

CAPACITIVE ELECTRONIC KILN MONITORS: SOME OBSERVATIONS OF THEIR PRINCIPLES OF OPERATION

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Introduction

General Theory of Operation

Capacitive kiln monitors indicate the instantaneous moisture condition of the kiln load essentially in terms of the audio frequency capacitive admittance of the load as a circuit element. The total circuit, of which the load is one element, consists of a coaxial cable carrying an audiofrequency signal to a flat-plate electrode, the load of lumber in intimate proximity to the electrode, and a stray capacitance ground return through all conducting components of the kiln, including the earth beneath the kiln. The kiln monitor measures and indicates the total admittance of this circuit, and it is assumed that the only variable in the total admittance is that of the load of lumber. The dielectric properties of the lumber vary with moisture content (MC), and consequently the admittance measured by the monitor depends on the MC of the load.

The Dielectric Properties of Wood

The capacitive admittance of the lumber load is a vector quantity composed of the conductance and susceptance (reciprocal of reactance). The susceptance depends on dielectric constant, and the conductance includes the influence of dielectric loss. The general trend is for all of these quantities to decrease as the MC of the wood decreases. Other variables, however, also influence these quantities; notably frequency, temperature, grain orientation, density, and various unknown factors in the chemical and structural details of the wood substance. Elucidating and controlling these extraneous variables is the key to successful monitoring of moisture in kiln loads using this type of instrument.

Details of the dielectric properties of wood have been published elsewhere;¹ these data can be helpful in understanding the behavior of electronic moisture-measuring devices.

Experimental Descriptions

General

The design of the experiment was, first, to generate basic

¹James, W.L. USDA For. Serv. Res. Pap. FPL 245. For. Prod. Lab., Madison, Wis. 1975.

calibration data relating monitor readings to the MC of the kiln load at various combinations of monitor parameters; and second to use the monitors in actual kiln runs, seeking practical insights regarding their performance.

Details of the Instruments

Two commercial kiln monitors were obtained:

- (1) A Kiln Scan, provided by the Irvington-Moore Company of Portland, Oreg.
- (2) A WINKLE, provided by Weyerhaeuser Company; this is an instrument used at Weyerhaeuser installations but not available on the general market.

These two instruments differ somewhat in circuit details, but basically they are similar. Figure 1 is a block diagram of a capacitive admittance monitor. A sine wave oscillator, working at about 10 kilohertz (kHz) drives a small operational amplifier which in turn drives the center conductor of the coaxial cable that is connected to the electrode. The coax center conductor is driven through an impedance element (a resistor or transformer winding), so variation in the admittance of the kiln load appears as a variation in either the current through this impedance element or in the voltage across it. A second amplifier drives the shield of the coax at very nearly the same instantaneous potential as the center conductor, thereby reducing the effective cable capacitance to a negligible level, and making cable length unimportant.

The signal derived from the 10 kHz current flowing capacitively into the kiln load is conditioned by typical amplifiers and demodulators and read quantitatively on a panel meter.

Modifications to the Monitors

The intent of this study was to gain a better understanding of the physical principles involved in measuring moisture in lumber as it dries, using the capacitive admittance as the measured quantity. For this reason the basic operating method of the two monitors was not changed, but rather provision was made for changing the frequency, waveform, and amplitude of the sensing signal. Then, using basic data on the dielectric properties of wood, information about the physical principles of the monitors could be inferred from variation in monitor response as the operating parameters were varied.

To do this, the 10 kHz oscillator was removed and replaced by an Intersil 8038 voltage-controlled oscillator. This device is in a standard 14-pin DIP configuration, and its frequency can be varied over a wide range by varying the voltage at one pin. Further, the device supplies sine, square, or triangle waves simultaneously, all at the same frequency. Switches were added to the front panels of the monitors to select a frequency of either 0.7, 3, 10, or 30 kHz, and to select one of the three waveforms mentioned previously. A third switch was added which selected various feedback resistors associated with the op-amp being driven directly by the oscillator in order to set the amplitude of the signal. Three amplitudes in the ratio of 1:3:10 were provided.

Trimming potentiometers were used to equalize the amplitudes of the three waveforms.

The Kiln Scan used type 741 op-amps extensively; these were too slow to pass good square waves, so the cable and shield drivers and the first signal conditioning amplifier were replaced by 531's, which are about 5 times faster but otherwise similar to 741's. Other relatively minor circuit modifications were made, such as revising the bias source of the WINKLE so it would work with square waves.

In both instruments, one selectable combination of frequency, wave-form, and amplitude essentially duplicated the original specifications of the instrument.

In addition to these electronic modifications, a variety of electrodes was also provided. The original electrode is a strip of bare aluminum 3 inches wide and long enough to reach across the width of the load. Two other electrode shapes were made: (1) a diamond, 1 foot wide at the center and pointed at the ends and (2) an hourglass form, 1 foot wide at the ends and 2 inches wide at the center. The electrodes whose area varied along their length were designed to investigate any interaction between electrode shape and horizontal moisture distribution in the kiln load. Also, each electrode shape was replicated with three surfaces: (1) bare, (2) with an insulating rubber coating a few mils thick, and (3) with 1/4-inch foam rubber cladding (see fig. 2). Electrode insulation was selected to investigate interaction between insulation properties and thickness moisture gradients in the specimen material. Figure 3 shows a typical load of lumber with an electrode in place.

Calibration Runs

With load at uniform MC.--The first calibration run was made using a load of green, 8-foot, red pine 2 by 4's in a metal experimental kiln of pre-fab construction and capable of achieving temperatures up to 250°F. The load consisted of 17 courses with seventeen 2 by 4's in each course, using 3/4-inch stickers. Six sample boards, three on each side of the load, were provided in the usual way for the purpose of providing an independent estimate of the average MC of the load. Electrodes were inserted, one at a time, into the load between the eighth and ninth course (near midheight and equidistant from the ends of the load, as shown in figure 3). All electrodes were 6 feet long, equal to the width of the load.

This load of lumber was dried using a "stop action" schedule; that is, instead of the drying proceeding continuously to completion as the load approached certain preselected levels of average MC the equilibrium moisture content (EMC) of the kiln was maintained at this particular MC for several days in order to approximate moisture equilibrium. Values of EMC attempted were 21, 16, 12, and 8 percent, at 120°F dry bulb. Even at this relatively low temperature, the 21 percent EMC corresponded to a wet bulb depression of only about 2°F, which is hard to control, but it appeared that a reasonably constant condition was obtained at this setting during the calibration run. The other EMC settings were easier to maintain.

At each EMC setting, after the weight of the sample boards had been reasonably stable for 24 hours, a complete set of data at all combinations of monitor parameters and electrode types was obtained. The same electrode was used for both monitors, with a special switch to select which monitor was connected to the electrode. All data using a given electrode were obtained in one time period, requiring about 1 minute for each monitor. Then the electrode was changed and the process repeated for each of the nine electrodes. It was necessary to enter the kiln to change the electrodes, which required the kiln to be shut down during this time. In the 15 to 20 minutes required to obtain all the data, the kiln cooled somewhat, but by repeating the first readings at the end of the data-taking period, it was shown that the effect of this cooling was unimportant.

This procedure provided monitor data at four levels of approximately uniform MC in the kiln load, from which the basic response charts shown in figures 4, 5, and 6 were compiled. Also, figure 7 illustrates that the monitors are essentially unresponsive to MC changes greater than fiber saturation.

With nonuniform MC in load.--Following the calibration process using loads with approximately uniform MC, a series of runs was made using loads constructed with various distributions of wet (green) and dry (about 8 pct MC) material, and also with various configurations of electric ground. The distributions of wet and dry pieces are diagramed in figure 8. Also, electrodes of various shapes (fig. 2) were used to investigate interaction of electrode shape and horizontal moisture distribution. These measurements all were made at room temperature.

Using dummy loads.--Interpretation of empirical monitor data in terms of basic dielectric properties of wood required a knowledge of the intrinsic response of the monitors to specimen capacitance. The basic characteristics of the monitors as capacitance gages therefore were observed by using calibrated variable capacitors in place of the usual electrode-kiln load combination. The calibrating capacitor was connected between the center conductor of the electrode cable and chassis ground of the monitors.

Experiments with different ground configurations.--As mentioned earlier, capacitive kiln monitors rely on the gross capacitance of the kiln and earth to provide the necessary ground return to complete the audiofrequency circuit in which the load of lumber is the circuit element of interest. To gain some insight as to the sensitivity of the method to details of the ground configuration, some experiments were conducted using various relative locations of the electrode and artificial ground planes. These experiments used composite load No. 5 (fig. 8) where the load was all dry except for two full courses of green material, separated by four dry courses, and located symmetrically around midheight of the load. The artificial ground planes were either (1) grounded sheets of aluminum, about 1 by 6 feet in size, inserted in the load where the electrode could easily be located at various distances from it or (2) one of the wet courses of lumber,

grounded by driving a nail into the end of each specimen and connecting all nails to a water pipe using a bare copper wire.

Data at various frequencies and amplitudes were taken with the electrode resting on a wet course and separated from the wet course by either one or two dry courses, and repeated with the wet course either grounded or not grounded. Also, data were taken with the grounded aluminum sheet directly beneath the electrode and with either one or two dry courses between. Finally, these experiments were repeated using the insulated electrodes.

Masonry versus metal kilns.--A load of green lumber was assembled in a dry kiln of all masonry construction and about the same size as the metal kiln used for the other experiment; the only metal in this kiln was in such things as the door, fans, piping, truck rails, and concrete reinforcing rods. A complete spectrum of data was taken in this kiln using both capacitive monitors, and immediately the same load was removed and reassembled in the metal kiln and the spectrum of data repeated for comparison. These data are summarized in table 1.

Subsequently, a composite load of nonuniform moisture was set up in the masonry kiln, and some of the experiments on nonuniform loads and various ground planes described earlier were repeated. The load used here was of southern pine studs, all at about 8 percent MC except two full courses which were green. The green courses were separated by four dry courses at midheight, as described earlier.

Temperature corrections for monitors.--The electrical properties measured by the monitors are affected by temperature as well as MC, so an experiment was conducted to determine the temperature effect. A load of nominally air-dried southern pine 2 by 4's, selected by moisture meter to be 20 to 22 percent MC, was assembled in the metal kiln. Attempts were then made to run the kiln through a range of temperatures, while holding EMC conditions in the kiln at 20 percent for one run and 12 percent for the other. An EMC of 20 percent is nearly impossible as temperatures exceed 120°F, but by heating the kiln solely by steam spray, the highest EMC possible was attained. Drying under these conditions was slow enough that temperature data up to 180°F were obtained at approximately 20 percent MC. The EMC was then set and held at 12 percent, and data were obtained over the temperature range of 80°F to 180°F. A constant temperature was maintained for about 2 hours before the set of data for that temperature was recorded. A thermocouple at the center of a representative specimen established that approximate temperature equilibrium was attained.

Actual Drying Runs

Several loads of lumber were dried in the same (pre-fab metal) kiln used for calibrating the monitors, following usual kiln drying practice. Loads were the same size as used for calibration. The capacitive monitors were used in all runs, using electrode No. 1 located near the center of the load. Various frequencies and amplitudes were used. Output from the two kiln monitors was recorded on a two-pen strip chart recorder, using a

timer-operated switch that connected the electrode alternately to each monitor on a 15-minute cycle.

The loads and schedules used in the various runs were: Douglas-fir studs, conventional schedule; mixed 4/4 elm and maple, high-temperature schedule; 6/4 oak, time-temperature schedule; red pine studs, conventional schedule; and mixed 4/4 elm, maple, and cherry, conventional schedule. The Douglas-fir schedule ran 34 hours and reached a maximum temperature of 200°F; the mixed 4/4 elm and maple high-temperature schedule ran 32 hours and reached 230°F; the 6/4 oak schedule ran 32 days, and reached 180°F after 20 days; the red pine studs dried 70 hours, reaching 200°F at 50 hours; and the mixed 4/4 elm, maple, and cherry ran 190 hours with maximum temperature of 180°F reached after 143 hours.

Results and Discussion

Calibration Using Quasi-equilibrated Load

Monitor parameters.--This calibration run began with the kiln load green and used the as-supplied electrode (No. 1, fig. 2). Initial readings of the WINKLE at its original parameter settings were above scale, but at lower amplitude settings onscale readings were obtained. Initial readings of the Kiln Scan were onscale for the original parameter settings, but were below scale for lower amplitudes. Under these conditions, changing to the No. 3 electrode (see fig. 2), which was covered with 1/4-inch foam rubber, reduced the monitor readings substantially. The effect of changing the electrode was progressively greater as the frequency was reduced.

These comments have no significance beyond describing the overall level of sensitivity of the monitors and how this sensitivity varies with changing monitor parameters. These and other factors will be discussed in more detail later. During the drying time, while the load was still green, monitor readings were generally erratic and quantitatively meaningless, as might be expected due to the fact that electrical properties of wood do not correlate well with MCs greater than fiber saturation (see figure 7).

Effect of signal waveform.--As the average MC of the load approached fiber saturation, the first constant EMC step was established with 120°F dry bulb and 118°F wet bulb temperatures. The monitor readings using sine or triangle wave excitation became less erratic as the MC of the load approached fiber saturation. The readings using square wave excitation remained somewhat irrational; that is, they would vary over wide ranges within time spans of as little as 1 hour, with no apparent correlation with the small, gradual changes in moisture in the load. Readings using sine or triangle wave excitation were nearly equal and, in general, varied smoothly with changes in load moisture near or below fiber saturation. It appeared that with square wave excitation the monitors were excessively sensitive to minor random fluctuations in kiln conditions or other external variables.

The unsatisfactory performance of the monitors when using square wave excitation is probably due to circuit details of the

monitors, not a fundamental characteristic of the dielectric behavior of wood. The possible unique performance that could result from the rich harmonic content of the square wave sensing signal will require a different electronic design in order to be exploited.

Effect of frequency.--The change in reading of both monitors for a given change in load moisture was progressively larger as the excitation frequency (sine and triangle wave forms) was reduced (figs. 4, 5, and 6). At a given MC in the load, the reading of the Kiln Scan decreased as the frequency decreased, while that of the WINKLE increased. The larger rate of change in reading with moisture changes at lower frequencies is consistent with the basic electrical properties of wood, but the variation in reading as the frequency varies at a given constant moisture level is determined partly by the variation of dielectric properties of wood with frequency, and partly by details of the instrument circuits, as indicated in the section on capacitance calibration.

Effect of signal amplitude.--The influence of varying the excitation amplitude was essentially as would be predicted assuming the amplitude was a simple scaling factor. This indicates that within the range of electric fields generated by the monitor electrodes, the dielectric properties of the wood specimens are independent of electric field strength.

Effect of different electrodes.--In general, there was a tendency for the monitor readings to be slightly larger when using the larger area electrodes (Nos. 4 through 9, fig. 2), and when using bare (uninsulated) electrodes. This tendency was significant and consistent, however, only when the specimen material was at relatively high MC, the monitors were operating at a frequency no greater than 3 kHz, and either sine or triangle wave excitation was used. If the specimen moisture was less than 20 percent or the monitor frequencies were 10 kHz or greater, all electrodes gave about the same data (with sine or triangle excitation). As mentioned earlier, data using square wave excitation were often unreasonable and unstable; for example, readings with square wave excitation were often substantially larger when using the electrodes with thick foam insulation than when using bare electrodes. This was most notable with the WINKLE meter and the larger area electrodes, but appeared in other cases as well. The relative influence of electrode insulation is illustrated in figure 9.

When the specimen material is at a relatively high average MC, but the shell moisture is reduced in the natural course of drying, a situation analogous to using an insulated electrode exists; that is, the dryer shell insulates the electrode from the wetter material within the specimens. The readings of the monitors on high-moisture specimens were smaller when using insulated electrodes, so it follows that the insulating effect of the dryer shell results in monitor readings smaller than would be commensurate with the average moisture of specimens with high core MC. This phenomenon is more significant, of course, to later phases of the present study, where the experimental conditions result in larger moisture gradients in the specimen material.

Calibration using loads with nonuniform MC.--Calibration data using loads with nonuniform MC were obtained for two main reasons: (1) to determine the response of the monitors to material at various distances from the electrode, and (2) to determine the interactions of electrode shape with distribution of moisture in the plane of the electrode. This phase of the calibration process also provided some insight regarding the influence of ground configurations on the readings of the monitors.

The configurations of wet and dry material used are diagramed in figure 8.

Configurations 1 and 2 simulate two extremes in horizontal moisture distribution, one with high moisture material concentrated in the middle of the load, and the other with the high moisture material concentrated at the edges. Configuration 1 commonly occurs in typical kiln drying. Data obtained with these two configurations may be summarized as follows:

Using electrode No. 1, data from the two configurations were nearly identical, as expected. Using electrodes 4 and 7, the data for the two configurations were slightly different, but this difference was considerably less than might be expected. With load configuration 1, where the wet material was in the center, electrode 4 should have given the larger readings; but in fact the readings with all three bare electrodes (1, 4, and 7) were nearly equal, with a weak trend for 7 to be larger than 4, and 4 larger than 1. With configuration 2, where the wet material was at the edges, electrode 7 could be expected to give the larger readings. This was actually observed, but again the differences were quite small. It seems, therefore, that the actual surface area of the electrode affects the monitor readings only slightly, at least when the electrodes are uninsulated. This may be because the admittance mechanism from bare electrodes to the specimens is essentially conductance, at least for material at higher moisture levels, and normal specimen and electrode unevenness limits actual contact to very few points regardless of electrode area.

On the other hand, using insulated electrodes resulted in consistent and recognizable differences in the responses of various electrodes to load configurations 1 and 2 (see table 2). These differences were generally as predicted but were more distinct and consistent in data from configuration 2. The fact that using insulated electrodes gives data that show a positive interaction between electrode area and MC substantiates the logical assumption that with insulated electrodes the admittance connecting electrode to specimen is essentially capacitive, where all of the electrode area is equally effective.

In general magnitude, readings on loads 1 and 2 made at 0.7 kHz were equal to readings on equilibrated loads at about 11 percent MC (ignoring temperature effects) and readings made at 30 kHz were equal to those on equilibrated loads at about 15.5 percent MC. This apparent inconsistency in the effect of frequency will be discussed in the next section.

The use of load 3, where the electrode was between two complete wet courses and resting on one of them, gave monitor readings substantially larger than what would correspond to the average MC of the load; the readings were biased by the material nearest the electrode. The readings were smaller, however, than

were obtained when the entire load was wet. The geometric relationship of the monitor probe to the kiln load appears to be analogous to that between the pin electrode of a resistance-type moisture meter and a specimen of solid wood. In either configuration, material properties in the immediate neighborhood of the electrode determine the overall circuit properties, so the instrument readings reflect moisture levels predominantly in material nearest the electrode.

For a numerical example illustrating the predominant influence of material near the electrode, consider readings of the WINKLE on load 3 (fig. 8), which had an average MC only slightly greater than 8 percent. After normalizing to constant temperature, the WINKLE reading on load 3 at 0.7 kHz was equal to that of an equilibrated load at about 14 percent MC. At 30 kHz, the reading on load 3 was equal to that for an equilibrated load at near 20 percent MC.

By contrast data on loads 4 and 5, which had the same average MC as load 3 but where the electrode rested on dry courses, gave readings only slightly greater than those obtained on equilibrated loads at about 8 percent MC, at any frequency.

Comparing data from loads 1, 2, and 3 gives some insights as to the integration of effects of varying MC along the length of the electrode. In loads 1 and 2, one-third of the material contacted by the electrode was green, and two-thirds was dry (8 pct MC), and gave readings corresponding to full loads at about 11 to 15 percent MC. In load 3, all the material in contact with the electrode was green, and gave readings corresponding to full loads at about 14 to 20 percent MC. Load 3 presented 3 times the area of green specimen material as loads 1 and 2, which affected the monitor reading roughly as much as would an increase of 3 to 5 percent in average MC.

The different influence of frequency on equilibrated and nonuniform loads will be discussed in the next section. The effect of moisture distribution on monitor data is summarized in table 2.

Capacitance calibration and its implication.--In order to interpret the response of the capacitive monitors in terms of the basic dielectric properties of wood, it was desirable to calibrate the monitors as capacitance gages, using ordinary variable capacitors as dummy kiln loads (see calibration using dummy loads, in "procedures"). This procedure revealed that the readings of the WINKLE were essentially a linear function of capacitance and at most a weak function of frequency; the readings of the Kiln Scan were a linear function of capacitance except that larger readings tended to be truncated at somewhat less than full scale, and the readings at a given capacitance increased with increasing frequency.

The direct influence of frequency on the monitors results from details of the circuitry, and has no significance for the use of the devices as kiln monitors. The truncation of larger readings of the Kiln Scan may be associated with the circuit modifications that were made in an attempt to make the device usable with square wave excitation.

Consideration of the monitor data obtained on various kiln loads, in light of the capacitive response of the monitors, indicated that the monitor response to actual lumber specimens reflected the basic variation of dielectric properties with MC and frequency shown in FPL 245 (see fig. 5). Further, with loads of lumber at uniform MC, interaction of frequency, temperature, and MC on monitor response also was consistent with the basic dielectric properties of wood.

When the specimen material was not at uniform MC, the influence of frequency on monitor data was often substantially less than when data of the same general magnitude were obtained on loads that were at essentially uniform MC. Actually, this was observed only when the electrode rested directly on a course or partial course of wet material in an otherwise relatively dry load.

For example, using high-amplitude sine wave excitation on an equilibrated load at about 12.5 percent MC, readings of the WINKLE ranged from 64 at 0.7 kHz to 29 at 30 kHz. With the same monitor settings, using built-up load No. 1, the readings ranged from 51 at 0.7 kHz to 37 at 30 kHz. From calibration data obtained on equilibrated loads the reading of 51 at 0.7 kHz corresponds to an average MC of 11 percent and the 37 at 30 kHz to an average MC of 16 percent. The corresponding data from built-up load No. 3 were 62 at 0.7 kHz and 47 at 30 kHz, which with equilibrated loads correspond to 12 percent and 17.5 percent average MC, respectively.

Built-up loads 1, 2, and 3 all resulted in the electrode testing directly on at least some wet (green) material. Built-up loads 4 and 5 each contained two complete courses of wet material, but the electrode was separated from the wet material by one (load 4) or two (load 5) courses of dry material. Data from loads 4 and 5 at all frequencies were nearly identical with corresponding data from loads uniformly at 8 percent MC, so again, the somewhat anomalous effect of frequency actually was observed with built-up loads only when the electrode was in direct contact with wet material.

The available data have not been sufficient to establish with certainty why the variation with frequency of dielectric behavior of kiln loads with uniform MC differs from that of loads with nonuniform MC. Clearly, it results from the relatively complex interaction of MC, frequency, and electric field geometry on the dielectric behavior of the loads. The reduced influence of frequency on data from loads with nonuniform moisture suggests that the impedance encountered by the electrode current is predominantly associated with the dryer portions of the load, since the influence of frequency is less at lower MC. The magnitude of the monitor readings under these conditions, however, is too large to be associated only with the higher impedance (lower admittance) of dry wood. A possible explanation of this is that the wet wood in contact with the electrode has an impedance so much less than the dry wood that it in effect becomes an extension of the electrode, with the dry wood acting as the specimen material. The larger readings then would be the consequence of the much larger effective electrode area.

The residual frequency effect could result from the small frequency effect of the dry wood plus the fact that the impedance of the wet wood, a relatively strong function of frequency, is not totally negligible. This basic principle could be effective in normally occurring kiln loads in practice, and have a significant effect on the practical calibration of capacitive kiln monitors.

Effects of ground configuration.--Grounded conducting planes in the load had relatively small influence on the monitor readings unless the electrode was touching or very close to the grounded plane. Introducing a grounded plane into the next course of lumber below the electrode increased the monitor readings an amount approximately equivalent to 2 or 3 percent MC. This result was essentially the same whether the grounded plane was a sheet of metal or a course of green lumber grounded as described in experimental procedures. If the grounded plane was two or more courses away from the electrode, the influence of the ground was small and erratic and practically negligible.

If the electrode was in direct contact with the ground, monitor readings were off-scale for most settings when using bare electrodes, as expected. Electrodes with thin insulation gave readings near top scale or off-scale, depending on monitor parameters, on grounded green material, and with thick insulation the corresponding readings were roughly midscale to top scale.

Summarizing or generalizing these results quantitatively would be difficult because of the many variables involved, but quantitatively these results suggest that details of grounded conductors in the kiln have relatively small influence on the monitor readings. It is clear, however, that the electrodes should be placed in the load well separated from grounded metal. On green loads, resting on a metal, grounded truck, the monitors would probably give off-scale readings until drying had progressed to where a substantial shell thickness was below fiber saturation, provided there was a path of green lumber from the electrode to the truck. Ordinarily, however, the stickers are dry, so the course of lumber contacting the electrode is isolated from ground by the stickers. Present data indicate that under these conditions readings near top scale but not off-scale would be attained on a load of green lumber at room temperature but would quickly go off-scale as the kiln heats up (the effect of temperature will be discussed later).

These comments regarding the magnitude of monitor readings assume a basic monitor sensitivity to give reasonable indications of the endpoint of the kiln schedule.

Effect of kiln construction.--Data taken on the same load of lumber in an all-metal kiln, and in a masonry kiln of about the same size showed significant, but not remarkable, differences (see table 1). The differences in readings in the two types of kiln were equivalent to changes in MC of roughly 2 to 6 percent, depending on monitor parameters (frequency and amplitude). The influence of kiln construction is not strictly equivalent to that of MC, of course, because of different interactions with frequency and temperature. The smaller relative effect of kiln construction

on readings of the kiln scan may be related to the truncation of larger readings of this device. The effect of kiln size is unknown at this time, but would not be expected to be a major effect. The influence of kiln structure emphasizes the need for calibrating kiln monitors for each individual kiln, but the magnitude of the structure effect is clearly not so great as to be a major problem in the use of monitors.

Data on the influence of moisture distribution, electrode insulation, and ground configuration were also collected on a load of lumber in the masonry kiln to define possible interaction of these variables with kiln effects. No such interaction was observed; the influences of moisture distribution, electrode insulation, ground configuration, and kiln construction appeared to be essentially independent and additive.

Effect of temperature.--The dielectric constant of wood increases with increasing temperature, and under many combinations of frequency and MC, the loss tangent does likewise. Therefore the capacitive admittance of wood usually increases as its temperature increases, and it follows that usually the readings of the kiln monitors increase as the load heats up.

This is seen immediately when the monitors are in use, because when the kiln is started up, the monitor readings begin to increase rapidly as the kiln temperature increases. Subsequently, throughout the kiln run, temperature changes will influence the monitor readings, so detailed analysis of monitor data requires quantitative data on the temperature effect.

Figures 10, 11, and 12 show variation in monitor readings with temperature, obtained as described in "Procedures." For clarity, only data for the WINKLE are shown, but the relative influence of temperature on readings on the Kiln Scan were the same. In fact, because the temperature effect results from the effect of temperature on the electric properties of the wood, not on the instruments themselves, these temperature corrections would be valid for any instrument that uses the capacitive admittance principle. Further, these data probably would be applicable with practical accuracy to any commercial North American species because of the relatively minor variation of the temperature effect on electric properties of typical North American species.²

The temperature effect shown in figures 10, 11, and 12 is consistent with basic data presented in FPL 245, but quantitative comparison of the monitor data with basic electric properties is meaningless without absolute calibration data for the monitors as impedance meters. Obtaining these calibration data was considered beyond the scope of the present study. For qualitative comparison, however, consider the data presented in table 3; these data indicate, by the ratio of the values at the higher temperature to those at the lower temperature, the influence of temperature on monitor readings and on basic properties. Again, there is no reason for these ratios to be numerically equal at a given set of conditions because of the arbitrary gain and offset

²James, William L. "Effect of temperature on readings of electric moisture meters." 1968. For. Prod. J. 18(10):23-31.

characteristics of the monitors, but the trends with changing MC and frequency are seen to be the same.

Figures 11 and 12 also indicate that there is an interaction between temperature and MC; the temperature effect is greater at higher moisture levels. This interaction, in conjunction with the influence of moisture gradients on the monitor response, produces an interaction between temperature and moisture gradients. When the lumber has a substantial drying gradient, the monitor readings are determined predominantly by the dryer shell material rather than the overall average MC, so the appropriate temperature corrections are associated with the MC of the shell rather than the average. The net result is that if temperature corrections are based on average MC, they will usually be too large, especially if the monitor has been empirically calibrated to indicate average MC. From a practical standpoint, the magnitude of this effect would not be large enough to be a major problem, and again empirical calibrations and temperature corrections would be compiled readily by the kiln operator once the potential problem was recognized.

Results of regular kiln runs.--The regular kiln runs here were described briefly in "Procedures." In these runs monitor data were, with some exceptions, consistent with expectations based on monitor performance observed in the calibration and basic evaluation experiments. The results of these runs are summarized in figures 12, 13, and 15, and in the following discussion.

Figure 13 shows the monitor readings and the corresponding average MC of the kiln load, as deduced from the sample boards, plotted against elapsed time in the kiln for the load of 6/4 red oak. This plot presents some interesting and some puzzling features.

At the beginning of the run, the monitor readings increased sharply as the load of lumber warmed up, but then quickly dropped off again in the first few hours of the run. This initial increase is easily attributed to the increased admittance of the lumber in response to increasing temperature. The reason for the rapid decrease early in the run is not as clear, as there was no major decrease in load MC during this period, and because for several days after this early rapid decrease in readings, when some drying did occur, the monitor readings showed only insignificant changes. Present data are not sufficient to explain this phenomenon with certainty, but it seems likely that it is related to the surface properties of the specimen material in contact with the electrode. It is clear that surface drying begins as soon as the surface is exposed, and in the kiln the surface rapidly comes to equilibrium with the kiln atmosphere. Under the electrode, drying would be retarded somewhat, but not prevented. This surface drying would increase the contact resistance between the electrode and the specimen, and result in smaller monitor readings because the conductance (inverse of resistance) is a part of the total admittance. In addition the generally observed degradation with time of electric contact between wood and metals would be

likely under these conditions.³ These factors could account for the rapid decrease in monitor readings shortly after the kiln load reached initial temperature equilibrium, with the important understanding that it was only the conductance component of the admittance that was likely to be decreasing significantly during this time. The following time period, where the monitor readings were roughly constant, could then be explained by assuming that the conductance had become negligible and the admittance was predominantly capacitive. At first, the total capacitive admittance, which includes the stray capacitance ground return, would probably change only slightly as the thin dry surface layer gradually increased in thickness, but as drying progresses the dry layer would eventually be thick enough to begin to decrease the admittance to a significant degree. This would correspond to the point on figure 13 at about 12 days elapsed time and average load MC near 55 percent where the monitor readings began to decrease substantially. This hypothetical explanation of the monitor response cannot be confirmed by the present data, but it is consistent with the data and general principles.

It is interesting to note that during the drying period where the monitor made no significant response, the readings nevertheless varied somewhat in a rather haphazard way, but both monitors showed about the same response. It appears that some unknown variable was influencing the monitors equally, but apparently not a recognizable factor in the conditions of the kiln or the load of lumber.

Another puzzling feature of this kiln run occurred about 19 days into the run. Both monitors had been running at medium amplitude; it appeared that the readings would soon be below scale, so the monitors were both switched to high amplitude. This caused the offset in the data on the 19th day. But, coincidentally about halfway through the 18th day the monitor readings began to increase, and this trend continued for about 3 days. The onset of this increase in monitor readings was not correlated with any change in kiln conditions or observable change in moisture condition of the load. About 36 hours after this increasing trend began, the kiln temperature (dry bulb) was increased 25°F according to the schedule, and this temperature change was detectable as a small glitch in the monitor response. The effect was so small, however, that it is not possible to explain the 3-day period of increasing readings by any possible increasing temperature of the specimens. At this time, no reasonable explanation for this period of increasing readings can be found.

Figure 14 shows similar data obtained on a load of red pine 2 by 4's. The data plotted here also demonstrate the initial spike, followed by a period of roughly constant readings before the period of falling readings corresponding to the final stages of drying. Also plotted in figure 14 are data from the WINKLE at

³This phenomenon is generally observed as a drift with time of readings of resistance type moisture meters when electrodes are driven into the specimen and left undisturbed. For more details, see James, W. L. "The influence of electrode design on dielectric measurements on wood"--in process.

all four frequencies, which show that the overall sensitivity of the method is progressively greater as the frequency is reduced, as predictable from basic dielectric properties of wood. As with the data plotted in figure 13, the monitors began responding measurably to the wood moisture when the average MC of the specimen material was between 50 and 60 percent.

The increase in monitor readings at the end of the drying run resulted from the equalization period, where the wet bulb temperature was increased greatly. This increased the surface MC sharply without greatly increasing the average MC; the monitors clearly respond predominantly to the surface conditions.

The data plotted in figure 15 were obtained on the load of mixed 4/4 hardwoods, mostly sugar maple. The most obvious remarkable feature of this set of data is the cyclic fluctuation of the monitor readings early in the schedule. These fluctuations correlate identically with the reversal of the fans in the kiln (every 6 hr), and suggest that there was a problem in the kiln such that essentially no drying occurred when the fans were running one of the two directions. This suggestion actually was supported independently by the data from another monitoring device also operating during this kiln run. After the run was completed a checkout of the kiln mechanism and controls failed to detect any problem, but the strong suggestion persists that an unknown malfunction of the kiln occurred. These data demonstrate the relative sensitivity of these devices to fairly rapid changes in kiln conditions.

These fluctuations were much more pronounced in the data from the Kiln Scan operating at 3 kHz than from the WINKLE operating at 10 kHz. Again, this reflects the basic interaction between frequency and moisture in their influence on dielectric properties of wood, but also includes the effect of different monitor response due to different circuit details.

Distinct response of the monitors to the decreasing average MC of this material began at average moisture levels near 40 percent, as compared to 50 to 60 percent with data in figures 13 and 14. This can be explained by the fact that this material was thinner, so that when the surface layers became dry enough to begin to decrease the monitor response the core moisture also was less than it would have been with thicker specimens.

Data from the other kiln runs confirm the data plotted in figures 13, 14, and 15, but add no significant information, so are not plotted here.

It should be noted that the data plotted in figures 12, 13, and 14 are not adjusted for temperature. The general forms of the plots would be altered slightly if the data were all normalized to a common temperature.

Summary

General

Capacitive kiln monitors, which establish a load of lumber drying in a kiln as an element of an AC electric circuit, respond to changes in MC of the load when the average MC of the load is near or less than fiber saturation. Monitor readings on green

lumber are not quantitatively reliable. Simple sheet metal electrodes, placed between two stickered courses of lumber, are adequate. No significant advantage is apparent from using insulated electrodes with present monitors.

The readings of these monitors are affected by factors other than MC. Some factors are: (1) temperature, (2) moisture gradients or distribution, (3) design of the electrode, (4) kiln structure, (5) grounded conductors in or near the load, and (6) operating parameters of the monitors, such as frequency and wave form of the sensing signal. Each of these will be summarized briefly.

Temperature

Temperature of the lumber had the greatest effect of any parameter except MC on the readings of the monitors studied here, and resulted in larger monitor readings as the temperature increased. The effect of temperature was somewhat greater at the higher moisture levels but did not appear to be influenced by species differences, even though species with major differences in density and structure were studied (red pine, Douglas-fir, sugar maple, and red oak). Temperature effects were generally repeatable and of reasonable magnitude, so correction for temperature in practice could be accomplished by the kiln operator.

Moisture Gradients and Distribution

Monitor response was influenced by the distribution of moisture levels of individual specimens in the load and also by distribution of moisture within the specimens that were in direct contact with the electrode.

The effect of moisture distribution within the load was essentially that material in intimate contact with the electrode determined the monitor response. Material separated from the electrode by as little as one course of lumber had a relatively small influence on the monitor reading. In this regard the electrode in the load of lumber is analogous to the pin electrode of a resistance moisture meter inserted into solid wood. Material in the immediate neighborhood of the electrode essentially controls the current flow in both configurations.

A related phenomenon was observed when the specimen material in contact with the electrode had a drying gradient; the dry surface layer of wood presented a high impedance to the electrode current and effectively controlled the current flow when this dry layer reached sufficient thickness to offer significant capacitive reactance.

Electrode Design

The shape of the electrodes had little effect on the monitor readings. There was a weak trend for monitor readings to increase as electrode area increased, but this was not large enough to use electrodes of nonuniform width to infer horizontal moisture gradients in the load of lumber.

Insulated electrodes gave slightly smaller readings than bare metal electrodes, but the difference was significant only when the load was at high moisture levels and monitors were operating at low frequencies. The effect of insulation was less as the load dried and as monitor operating frequency increased.

Kiln Structure

Calibration of impedance-type kiln monitors is affected by the size, shape, and predominant materials of the kiln construction. The effect is not large, however, for example, the difference between monitor readings in a masonry kiln and in an all-metal kiln was equivalent to about 2 to 6 percent difference in MC. Details of the influence of the size and shape of the kiln are unknown, but are not likely to be highly significant.

Grounded conductors in the kiln.--The influence of grounded conductors in the kiln is a special case of the influence of kiln construction but consider such things as the car rails, metal baffles, and kiln doors. In general the influence of such grounded conductors was found to be small unless the electrode actually touched or was very close to the grounded conductor. Placement of the electrode near grounded metal should be avoided.

Monitor Parameters

Monitor parameters that could be varied were frequency, waveform, and amplitude of the sensing signal.

The overall sensitivity of the method increased as the frequency was decreased, but the relative sensitivity to moisture was not substantially improved because sensitivity to other factors such as temperature also increased.

Response of the modified monitors when using a sensing signal of sine or triangle waveform was essentially the same, but response using a square wave signal was quite different and generally useless. The basic design of these monitors was not intended for use with square wave excitation, and the modifications were not sufficiently extensive to assure reliable operation using square waves. Square wave operation of capacitance monitors in general would not be considered impossible.

Amplitude of the sensing signal influenced the monitor response as a simple scaling factor, indicating that the dielectric properties of the lumber were essentially constant over the range of electric field strengths used.

Conclusions

Capacitance-type kiln monitors, as presently designed and commercially available, can provide useful information to the kiln operator as long as extraneous variables such as temperature and moisture distribution that affect the monitor readings are recognized and considered.

The present study provided some insight of the basic dielectric properties of a mass of lumber in a dry kiln, but some potentially important data could not be obtained because the

monitors could not indicate the relative magnitudes of the resistive and reactive components of the impedance. A more fundamental study, using laboratory instruments, could be performed in order to get these data. From these data monitors of improved accuracy possibly could be designed by exploiting the separate effects of capacitance and conductance.

Recommendations

The results of this study do not indicate any obvious improvement to the basic design of kiln monitors as they now exist on the market. Consideration of the effects of temperature and moisture distribution, however, could probably improve the reliability of interpretation of the monitor data.

It is recommended that future research be carried out to study the capacitive admittance of kiln loads using instruments and techniques that would permit measurements of the conductance and susceptance components of the admittance. These data would provide a broader base for design of a capacitive monitoring device; an instrument that could respond specifically to the conductance or susceptance of the load, in a known manner, and would have a dimension of sensitivity not present in available instruments. For example, as drying progresses from the green, the present data suggest that the admittance changes from predominantly conductance to predominantly capacitive. Within the capacitive regime, a further orderly progression of capacitance and conductance could be expected. It seems reasonable that closer correlation could exist between moisture conditions (MC and distribution) and independent determinations of conductance and capacitance than are observable with only their vector sum (admittance). Further, independent sensitivity to conductance could provide empirical but useful monitor response to drying progress while the average MC is yet well in excess of fiber saturation, because of the strong influence of surface drying on conductance when it is measured using surface electrodes. Whether this design philosophy would actually result in a superior monitor is not certain, but the recommended research would help make it possible.

Table 1.--A comparison of monitor readings in small
 experimental metal and masonry kilns^{1/}

Monitor settings	Masonry kiln		Metal kiln	
	WINKLE	Kiln scan	WINKLE	Kiln scan
Med, sine, 0.7 kHz	35	--	52	--
Med, sine, 3 kHz	33	0	48	4
Med, sine, 10 kHz	30	29	41	30
Med, sine, 30 kHz	27	40	37	40
Hi, sine, 3 kHz	78	13	92	16
Hi, sine, 10 kHz	68	38	76	39
Hi, sine, 30 kHz	58	27	61	27

^{1/} The relative influence of the size of the kiln has not been determined, but basic principles suggest it would not be a major effect.

Table 2.--Influence of moisture distribution on readings of kiln monitors^{1/}

Electrode	Built-up loads ^{2/}															
	1				2				3				5			
	Frequency (kHz)															
	0.7	3	10	30	0.7	3	10	30	0.7	3	10	30	0.7	3	10	30
1	51	43	39	37	51	44	39	38	62	56	51	47	30	25	23	24
2	46	41	38	37	<u>3/</u> 46	<u>3/</u> 41	<u>3/</u> 38	<u>3/</u> 38	--	--	--	--	--	--	--	--
3	44	37	32	32	42	37	33	32	60	50	44	41	--	--	--	--
4	51	45	41	39	51	46	42	39	62	57	52	49	33	28	26	26
<u>3/</u> 5	49	43	39	37	41	38	35	34	--	--	--	--	--	--	--	--
6	44	39	36	35	39	34	32	32	55	49	45	43	--	--	--	--
7	52	46	42	40	55	50	46	43	62	57	54	50	34	30	28	28
<u>3/</u> 8	48	39	37	36	49	44	42	40	--	--	--	--	--	--	--	--
9	42	36	34	34	37	42	40	38	55	50	47	45	--	--	--	--

^{1/} Readings taken using hi amplitude, sine wave excitation; only WINKLE data shown, as trends were same for both monitors.

^{2/} Data from load 4 were slightly larger than from load 5; not shown to keep table smaller.

^{3/} These data interpolated from data on uniform loads; direct measurements were not made.

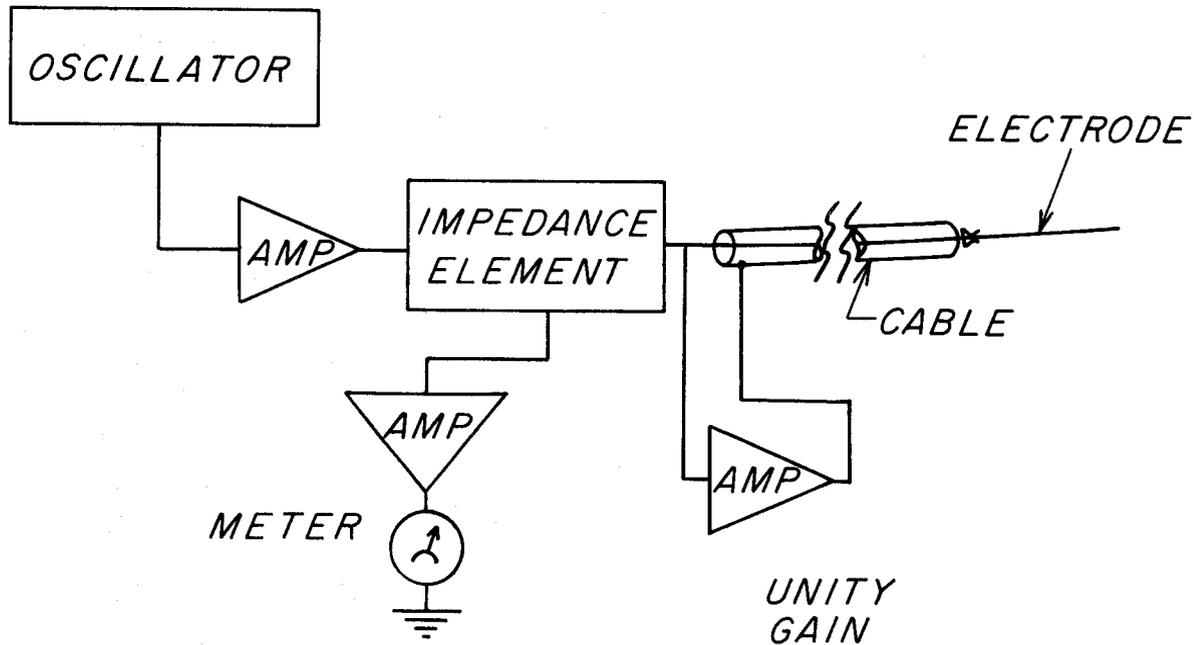
Table 3.--Ratios of monitor readings^{1/} at 180° F to those at 80° F, compared to corresponding ratios for basic admittance^{2/} data

Frequency (kHz)	Moisture content					
	8 percent		12 percent		20 percent	
	Monitor	Basic	Monitor	Basic	Monitor	Basic
0.7	3.0	2.5	5.2	4.4	<u>3/</u> 4.8	<u>3/</u> 5.2
10.0	2.5	1.2	3.4	1.4	3.5	3.0

^{1/} Based on WINKLE data.

^{2/} Admittance represented by $\sqrt{DK^2 + \tan^2\delta}$, where DK is dielectric constant and $\tan\delta$ is loss tangent.

^{3/} Temperature ratio 150° F to 80° F.



M 148 861

Figure 1.--Block diagram of a typical capacitive admittance kiln monitor.

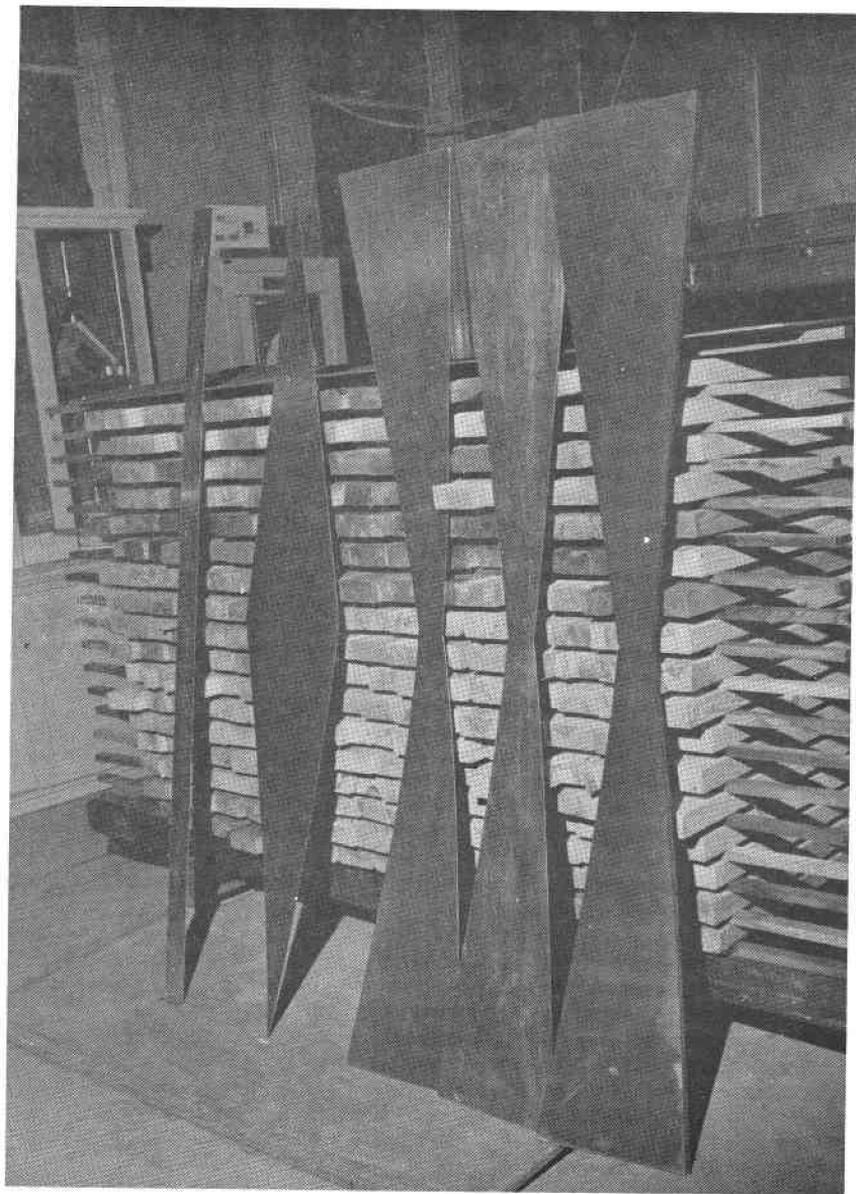


Figure 2.--The three electrode shapes used in the present study. Shown, from left to right, are electrodes 1, 4, 7, 8, and 9. Electrode 2 and 3 (not shown) are same shape as 1, but with thin and thick insulation, respectively. Likewise insulated electrodes 5 and 6 (not shown) are same shape as 4.

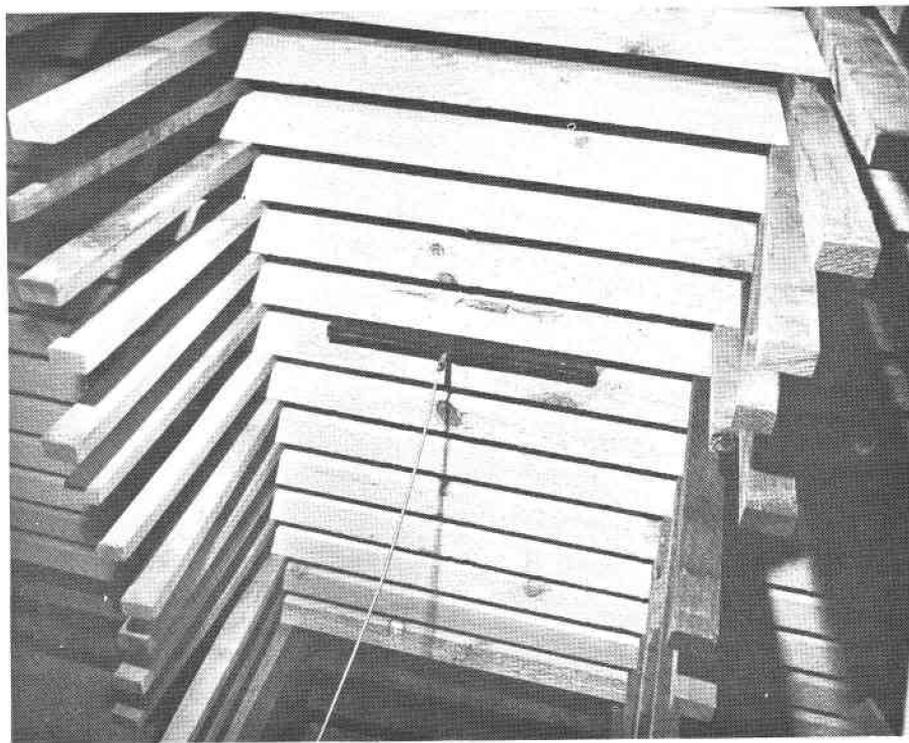
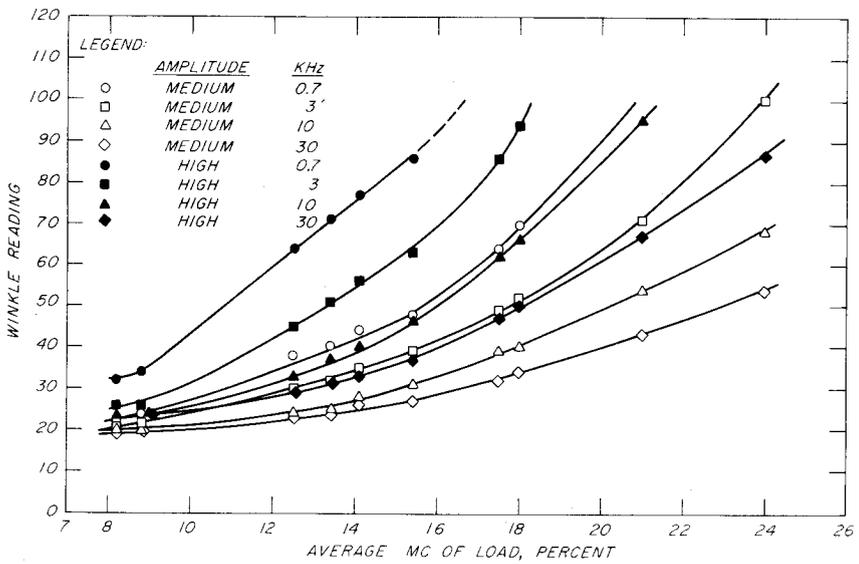
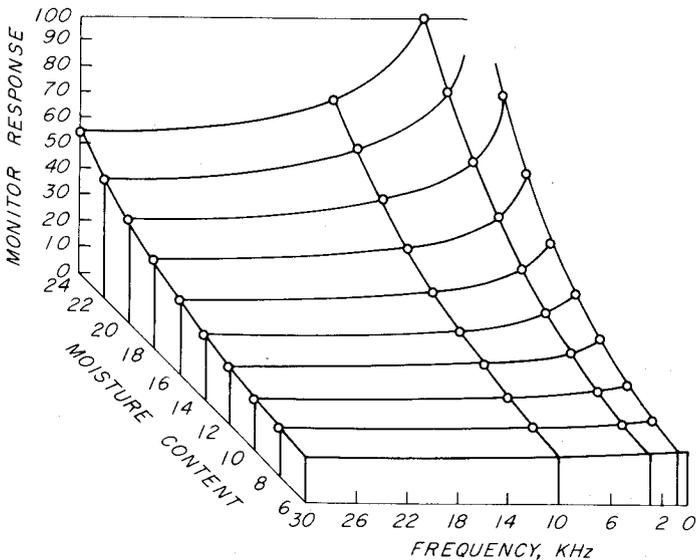


Figure 3.--Showing a typical installation of the electrode in the load of lumber. Electrode No. 9.



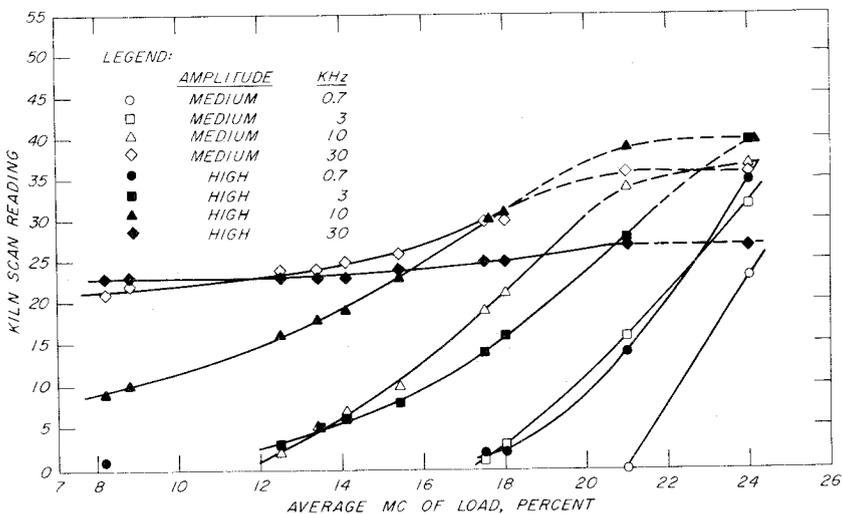
M 148 859

Figure 4.--Basic response of the WINKLE monitor, for a load of red pine 2 by 4's at various quasi equilibrated moisture levels. Present data suggest that the response curves for other species and sizes would be similar with moderate differences in scale. These data were obtained using sine wave excitation at the amplitudes and frequencies shown.



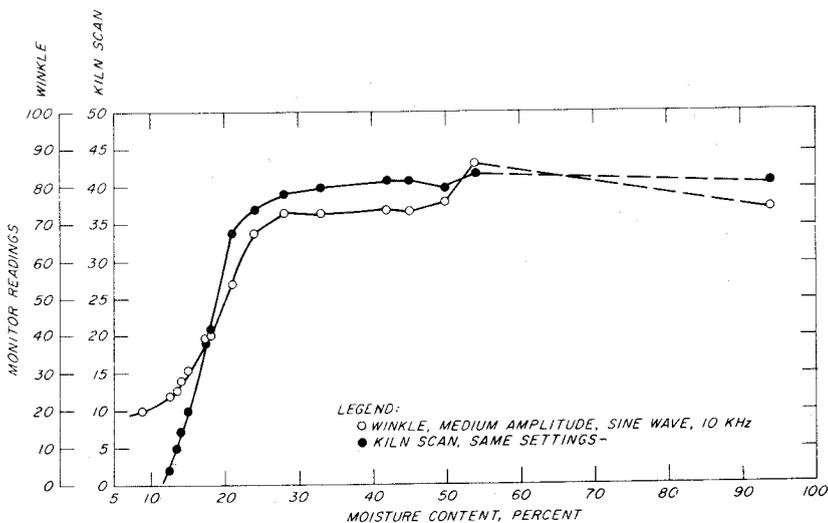
M 148 854

Figure 5.--The medium amplitude data of figure 4 replotted in three dimensions to illustrate more clearly the interaction of MC and frequency on monitor response.



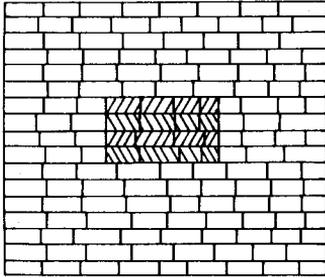
M 148 855

Figure 6.--Same as figure 4, except data are for the Kiln Scan. The larger influence of frequency is due to details of the circuit. The truncation of the upper scale readings (indicated by dashed lines) appears to result from circuit modifications that were made for the present study to improve the square-wave response of the monitor. These data were obtained using sine wave excitation at the amplitudes and frequencies shown.

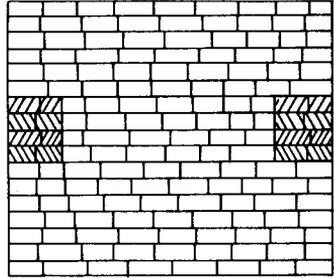


M 148 863

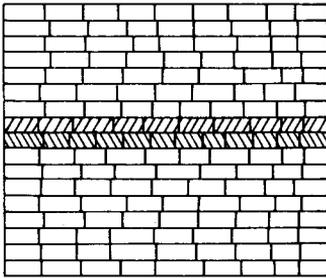
Figure 7.--Illustrating the general lack of meaningful response of a capacitance monitor to moisture levels greater than fiber saturation.



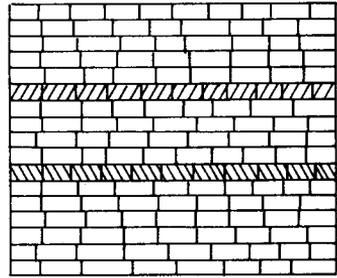
1



2



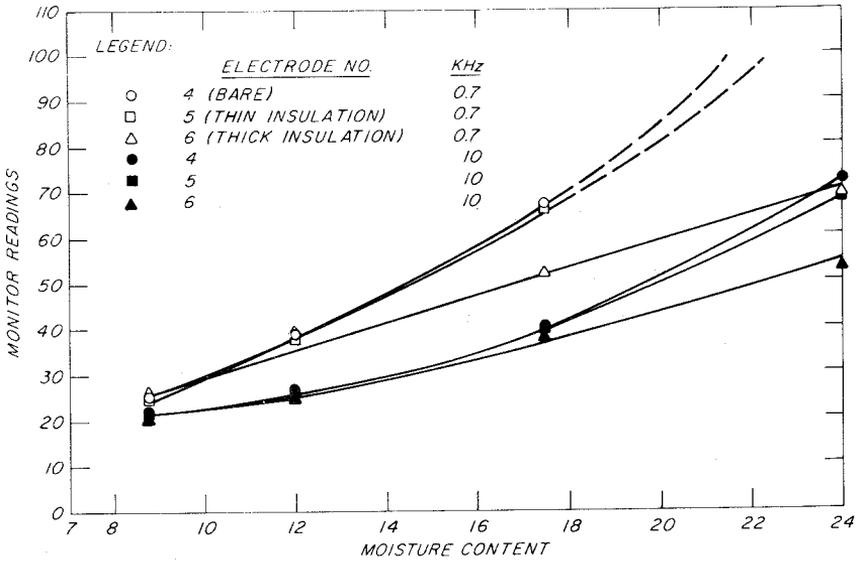
3



5

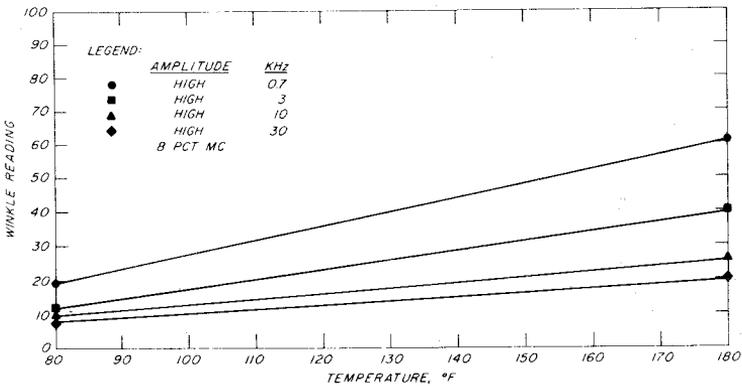
M 148 856

Figure 8.--Diagrams of the loads with artificial moisture distributions. The shaded areas represent end views of green specimens, with the balance of the load at near 8 percent MC. Load 4 is not shown; it was similar to load 5 except there were only 2 dry courses between the green courses instead of the 4 dry courses as in load 5.



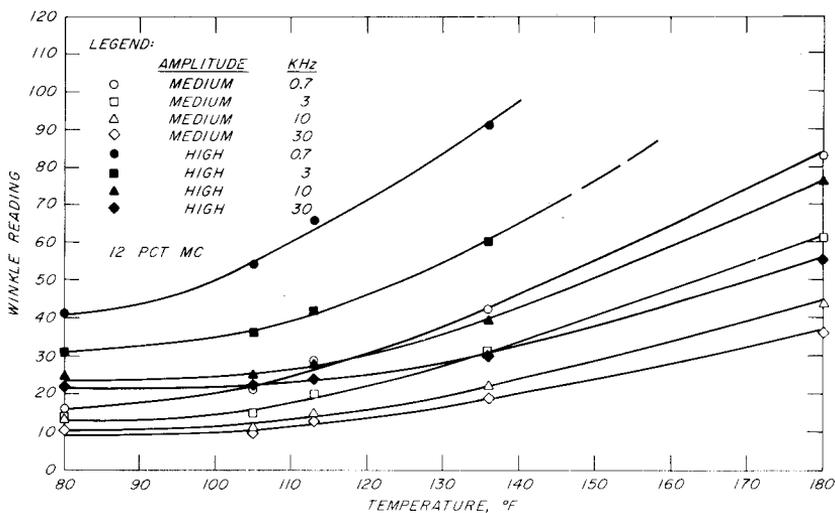
M 148 862

Figure 9.--Illustrating the influence of electrode insulation on monitor response. Insulation had very small influence at 30 kHz, so these data are not shown. The data shown were obtained using the WINKLE, sine wave excitation, and high amplitude at the frequencies shown.



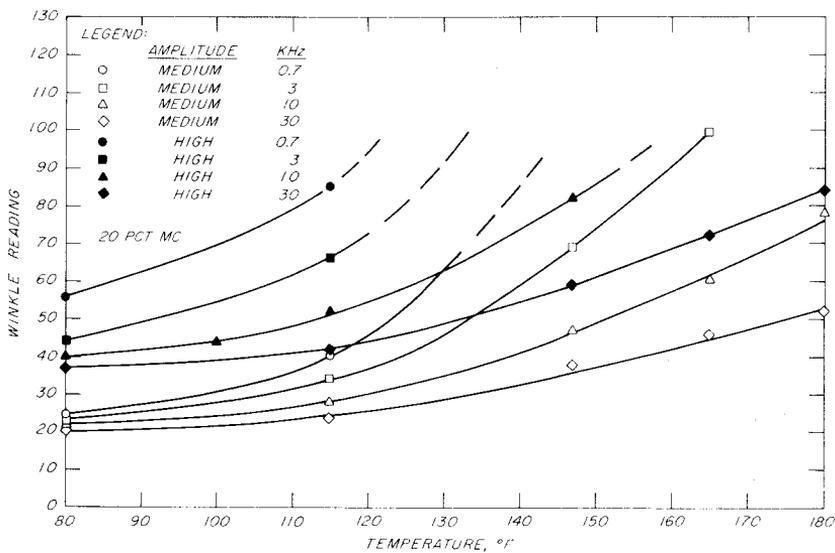
M 149 154

Figure 10.--Typical effect of temperature on monitor data when the load is about 8 percent MC. These data were obtained using the WINKLE, sine wave excitation, and high amplitude at the frequencies shown.



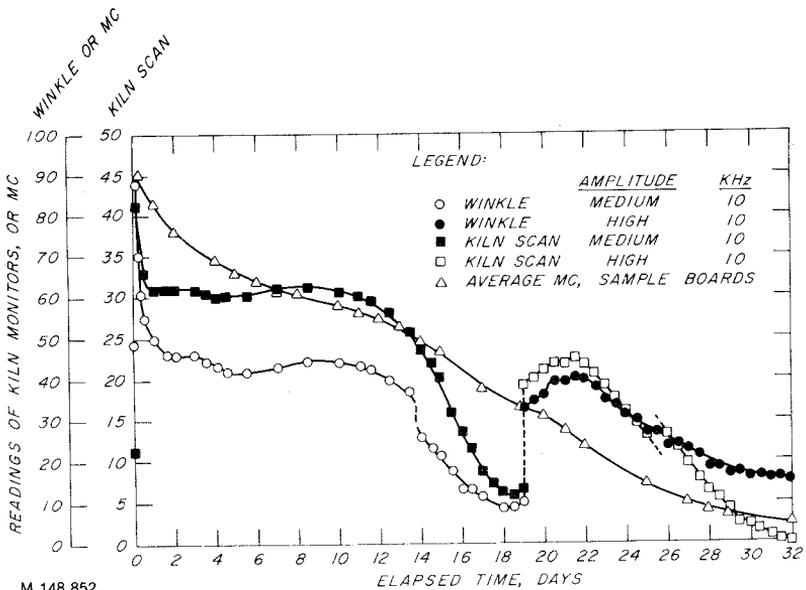
M 148 858

Figure 11.--As figure 7 except for material near 12 percent MC. These data were obtained using the WINKLE, sine wave excitation, at the amplitudes and frequencies shown.

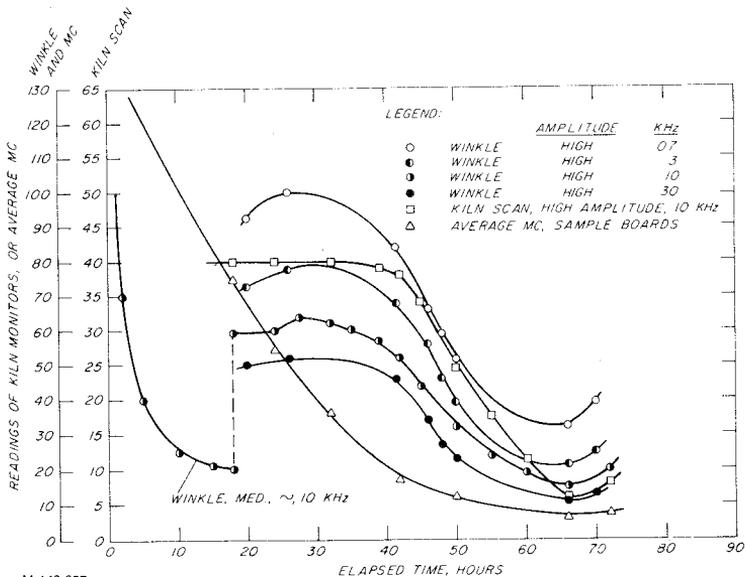


M 148 853

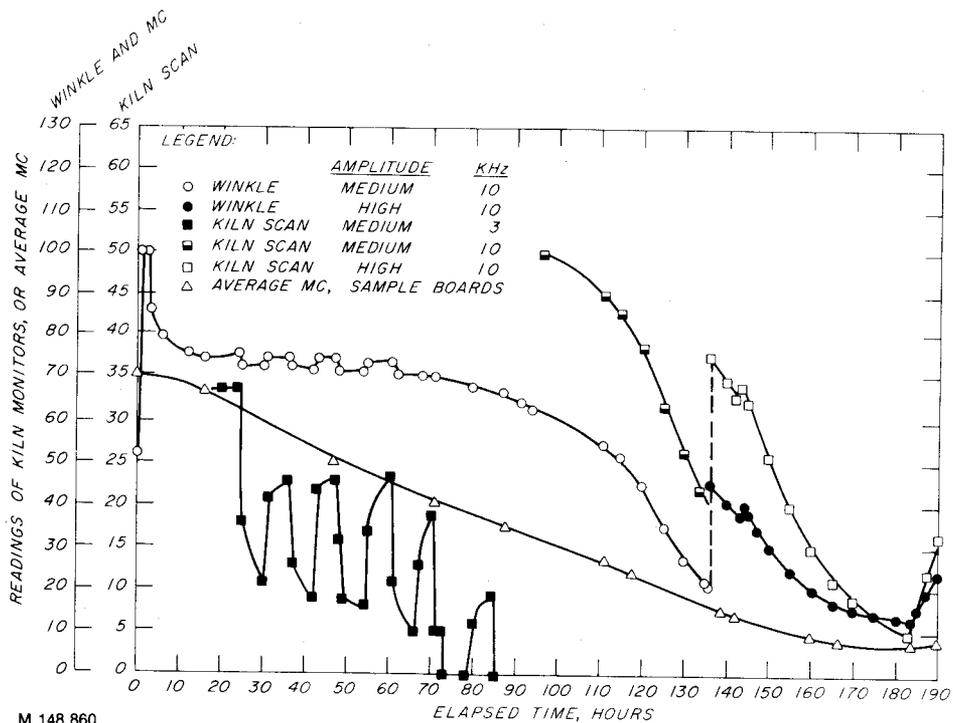
Figure 12.--As figure 7 except data are for material near 20 percent MC. These data were obtained using the WINKLE, and sine wave excitation at the amplitudes and frequencies shown.



M 148 852
 Figure 13.--Response of kiln monitors to a load of 6/4 red oak drying under an experimental schedule. The offset in the WINKLE data near the end of the 13th day is not explained; the offset in Kiln Scan data on the 25th day is due to switching channels because of a failure in the electronics of the channel being used. Small glitches in the data on days 20 and 21 are due to step increases in kiln temperature. These data were obtained using sine wave excitation with the monitors, amplitudes and frequencies shown.



M 148 857
 Figure 14.--Response of monitors to a load of red pine 2 by 4's drying under a conventional schedule. The four curves of WINKLE data demonstrate the effect of frequency on the monitor response. The increased readings after 24 hours resulted from an increase in kiln temperature. The increased readings at the end of the run are response to the equalization treatment which increase surface MC. These data were obtained using sine wave excitation with the monitors, amplitudes and frequencies shown.



M 148 860

Figure 15.--Response of the monitors to a load of mixed 4/4 hardwoods drying under a conventional schedule. The strong cyclic response early in the schedule coincides with kiln fan reversals, but the basic cause is unknown. The increased readings at the end resulted from the equalizing treatment. These data were obtained using sine wave excitation with the monitors, amplitudes and frequencies shown.