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Dielectric Properties of Douglas Fir at High Frequencies

By

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Bulletin No. 28

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I. INTRODUCTION

The use of high frequency energy as a source of heat to cure synthetic resin glue lines in wood assemblies is comparatively new to the wood products industry. To facilitate the proper use of this form of energy, it is essential that a more complete knowledge of the dielectric properties of wood be made available. These properties, namely, dielectric constant and power factor, must be known in order to determine the optimum circuit conditions for a particular process and material.

In Oregon and the remainder of the Pacific Northwest region, Douglas fir [*Pseudotsuga taxifolia* (Poir) Britt] is widely used in the manufacture of wood products, and hence, it is desirable to have information concerning its dielectric properties. The purpose of this bulletin, therefore, is to present extensive data for the dielectric constant and power factor of Douglas fir. The data are presented in terms of four variables, (1) frequency, (2) moisture content, (3) specific gravity, and (4) grain direction.

In addition to a discussion of the dielectric properties of Douglas fir, a short discussion of dielectric heating fundamentals is included. The relationship between power density, dielectric constant, power factor, frequency, and potential gradient is derived in Section II. This relationship finds practical use in determining frequency and potential gradient for any specific heating problem. Design considerations are discussed in Section IV, and a sample problem is included to illustrate the use of data and information included in this bulletin.

II. DIELECTRIC HEATING

1. **The electric field.** Whenever a potential difference (or voltage) is impressed on two electrodes, an electric field is produced in the medium between the electrodes. This medium in which the electric field exists is called a "dielectric." Various materials have

different dielectric properties, and hence, the electric field will have different characteristics in different media. Two of these dielectric properties that are important in dielectric heating are the "dielectric constant" and "power factor" of the dielectric. It is necessary that both of these quantities be determined in order to perform calculations for a particular dielectric material.

2. **Capacitance.** If a potential difference is impressed on two electrodes they will become charged equally with electricity of opposite sign. The ratio of the charge on one electrode to the potential difference between them is called "capacitance." Capacitance is a particularly significant quantity in the analysis of circuits containing elements in which an electric field exists. The capacitance between electrodes of simple geometry can easily be calculated. For example, the capacitance between two parallel plane electrodes that are large compared to the spacing between them is given by the following formula:

$$C = \frac{0.225 \times 10^{-12}\, \varepsilon A}{s} \text{ farads} \qquad (1)$$

ε = the dielectric constant of the medium between the electrodes,

A = area of one plane in square inches,

s = distance between electrodes in inches.

3. **Potential gradient.** Potential gradient is defined as the rate of change of potential with respect to distance. The potential gradient in a uniform electric field such as would occur between two large parallel plane electrodes would be equal to the potential difference (voltage) between the electrodes divided by the distance between them. In a nonuniform electric field such as would occur between two concentric cylinders, the potential gradient varies from point to point along a radial.

4. **Power loss in a dielectric.** If a d-c voltage is applied between two electrodes, a static electric field will be set up. If the dielectric material is not a perfect insulator there will be a small conduction current flowing through the dielectric. This will cause power to be produced in the dielectric material equal to the product of the voltage times the current. Such power loss in the dielectric material will be called "conduction loss."

If a high-frequency alternating voltage be applied between the electrodes, the conduction loss still occurs though it may be somewhat different in magnitude than for an applied d-c voltage. However, in addition to the conduction loss there will be another component of power produced with a-c voltage that was not present when a d-c voltage was applied. This additional loss will be called "dielectric loss."

When a-c voltage is applied to the electrodes, the resultant rapid alternation of the electric field produces changing stress conditions in the dielectric material. This causes a loss of power within the dielectric. Dielectric materials that possess good insulation qualities may have a very small conduction loss but a rather large dielectric loss. It is the power produced due to dielectric loss that is of chief interest in the dielectric heating problem.

5. **Analysis of dielectric loss.** If a uniform alternating electric field is caused to exist in a dielectric material having cross-sectional area A (perpendicular to electric field) and thickness s, there will be power dissipated in the dielectric due to dielectric loss. The analysis of such a problem is most easily approached by setting up the equivalent circuit of Figure 1.

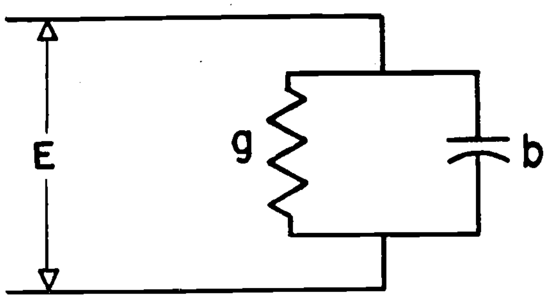

Figure 1. Equivalent circuit of a dielectric having losses.

The rms voltage appearing across the dielectric is shown in the equivalent circuit as E. If the applied alternating voltage is sinusoidal, and it is usually nearly so, the rms voltage is equal to the peak voltage divided by 1.414. Very often voltmeters that might be used to measure large a-c voltages indicate the peak voltage and not the rms voltage.

The conductance term g in the equivalent circuit represents the power loss in the dielectric. The capacitive susceptance term b represents the capacitance between opposite faces of the dielectric. Capacitive susceptance is related to the capacitance C by equation (2).

$$b = 2\pi f C \text{ mhos} \tag{2}$$

$f =$ frequency in cycles per second,
$C =$ capacitance in farads.

The capacitance between the parallel faces of the dielectric is given by equation (1), and if this is substituted in equation (2), the following is obtained:

$$b = 2\pi f \left[\frac{0.225 \times 10^{-12}\, \varepsilon A}{s} \right] \text{ mhos} \qquad (3)$$

The power dissipated in the dielectric can be calculated from the equivalent circuit.

$$\text{Power} = gE^2 \text{ watts} \qquad (4)$$

g = equivalent conductance in mhos,
E = rms voltage across the dielectric.

The power factor of a dielectric is defined as the cosine of the dielectric phase angle which from the equivalent circuit of Figure 1 is determined to be:

$$pf = \frac{g}{\sqrt{g^2 + b^2}} \qquad (5)$$

If equation (5) is solved for g and substituted in the power expression given in equation (4), the following is obtained.

$$g = \frac{(pf)(b)}{\sqrt{1 - (pf)^2}}$$

$$\text{Power} = \frac{(pf)(b)}{\sqrt{1 - (pf)^2}} \cdot E^2 \qquad (6)$$

Replacing b in equation (6) by its value given in equation (3) yields the following expression:

$$\text{Power} = 2\pi f \left[\frac{pf}{\sqrt{1 - (pf)^2}} \right] \left[\frac{0.225 \times 10^{-12}\, \varepsilon A}{s} \right] E^2 \qquad (7)$$

It is usually desirable to express the power density (power per unit volume), and this may be determined by dividing both sides of equation (7) by the volume of the dielectric which is $(s \times A)$.

$$\text{Power density} = 2\pi f \left[\frac{pf}{\sqrt{1 - (pf)^2}} \right] \left[\frac{0.225 \times 10^{-12}\, \varepsilon}{s^2} \right] E^2 \qquad (8)$$

The quantity E^2/s^2 appearing in equation (8) is the square of the potential gradient. This follows from the uniform electric field that was specified. The specification of a uniform field for analysis does not place restrictions upon the use of the results of this analysis for nonuniform fields. This will be discussed later herein.

Combining the constants of equation (8) and writing *grad E* for potential gradient yields the following general expression:

$$\text{Power density} = 1.414 \times 10^{-12} \left[\frac{pf}{\sqrt{1 - (pf)^2}} \right] (\varepsilon)(f)(\text{grad } E)^2 \text{ watts per cu in.} \quad (9)$$

pf = power factor of the dielectric,
ε = dielectric constant of the dielectric,
f = frequency in cycles per second,
grad E = potential gradient in rms volts per inch.

Most materials for which dielectric heating is being used have a power factor less than 0.1. When such is the case the quantity $\sqrt{1 - (pf)^2}$ is very nearly equal to unity and hence, it may be dropped with negligible error. The following equation then is most often used in dielectric heating problems:

$$\text{Power density} = 1.414 \times 10^{-12} (pf)(\varepsilon)(f)(\text{grad } E)^2 \text{ watts per cu in.} \quad (10)$$

It will be noted from equation (10) that the power density increases directly with the frequency for a fixed value of potential gradient. However, the power factor and dielectric constant of most materials varies with frequency. Hence, these quantities must be determined at the frequency to be used. Generally it will be found that the product of power factor and dielectric constant does not vary widely with frequency over a small range of frequencies.

III. DIELECTRIC PROPERTIES OF DOUGLAS FIR

1. **Variables that affect dielectric properties.** A considerable amount of preliminary data was obtained for Douglas fir wood to determine the major variables affecting the dielectric properties. The results of this work indicated that the following variables had a major effect upon the dielectric constant and power factor:

(a) Frequency
(b) Moisture content
(c) Wood density
(d) Grain direction

Therefore, it seemed desirable to obtain sufficient data to indicate the dielectric constant and power factor for any condition in which Douglas fir might normally be used.

2. **Frequency.** Data were taken in the frequency range from two to forty megacycles per second. The dielectric constant and power factor data are presented on graphs as a function of frequency. Within the frequency range investigated, the dielectric constant decreases with increasing frequency while the power factor shows an increase.

3. **Moisture content.** The moisture content of the wood is expressed as a per cent of the oven-dry weight of wood. Data were taken for nominal moisture contents of oven-dry, 5, 8, 12, and 15 per cent. The data are presented by graphs, each depicting a different moisture content. The dielectric constant shows a large increase as the moisture content is increased from oven-dry to 15 per cent. The power factor in general shows a lesser increase as the moisture content increases in this range.

4. **Wood density.** The specific gravity of the wood at oven-dry condition was measured. Data were obtained on wood samples having nominal specific gravities of 0.45, 0.55, and 0.65 and are plotted as three sets of curves on each graph. The more dense wood has a greater value of dielectric constant and generally a somewhat larger value of power factor.

5. **Grain direction.** Vertical grain wood has a grain direction perpendicular to the electrode surfaces and parallel to the electric field. Flat grain wood has a grain direction parallel to the electrode surfaces and perpendicular to the electric field. Data were obtained for both grain directions, and two curves (one for each grain direction) are plotted in each set on the graphs. Both dielectric constant and power factor are somewhat larger for vertical grain wood in the range of variables investigated.

6. **Other variations.** There are probably other differences in Douglas fir wood specimens that may cause small deviations in the dielectric properties. For sound wood these seem to have only a minor effect. Each point indicated on the graphs has a value that is the average for five wood samples. All five of these samples were similar in moisture content, density, and grain direction, but may have differed in other respects. Nevertheless the measured values of dielectric constant and power factor of all were nearly the same.

The dielectric constant and particularly the power factor of a piece of wood tend to change as the temperature rises during the heating cycle. Normally, slight circuit adjustments must be made during the heating cycle if the input power is to be held constant. All data in this bulletin were taken at temperatures near normal room temperature. Hence, design calculations using these data are for the initial conditions existing at the start of the heating cycle.

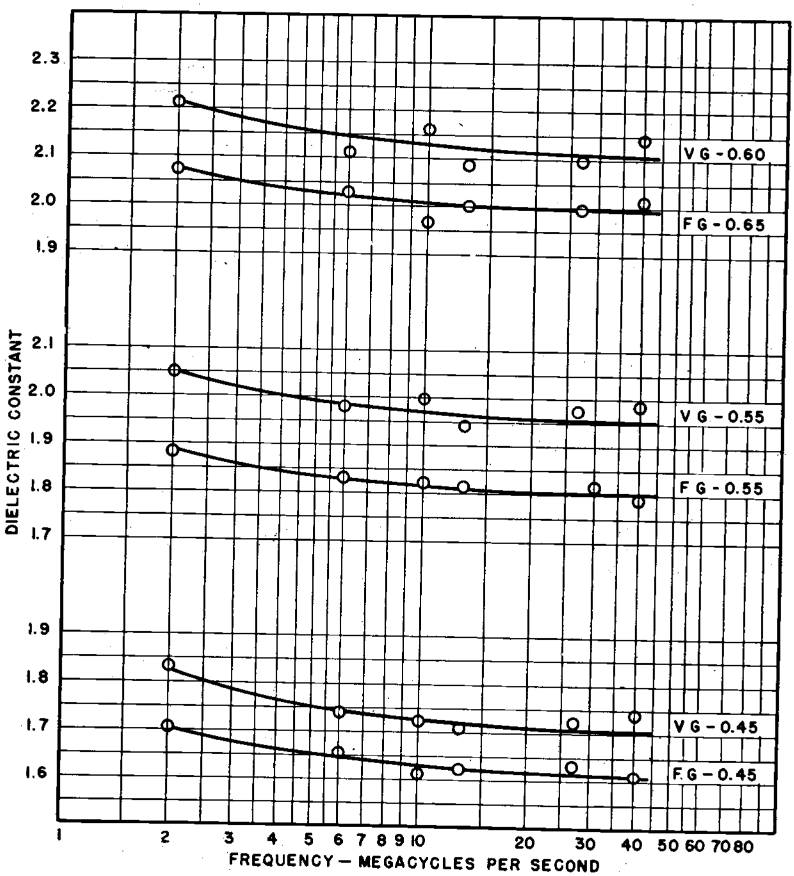

Figure 2. Dielectric constant of oven-dry Douglas fir. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

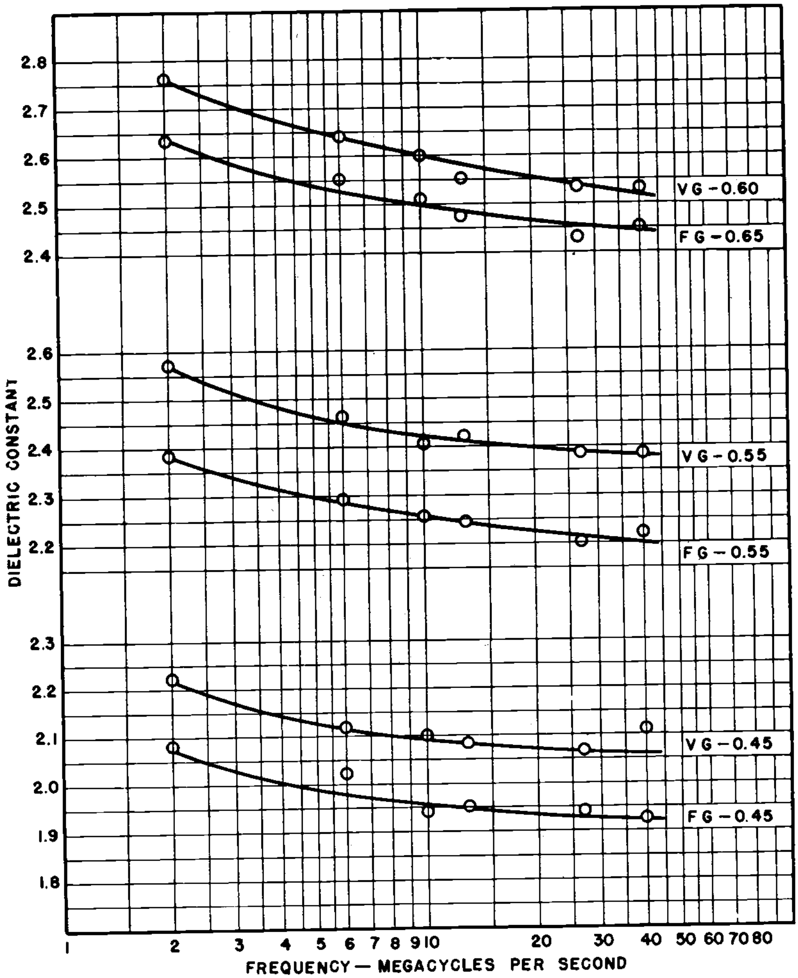

Figure 3. Dielectric constant of Douglas fir at 5% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

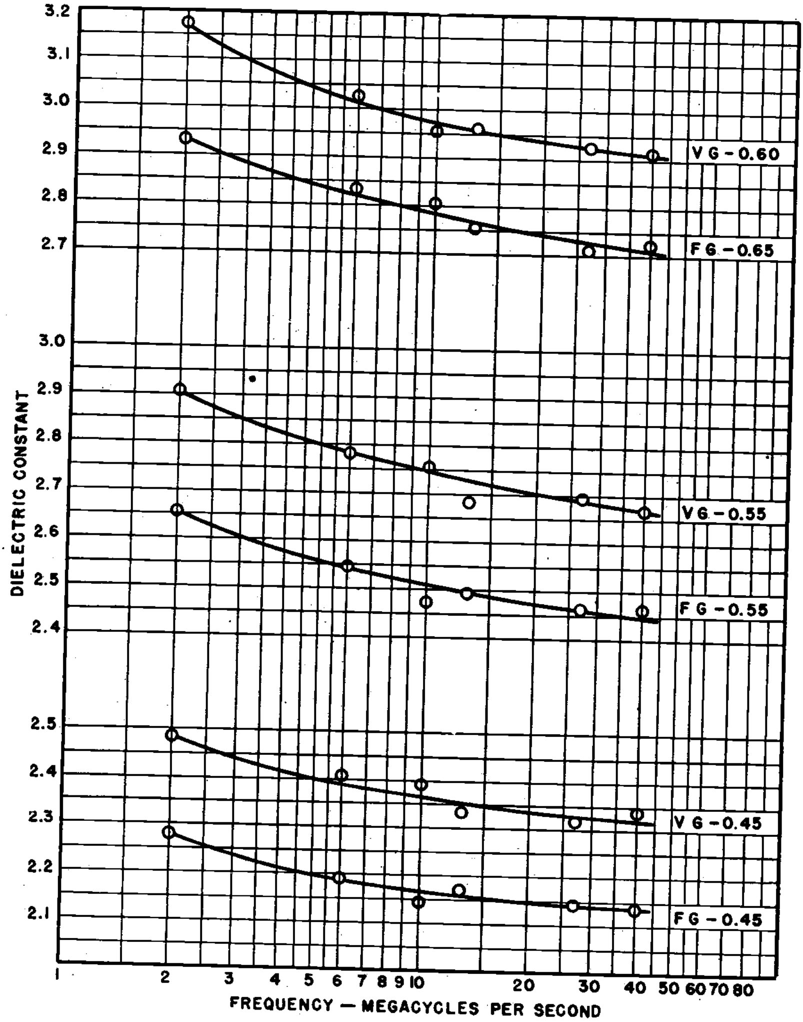

Figure 4. Dielectric constant of Douglas fir at 8% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

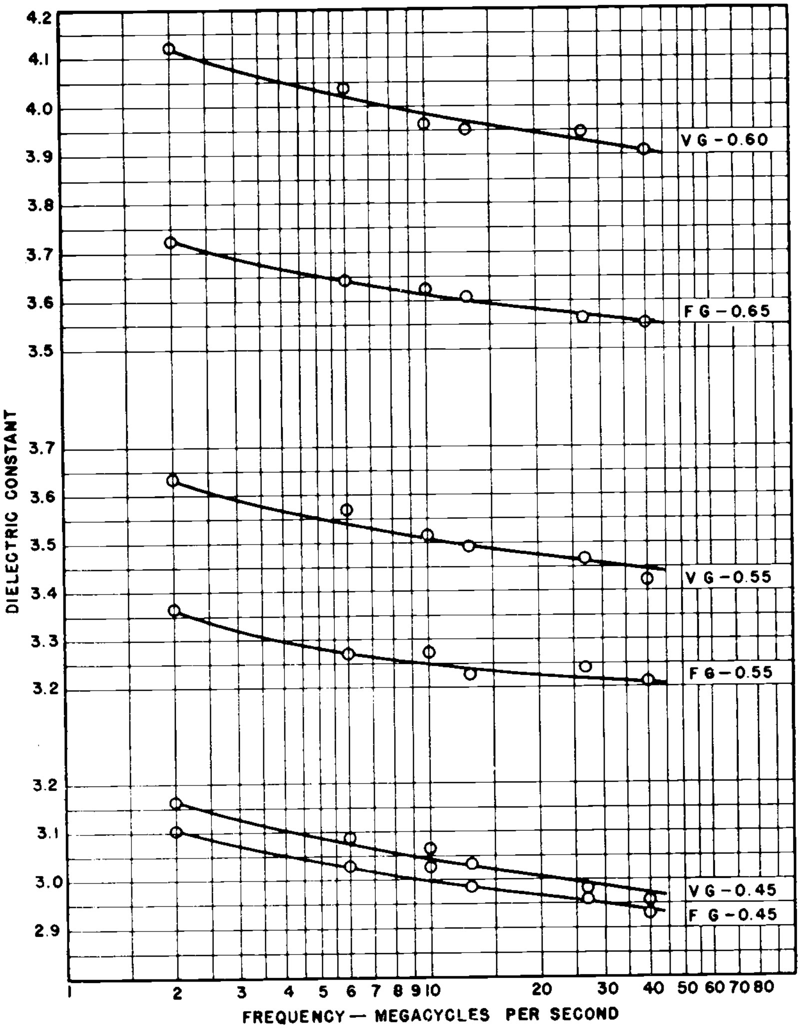

Figure 5. Dielectric constant of Douglas fir at 12% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

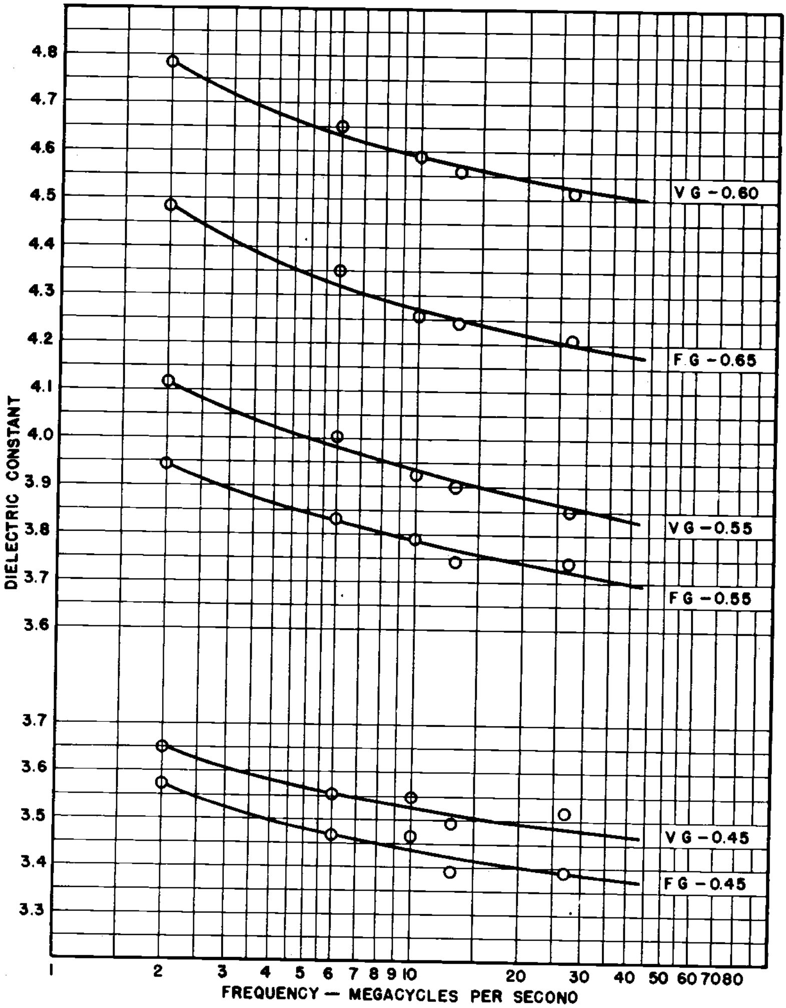

Figure 6. Dielectric constant of Douglas fir at 15% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

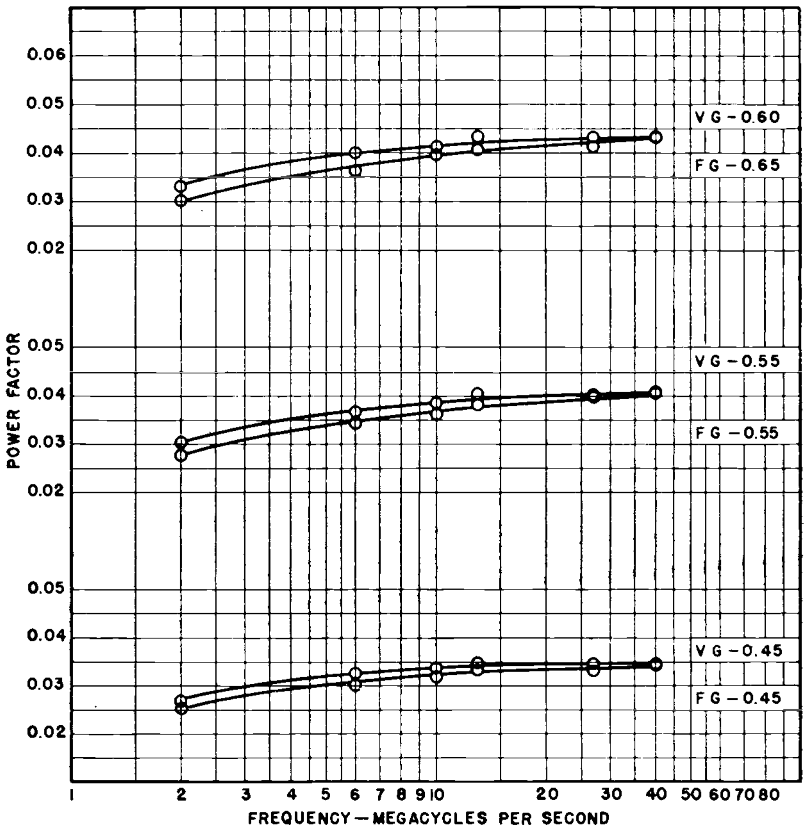

Figure 7. Power factor of oven-dry Douglas fir. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

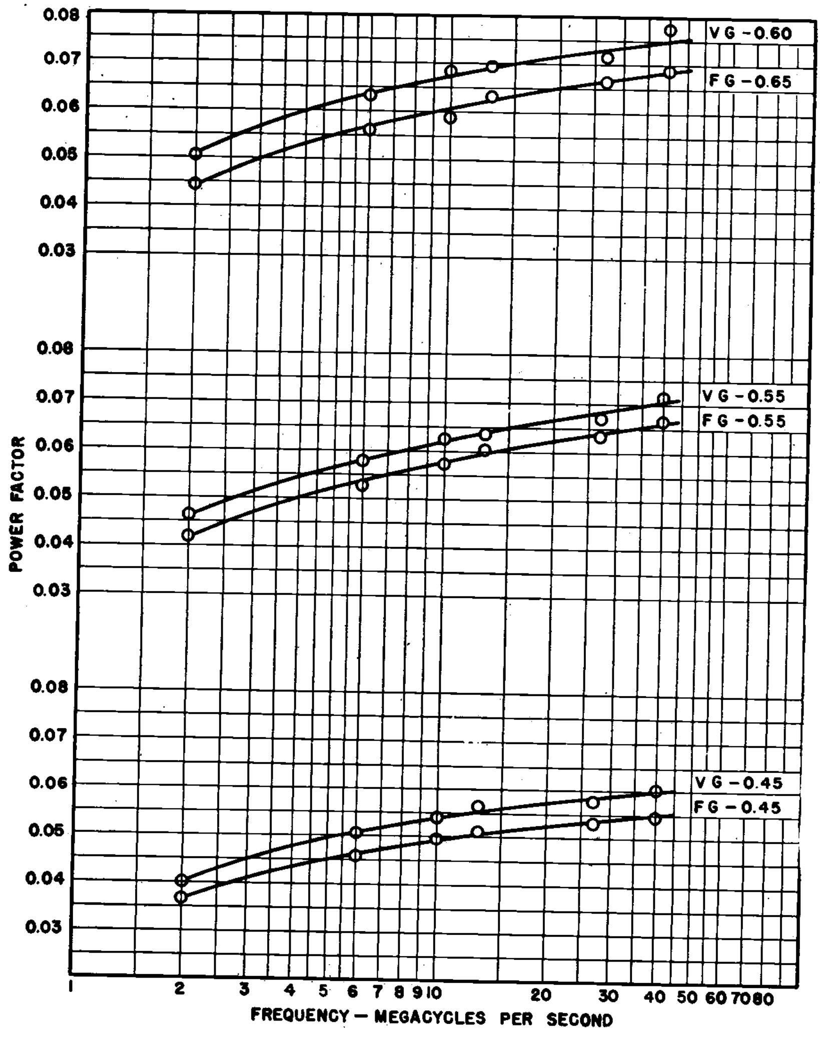

Figure 8. Power factor of Douglas fir at 5% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

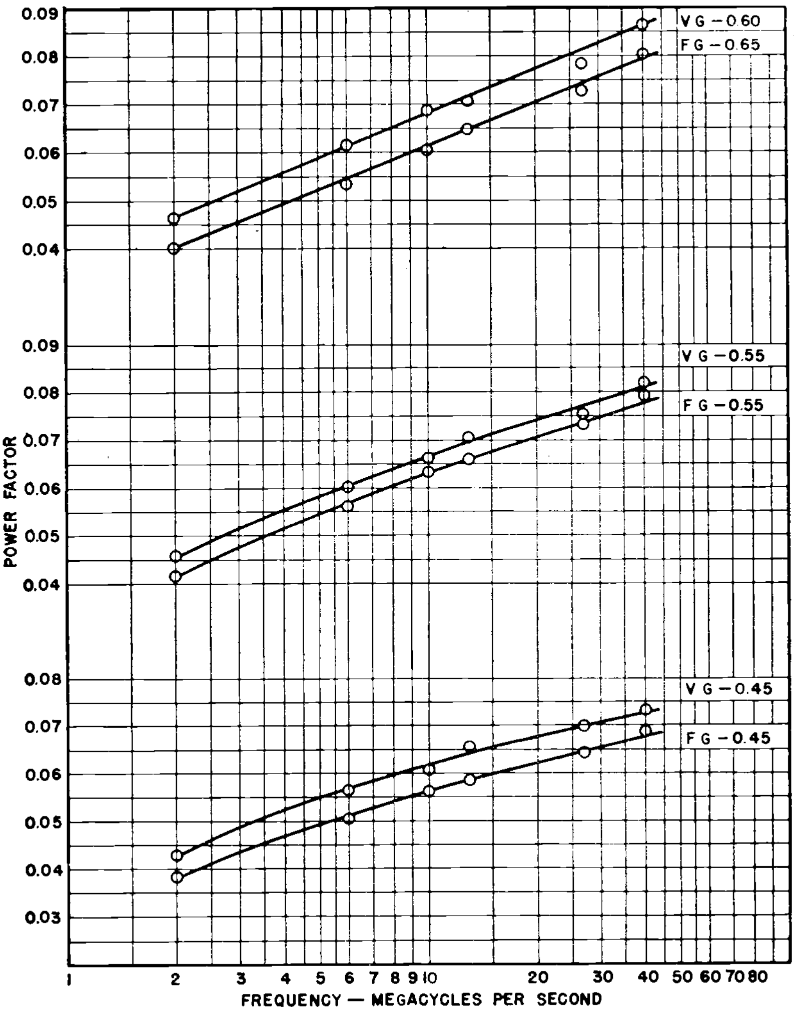

Figure 9. Power factor of Douglas fir at 8% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

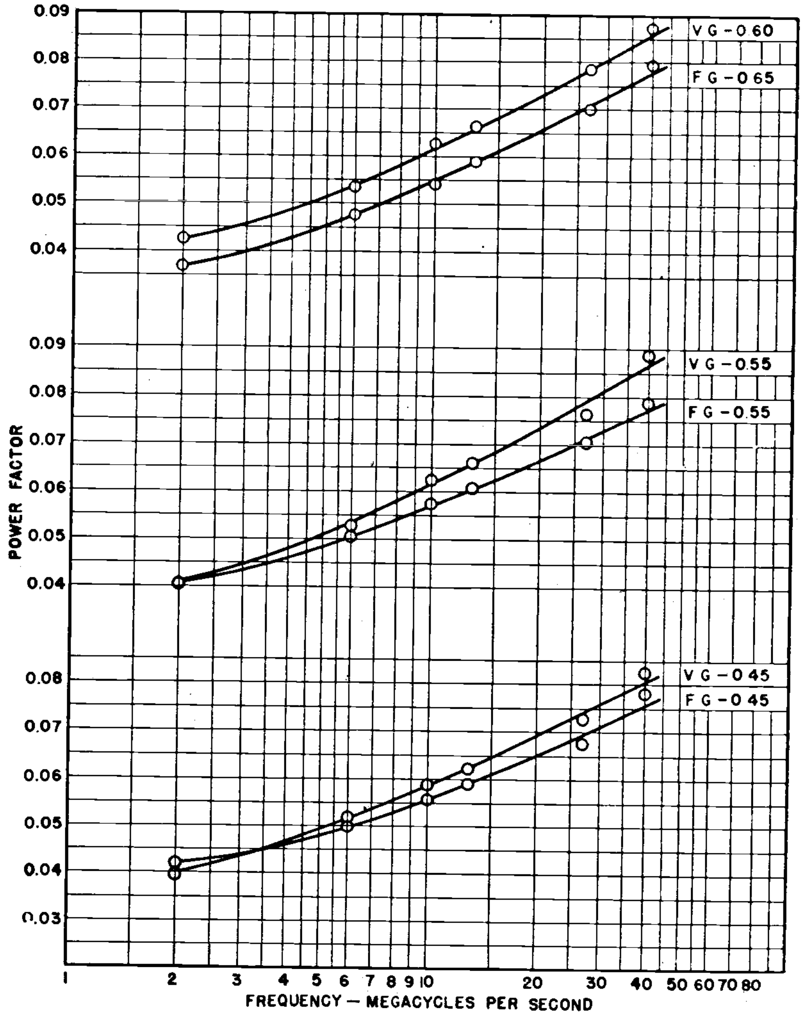

Figure 10. Power factor of Douglas fir at 12% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

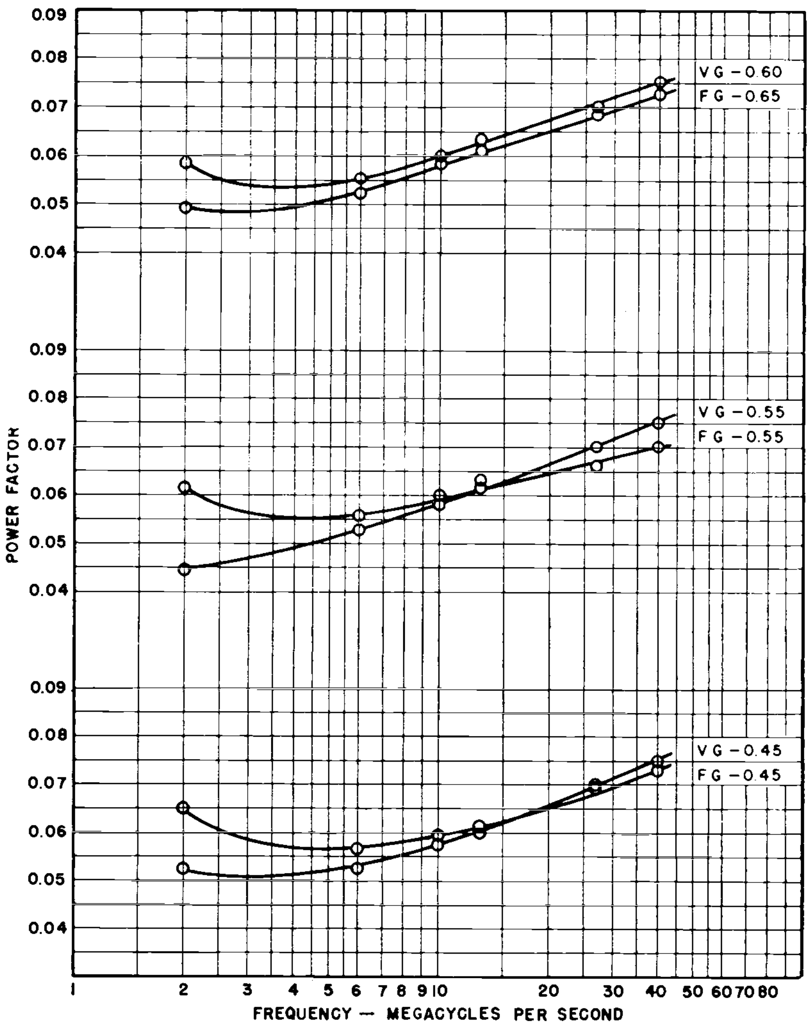

Figure 11. Power factor of Douglas fir at 15% moisture content. Letters indicate vertical grain (VG) or flat grain (FG). Numbers indicate specific gravity. Each point shown is the average for 5 samples.

IV. DESIGN CONSIDERATIONS

1. **Specific heat.** The mean value of the specific heat of oven-dry wood in the temperature range from 32 F to 212 F has been determined by Dunlap (1) to be 0.327 Btu per lb per deg F. The effective value of specific heat for wood having moisture content MC per unit may be calculated from the following expression:

$$c = \frac{0.327 + MC}{1 + MC} \text{ Btu per lb per deg F} \qquad (11)$$

c = effective specific heat,
MC = moisture content in lb per lb of dry wood.

2. **Maximum frequency and potential gradient.** The physical size of electrodes limits the maximum frequency that may be used without resultant non-uniform heating. When frequency is sufficiently high that the electrode size is an appreciable fraction of a wave length, it will be found that the voltage between electrodes differs from point to point. Since the power dissipated in the dielectric is proportional to the square of the voltage, heating will differ from point to point. The maximum electrode dimension should not exceed approximately one-sixteenth to one-eighth of a wave length. The wave length is expressed in terms of frequency and dielectric constant by the following expression:

$$\text{Wave length} = \frac{984}{f\sqrt{\varepsilon}} \text{ feet} \qquad (12)$$

f = frequency in megacycles per second,
ε = dielectric constant of material being heated.

The maximum electrode voltage is dependent upon several factors. Some of these are thickness of dielectric, moisture content, mechanical forces, and shape of electrodes. The evolution of steam or vapor may limit electrode voltage. Excessive voltage will cause the formation of corona and may cause arc-over between the electrodes either through the dielectric or around an outside edge. Present practice is to limit the maximum electrode voltage to about 15,000 rms volts, or for thin dielectrics, limit the voltage gradient to about 2,000 or 3,000 rms volts per inch. If special design precautions are followed, higher voltages may be used but the installation cost may be materially increased.

3. **Power requirements.** The power which is supplied to the dielectric from a radio frequency generator is partly lost by heat

radiation, convection, and conduction to electrodes if they are unheated. Generally the heat loss may be of the order of 10 to 20 per cent, but this depends upon the particular conditions present. The useful thermal power is given by the following expression:

$$\text{Power} = 17.6 M c \Delta T \text{ watts} \quad (13)$$

M = pounds of material heated per minute,
c = effective specific heat in Btu per lb per deg F,
ΔT = temperature rise of material heated in deg F.

The amount of heat loss must be added to this useful power. The power density can then be calculated.

$$\text{Power density} = \frac{\text{useful thermal power} + \text{heat losses}}{\text{volume of material being heated}} \frac{\text{watts per}}{\text{cu in.}} \quad (14)$$

This power density must be produced in the material by the dielectric heating process to actually raise the temperature the desired amount in a specified period of time.

The high frequency generator and associated circuits will in themselves have power losses so that the actual power input to the entire unit will be considerably larger than the useful thermal power in the load. An overall efficiency figure of 50 per cent is often used for estimation, but the actual efficiency is dependent upon many factors and can be improved by careful design.

4. **Sample problem.** The following problem is included to illustrate the use of the information included herein. Suppose it is desired to bond a packet of veneer with thermo-setting adhesive. The following specifications are set forth:

(a) Douglas fir veneer, flat grain, medium density.
(b) Assume the average moisture content to be 12 per cent after adding adhesive.
(c) Size of packet to be 24 in. by 36 in. by 8 in. thick.
(d) Temperature rise from 70 F to 200 F in 5 minutes.

The weight of the stack of wood is calculated on the basis of an average specific gravity of 0.55 for oven-dry Douglas fir. The weight may be calculated as follows:

$$\text{Weight} = 62.4\,(sp\ gr)\,(1 + MC)\,(vol) \text{ lb} \quad (15)$$

$sp\ gr$ = specific gravity of oven-dry wood,
MC = moisture content in lb per lb of dry wood,
vol = volume of wood in cubic feet,

$$\text{Weight} = 62.4(0.55)(1+0.12)(2)(3)(0.667) = 153.8 \text{ lb},$$

$$\text{Pounds heated per minute } \frac{5}{153.8} = 30.75 \text{ lb per min.}$$

The effective specific heat at 12 per cent moisture content is:

$$c = \frac{0.327 + 0.12}{1 + 0.12} = 0.399 \text{ Btu per lb per deg F}$$

The useful thermal power is:

$$\text{Useful thermal power} = 17.6(30.75)(0.399)(200-70)$$
$$= 28{,}000 \text{ watts.}$$

If it is assumed that there is a 10 per cent heat loss, the total power that must be supplied to the dielectric is:

$$\text{Power} = (1+0.1)(28{,}000) = 30{,}800 \text{ watts.}$$

The power density in the dielectric is:

$$\text{Power density} = \frac{30{,}800}{(24)(36)(8)} = 4.46 \text{ watts per cu in.}$$

An electrode arrangement as shown in Figure 12 will be selected because it does not require insulation of the high voltage electrode.

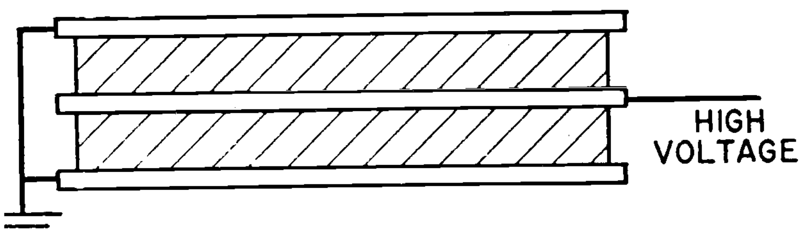

Figure 12. Electrode arrangement not requiring insulation of high-voltage electrode.

The electrical calculations will be made for three different frequencies so that they may be compared. Those selected are 5, 10, and 15 megacycles per second. The wave length at 15 megacycles per second is about 36.6 feet, and hence, the electrodes are sufficiently small that the heating will be reasonably uniform.

Data from the graphs of Section III are obtained for dielectric constant and power factor at the three frequencies selected.

	5 megacycles per second	*10 megacycles per second*	*15 megacycles per second*
Dielectric constant	3.28	3.25	3.23
Power factor	0.048	0.057	0.0625

The potential gradient required to produce the necessary power density in the dielectric can be calculated for each of the three frequencies by use of equation (10).

$$\text{Power density} = 1.414 \times 10^{-12}(pf)(\varepsilon)(f)(grad\ E)^2 \text{ watts per cu in.}$$

Potential gradient and electrode voltage at 5 megacycles per second.

$$\text{Grad } E = \sqrt{\frac{4.46}{(1.414 \times 10^{-12})(0.048)(3.28)(5 \times 10^6)}}$$
$$= 2{,}000 \text{ rms volts per in.}$$

The electrode voltage required to obtain this gradient is equal to the electrode spacing multiplied by the potential gradient. The arrangement of electrodes selected gives an electrode spacing of four inches.

$$\text{Electrode voltage} = (4)(2{,}000) = 8{,}000 \text{ rms volts}$$

Potential gradient and electrode voltage at 10 megacycles per second.

$$\text{Grad } E = \sqrt{\frac{4.46}{(1.414 \times 10^{-12})(0.057)(3.25)(10 \times 10^6)}}$$
$$= 1{,}304 \text{ rms volts per in.}$$

$$\text{Electrode voltage} = (4)(1{,}304) = 5{,}216 \text{ rms volts}$$

Potential gradient and electrode voltage at 15 megacycles per second.

$$\text{Grad } E = \sqrt{\frac{4.46}{(1.414 \times 10^{-12})(0.0625)(3.23)(15 \times 10^6)}}$$
$$= 1{,}022 \text{ rms volts per in.}$$

$$\text{Electrode voltage} = (4)(1{,}022) = 4{,}088 \text{ rms volts}$$

The lower potential gradient and electrode voltage at 15 megacycles per second is an advantage because it lowers the possibility of corona and arc-over. The selection of frequency to be used is dependent upon other factors such as generator capabilities and so on, but the lower voltage at the higher frequency is particularly desirable. Frequencies much lower than 5 megacycles per second should not be used for an installation such as this because of high required values of potential gradient and electrode voltage.

5. **Non-uniform electric fields.** If the shape of the electrodes is such that the electric field is not uniform, care must be exercised in performing calculations. If the electrode geometry is simple, like concentric cylinders for example, the calculation of required power and such is not too difficult (3). But for complex electrode shapes, the problem becomes complicated. Since the electric field is not uniform, the potential gradient differs from point to point throughout the dielectric. This results in different power density and resultant different heating throughout the dielectric. Regions where the potential gradient is high rise to higher temperatures than where low potential gradients exist. For example, consider the electrode arrangement of Figure 13.

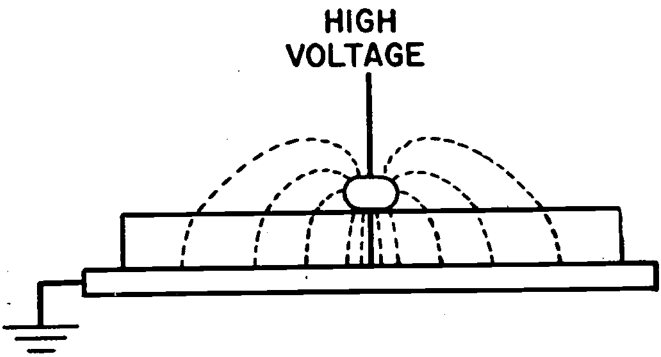

Figure 13. Electrode arrangement that results in a non-uniform electric field.

This might be an example of parallel bonding wherein two pieces of wood are to be edge-bonded as shown. This problem is complicated not only by the non-uniform electric field, but also by the fact that the dielectric properties are different in and near the glue line from those for the wood on either side.

The lines sketched to show the approximate shape of the electric field indicate that the potential gradient is greatest near the top surface at the glue line. It is helpful if the shape of the electric field can be visualized because the potential gradient is directly proportional to the electric flux density. Hence, in regions where the electric field is concentrated, the potential gradient will be large. If the thickness of the dielectric is relatively small compared to the least dimension of the electrodes, the fringing of the electric field at the edges of the electrodes may be neglected without appreciable error.

6. **Dielectrics in series.** Sometimes it is necessary to have two or more dielectrics of different characteristics in series in the electric field. When such is the case, the voltage appearing between opposite faces of each dielectric is dependent upon the thickness and dielectric constant of each material. If two dielectrics are in series in a uniform alternating electric field, the voltage appearing across each may be calculated from the following formula:

$$E_1 = \frac{E}{1 + \frac{s_2}{s_1} \cdot \frac{\varepsilon_1}{\varepsilon_2}} \text{ volts} \qquad (16)$$

E_1 = voltage across dielectric (1),
E = total electrode voltage,
s_1 and s_2 = thicknesses of dielectrics (1) and (2) respectively,
ε_1 and ε_2 = dielectric constants of dielectrics (1) and (2) respectively.

The voltage E_2 across the second dielectric can be determined in a like manner or it may be determined by merely subtracting E_1 from the total voltage E.

V. PROCEDURE

1. **Selection of samples.** Inadequacy of available information concerning the dielectric properties of wood necessitated a preliminary investigation designed to provide background data so that satisfactory testing techniques could be established. As a result of that work, it was determined that the dielectric properties of Douglas fir are affected by the following wood variables:

(a) Moisture content,
(b) Specific gravity,
(c) Grain direction.

Variation in amount of sapwood and heartwood, growth site, fungus stain, other discolorations, and presence of small pitch streaks were found to have negligible effect on the dielectric properties. As a result of the foregoing disclosures, sample categories were established to include specimens that would be representative of the normal range of specific gravity found in Douglas fir. Nominal values for specific gravity were set at 0.45, 0.55, and 0.65. Each of these categories was represented by five flat grain specimens (grain oriented parallel to electrode surfaces), and five vertical grain specimens (grain oriented perpendicular to electrode surfaces). An exception to this grouping was occasioned by the fact that representative vertical grain specimens were of necessity grouped at 0.60 rather than 0.65 specific gravity. This comprised a total requirement of 30 sample pieces.

2. **Preparation of samples.** Sample pieces were cut from kiln dried billets 0.5 inch thick by two or more feet long having a moisture content of 8 per cent. The billets, cut from rough timber, were selected to be consistent with established requirements for direction of grain and range of specific gravity. Moisture content was maintained at 8 per cent, the midpoint of variation during testing, so that dimensional change would be minimized as the moisture content was varied.

Samples were cut 4 inches square by 0.25 inch thick with a tolerance of ±0.003 inch. After cutting and extremely light sanding of the edges to remove loose fibers, the samples were reconditioned to 8 per cent moisture content. Weights were then taken and the approximate specific gravity of each individual piece was determined on the basis of calculated oven-dry weight. Selection of the final 30 samples was made from a larger quantity of original specimens and was based on the physical appearance and specific gravity of individual pieces.

3. **Establishing moisture content values.** To enable investigation of the effect of varying moisture content on dielectric properties, samples were tested at nominal values near oven-dry, 5, 8, 12, and 15 per cent. The upper limit of this range was selected as being consistent with the requirements of most synthetic resin adhesives and with the practical maximum moisture content desirable with dielectric heating of wood.

Samples were conditioned in two steps. First, they were brought to the desired moisture content value in a small experimental dry kiln. This procedure amounted to pre-conditioning. Second, the samples were confined in desiccators in which saturated salt solutions were used to maintain desired equilibrium moisture conditions (2). During this period of conditioning, temperature was established as near to normal room temperature as the nature of the particular salt solution would permit. Each desiccator (Figure 14) was equipped with a fan for air circulation and an agitating paddle in the salt solution, thereby obtaining the maximum effect from the solution and avoiding air stratification within the chamber.

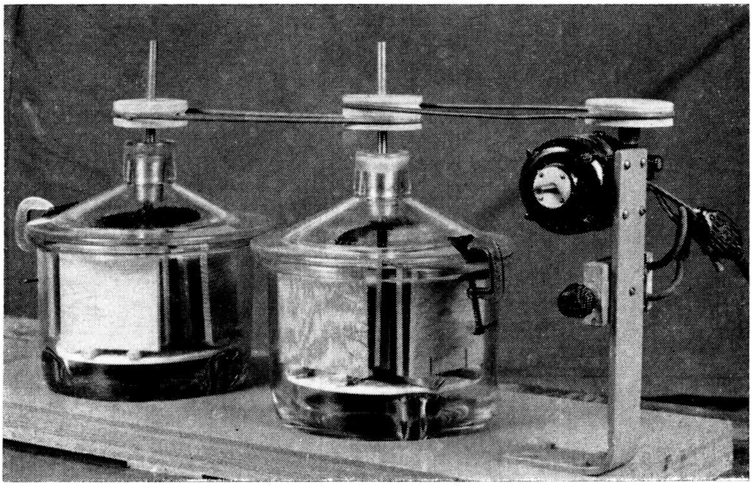

Figure 14. Moisture conditioning apparatus.

When possible, moisture content values were established without elevating temperatures in excess of 83 F. Oven-dry samples, which were necessarily exposed to a temperature of 212 F, were allowed to cool approximately to room temperature before electrical measurements were made.

4. **Determination of specific gravity.** Original grouping of samples as described previously, was based on a specific gravity value for oven-dry Douglas fir derived from the calculated oven-dry weight and calculated volume of each sample. At the termination of testing, the samples were oven dried, weighed, and immersed in mercury as a means of measuring volume by displacement. All data in this bulletin are based on true values for specific gravity established by the final procedure.

5. **Q-meter.** All electrical measurements were made with a Boonton Radio Corporation Type 160-A Q-meter. This instrument may be used for determining dielectric properties of materials in the frequency range from 50 kilocycles to 75 megacycles per second. Fundamentally, the measuring circuit consists of a series circuit which may be adjusted to resonance with a calibrated variable capacitor. Plug-in coils having different inductances are used to cover the wide frequency range. A built-in vacuum tube voltmeter measures the voltage across the variable capacitor and is calibrated to indicate the Q of the entire series circuit. The circuit quantity Q is defined as the ratio of reactance to resistance. For example, a series resonant

circuit having resistance, inductance, and capacitance would have a Q as follows:

$$Q = \frac{2\pi f L}{R} = \frac{1}{2\pi f C R} \qquad (17)$$

f = frequency in cycles per second,
R = resistance in ohms,
L = inductance in henrys,
C = capacitance in farads.

6. **Press.** A small press to hold the wood sample was constructed with parallel brass plate electrodes four inches square. A screw arrangement is provided so that considerable pressure can be placed on the sample after it is inserted between the electrodes. The bottom electrode is insulated and supported by four polystyrene columns 0.75 inch diameter and two inches high. The press sits atop the Q-meter and has two short 0.75 inch wide copper straps connecting the electrodes to the Q-meter terminals.

The photograph, Figure 15, shows the Q-meter with all accessories in normal position. The shielded coil is at the left atop the Q-meter and the press with a sample in place is at the right. A constant-voltage transformer, shown alongside the Q-meter, is required so that changes in line voltage do not affect the Q-meter calibration.

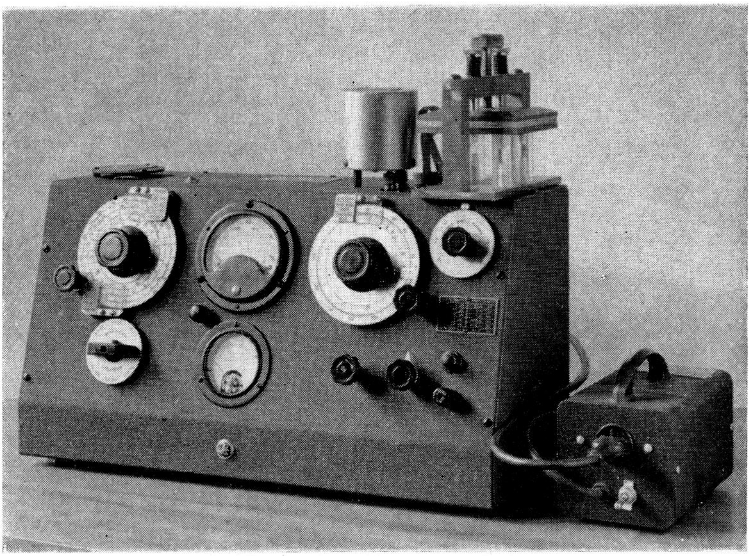

Figure 15. Boonton Q-meter and accessories.

7. **Electrical measurements.** Any set of electrodes to hold the sample while taking measurements will inherently have distributed inductance and capacitance and may have small losses. These either must be kept very small or data must be taken in such a manner as to account for these electrode constants, otherwise the accuracy of the results will not be good. The higher the frequency of measurement, the more difficult is the problem of minimizing the effects of the distributed inductance and capacitance of the electrodes and associated leads. Therefore, a method of taking data to account for these effects was worked out and is presented here. All data for this bulletin were taken in this manner.

It is necessary to take three sets of readings from the Q-meter to account for the distributed constants of the press and determine accurately the dielectric properties of the wood sample.

(1) Observe the Q reading and the calibrated capacitor setting at resonance with the coil in place but without the press connected.

(2) Observe the calibrated capacitor setting at resonance with both the coil and press connected but without a sample in place. The press must be adjusted so that the electrode spacing is equal to the sample thickness for this measurement.

(3) Observe the Q reading and the calibrated capacitor setting at resonance with both the coil and press connected and with a sample in place.

The circuits of Figure 16 show the equivalent measuring circuits for each of the three conditions described.

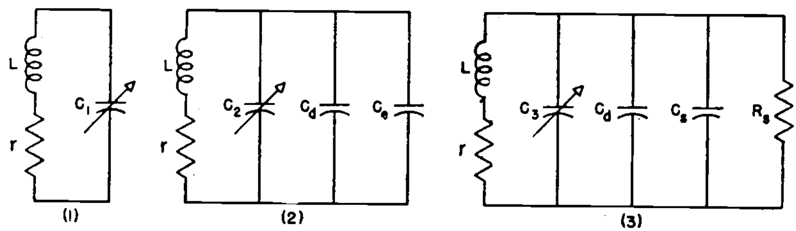

Figure 16. Equivalent measuring circuits of Q-meter: (1) without press connected, (2) with press connected but without sample in place, (3) with press connected and with sample in place.

The quantities indicated in the three equivalent circuits are as follows:

$L =$ coil inductance.

$r =$ coil resistance.

C_1, C_2, and C_3 = capacitance of the Q-meter calibrated variable capacitor at resonance. Resonance is obtained by adjusting this capacitor for maximum deflection of the Q indicating meter.

C_d = the effective distributed capacitance of the press viewed from the Q-meter terminals.

C_e = the direct capacitance between the electrode faces when the spacing between them equals the sample thickness.

C_s = the direct capacitance between the electrode faces with the sample in place.

R_s = the effective resistance of the sample.

It will be noted that in circuit (2) there is no component to represent power loss in the press. The loss in the press was experimentally determined to be negligible even at the highest frequency used and therefore need not be considered.

In addition to the circuit quantities indicated in the equivalent circuits, the Q reading was observed for parts (1) and (3). These are indicated as Q_1 and Q_3 respectively. The symbol ω will be used throughout to indicate the quantity $2\pi f$ which appears very frequently. It should be kept in mind that in each of the three sets of measurements, the circuit is tuned to series resonance with the same coil in place for all. This results in the total effective series capacitance being equal in each of the three equivalent circuits.

From equation (17), the Q of circuit (1) is:

$$Q_1 = \frac{1}{\omega r C_1} \tag{18}$$

In circuit (2) the total effective series capacitance must equal C_1.

$$C_1 = C_2 + C_d + C_e \tag{19}$$

The value of C_e can be calculated from equation (1) because the dielectric constant of air is known to be unity.

$$C_e = \frac{0.225 \times 10^{-12} A}{s} \text{ farads} \tag{20}$$

The total effective series capacitance of circuit (3) must also equal C_1. If this circuit is simplified by replacing the parallel resistance and capacitance by the equivalent series combination, the circuit of Figure 17 is obtained.

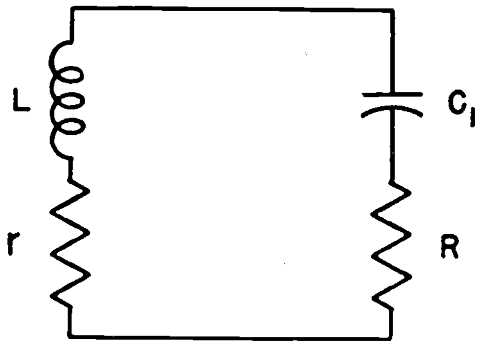

Figure 17. Simplified equivalent circuit of Figure 16 (3).

The series capacitance C_1 and resistance R can be determined from circuit (3) as follows:

$$R + \frac{1}{j\omega C_1} = \frac{R_s\left[\dfrac{1}{j\omega\,(C_3 + C_d + C_s)}\right]}{R_s + \dfrac{1}{j\omega\,(C_3 + C_d + C_s)}}$$

$$C_1 = \frac{1 + \omega^2 R_s^2\,(C_3 + C_d + C_s)^2}{\omega^2 R_s^2\,(C_3 + C_d + C_s)^2} \cdot (C_3 + C_d + C_s)$$

$$C_1 \cong C_3 + C_d + C_s \tag{21}$$

$$R = \frac{R_s}{1 + \omega^2 R_s^2\,(C_3 + C_d + C_s)^2}$$

$$R \cong \frac{1}{\omega^2 R_s\,(C_3 + C_d + C_s)^2} = \frac{1}{\omega^2 R_s C_1^2} \tag{22}$$

From the simplified circuit of Figure 17, the Q is determined to be:

$$Q_3 = \frac{1}{\omega(r + R)\,C_1} \tag{23}$$

The result sought from this analysis is the determination of the power factor and dielectric constant of the wood sample from measurable quantities. The power factor of a dielectric is directly related to the Q of the dielectric. The Q of the wood sample in terms of its equivalent circuit quantities in Figure 16 (3) is:

$$Q_x = \omega R_s C_s \tag{24}$$

From equation (18)

$$r = \frac{1}{\omega C_1 Q_1}$$

and from equation (23)

$$R = \frac{1}{\omega C_1 Q_3} - r = \frac{1}{\omega}\left[\frac{1}{C_1 Q_3} - \frac{1}{C_1 Q_1}\right]$$

From equation (22)

$$R_s = \frac{1}{\omega^2 C_1^2} \cdot \frac{1}{R} = \frac{1}{\omega^2 C_1^2} \cdot \frac{1}{\frac{1}{\omega C_1}\left[\frac{1}{Q_3} - \frac{1}{Q_1}\right]}$$

$$R_s = \frac{1}{\omega C_1} \cdot \frac{Q_1 Q_3}{Q_1 - Q_3}$$

and from equations (21) and (19)

$$C_s = C_1 - C_3 - C_d = C_1 - C_3 - (C_1 - C_2 - C_e)$$

$$C_s = C_2 - C_3 + C_e \tag{25}$$

If the values of R_s and C_s be substituted in equation (24), the following expression for Q_x is obtained.

$$Q_x = \frac{(C_2 - C_3 + C_e)(Q_1 Q_3)}{C_1(Q_1 - Q_3)} \tag{26}$$

$Q_x = Q$ of the wood dielectric,

C_1, C_2, C_3, and C_e = capacitances in micro-microfarads,

Q_1 and $Q_3 = Q$ readings (no dimensions),

$$C_e = \frac{0.225\,A}{s} \text{ micro-microfarads.}$$

The power factor of the dielectric and Q_x are related as in the following expression:

$$pf = \frac{1}{\sqrt{1 + Q_x^2}} \tag{27}$$

If the value of Q_x is greater than about 10, the value of the power factor becomes essentially equal to the reciprocal of Q_x.

$$pf = \frac{1}{Q_x} \text{ if } Q_x > 10 \tag{28}$$

The dielectric constant of the sample can be determined from equations (1) and (25) which are repeated here for convenience.

$$C = \frac{0.225 \times 10^{-12} \varepsilon A}{s} \tag{1}$$

$$C_s = C_2 - C_3 + C_e \tag{25}$$

From equation (1)

$$C_e = \frac{0.225 \times 10^{-12} A}{s}$$

$$C_s = \frac{0.225 \times 10^{-12} \varepsilon A}{s} \varepsilon C_e$$

Substituting for C_s in equation (25) yields the following:

$$\varepsilon C_e = C_2 - C_3 + C_e$$

$$\varepsilon = 1 + \frac{C_2 - C_3}{C_e} \tag{29}$$

$$\varepsilon = 1 + \frac{4.45 (C_2 - C_3) s}{A} \tag{30}$$

C_2 and C_3 = capacitance in micro-microfarads,

s = sample thickness in inches,

A = cross-sectional area of sample in square inches.

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