21	44	6.0	22	1.6	13	.55	9.9	.56
	25	33,000	90	5,700	100	690	83	170	34	61	9.8	27	2.4	14	.75	11	.31
	45	78,000	68	8,900	120	840	130	190	60	70	17	32	4.1	17	1.1	12	.67
	70	140,000	74	17,000	120	1,100	180	190	110	73	30	43	5.6	19	1.5	12	1.0
	90	280,000	37	30,000	70	1,700	120	230	89	83	25	47	4.2	21	1.1	12	.83

Table 11.--Dielectric constant (DK) and loss tangent (tan δ) for hardboard No. 4

Relative humidity:		Temperature:		Frequency, Hz															
				20		100		1 K		10 K		100 K		1 M		10 M		50 M	
				DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ	DK	Tan δ
Pct.	°C.																		
0	-20	4.0	0.033	3.6	0.022	3.3	0.025	3.2	0.034	3.0	0.048	3.1	0.055	3.0	0.052	2.9	0.052		
	5	4.0	.046	3.8	.020	3.4	.025	3.2	.036	3.2	.039	3.4	.057	3.4	.054	3.1	.067		
	25	4.1	.041	3.8	.020	3.5	.020	3.3	.027	3.2	.034	3.5	.049	3.5	.062	3.2	.079		
	45	4.1	.045	3.9	.031	3.5	.020	3.3	.021	3.3	.027	3.7	.040	3.5	.065	3.4	.080		
	70	4.1	.15	4.2	.059	3.7	.031	3.5	.021	3.5	.024	3.9	.037	3.7	.067	3.5	.091		
	90	4.5	.29	4.6	.11	4.1	.047	3.9	.026	3.8	.014	4.0	.038	3.8	.061	3.6	.086		
30	-20	5.5	.089	5.1	.093	4.6	.077	4.3	.063	4.0	.070	3.8	.072	3.4	.073	3.2	.076		
	5	5.3	.20	5.1	.070	4.8	.041	4.6	.041	4.4	.052	4.1	.073	3.7	.094	3.5	.10		
	25	6.4	.29	5.7	.16	5.2	.072	4.9	.044	4.7	.049	4.4	.066	4.0	.090	3.7	.10		
	45	9.4	.80	7.2	.42	5.7	.16	5.2	.071	4.9	.049	4.7	.052	4.3	.076	4.0	.11		
	70	19	3.4	13	1.4	7.6	.50	5.9	.18	5.3	.078	4.9	.061	4.6	.077	4.2	.12		
	90	34	11	18	3.8	8.6	.91	6.4	.30	5.4	.11	7.0	.054	6.5	.055	6.1	.093		
65	-20	8.5	.35	7.2	.21	6.2	.11	5.6	.075	5.2	.079	4.7	.10	4.1	.12	3.7	.13		
	5	16	1.3	11	.70	7.8	.29	6.5	.13	5.9	.082	5.4	.087	4.7	.12	4.3	.15		
	25	37	3.6	20	1.8	11	.67	7.6	.26	6.4	.12	5.8	.085	5.2	.085	4.7	.13		
	45	72	15	38	5.3	18	1.8	9.8	.59	7.2	.22	6.3	.11	5.6	.10	5.1	.14		
	70	160	70	71	31	33	6.6	15	1.8	9.0	.58	7.2	.23	6.1	.12	5.6	.14		
	90	450	97	110	66	30	21	17	3.7	10	1.0	8.6	.42	6.7	.17	6.0	.15		
80	-20	29	2.0	17	1.1	11	.42	8.0	.22	6.9	.12	6.1	.11	5.2	.15	4.5	.19		
	5	75	12	42	4.7	19	1.5	11	.52	8.2	.22	7.0	.13	6.0	.13	5.4	.18		
	25	160	41	73	19	34	4.6	16	1.4	9.7	.48	8.0	.20	6.7	.13	6.0	.16		
	45	280	100	110	52	48	11	23	2.9	12	.89	8.8	.35	7.1	.16	6.3	.16		
	70	1,300	140	250	140	67	51	36	9.4	18	2.3	12	.69	8.1	.22	6.9	.17		
	90	3,200	120	530	140	91	85	41	19	22	3.8	14	.96	8.7	.37	7.2	.22		
90	-20	91	18	51	6.4	26	1.8	15	.62	10	.33	7.9	.15	6.6	.12	5.8	.22		
	5	220	83	140	28	43	9.8	22	2.4	13	.73	9.2	.31	7.8	.13	6.9	.16		
	25	770	140	250	84	73	30	34	6.8	17	1.7	12	.53	8.6	.18	7.5	.18		
	45	1,770	150	310	170	88	62	42	14	23	2.9	14	.80	9.1	.27	7.8	.21		
	70	7,200	130	830	220	100	160	45	37	26	6.4	17	1.6	10	.47	8.3	.31		
	90	16,000	95	2,000	150	160	180	48	70	28	12	20	2.2	12	.55	8.7	.37		
99	-20	270	57	130	25	54	7.2	21	2.2	13	.62	9.0	.21	7.9	.10	7.0	.19		
	5	2,600	150	490	150	99	79	43	19	25	3.6	22	.71	10	.34	8.6	.22		
	25	19,000	75	3,000	92	310	84	64	41	33	8.2	18	1.5	11	.43	11	.17		
	45	21,000	115	2,800	170	290	160	67	70	34	14	21	2.4	13	.64	9.8	.38		
	70	59,000	74	7,800	110	570	150	79	110	33	26	23	4.4	14	.90	10	.53		
	90	120,000	38	16,000	62	1,100	98	130	87	40	28	33	3.1	15	.94	10	.59		

Table 12.--Calculated and observed values of dielectric constant and $\tan \delta$ for longitudinal Douglas-fir at 25° C.

	0 Relative humidity				30 Relative humidity				65 Relative humidity				80 Relative humidity				90 Relative humidity				Sunked			
	a	b	c	R_g/R_p	a	b	c	R_g/R_p	a	b	c	R_g/R_p	a	b	c	R_g/R_p	a	b	c	R_g/R_p	a	b	c	R_g/R_p
ϵ	3.0	1.0	10	0.010	4.5	2.0	10	0.0050	7.0	8.0	1,450	0.020	9.0	25	120,000	0.008	13	30	800,000	0.008	52	100	16 x 10 ⁶	0.006
	k/R_p	1.8	1	1.0	k/R_p	25	1	1.0	k/R_p	25,000	1	0.9	k/R_p	1.1 x 10 ⁶	1	1.10	k/R_p	12 x 10 ⁶	1	1.2	k/R_p	25 x 10 ⁷	1	1.25
	m	0	n	0.15	m	0.2	n	0.2	m	0.1	n	0.1	m	0.05	n	0.2	m	0	n	0.2	m	0	n	0.2
	DK		Tan δ		DK		Tan δ		DK		Tan δ		DK		Tan δ		DK		Tan δ		DK		Tan δ	
	Calcu- lated	Ob- served	Calcu- lated	Ob- served	Calcu- lated	Ob- served	Calcu- lated	Ob- served	Calcu- lated	Ob- served	Calcu- lated	Ob- served	Calcu- lated	Observed	Calcu- lated	Ob- served	Calculated	Observed	Calcu- lated	Ob- served	Calcu- lated	Observed	Calcu- lated	Ob- served
10 Hz	5.0	5.0	0.050	0.060	7.5	7.5	0.50	0.40	197	195	13	18	9,500	10,000	11	10	50,000	58,000	24	19	900,000	900,000	28	21
100 Hz	4.1	4.1	.024	.014	6.6	6.5	.11	.12	38	38	7.7	7.2	790	790	14	14	3,200	3,200	37	35	51,000	53,000	49	49
1 KHz	4.0	3.8	.028	.024	6.5	6.2	.035	.042	18	20	2.4	1.7	94	94	13	13	240	230	49	44	3,000	3,100	83	90
10 KHz	3.9	3.5	.040	.038	6.3	6.0	.034	.029	15	12	.46	.52	36	37	4.5	3.9	53	45	23	21	303	307	83	93
100 KHz	3.5	3.4	.056	.059	5.5	5.7	.050	.043	11	9	.13	.19	22	19	.96	1.1	29	32	4.2	3.2	111	93	23	32
1 MHz	3.1	3.5	.079	.090	4.7	5.4	.079	.080	7.7	8.5	.09	.09	11	13	.32	.40	16	19	.89	.83	62	62	4.2	1.3
10 MHz	3.0	3.2	.112	.113	4.5	4.7	.13	.14	7.1	7.5	.10	.09	9.2	10	.23	.17	13.3	13.3	.29	.28	53	53	.62	.26
50 MHz	3.0	2.9	.143	.137	4.5	4.1	.17	.19	7.0	6.7	.12	.19	9.0	8.8	.28	.23	13.1	11.4	.30	.21	52	52	.29	.30

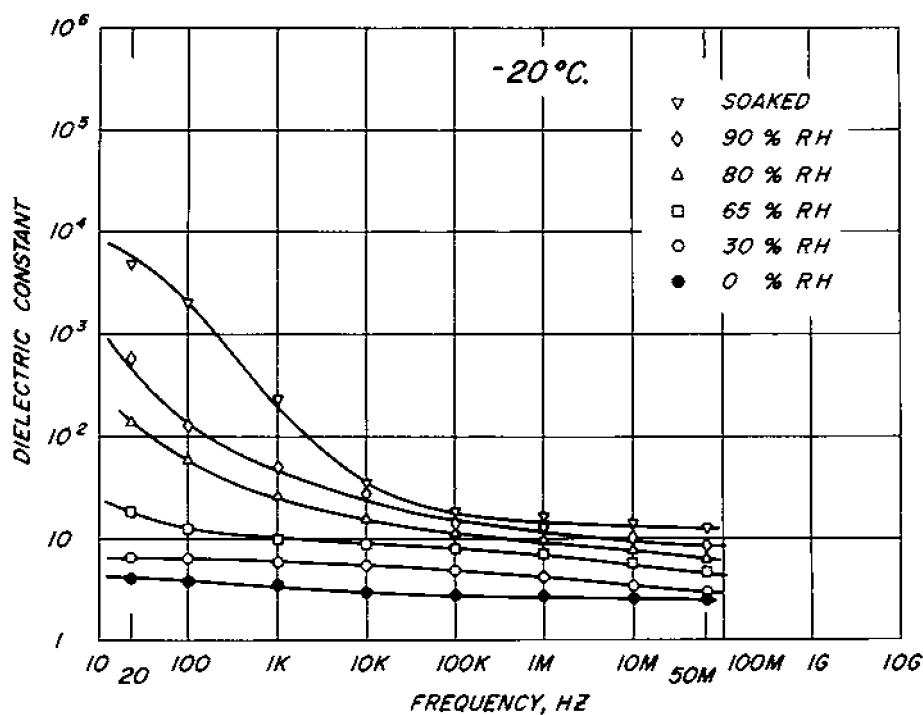


Figure 2.—Dielectric constant of Dough-fir, field parallel to the grain, at various frequencies and humidities, at -20°C. Curves in Figures 2 through 14 are estimated fits to data points.

M 142 123

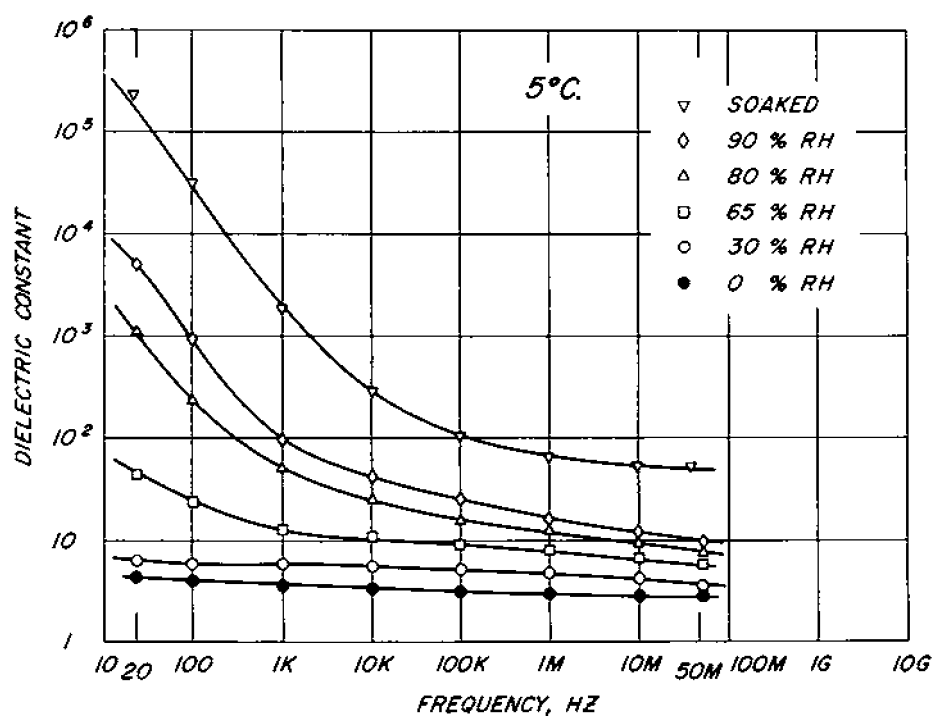


Figure 3. – Dielectric constant of Doughs-fir, field parallel to the grain, at various frequencies and humidities, at 5°C.

M 142 124

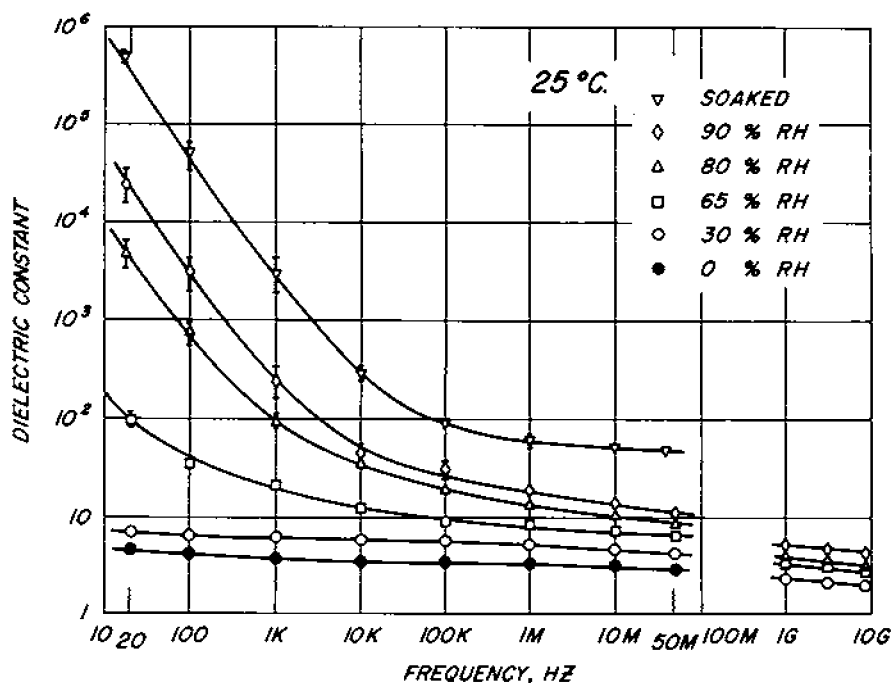


Figure 4. – Dielectric constant of Douglas-fir, field parallel to the grain, at various frequencies and humidities, at 25° C. Data plotted at frequencies at and above 1 GHz are from previous work (6). Vertical bars indicate 85 percent confidence intervals deduced from observed variability of the 5 specimen samples. Where no bars are seen, intervals are smaller than the vertical size of the data symbol.

M 142 125

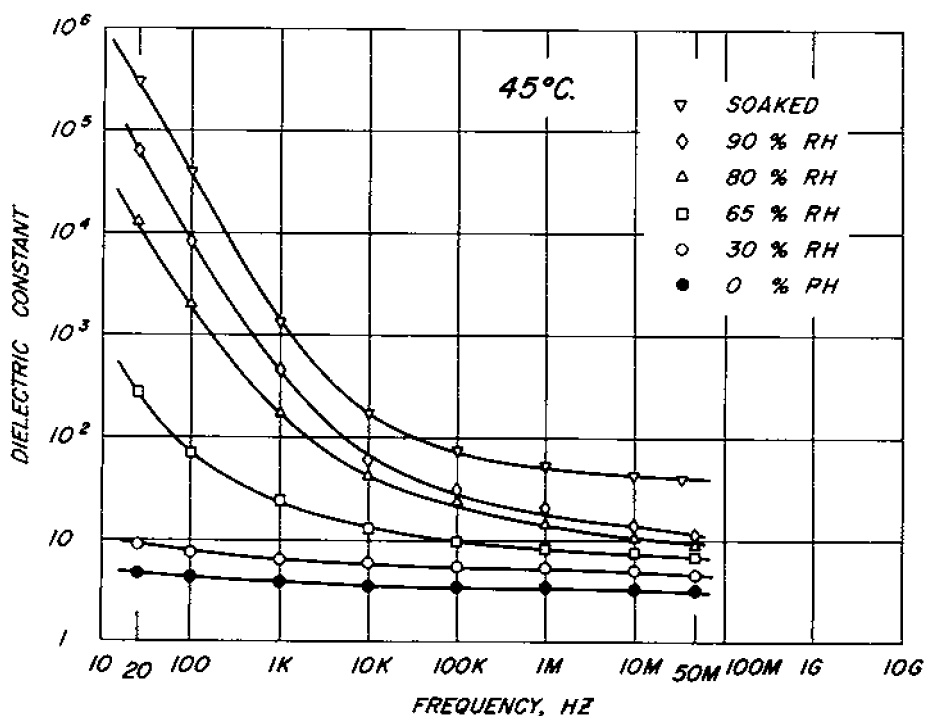


Figure 5. – Dielectric constant of Douglas-fir, field parallel to the grain, at various frequencies and humidities, at 45° C.

M 142 126

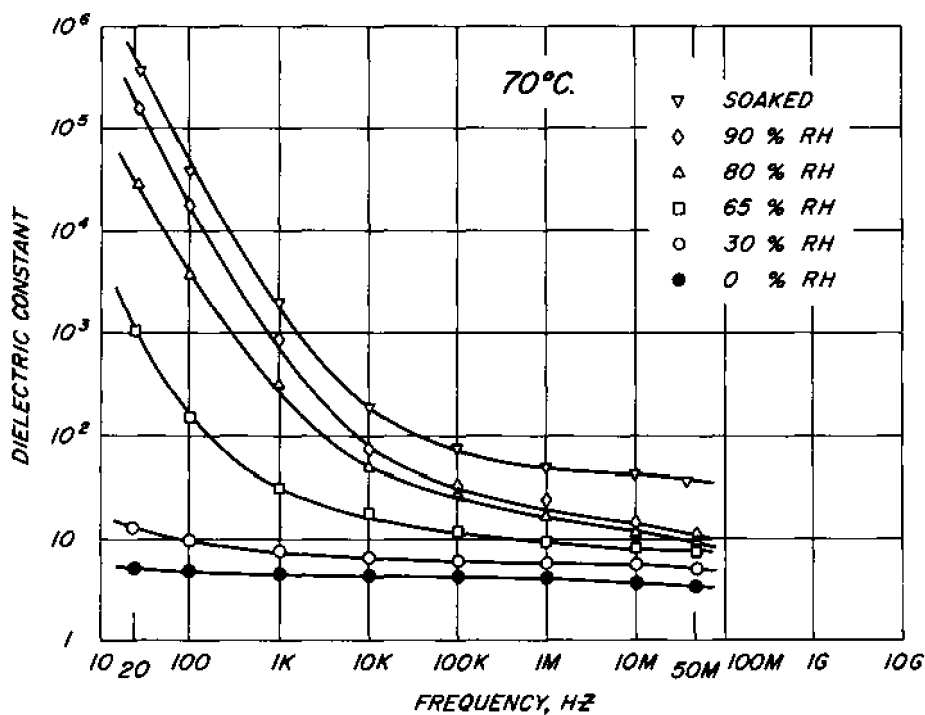


Figure 6 – Dielectric constant of Douglas-fir, field parallel to the grain, at various frequencies and humidities, at 70° C.

M142127

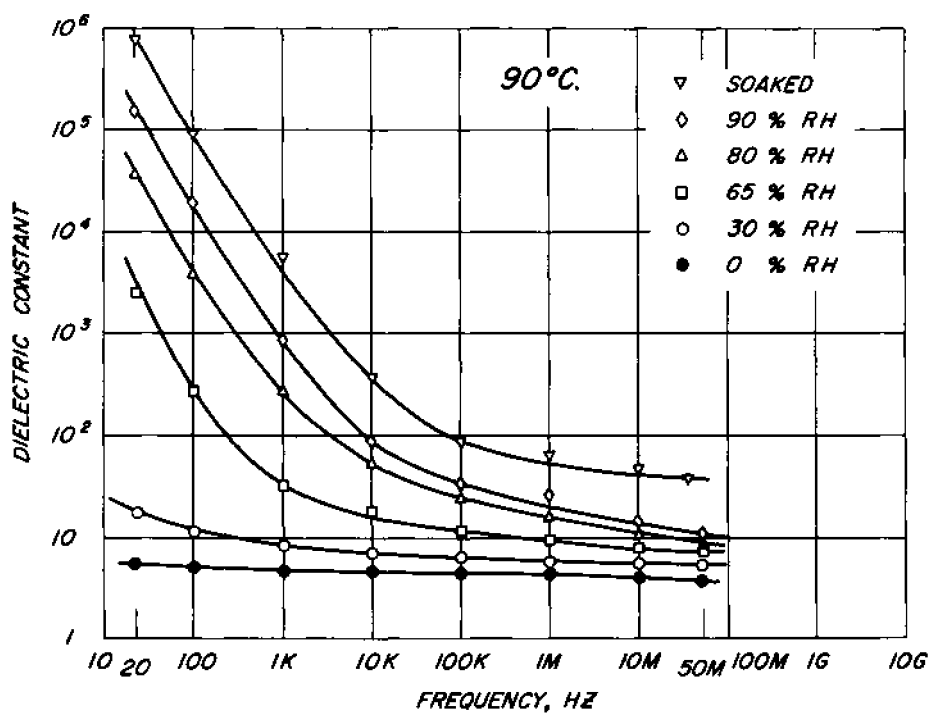


Figure 7. – Dielectric constant of Douglas-fir, field parallel to the grain, at various frequencies and humidities, at 90° C.

M 142 128

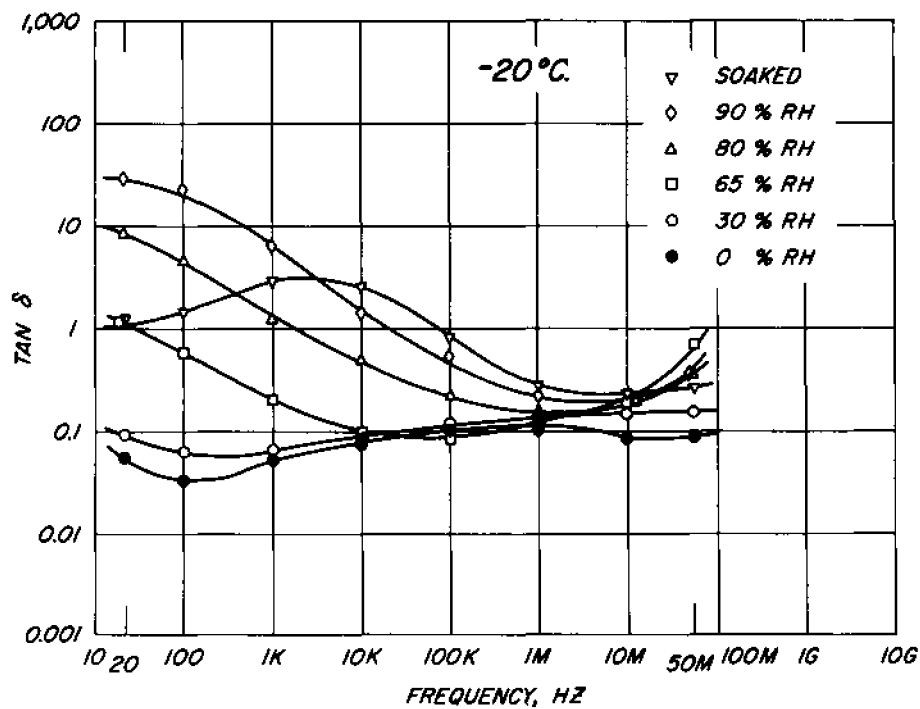


Figure 8. - Loss tangent of Douglas-fir, field parallel to the grain, at various frequencies and humidities, at -20° C. M 142 129

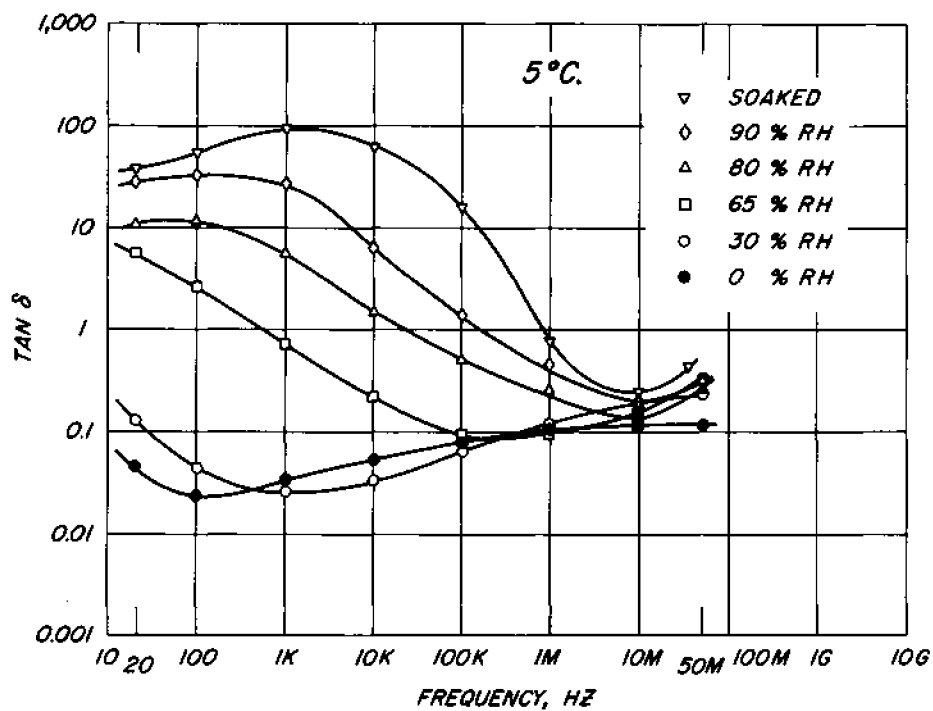


Figure 9. - Loss tangent of Douglas-fir, field parallel to the grain, at various frequencies and humidities, at 5° C. M 142 130

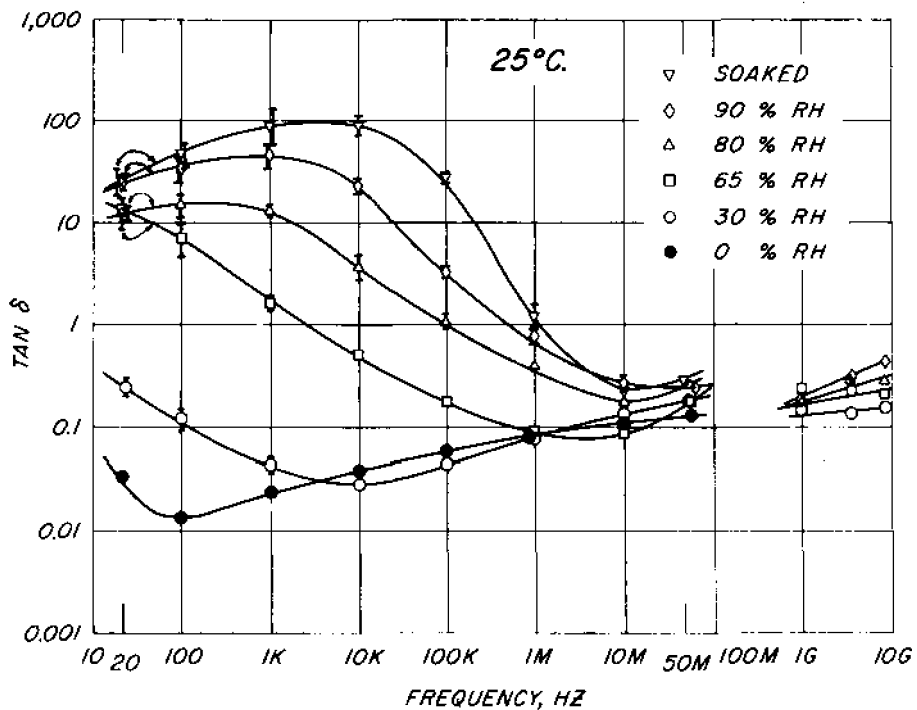


Figure 10. – Loss tangent of Douglas-fir, field parallel to the grain, at various frequencies and humidities, at 25° C. Data plotted at frequencies at and above 1 GHz are from previous work (6). Vertical bars indicate 95 percent confidence intervals deduced from the observed variability of the 5 specimen samples. Where no bars are shown, intervals are smaller than the vertical size of the data symbol.

M142131

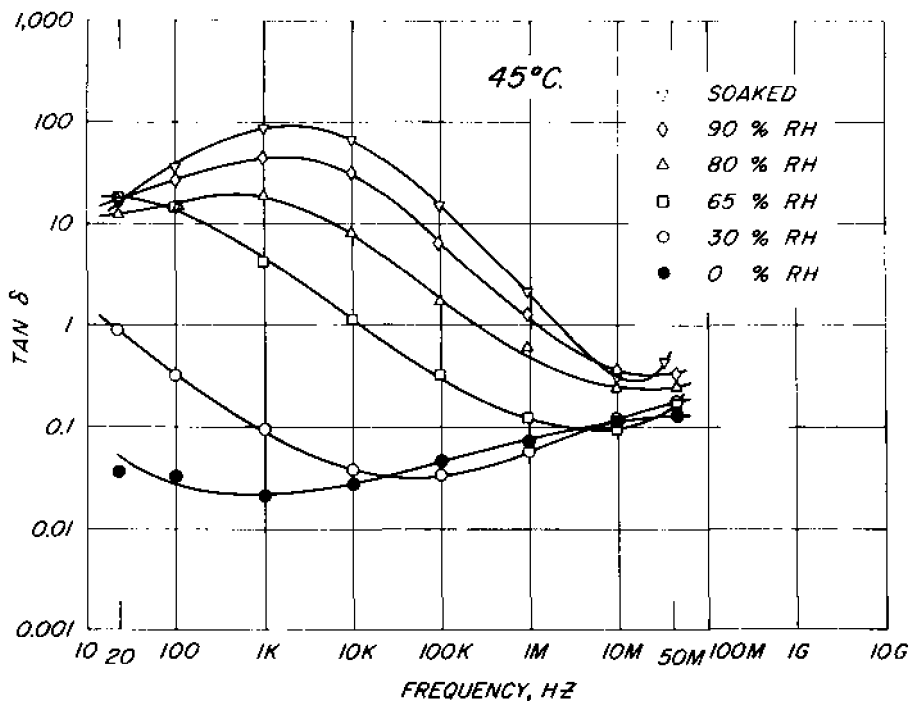


Figure 11. – Loss tangent of Douglas-fir, field parallel to the grain, at various frequencies and humidities, at 45° C.

M142132

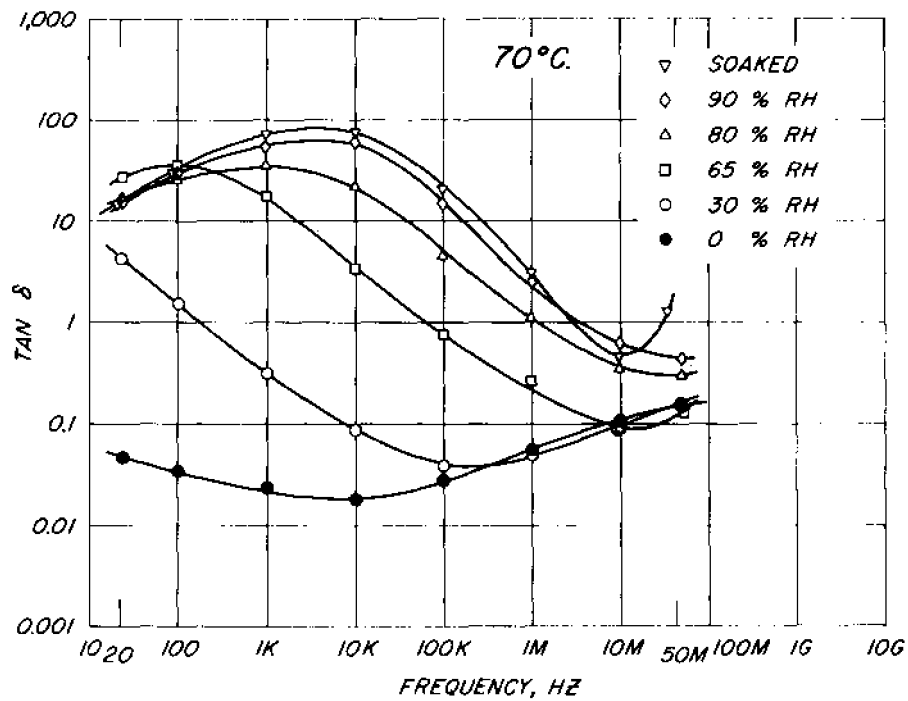


Figure 12. – Loss tangent of Douglas-fir, field parallel to the grain, at various frequencies and humidities, at 70° C.

M142133

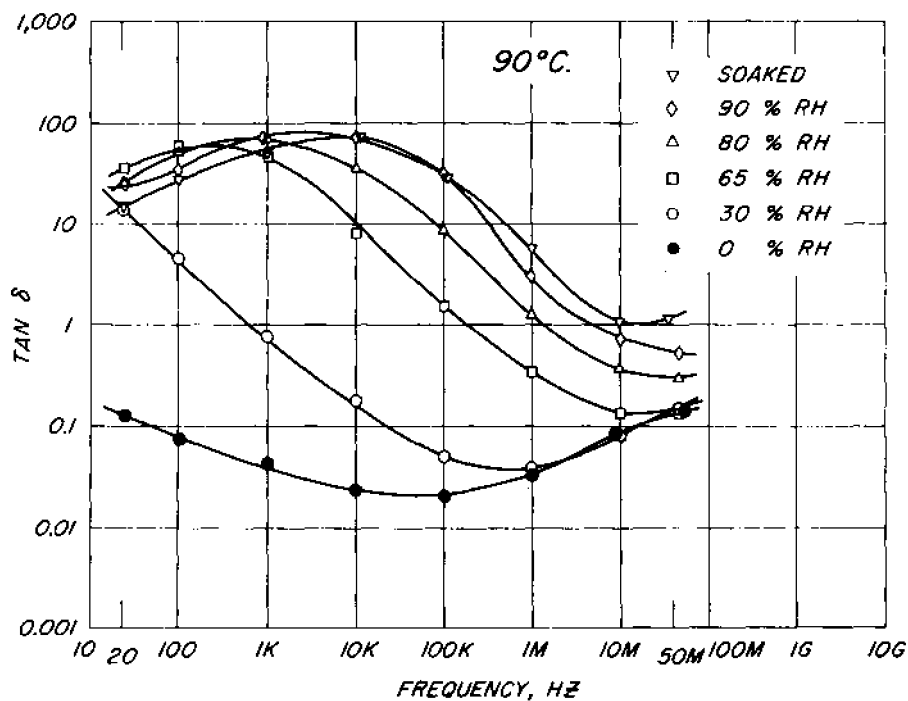


Figure 13. – Loss tangent of Douglas-fir, field parallel to the grain, at various frequencies and humidities, at 90° C.

M 142 134

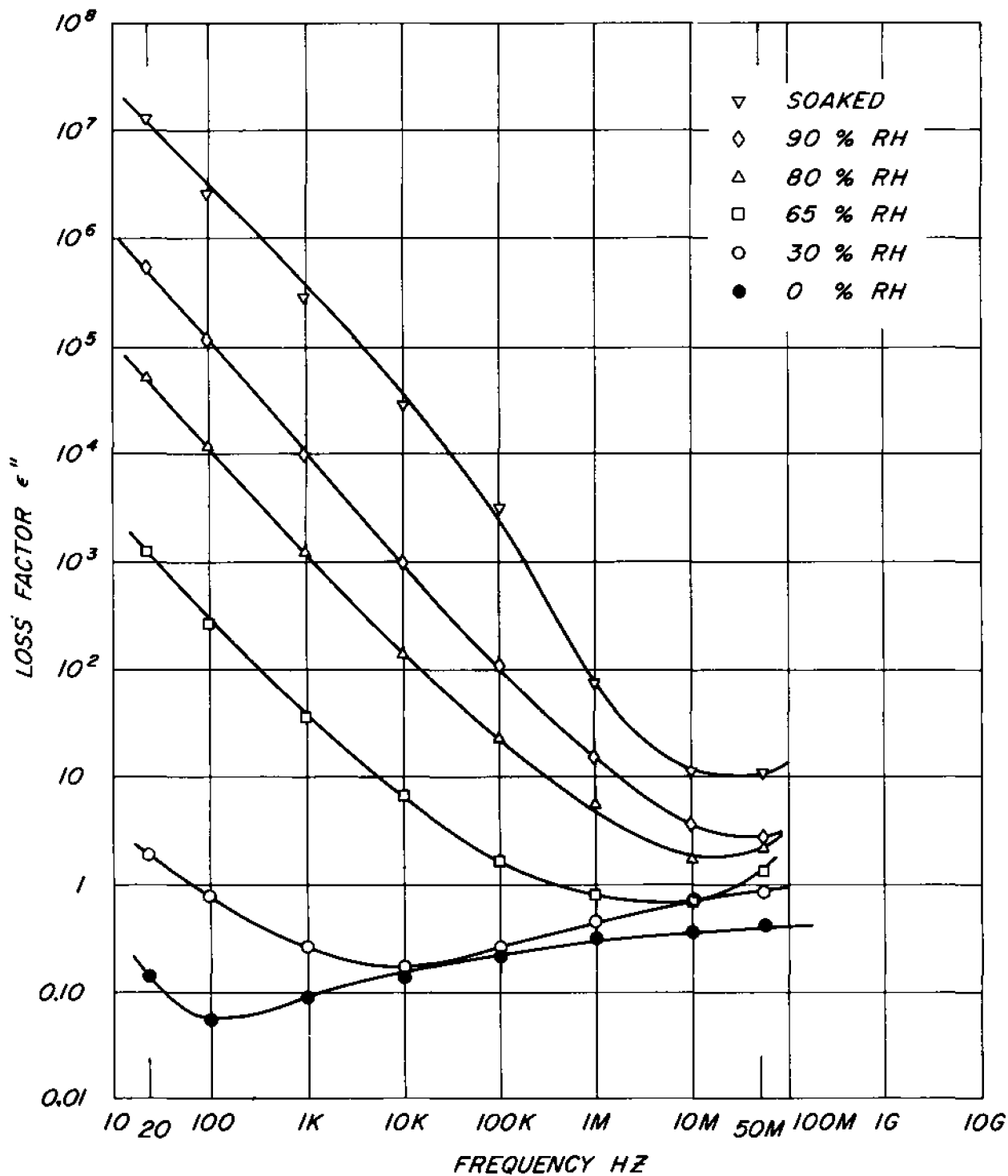


Figure 14. – Loss factor of Douglas-fir, field parallel to the grain, at various frequencies and humidities, at 25° C.

M142135

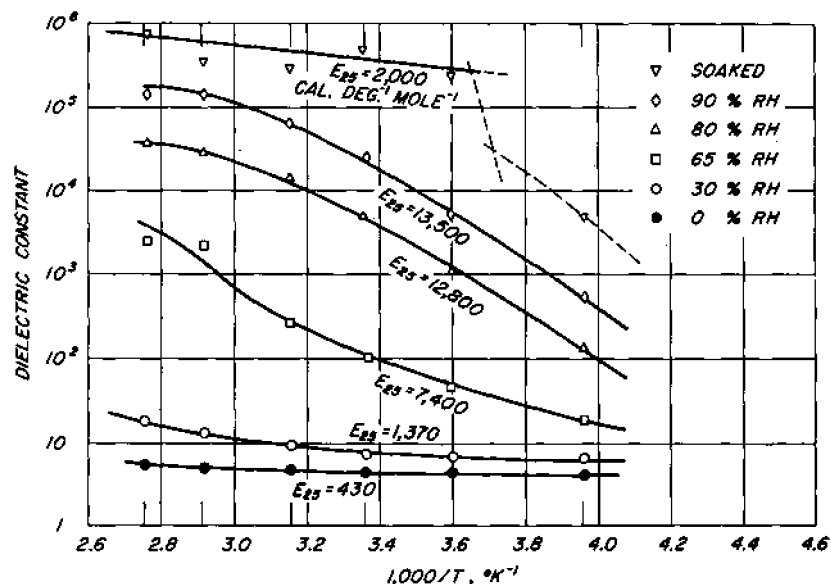


Figure 15. – The influence of temperature on the polarizability of Douglas-fir along the grain at 20 Hz, plotted so the slopes of the lines are proportional to the apparent activation energy of the polarization process. Numbers on the curves are room temperature values of activation energy, expressed in calories per degree per mole. Broken lines are estimates of what curves would be if more data points were available. A discontinuity is assumed at the freezing temperature of water,

M 142 136

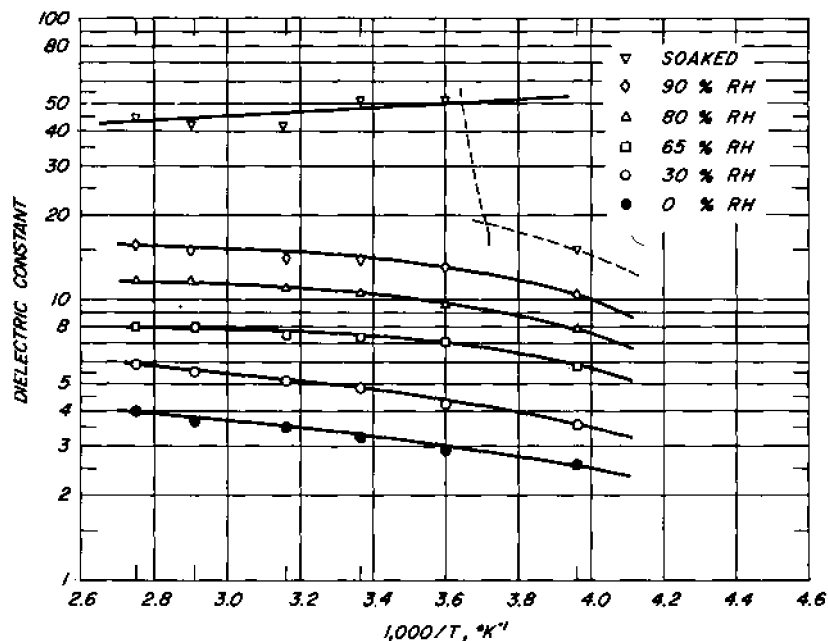


Figure 16. – The influence of temperature on the polarizability of Douglas-fir along the grain at 10k Hz, plotted so the slopes of the lines are proportional to the apparent activation energy of the polarization process. Values of activation energy at 25° C. are about the same for all moisture levels except soaked, and equal to about 650 calories per degree per mole. Broken lines are estimates what the curves would be if more data points were available; a discontinuity is assumed at the freezing temperature of water.

M 142 137

Theoretical Considerations

An attempt will be made to develop a theoretical interpretation of the results, using the simplest models and assumptions that are physically plausible and provide reasonably accurate description of the data obtained. Consider the model in figure 17 where C is the total polarizability of the specimen of wood, R_p is the resistance of the conduction paths bypassing the polarizable elements, and R_s is the effective resistance limiting the current that charges the polarizable elements. Assume that C is the sum of three classes of polarization mechanism: a , electronic, atomic, and fast molecular polarizations, with short relaxation times; b , slow molecular, fixed dipole, and fast interfacial polarizations, with intermediate relaxation times; and c , slow dipole and interfacial polarizations with long relaxation times,

The contribution of a given element of polarization within each of these classes will essentially vanish when the period of the applied alternating electric field is substantially less than the time constant of the element. Thus, if the time constants of a group of elements are uniformly distributed within a given interval, there will be a corresponding frequency interval over which the polarization will decrease linearly with increasing frequency. If the distribution is slightly skewed, the relationship between polarization and frequency will vary approximately as the frequency to a power slightly different from unity.

If we assume that the time constants of the polarizable elements in a given class are distributed approximately uniformly within their appropriate intervals, the total polarization as a function of frequency for frequencies not too near zero can be written:

$$P = a + b/(1 + f/f_0) + c/(f/f_0)^l \quad (1)$$

where

a , b , and c are the polarizations defined earlier,

f is frequency,

f_0 is the frequency at which effectively half of the b elements have vanished,

l is an exponent that may differ from 1.0, by small amounts, due to slight nonuniformity in the distribution of time constants c , and

f_0 is unit frequency, inserted to make the coefficient of c dimensionless.

The constant a is frequency invariant over the frequency range covered here, because all time constants in this class are much shorter than the period of the highest frequency used.

The dielectric constant is proportional to the total polarizability, so assuming the constant of proportionality to be implicit in the values of a , b , and c we can write:

$$DK = a + b/(1 + f/f_0) + c/(f/f_0)^l \quad (2)$$

The loss tangent is the ratio of the joule or conduction current to the charging current in the material. In terms of the impedances, which are inverse to the currents, we can write:

$$\tan \delta = (X_c + R_s)/R_p \quad (3)$$

where X_c is the capacitive reactance, and R_s and R_p are the series and parallel resistances in figure 17. Strictly speaking, X_c , R_s and R_p should be combined in vector rather than algebraic expressions, but the formal variation of the dielectric properties with frequency is affected only slightly by treating these as algebraic quantities.

Equation (3) can be separated:

$$\tan \delta = X_c/R_p + R_s/R_p \quad (4)$$

and X replaced by its equivalent:

$$X_c = 1/(2\pi fC) \quad (5)$$

so that

$$\tan \delta = 1/(2\pi f C R_p) + R_s/R_p \quad (6)$$

But as C is proportional to the dielectric constant DK , we can write

$$2\pi C = (1/k)DK \quad (7)$$

and then, using equation (2), we have

$$\tan \delta = k/R_p \left\{ [a + b/(1 + f/f_o)]f + c \left(\frac{f^{1-l}}{f_o^{1-l}} \right) \right\} + R_s/R_p \quad (8)$$

The conduction processes represented by R_p and R_s are primarily ionic, and thus are themselves somewhat dependent on frequency; specifically the resistances should decrease slightly with increasing frequency due to the fact that, as the frequency increases, the ions need not move as far to transfer the same charge over unit time. To express this decrease in R with increasing frequency, replace R_p by R_p/f^m and R_s/R_p by $(R_s/R_p)f^n$. It is expected that both m and n will be small in respect to unity. With these substitutions, equation (8) becomes:

$$\tan \delta = k/R_p \left\{ [a + b/(1 + f/f_o)]f^{1-m} + c \left(\frac{f^{1-l}}{f_o^{1-l}} \right) \right\} + (R_s/R_p)f^n \quad (9)$$

where the influence of m is now implicit in a new value of l .

With the present specimens, k will be in the order of 10^{-11} , R_p will vary from about 10^3 for soaked wood to 10^{10} for ovoidry wood, and R_s/R_p will be in the order of 10^{-2} . The constants of a , b , c , l , m , and n will depend on the dielectric properties of the wood at the temperature, moisture content, etc., being considered. These constants can be determined by a combination of logical estimates and trial and error fitting to the observed data. There is a well-defined set of constants that gives the best fit to the observed data. Table 11 and figures 18 and 19 illustrate the degree to which this simple theory explains the observed dielectric behavior of Douglas-fir at room temperature. The fit is generally good, with the notable exceptions of loss tangent of soaked material at high frequencies and ovoidry material at low frequencies. These are areas where experimental values are least precise, so the lack of fit is least significant; the lack of fit is, however, greater than the probable experimental error.

The values of l are greater than 1.0 for the moist material, which indicates that there is a preponderance of the longest time constants within the class of slow polarizations. At lower moisture levels, the distribution is nearly uniform, but the material conditioned at 65 percent relative humidity shows a slight preponderance of the shorter time constants.

Values of m indicate the effect of frequency on R_p for frequencies up to about 1 MHz; m is nonzero only for intermediate moisture levels, which indicates that for very dry or very moist wood R_p does not vary with frequency, at least up to about 1 MHz. The values of n , however, reflect the effect of the higher frequencies on both R_s and P_p and n being nonzero for all moisture levels indicates that above 1 MHz R_p decreases with increasing frequency at all moisture levels.

This same formalism describes the observed dielectric behavior at temperatures other than 25° C. by changing the various constants. There seems to be a discontinuity in the dielectric behavior of wood containing free water at the freezing temperature of water, but details of this phenomenon could be determined only by measurements repeated in the neighborhood of the freezing temperature. This discontinuity is probably due entirely to the change in dielectric properties of water as it changes state, and therefore has little interest as a property of wood.

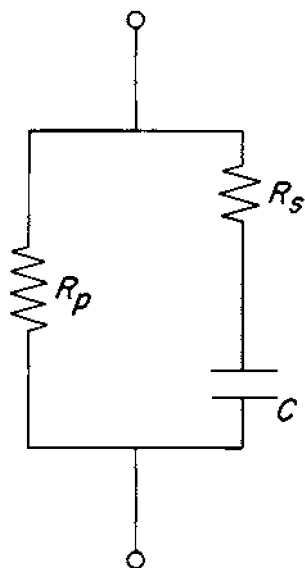
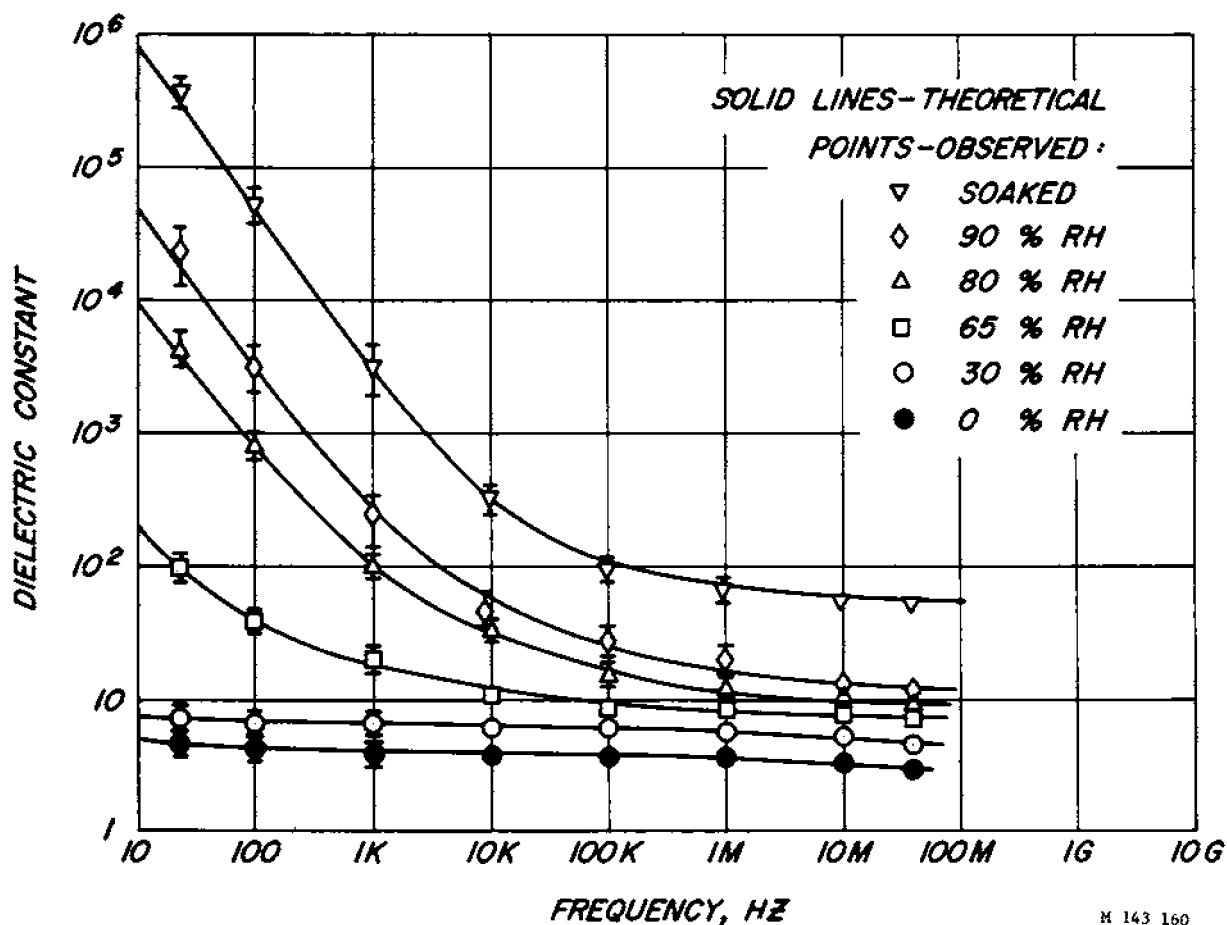


Figure 17. – Physical model of the dielectric characteristics of cellulose.

M 142 138



M 143 160

Figure 18.—Plot of observed data onto theoretically calculated curves, for field parallel to the grain, at 25° C. Vertical lines are 95 percent confidence intervals based on the observed variability of 5 specimen

samples. Where no intervals are shown, they are either smaller than the data symbol or difficult to show due to congestion.

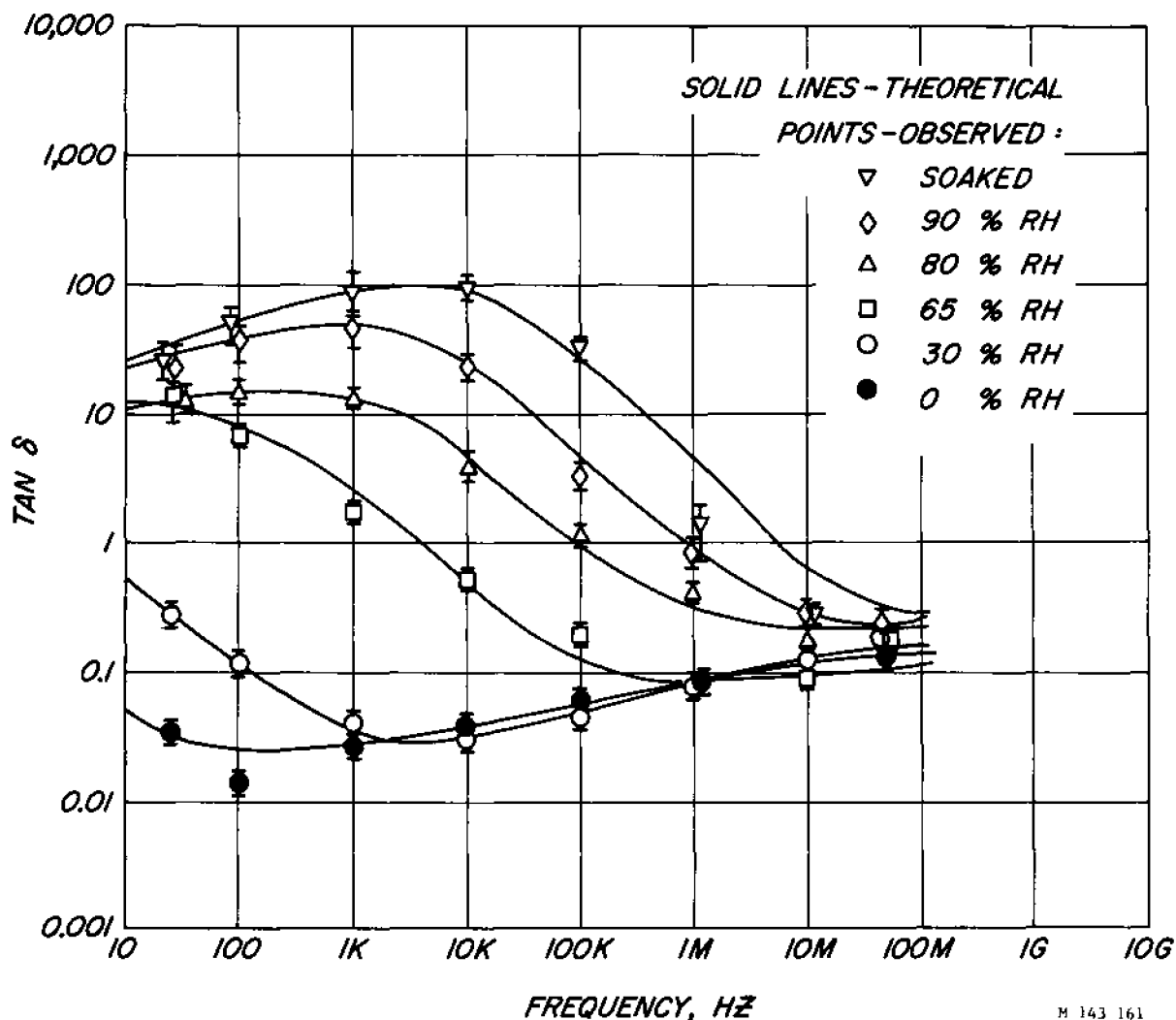


Figure 19. - Plot of observed data onto theoretically calculated curves, for the dielectric loss tangent of Douglas-fir, field parallel to the grain, at 25° C. Vertical lines are 95 percent confidence intervals based on

the observed variability of 5 specimen samples. Where no intervals are shown, they are either smaller than the data symbol or difficult to show because of congestion.

Conclusion

The essential character of the dielectric properties of wood and hardboard as studied here are strongly influenced by frequency and moisture content, and to lesser degrees by temperature and grain direction. Source of cellulose (species, hardboard type) has only a small effect on dielectric behavior.

A physical theory of dielectric behavior developed here demonstrates that within three basic mechanisms of polarization there are nearly uniform distributions of polarization time constants.

The data presented should satisfy most needs for designing wood or hardboard into situations where it is subjected to electric fields. Potentially profitable extensions of this work would include investigating the influence of chemical impregnants on the dielectric behavior of cellulosic materials, and continuing the work of Nanassy (9) regarding the influence of electric field strength on dielectric behavior.

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