

United States
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FPL 436



Dielectric Properties of Lumber Loads in a Dry Kiln

William L. James



Abstract

The dielectric properties of wood were studied in a laboratory configuration that simulated typical lumber loads in a dry kiln. The transient effect of kiln conditions on the lumber stickers was found to influence dielectric properties more than had been recognized previously. Other details of the dielectric properties apparently depended on interaction of transverse moisture gradients with other variables in the kiln and in the electrical instruments.

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August 1983

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Introduction

Electronic devices are commercially in use that infer the moisture conditions of lumber drying in a kiln from measurements of dielectric properties of the lumber load. These devices respond to the overall capacitive admittance (inverse of impedance) of the lumber load, but cannot indicate independently the capacitive or conductive components of the admittance.

An empirical study of the dielectric properties of kiln loads was made previously, using typical commercial capacitive admittance monitors as the measuring instruments². The objective was to clarify some of the basic physical principles that relate to the operation of these devices. In that study, some important recurring observations could not be explained because the monitors could not discriminate between the capacitive and conductive components of the admittance.

Understanding these details of the monitor response is essential to correct interpretation of monitor data. Accordingly, the design of the present study is to measure the dielectric properties of wood in configurations and in environments that simulate a load of lumber in a dry kiln, using laboratory instruments that provide details of the dielectric response.

The specific objective is to establish a realistic equivalent circuit for a kiln and its load of lumber, and to determine how the elements of this equivalent circuit vary with kiln conditions, moisture condition of the load (average MC and distribution), and measurement parameters (primarily frequency). This information should enable more reliable inference of the moisture status of lumber as it dries in a kiln, using capacitive admittance monitors.

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

² James, William L. and R. S. Boone. 1982. Capacitive in-kiln wood moisture content monitors: principles of operation and use. *Wood Sci.* 14(4):146-164.

Background

The electric circuit traversed by the sensing signal from a capacitive admittance kiln monitor is from the electrode into the load of lumber and back to the monitor. The return path includes random capacitance and leakage conductance between the lumber and grounded structure of the kiln, and then through the ground back to the instrument. The impedance of this return path introduces an unknown and uncontrolled quantity into the monitor readout. The impedance of the actual ground portion of this path would be expected to be negligible, so the significant unknown is the admittance between the load and ground.

Clearly, the variable of primary interest is the impedance (or its inverse, admittance) of the load of lumber, because it is this quantity that reflects changes in moisture content (MC) of the lumber. Details of the variation of the dielectric properties of wood with MC under laboratory conditions are fairly well known³. But again, in the environment of a dry kiln, conditions that influence the apparent dielectric behavior of the load are not as well controlled and cannot be recognized independently from readings of typical capacitive admittance monitors.

For example, in the previous study,² at the beginning of a typical kiln run, the monitors showed a rapid spike response that quickly went off scale, and remained for an hour or more before dropping down to on-scale readings again. This rapid increase in response was tentatively explained by the expected increase in the admittance of the lumber with increasing temperature, but both the rate and magnitude of the increase were larger than might be expected from a pure temperature effect. The rate of the increase seemed to be appreciably greater than could be expected from the actual rate of increase of the temperature of the lumber, and the magnitude of the increase seemed excessive considering that the effective admittance of the lumber should have been limited to that of the fixed capacitance between the load of lumber and the overall earth-potential mass of the kiln.

Further, the correspondingly rapid decrease in monitor response, 1 or 2 hours into the run, to a relatively constant or slowly changing value, could not be explained with certainty, and in particular could not be a temperature effect.

Another unexplained observation was the rapid response of the monitors to certain relatively large changes in kiln conditions, particularly to rapid increases in humidity. Specifically, the monitors responded faster than could be explained by changes in the actual MC of the lumber.

Understanding these and other monitor characteristics is important for correct interpretation of monitor data, and improving this understanding is the objective of this study.

Theory and Experimental Design

The equivalent circuit of the kiln and its load of lumber could be hypothesized in various ways, depending on what kiln-load details are selected to be represented by circuit elements. I propose that a reasonable and potentially useful equivalent circuit would be as shown in figure 1. The first elements are a capacitor with a parallel conductor, representing the interface between the electrode and the kiln load. The parallel conductance could be reduced to near zero by electrode insulation.

The next elements are a capacitor with a series resistor, these elements shunted by a parallel conductor; these three elements represent the load of lumber. The conductances include actual leakage conductance through the load and resistive impedance to the current that polarizes the wood, as well as the dielectric loss components of the lumber capacitance. The capacitance simply represents the total polarizability of the lumber load. The load is actually a complex array of conductors and capacitors composed of the individual pieces of lumber and stickers, but lumping these into the three basic elements seems to be a potentially useful simplification.

The last elements again are a parallel capacitor and conductor, representing the admittance between the lumber load and the ground-potential parts of the kiln. The conductance element would be predominantly leakage through the stickers into the truck and rails or kiln floor.

The only capacitive element that varies substantially with frequency is that of the lumber load. The air dielectric capacitance between the load and ground would not be frequency-dependent because the dielectric constant of air is not appreciably frequency-dependent.

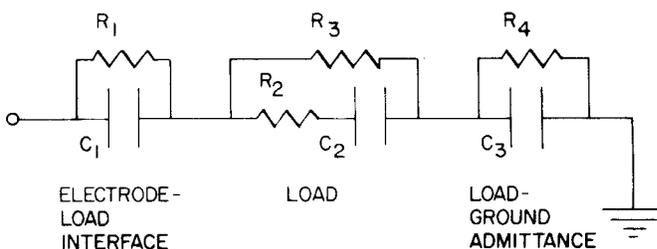


Figure 1.—A proposed equivalent circuit of a dry kiln and its load. C_1 and R_1 are the capacitive and conductive components of the connection of the electrode to the load; C_2 is the capacitance of the load; R_2 the resistance to the charging current in the load, R_3 is the leakage conductance around the load; C_3 and R_4 are the capacitance and leakage conductance from the load to grounded conductors in the kiln structure. (ML83 5135)

³ James, William L. 1975. Dielectric properties of wood and hardboard: variation with temperature, frequency, moisture content and grain orientation. USDA For. Serv. Res. Pap. FPL 245. For. Prod. Lab., Madison, Wis.

Experimental Descriptions

The capacitances of the electrode insulations were determined experimentally to vary only slightly with the frequencies covered here. It follows that the degree of variation of the total capacitance with frequency is a qualitative measure of the magnitude of the load capacitance relative to the other capacitances. Accordingly, the frequency effect is a factor in the experimental design not only for empirical evaluation of monitor performance, but also for determining a realistic equivalent circuit for the kiln and its load.

Similarly, the influence of electrode insulation can be used to deduce the relative importance of the capacitive and conductive components of the impedance of the wood-electrode interface, and different sticker designs can show the relative importance of conductance and capacitance components of the admittance between the load and grounded kiln structure.

Measurements of the capacitance and dissipation factor of simulated kiln loads were made at frequencies of 0.1, 1, 10, and 100 kilohertz (kHz), using four types of electrode and three types of specimen support (sticker). Data were obtained principally on one species, Douglas-fir, but several electrode-sticker combinations were repeated using specimens of cottonwood, basswood, or beech. The species other than Douglas-fir served to indicate any qualitative species effects, and also served as replicates of the electrode-sticker combinations. Kiln conditions used simulated various phases of commercial kiln-drying practice.

Specimens

The specimens were 18-inch-long segments of rough-sawn green 2 X 4's, prepared from logs. The green specimens were stored wrapped in plastic in a room maintained at 38°F to retard drying and molding.

Apparatus

Chamber

The test chamber was a miniature dry kiln (fig. 2) 10 by 12 by 30 inches inside dimensions. An internal fan and baffles provided airflow of 200 to 300 feet per minute over the central third of the specimen. Wet- and dry-bulb temperatures were controlled by thermistor controllers. Heat was supplied by a 500-watt open electric element. Humidity was obtained with a peristaltic pump, controlled by the wet-bulb temperature, that forced distilled water through a 0.004-inch-diameter orifice. The resulting fine jet of water was projected into the heater, where it quickly vaporized.

The chamber was lined with aluminum foil that was electrically grounded. Insulated feed-through connectors were provided for thermocouple- and conductance-type moisture-meter probes, which were used to monitor temperature and moisture gradients in the specimens.

Dielectrometer

The dielectric properties of the miniature simulated kiln loads were measured using a Shering resistance-capacitance bridge, driven by a function generator (sine wave), with bridge balances determined using a tuned null detector. Connection to the electrodes in contact with the specimens was through a 30-inch length of low-capacitance coaxial cable. The center conductor of the cable ended in an ordinary copper alligator clip to clip onto the electrode. The end of the cable was sealed with a high-temperature elastomer so the chamber humidity would not condense water inside the cable. A decade resistance and capacitance box was made as an accessory for the bridge to extend its range to large values of capacitance and loss tangent (equivalent parallel conductance).

Electrodes

Electrodes were made in four forms (fig. 3) each 3 by 5 inches. This covered the central 3 inches of each specimen, in similitude of actual dry kiln practice, with sufficient overhang to permit clipping the cable to the electrode. Three electrodes were solid aluminum sheet; one was bare, one was coated with a layer of rubber adhesive about 0.003 inch thick, and one was clad with 1/4-inch-thick rubber foam. The surface of the foam was sealed to prevent moisture absorption. The insulating coatings eliminated the conductance component from the electrode-load admittance, and added two different levels of capacitive reactance to the electrode-load inter-face. Theoretically, this should facilitate estimation of the effective capacitance of the load itself, especially as modified by the influence of moisture gradients.

The other 3- by 5-inch electrode was of aluminum window screen which provided electric contact while not interfering with drying under the electrode.

The electrodes were held firmly on the specimen by a small, weighted table made from a piece of 1/4- by 3- by 4-inch tempered hardboard, with 1/16-inch-diameter by 1 -inch-long wooden legs fitted perpendicular to the hardboard near each corner. The thin legs held the electrodes firmly in place without serious interference with airflow (fig. 4).

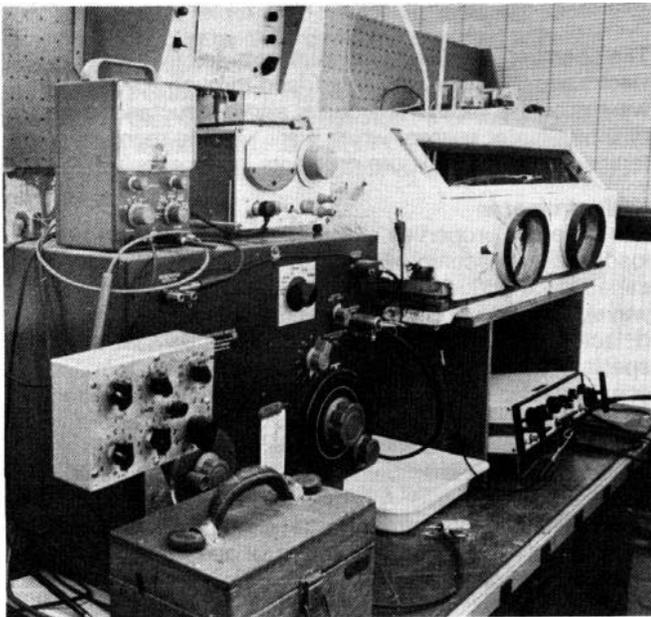


Figure Z.—The model kiln with associated controls and electric instruments. (M 150884)

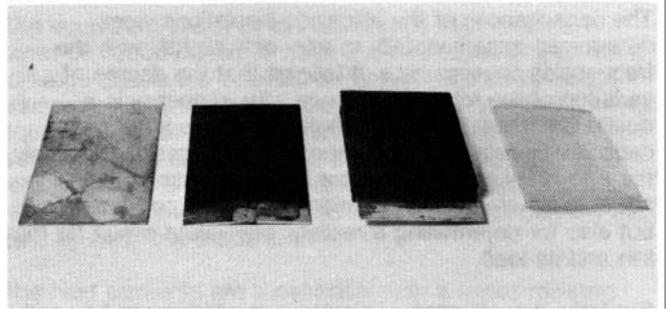


Figure 3.—Electrodes used in this study were (left to right) bare aluminum, aluminum insulated with 0.003-inch rubber adhesive, aluminum insulated with 1/4-inch foam rubber, and aluminum screen. (M 150887)

The solid electrodes were distorted slightly to simulate the typically imperfect contact between the electrode and specimens in actual practice; this permitted some drying under the electrode.

Specimen Supports

Data were obtained with the specimens supported on typical stickers, and also when resting on special supports designed either to be electrically conductive or to eliminate electric leakage that could occur from moisture condensing on the stickers (fig. 5).

The typical stickers were 4-inch lengths either of a heavily resin-impregnated paper laminate with a cross section of 11/16 by 1-1/4 inches, or of solid natural oak, about 3/4 by 1-1/4 inches. The oak stickers were kiln dry (less than 8 pct MC) at the beginning of each run in which they were used.

The special low-leakage stickers consisted of a pair of 1/4- by 1-3/4-inch dowels mounted vertically about 3 inches apart in a hardboard base. Each dowel was covered by a small plastic cup inverted over the dowel and secured using a cellulose glue. The specimen rested on two such supports, one near each end of the specimen. These supports provided a long leakage path (the inverted cups), with a small probability of condensation on the cups because of their small heat capacity.

The other special stickers were electrically conducting to eliminate the load-ground impedance; the conductance (R_4 , in fig. 1) then would be effectively infinite. These were made simply by wrapping the solid wood stickers in aluminum foil.

Other Instrumentation

The specimens were fitted with probes to indicate both the temperature and MC profiles across the thickness of the specimen. Two copper-constantan thermocouples of No. 30 wire were located in the middle of a 4-inch face, one about 1/8 inch below the specimen surface and the other about 1/2 inch below the specimen surface. Holes for the thermocouples were drilled just big enough to accept them; the near-surface hole was drilled at an angle of about 5° from the specimen surface to provide a fairly long wire length from the thermojunction to the surface.

Thermocouple potentials were read using a portable temperature-compensated potentiometer calibrated in degrees Fahrenheit.

Moisture gradients were inferred from a measurement of MC, using a conductance-type moisture meter, at the specimen surface and about 1/2 inch below the surface of the specimen. To do this, three probes were implanted in the specimen: one essentially at the center, one to a depth of 1/2 inch, and one at the surface. The probes were 16-gauge bare copper wire inserted into snug-fitting holes drilled to the appropriate depth. Electric contact was stabilized by inserting a small drop of silver-loaded lacquer at the bottom of each hole, with a hypodermic syringe, just before pushing the wire in place. The silver paint was thinned as needed to enable it to be injected.

The surface probe was mechanically stabilized by shaping it to lie on the surface of the specimen with about 1/8 inch of the end bent at a right angle so as to bear against the surface. The probe was secured to the specimen by staples insulated from the specimen and probe by strips of electric insulating tape. The contact point was electrically stabilized through a small drop of the silver-loaded conductive paint.

Procedures

The basic procedure was to measure the capacitance and effective loss tangent of the simulated kiln loads under various kiln conditions and combinations of electrode and sticker type. These data were then related to temperature and moisture gradients in the specimen and to other recognizable variables of the kiln environment. Past experience (2) has shown that the most important electric variable regarding capacitance kiln monitors is frequency; accordingly, data were taken at frequencies of 0.1, 1, 10, and 100 kHz at each combination of the other variables (such as electrode type, kiln conditions, and elapsed time).

Two categories of data were obtained: (1) When kiln conditions were changing rapidly, such as at startup or at step changes in kiln settings, and (2) when kiln conditions were constant and moisture and temperature profiles in the specimen were changing with time. Typically, both categories of data were obtained in each experimental run by setting the kiln controls to various conditions and observing the specimen response to the transient effects as the kiln approached these settings, and then observing the specimen response as a function of time after the kiln reached constant conditions.

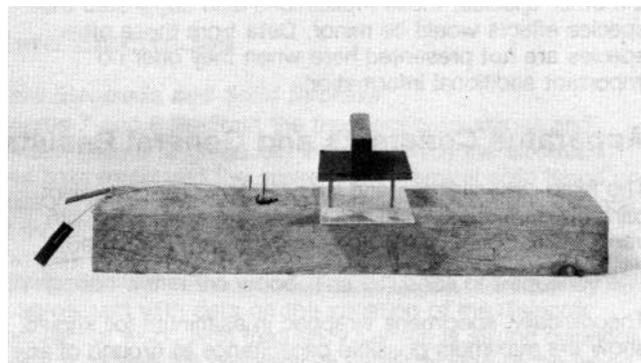


Figure 4.—A typical specimen, showing moisture and temperature probes and means of securing the electrodes on the specimen surface. (M150886)

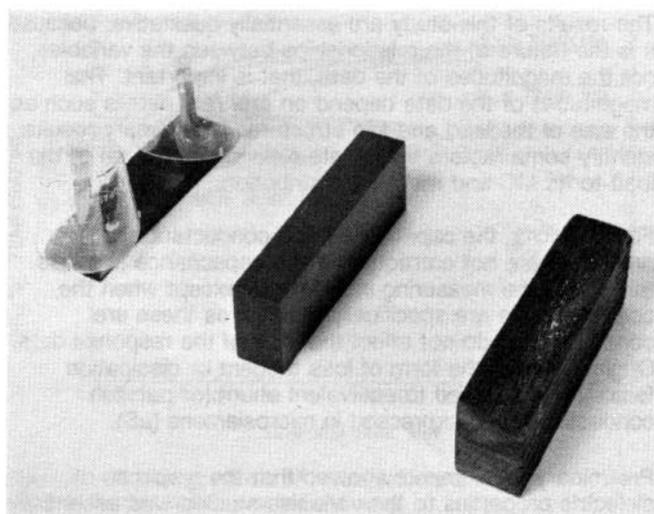


Figure 5.—Stickers used in this study were (left to right) special low-leakage stickers, synthetic stickers, and solid-wood stickers. (M 150885)

When the kiln conditions were changing rapidly, data were taken at 5-minute intervals. Even though the readings were made very quickly, it still took typically 2 minutes to record all the data. Therefore, the relationships between the four frequencies, temperature, and moisture are only approximate with respect to time.

Results and Discussion

The results of this study are essentially qualitative, because it is the nature of the relationships between the variables, not the magnitudes of the data, that is important. The magnitudes of the data depend on arbitrary details such as the size of the load and kiln structure. The primary results identify some factors that relate dielectric response of the load to its MC and moisture distribution.

For simplicity, the capacitance and conductance data presented are not corrected for the capacitance and loss tangent of the measuring instruments except when the corrected data are specifically needed, as these are constants that do not affect the form of the response data. Original data in the form of loss tangent or dissipation factor are converted to equivalent shunt (or parallel) conductance and expressed in microsiemens (μS).

Preliminary experiments showed that the response of dielectric properties to the variables studied was essentially the same with either one or two specimens simulating the kiln load, so data were taken using a single specimen for each load.

The data plots (figs. 6 through 16) are each from a single kiln run. The general form of each plot and the order of magnitude of the data were verified by replications using the other species; these replications also suggested that species effects would be minor. Data from these other species are not presented here when they offer no important additional information.

Apparatus Constants and General Results

The fixed capacitances and loss tangents (or equivalent parallel conductances) of the measuring apparatus with various electrodes and configurations were measured (table 1).

Theoretically, specimens wrapped in aluminum foil should show the maximum possible capacitance to ground of any specimen of that size and shape resting on the same supports (stickers). Specimens of lesser conductivity should show smaller effective capacitance, so the foil-wrapped specimen defines an upper limit to the load-ground capacitance in this study.

It is obvious (table 1) from the substantial parallel conductances and the variation of capacitance with frequency that data obtained when the foil-wrapped specimen was supported on the laminated paper stickers were distorted by leakage conductance of the stickers, even though they had been baked for several hours. Measurements of actual direct current resistance of the stickers at the end of several kiln runs revealed that the laminated paper stickers were affected to a greater degree and more persistently (as to leakage conductance) by the hot, humid kiln conditions than were the solid oak stickers. This apparently is a permanent characteristic of these synthetic stickers, and could be a significant source of variability in the data from capacitive kiln monitors where such stickers are used.

Table 1 .—Some constant capacitance and loss tangent values¹ of the experimental apparatus

Configuration	Frequency (kHz)	Capacitance (pF)	Loss tangent (or equivalent parallel conductance) (μS)
Measuring system, no electrode		213	< 0.001
Specimen wrapped in aluminum foil on dry, laminated paper stickers	0.1	311	(0.008)
	1	287	(0.083)
	10	262	(0.36)
	100	256	(1.0)
on dry, solid oak stickers		256	< 0.001
on special low-leak stickers		251	< 0.001
Any 3- by 5-inch electrode on 1-inch-thick Styrofoam		221	< 0.001
3- by 5-inch electrode, thin insulation, on grounded metal plate	0.1	390	(0.005)
	100	380	(0.008)
Peak values in hot, humid kiln	0.1	680	(0.62)
	1	580	(0.84)
	100	500	(12)
3- by 5-inch electrode, thick insulation, on grounded metal plate		240	< 0.001

¹ At room conditions except where noted. Where no reference to frequency is made, data did not vary with frequency.

Corresponding data using the ordinary solid wood or the special low-leakage stickers appear valid, however. The maximum load-to-ground capacitances in the present configuration for solid wood stickers are 43 picofarads (pF) (256 pF minus the system capacitance of 213 pF) and 38 pF (251-213) for the low-leakage stickers.

Similarly, the net series capacitances of the two electrode insulations are about 170 pF for the thin and 27 pF for the thick insulation.

These data are useful for interpreting the results of this study and inferring details of the equivalent circuit of the kiln and its load. For example, in kiln runs in this study, the differences in total capacitances observed using the two different thicknesses of electrode insulation did not reflect the 143-pF difference in series capacitance of the two insulations. Differences in total capacitance were much less, which establishes the limiting effect of other series capacitances, particularly the load-ground capacitance. The form of the response curves was essentially the same for either type of insulation, so only data obtained using the thin insulation are shown in this report.

On the other hand, these data in conjunction with data from the kiln runs reveal some of the complexity of the composite dielectric properties of the kiln and its load. For example, it was common, especially when using insulated electrodes, for the total measured capacitance of the electrode-load-kiln to exceed the capacitance calculated for the two- or three-series capacitances in the equivalent circuit, even in later stages of drying. This could be explained only by significant conductances shunting one or two of the capacitances, but I did not expect the persistence of these conductances as the kiln went to drier conditions. In commercial practice, the existence of these conductances even in the later stages of drying, where capacitance naturally is the principal mode of admittance, could be a source of variability in readings of an admittance-type monitor. This is consistent with the somewhat erratic progression of conductances illustrated in figure 16, which simulates late stages in a drying program typical of commercial practice.

Temperature and MC Gradients

Figure 6 shows the typical moisture and temperature distributions for green Douglas-fir specimens exposed to the kiln conditions plotted. The response of all Douglas-fir specimens to these conditions was similar; the differences observed were not sufficient to change the characteristics of the dielectric responses.

The apparent small decrease and momentary recovery in surface MC in the first 20 minutes of a typical run were deduced from readings of a conductance-type moisture meter. These readings were made when the specimen temperature was changing rapidly, so accurate temperature corrections were difficult. For this reason, this momentary variation in surface MC may be spurious.

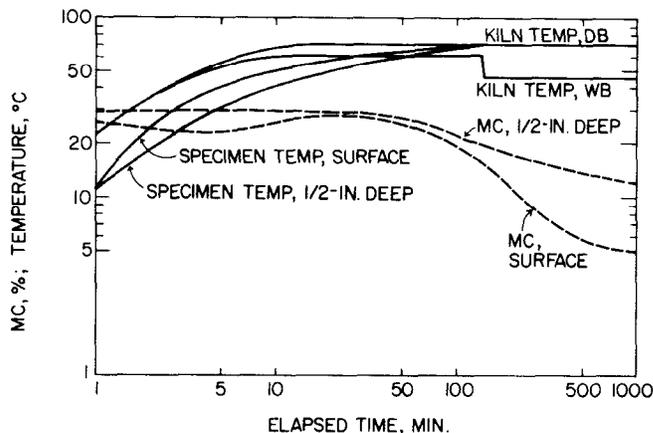


Figure 6.—Typical gradients of temperature and MC that formed in Douglas-fir heartwood specimens under the kiln conditions in this study, in which the wet-bulb depression was increased after about 2 h of drying. The apparent minimum in surface MC at about 5 min may be due to imperfect temperature corrections, and therefore may not be real. (ML83 5136)

Bare Electrodes

Bare Electrode and Solid Stickers

Figures 7 and 8 illustrate the transient capacitance and conductance of a green kiln load for which the electrode was bare metal and the stickers were typical solid wood or resin-impregnated paper. The rapid increase in capacitance at the lower frequencies, as the kiln temperature and humidity increase, indicates a large increase in the electric polarization within the wood. The influence of frequency is in agreement with data on the variation of the dielectric constant of wood with frequency,³ which is strong evidence that it is indeed the capacitance (polarizability) of the wood that causes this large total capacitance. Also, it is very likely that this is the same phenomenon as observed at startup of actual kiln runs using commercial-type monitors.²

If the equivalent circuit (fig. 1) is valid, it is clear that for the total capacitance to have values in the thousands of pF, arising from the very large dielectric constant of the wet lumber load, both the electrode-wood admittance and the load-ground admittance would have to be very large. With a bare metal electrode on green lumber, the electrode-wood admittance would indeed be large because of the large conductance, but the load-ground admittance would be limited to the vector sum of sticker conductance and the susceptance of the load-to-ground capacitance. This latter capacitance was shown earlier to be about 43 and 38 pF for the solid wood and special stickers, respectively. Kiln conditions could increase these capacitances appreciably only by increasing the effective dielectric constant of the stickers, which, because of the relatively small area of the stickers, would remain a limited contribution to the load-ground admittance.

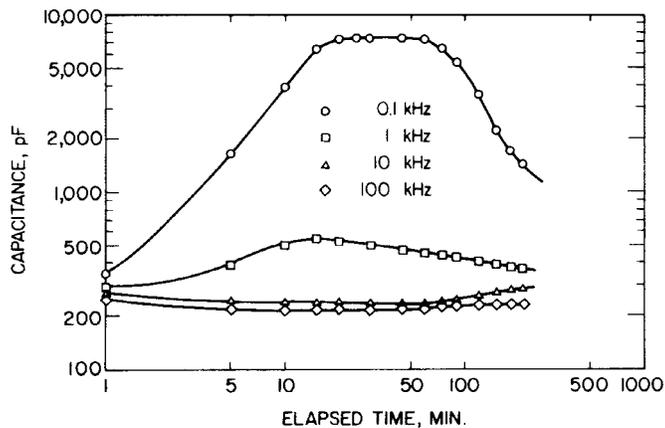


Figure 7.—Capacitance of a load of Douglas-fir heartwood at various frequencies, using a bare metal electrode and solid wood stickers, as conditions changed according to fig. 6. (ML83 5138)

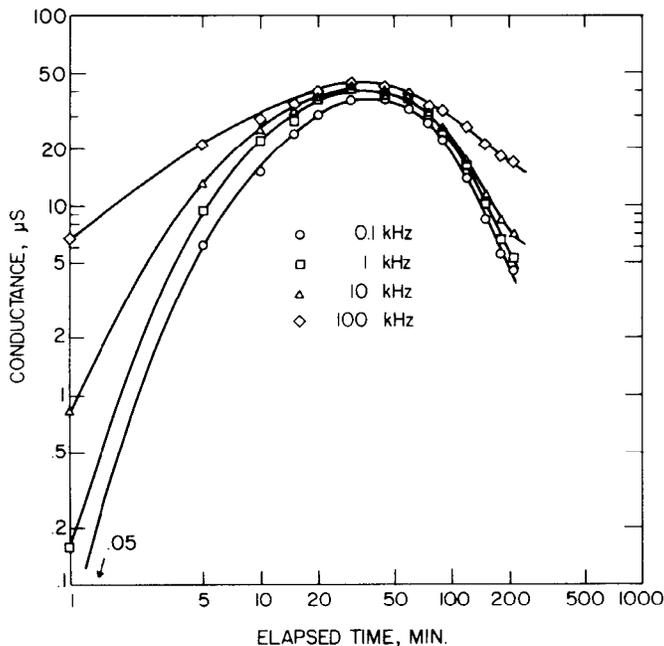


Figure 8.—Conductance of a load of Douglas-fir heartwood at various frequencies, using a bare metal electrode and solid wood stickers, as conditions changed according to fig. 6. (ML83 5139)

On the other hand, large load-ground admittance could be provided by leakage conductance across the stickers if moisture condenses on them. The data in figure 8 are consistent with this hypothesis: The initial values of conductance plotted in figure 8 (shown at 1 min elapsed time—this is actually zero elapsed time, but the log plot cannot show zero) are the equivalent parallel conductances associated with the loss tangents of the kiln and its load at the four frequencies, and when the stickers are still cool and dry. These conductances are roughly proportional to the frequencies, because the loss tangents vary only from about 0.2 at 0.1 kHz to 0.04 at 100 kHz, a factor of 5.³ But as the kiln heats up, with both the dry- and wet-bulb temperatures increasing rapidly, the conductances increase greatly and, more important, approach peak values that are nearly independent of frequency. This frequency invariance identifies these conductances as real, not equivalent dielectric loss. This requires that both the stickers and the load of lumber be moist and therefore relatively highly conductive.

In the run represented in figures 7 and 8, and in subsequent runs, the capacitance and conductance reach peak values at about the same time as the surface MC also shows a small peak. As noted earlier, this peak in surface MC is not absolutely established, but the simultaneity of the three peaks is consistent with the assumption that they result from condensation of kiln humidification on the still-cool kiln load.

Bare Electrode and Low-Leakage Stickers

The role of the stickers in the previous situation is indicated further by the data plotted in figure 9, where both capacitance and conductance data are plotted on the same graph. These data were obtained with the specimen supported on special stickers designed to minimize condensation and leakage conductance. With these stickers, the capacitance increase is small and, in fact, at 1 kHz or greater is essentially zero. The corresponding increase in total conductance is an order of magnitude less than that for solid stickers. It follows then that the large increase in total admittance typically observed with capacitive monitors as the kiln starts is due to moisture condensation on the stickers and other elements in the path from the load to ground. This condensation occurs early in the kiln schedule or at any other time that kiln humidification increases so rapidly that parts of the kiln or load are momentarily cooler than the dewpoint inside the kiln.

It was hypothesized earlier² that the spike increase in admittance at startup of the kiln resulted from the effect of temperature on dielectric properties, in conjunction with a surface phenomenon at the electrode-wood interface. The surface hypothesis was that the conductance between electrode and wood would decrease quickly as the surface dried, with the capacitance decreasing later as the dry surface layer deepened. The fact that the conductance and capacitance peak at about the same time shows that this hypothesis is not valid, and confirms the involvement of the stickers to a degree not recognized earlier.

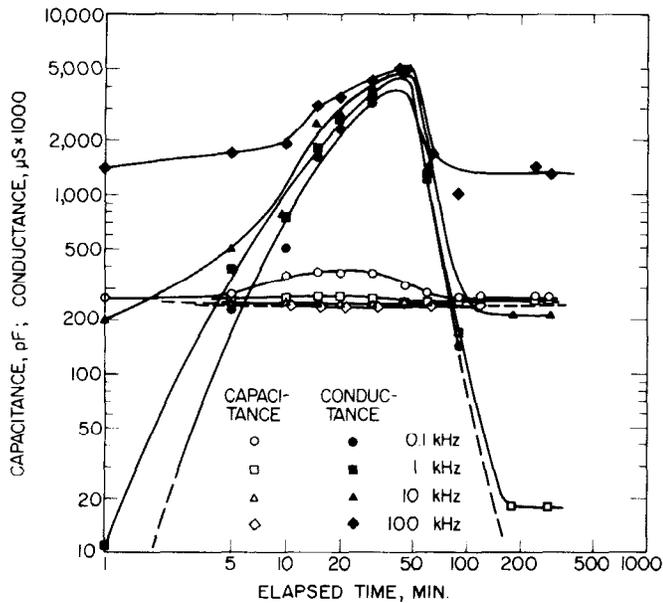


Figure 9.—Capacitance and conductance of a Douglas-fir heartwood load at various frequencies, with a bare metal electrode and special lowleakage stickers, as conditions changed according to fig. 6. (ML83 5140)

Bare Electrode, Metal Stickers

The marked difference in data obtained with solid stickers and with low-leakage stickers confirms the significant influence of sticker design. It would seem that the opposite extreme in sticker design, electrically conducting stickers, should result in data that maintain, from time zero, values at least as large as the peak values observed with solid, nonconducting stickers. To prove this, runs were made on Douglas-fir and basswood, with the bare electrode and solid stickers wrapped in aluminum foil to make them electrically conductive (figs. 10 and 11, respectively).

The data for Douglas-fir (fig. 10) are essentially the same as corresponding data obtained with solid nonconducting stickers (figs. 7 and 8). In particular, the total conductance even when using electrically conducting stickers increases rapidly in response to the rapid kiln humidification at startup. This indicates that the kiln humidity not only induces leakage paths around the stickers but also simultaneously greatly increases the admittance of the specimen material. The specimen material itself reacts to the kiln humidity in this case because it is Douglas-fir heartwood and has therefore a moderately low initial MC—somewhat less than 30 percent. By contrast, the data for green basswood (fig. 11), show very large values of admittance without any kiln humidification, because of the much greater initial MC of the basswood. For this material, kiln humidification would have little effect because the specimen material is already nearly saturated with water. The small increase in conductance and capacitance in this run is probably a temperature effect.

These runs, using conducting stickers, emphasize that superficial moisture condensing on the specimens has a strong effect on the total capacitive admittance of the kiln load, at least when the initial MC of the load is not appreciably greater than fiber saturation. The superficial moisture resulting from high kiln humidities would be expected to increase strongly the conductance denoted by R_3 (fig. 1), but the data in figure 10 show that the capacitance C_2 may be strongly increased as well.

Insulated Electrodes

There was no important difference between results from using thin or thick electrode insulation, so only data for thin insulation are shown.

Figure 12 shows the startup transient peak of capacitance when using an electrode with thin insulation and with the load supported on solid stickers. Comparing this with the corresponding data for a bare electrode (fig. 7) reveals some interesting relationships. At the highest frequency, 100 kHz, the electrode insulation has no effect on the total capacitance. This shows that the reactance of the insulating film is negligible compared to the impedance of the kiln and its load, so the insulated electrode is equivalent to the bare electrode. The impedance of the kiln plus load is a complex combination of reactances and resistances, including leakage across the stickers. At 100 kHz, however, the total capacitance of the electrode, load, and kiln is nearly independent of the leakage conductance across the stickers (as indicated by the constant value with time in figs. 7 and 12) and, in fact, is roughly equal to the capacitance of a specimen wrapped in metal foil resting on the same stickers and located in the same place in the kiln (table 1). This latter capacitance was measured at 256 pF (including apparatus capacitance). It follows from this that at 100 kHz the green specimen experiences negligible polarization and acts essentially as a conductor. For a bare electrode this is true not only at 100 kHz but also at 10 kHz (fig. 7). With an electrode with thin insulation, however, there is at 10 kHz an increase in total capacitance when leakage conductance across the stickers increases (fig. 12). The electrode insulation effectively introduces a series capacitance, which from first principles cannot increase the total capacitance of a network. This apparent contradiction is resolved when the associated conductances are considered (figs. 8 and 13); the electrode insulation reduces the total admittance of the network by sharply reducing the conductance, and the apparent increase in capacitance is probably due only to the increase in the fraction of the total impedance that is due to capacitive reactance.

As the frequency is reduced further, the relative contribution of capacitive reactance to the total impedance continues to increase, enhanced by the strongly increasing polarizability of moist wood as the frequency decreases.³ The total admittance of the electrode-load-kiln circuit of course continually decreases as the frequency decreases when using an insulated electrode, and the total admittance cannot be as large as that observed when using a bare electrode.

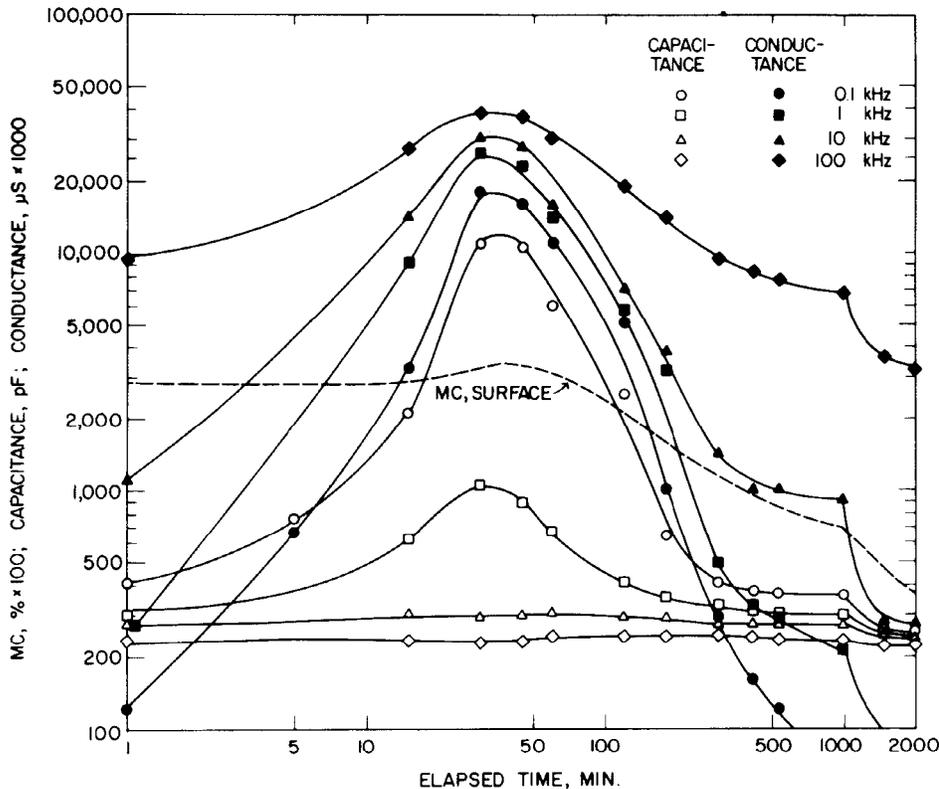


Figure 10.—Capacitance and conductance of a load of Douglas-fir heartwood at various frequencies, with a bare metal electrode and metal stickers, as conditions changed essentially according to fig. 6, but with the slightly different history of surface MC shown. (ML83 5141)

The conductances observed with use of an insulated electrode (fig. 13) depend strongly on frequency, because they are largely the equivalent parallel conductances of the dielectric losses in the system, which are frequency dependent. In addition, the electrode insulation itself displayed equivalent leakage conductances in the hot, moist kiln environment of about $1 \mu\text{S}$ at 0.1 kHz to about $10 \mu\text{S}$ at 100 kHz. These conductances would add vectorially to the susceptance of the insulation and thereby increase the admittance of the electrode.

Insulated Electrode and Low-Leakage Stickers

The dielectric properties of the kiln and load when using an insulated electrode and special low-leakage conductance stickers are shown in figure 14 where both conductance and capacitance are plotted.

Before the kiln is **started**, the solid stickers are dry and act the same as the special stickers. This is reflected in the rough similarity in initial values of conductance when the two types of stickers are used (see figs. 13 and 14). When the near-saturation conditions in the kiln are established at startup, even the low-leakage stickers show some increase in conductance, except at the highest frequency. The overall response of the conductance to frequency and time (essentially condition of leakage conductance) is similar in form to that when using an insulated electrode and solid stickers, but is an order of magnitude smaller. The corresponding similarity between conductances as a function of frequency and time when using a bare electrode with either solid or special stickers, again with a magnitude difference between sticker types of about a factor of 10 (compare figs. 8 and 9) shows that the leakage conductances in either case are real, essentially frequency invariant. The frequency effect on the overall response when using the insulated electrode results because the component of the conductance that is associated with dielectric loss becomes relatively more prominent when the direct electrode-specimen conductance is removed by the electrode insulation.

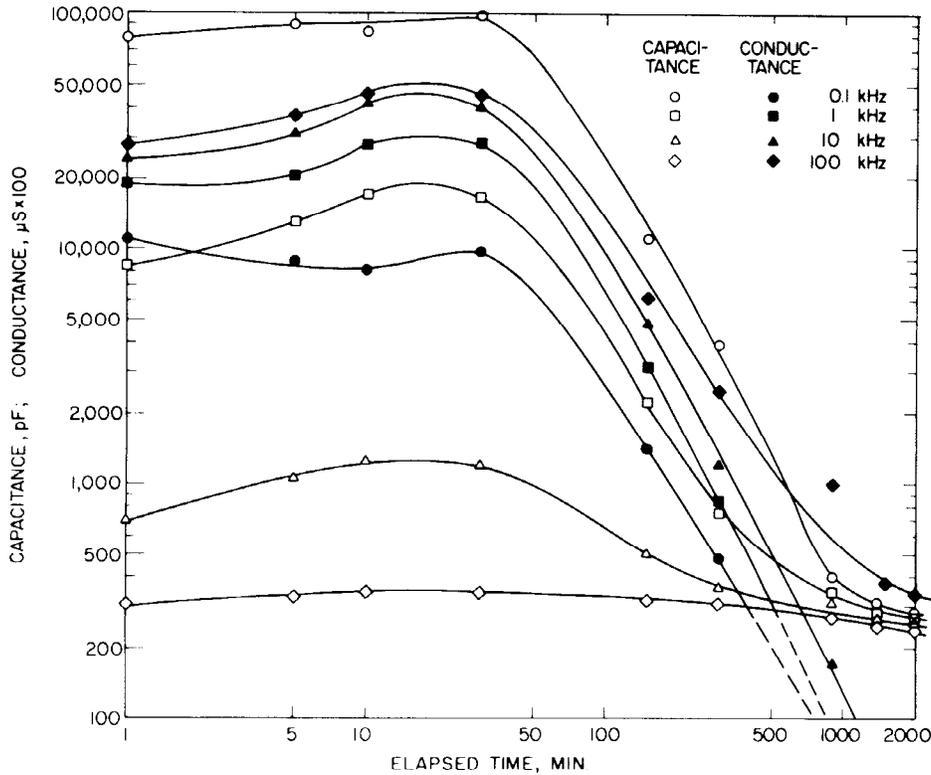


Figure 11.—Capacitance and conductance of a load of green basswood at various frequencies, with a bare metal electrode and metal stickers, as the dry bulb temperature changed according to fig. 6, but with no kiln humidification. (ML83 5142)

Screen Electrode, Solid Wood Stickers

Figure 15 shows dielectric data from use of a screen electrode and solid stickers. These results are similar to those observed for a bare sheet metal electrode, except that the response to changing the kiln conditions seems to be somewhat more pronounced. At 300 minutes into the run, the wet-bulb depression was increased from 10° to 25° C. The resulting accelerated drying is apparent from most data, although plotting limitations prevent showing this clearly for the conductances at the two lower frequencies. Also, the capacitance change at the two higher frequencies is not clearly definable.

At 1,200 minutes, the wet-bulb depression was decreased to 5°C and the resulting increase in surface moisture is apparent again in all data except the capacitance at the two higher frequencies.

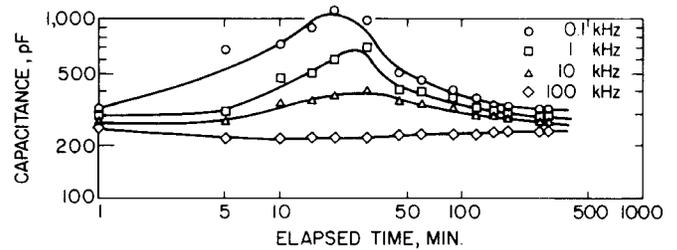


Figure 12.—Capacitance of a load of Douglas-fir heartwood at various frequencies, using an electrode with thin insulation and solid wood stickers, as conditions changed according to fig. 6. (ML83 5137)

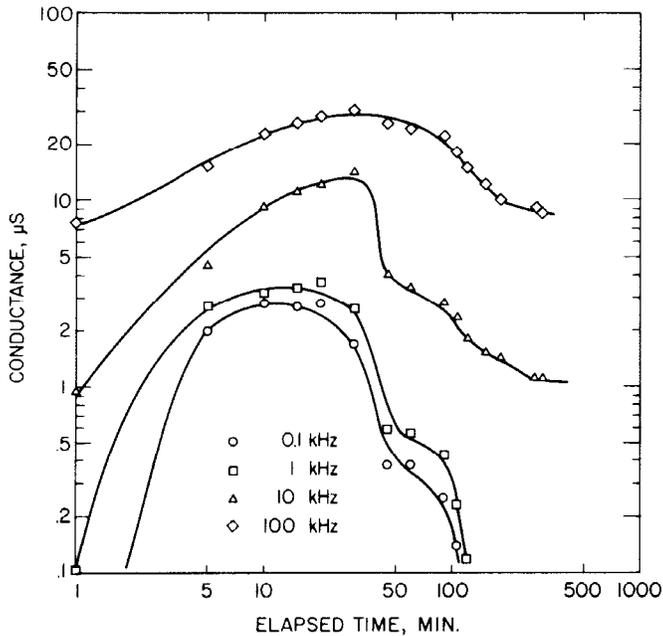


Figure 13.—Conductance of a load of Douglas-fir heartwood at various frequencies, using an electrode with thin insulation and solid wood stickers, as conditions changed according to fig. 6. (ML83 5143)

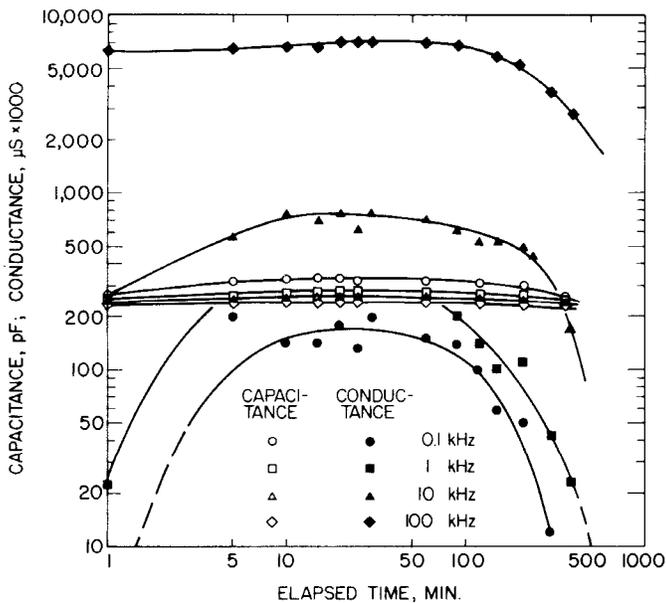


Figure 14.—Conductance and capacitance of a load of Douglas-fir heartwood, using an electrode with thin insulation and special low-leakage stickers, as conditions changed according to fig. 6. Note that the conductance scale is one-tenth as large as in fig. 13. (ML83 5144)

These data indicate the strong influence of surface conditions on the dielectric properties that relate to kiln monitors. In this run, as in other runs where kiln humidification was used to minimize drying gradients, the conductance or dielectric loss appeared to be more responsive to drying progress than was the capacitance when the rate of moisture change was relatively large.

No Kiln Humidification

Figure 16 shows data on capacitance and conductance of a load, using a bare metal electrode and dry, solid wood stickers, as it dried in a kiln at 70°C and no humidification. The wet-bulb depression was about 25°C after the kiln temperature was reached (about 10 min after the run began). The specimen was Douglas-fir heartwood, with an initial MC slightly less than 30 percent as indicated by a conductance-type moisture meter.

The capacitance data were corrected for the fixed capacitance of the measuring apparatus to show more clearly the relatively small changes in capacitance of the kiln load as it dried. The plotted values are the total capacitance of the kiln and load corresponding to the equivalent circuit (fig. 1) and therefore include the series load-ground capacitance. The total capacitance is limited to the value of this fixed, relatively small series capacitance, so the changes in the actual capacitance of the load alone would be larger than the capacitance data plotted in figure 16. The variation in capacitance indicated by a capacitive admittance monitor as the load dries theoretically would be substantially greater if the effective load-ground capacitance could be increased or eliminated. Achieving this in practice apparently would not be a trivial exercise, because the obvious solution of using electrically conducting stickers to shunt the load-ground capacitance produced conflicting results. The data for metal stickers (fig. 10) are not greatly different from those for wood stickers (fig. 15) but, where metal stickers were used (fig. 11) and drying was quite rapid because of low kiln humidity, the response of electrical properties to drying progress was particularly strong. Apparently, the use of conducting stickers in conjunction with capacitive kiln monitors needs further study.

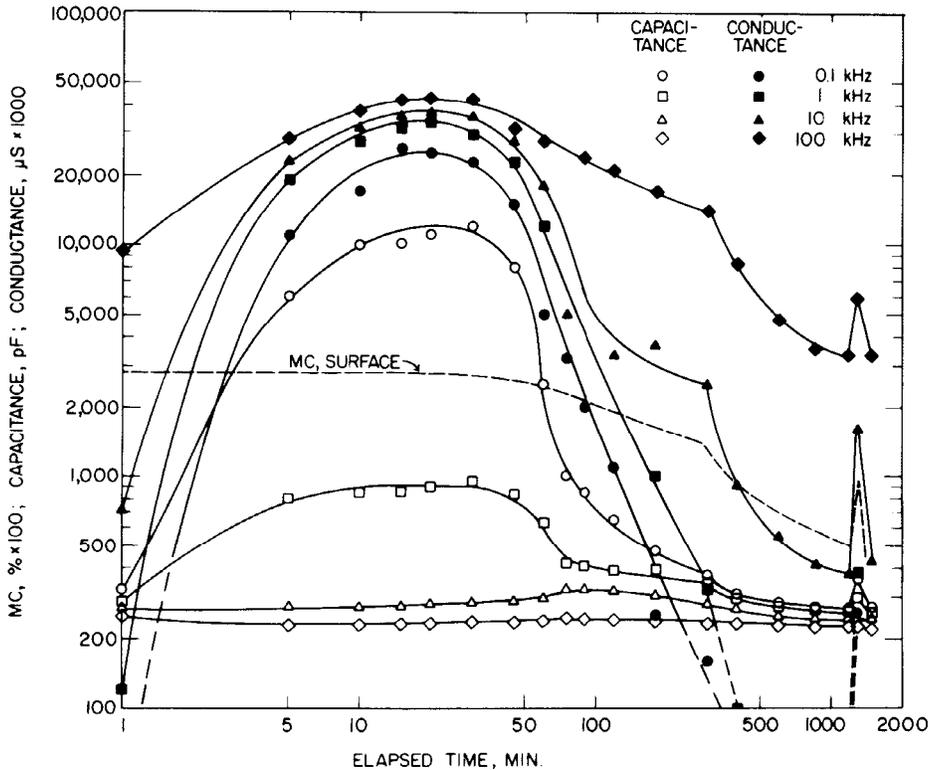


Figure 15.—Conductance and capacitance of a load of Douglas-fir heartwood at various frequencies, with a bare aluminum screen electrode and solid wood stickers, as conditions changed essentially according to fig. 6, but the wet-bulb depression was increased from 10° to 25°C at 300 min and decreased to 5°C at 1,200 min. (ML83 5145)

Conductance was erratic and unresponsive to the drying process after the surface MC had been reduced to about 18 percent (fig. 16). In this case, where no kiln humidification was used, a surface MC of 15 percent was achieved within 10 minutes. Only the conductance at 100 kHz fell monotonically as the drying continued to the end conditions. The early stages of rapid drying are confounded by corresponding rapid changes in temperature. The increase in conductance that occurred at the three lower frequencies between 10 and 100 minutes may be explained by the increasing temperature of the specimen material. Temperature equilibrium was reached about 200 minutes into the run, so temperature changes cannot explain the continual increase in conductance at 10 kHz as the load

dried. In short, these conductance data are not consistent with basic dielectric properties of wood, nor are they correlated with any clearly defined factor in the drying process. The conductance values are very small, so the variations observed are due most likely to random effects, rounding errors, or similar sources of variation. Again, the measurable electric quantity best correlated with MC in the later stages of drying is capacitance.

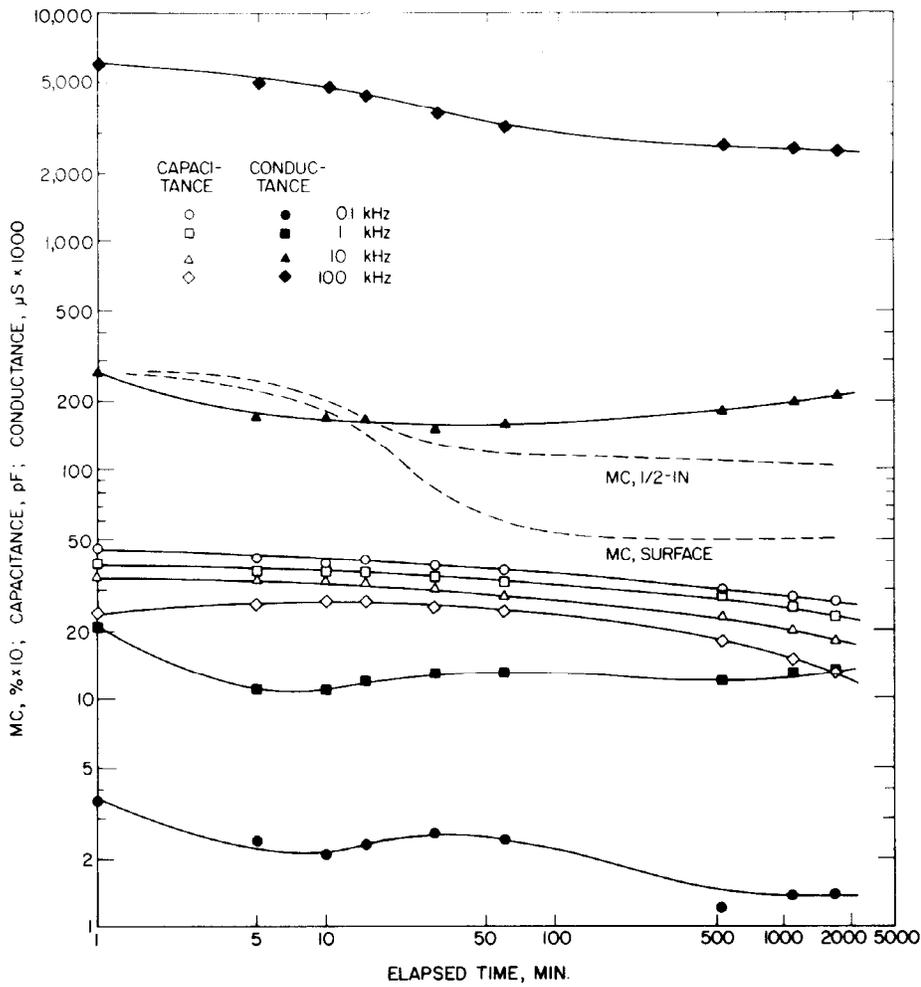


Figure 16.—Conductance and capacitance of a load of Douglas-fir heartwood at various frequencies, with a bare metal electrode and solid wood stickers, as the dry-bulb temperature changed according to fig. 6, but with no kiln humidification. The resulting MC profiles are also plotted. Note that the conductance and capacitance scales are one-tenth as large as in fig. 15. (ML83 5146)

Summary and Conclusions

A study was made of the dielectric properties of wood in the configuration and environment of a lumber dry kiln to obtain information for improving the design and application of capacitance dry kiln monitors. Variation in apparent capacitance and loss tangent (equivalent parallel conductance) of the kiln loads was measured in response to both changing and steady kiln conditions, and as a function of time, sensing frequency, MC of the load, and design of the electrodes and stickers. From observed relationships between these variables, some details of the equivalent circuit of the kiln load were inferred.

When the kiln is started, dewpoints are established that may be higher than the temperature of the load and stickers, so moisture condenses on these surfaces. This results in a large temporary increase in the admittance of the load. Under these conditions, capacitance and conductance reach maximum values at the same time, which indicates that this phenomenon is due to properties of the load as a whole, not just an electrode-wood contact effect. The peak conductances when a bare metal electrode is used are nearly independent of frequency, so are real as opposed to equivalent dielectric loss. The peaks are greatly reduced when using special stickers designed to minimize condensation and electric leakage, confirming that the effect is dependent upon leakage conductance across the stickers. Experiments using metal stickers demonstrated that condensation on the load itself also can be important when the initial MC of the load is not much greater than fiber saturation.

As drying continues and the leakage conductances become small, the load-to-ground admittance becomes predominantly capacitive, although sometimes a surprising degree of overall conductances may persist. The load-ground capacitance can be substantially smaller than the effective capacitance of the load, and as these capacitances are in series, relatively large changes in the load capacitance may appear small because of the limiting effect of the small load-ground capacitance. If the load-ground admittance could be increased, the overall sensitivity of the system possibly could be increased, but it appears that this would complicate application of the method to kiln monitoring. For example, the simple expedient of using electrically conducting stickers to increase the load-ground admittance was found to produce inconsistent results.

When the electrode was insulated from the load, so the electrode-load admittance was essentially pure capacitive susceptance, the observed total conductances were strong functions of frequency under all kiln conditions. This confirms that these effective conductances were due mostly to dielectric loss, not real conductances as observed under high-humidity kiln conditions with bare metal electrodes. When drying had progressed to where leakage conductance across the stickers was small, the observed conductances were strongly frequency dependent for all electrode types.

The conductance seemed to be a somewhat more sensitive indicator of drying progress in the first stages of drying, with the capacitance being somewhat more sensitive near the end of drying.

The results of this study are consistent with a simple assumed equivalent circuit (fig. 1), but do not preclude other forms. In particular, representing the load by three elements (two resistors and a capacitor) is a recognized oversimplification because of the complex structure of the load, but even this simple approximation provides adequate description of the observed dielectric properties of the electrode-load-kiln assembly.

Most variability in the response of a capacitive admittance kiln monitor seems to be associated with the conductances that shunt the entire load and that shunt the load-ground capacitance. These conductances may be affected by changing kiln conditions to a degree that confounds somewhat the effect of changing MC of the load. Physically, these conductances involve the stickers used to assemble the load. Specially designed stickers could possibly reduce this source of variability, but probably only with considerable cost and complication.

Glossary

Admittance — A property of a circuit that permits current to flow through it when a voltage is applied; numerically equal to the current flow with 1 volt* applied. It is the reciprocal of impedance and the vector sum of conductance and susceptance.

Capacitance — The property of a circuit element that permits it to store electric energy in the form of polarization.

Conductance — The property of a circuit element that permits it to carry or transport electric charge. Numerically equal to the current flow with 1 volt* applied across the conductor.

Equivalent parallel conductance — The conductance in parallel with a pure capacitor that results in the same energy dissipation as a given practical capacitor of the same capacitance.

Impedance — The reciprocal of admittance; the vector sum of resistance and reactance.

Reactance — The property of a capacitor or inductor that impedes current flow through it. Numerically equal to the voltage* required to produce unit current flow.

Resistance — The reciprocal of conductance.

Susceptance — The reciprocal of reactance.

*The voltage here is the effective or RMS alternating current voltage.

U.S. Forest Products Laboratory

Dielectric Properties of Lumber Loads in a Dry Kiln, by William L. James,
Madison, Wis., FPL, 1983.

16 p. (USDA For. Serv. Research Paper FPL 436).

The dielectric properties of wood were studied in a laboratory configuration that simulated typical lumber loads in a dry kiln. The transient effect of kiln conditions on the lumber stickers was found to influence dielectric properties more than had been recognized previously. Other details of the dielectric properties apparently depended on interaction of transverse moisture gradients with other variables in the kiln and in the electric equipment.

Keywords: Dielectric properties, kiln control, kiln drying, sticker design, moisture gradients, moisture measurement.
