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TECHNICAL NOTES

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

No. 874

CURING OF RESIN-WOOD COMBINATIONS BY HIGH-FREQUENCY HEATING

By Arthur R. von Hippel and A. G. H. Dietz
Massachusetts Institute of Technology

Washington
December 1942

ERRATA

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Equation 6:
Change tan θ to tan δ.

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Equations 2, 3, 4, and the first expression in equation 7 refer to the practical m.k.s. system.

In the second expression of equation 7, the authors refer to the customary expression in the electrostatic system.

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SUMMARY

The results of an investigation of the curing of resin-wood combinations by high-frequency heating are summarized in the present paper. The physical facts pertinent to high-frequency heating are introduced. The procedure is described for measuring dielectric constant and loss from 1 to 100 megacycles, and the results of such measurements are given for several species of wood and thermosetting resins representative of those employed in aircraft. The effects of humidity, temperature, impregnation, and state of polymerization are demonstrated. From these facts the most favorable combination of wood, resin, and frequency range may be selected and a calculation of the heat input may be made. Experimental gluing and curing of wood in the field of a 500-watt oscillator is described. In addition to the experiments relating strictly to high-frequency heating, an attempt was made to save time by shortening the impregnation time and by reducing the setting temperature.

The results indicate that the high-frequency heating process is feasible, flexible, and timesaving. Possibilities of more extensive application are discussed.

INTRODUCTION

Within recent years combinations of wood and synthetic resins have played an increasingly important role in aircraft manufacture. The earliest development was the use of resins, such as phenol and urea formaldehydes, as adhesives possessing superior resistance to deteriorating influences of moisture and decay. A series of highly moisture-resistant plywoods and laminated wood parts of many kinds followed. Later it was discovered that the resins could be used as impregnants and that impregnation increased some of the mechanical properties and introduced a large measure of dimensional stability. Finally, it was found that resin-impregnated wood could be compressed at elevated temperatures and pressures to a hard, dense mass of specific gravity as high as 1.4 or more.

Certain of the resins employed as adhesives can be made to "set" at ordinary temperatures, but the best of them require heat, and even the "cold-setting" adhesives cure more rapidly as their temperatures are increased. The impregnants are almost universally thermosetting.

Heat is customarily introduced into the wood-resin combination by pressing between hot plates. Heat flows into the mass from the heated surface, but, on account of the poor heat conductivity of both wood and resin, hours may be required to raise the centers of heavy masses to the curing temperature. Furthermore, the surface may have to be maintained at a higher temperature than is desirable in order that the center may be brought to the minimum necessary temperature in a reasonable time. Simultaneous, uniform, and rapid heating throughout the whole mass is the ideal process for resin-impregnated parts, such as propellers. Selective heating of the bonding layers in glued-up stock, irrespective of its thickness, is desirable in laminated or cross-banded construction.

Such heating is possible if the part to be glued or cured is inserted in a high-frequency electrical field. The heat, instead of being conducted from the outside, can be generated inside by making use of the dielectric loss of the material. In this way the curing may be accelerated, no temperature gradient is involved, and the heat input may be controlled with great flexibility. In addition, selective heating of single layers becomes possible if they can be made to absorb more field energy than the rest of the mass.

High-frequency heating, however, can be applied intelligently only if the interaction can be predicted between the electromagnetic field of the oscillator and the sample; that is, if the dielectric constant and loss of the wood, of the resin, and of the impregnated material are known. Since such information was not available, the research project described herein was set up to secure this and related information. The study is exploratory rather than comprehensive. It attempts to lay the groundwork for further development by gathering information about the frequency response of representative species of wood and types of thermosetting resins from which conclusions for practical applications may be drawn. The tentative experiments with altered phenolic compounds are indicative of the directions in which the development might go. The problem of treating complicated shapes remains to be solved. Apparatus can undoubtedly be improved and much progress probably can be made in the technique of impregnation. These detailed investigations are beyond the scope of the present research, of which the chief objective is to gather information of a fundamental nature in the shortest possible time.

This investigation, carried through in the period from April to June 1942 in the Laboratory for Insulation Research of the Massachusetts Institute of Technology, was sponsored by, and conducted with financial assistance from the National Advisory Committee for Aeronautics.

The authors wish to acknowledge the invaluable assistance rendered by Mr. W. B. Westphal in the planning and operation of the susceptance-variation equipment and the high-frequency oscillator. Messrs. J. J. Donovan, D. G. Jelatis, and G. M. Lee gave valuable assistance on special problems. Mr. Randolph Charles and Miss Louise Muldoon served as able operators.

ANALYSIS OF PROBLEM

The Physics of High-Frequency Heating

A dielectric material like wood, introduced into the condenser field of an oscillator circuit, produces two effects. The capacitance of the condenser increases and energy is absorbed in the dielectric medium. A more quantitative description of this situation can be given by plotting the current I oscillating through the capacitor as a function of the periodic voltage V applied (fig. 1). In an ideal condenser the current precedes V by 90°; it is purely a charging current that serves for reversible storage of field energy. The introduction of the dielectric material increases the current and simultaneously diminishes the phase angle θ between I and V. A loss current has appeared in phase with the voltage applied, producing a power absorption. Thus,

$$W = I_{eff} V_{eff} \cos \theta \qquad (1)$$

A dielectric material can consequently be characterized by the charging and loss current produced under standard conditions: One cubic centimeter of the material exposed to a homogeneous field of the intensity $E = E_0 e^{j\omega t}$ (fig. 2) carries a current density (displacement current)

$$J = \frac{\partial(\epsilon E)}{\partial t} = \epsilon \frac{\partial E}{\partial t} + E \frac{\partial \epsilon}{\partial t} = \frac{\partial E}{\partial t}\left\{\epsilon - \frac{j}{\omega}\frac{\partial \epsilon}{\partial t}\right\} = \frac{\partial E}{\partial t}\left\{\epsilon' - j\epsilon''\right\} \tag{2}$$

If the dielectric constant ϵ of the medium is constant, only a charging current results

$$J_{charging} = \epsilon' \frac{\partial E}{\partial t} = j\omega\epsilon' E \tag{3}$$

If ϵ changes with time, that is, if the polarization of the medium needs time to develop and to disappear and consequently lags behind the field, a loss current arises

$$J_{loss} = -j\epsilon'' \frac{\partial E}{\partial t} = \epsilon''\omega E \tag{4}$$

A material is therefore described in its dielectric behavior by its complex dielectric constant

$$\epsilon_{co} = \epsilon' - j\epsilon'' \tag{5}$$

The real dielectric constant ϵ' and the loss tangent (fig. 2)

$$\tan\theta = \frac{\epsilon''}{\epsilon'} \tag{6}$$

or ϵ' and the dielectric conductivity in $ohm^{-1} - cm^{-1}$

$$\sigma = \epsilon''\omega = \frac{\epsilon''}{60 \cdot \lambda_{cm}} \tag{7}$$

(where λ_{cm} is the wave length in centimeters of the oscillator) are two alternative sets of parameters characterizing a dielectric medium. Because the power absorbed is given by

$$W = E_{eff}^2 \sigma \tag{8}$$

our measurements given hereinafter have, in general, been reported in ϵ' and σ characteristics.

The field strength E, which can be produced by an oscillator, is normally limited by corona losses and insulation requirements. It is therefore essential to select the woods, resins, and methods of impregnation procuring the highest dielectric conductivity. The atomistic sources of this conductivity are charge carriers migrating in the electric field and dipoles orienting themselves in field direction. In both cases the movement is impeded by the surrounding molecules, which are thrown out of equilibrium by the motion of the charges and dissipate energy in heat vibrations.

Method of Measuring the Complex Dielectric Constant

High dielectric conductivity normally means high frequency (equation (7)). An upper limit for the frequency range, however, is set by the size of the condenser needed for treating the stock and the power producible at shorter wave lengths. In compromising between these requirements, the frequency range between 1 and 100 megacycles has been selected as the most useful one for high-frequency heating.

The dielectric measurements in this wave-length band have been made by the method described in reference 1 and schematically illustrated in figure 3. A signal generator is coupled loosely to a resonance circuit, consisting of the coil L and three condensers C, C_s, and C_m in parallel; a resistance R represents the resistance of the coil and wiring. C is a large precision condenser, C_s, the sample holder, and C_m, a micrometer condenser of about 5 micro-microfarad total capacitance. C_s is a plate condenser of 2-inch plate diameter; one of the plates stays in fixed position, the other can be set by a micrometer drive to any distance between 0 and 3/10 inch.

After the sample is inserted, the circuit is tuned to resonance by adjusting C. The resonance voltage V_r across C_s is measured by a vacuum voltmeter. The voltage is lowered to a value V by detuning the circuit with C_m. The value of V is reached above and below the resonance frequency (fig. 4); the capacitance change of C_m between A and B is ΔC. After the sample is taken out, the circuit is retuned to resonance by diminishing the plate distance of C_s, thus increasing its air capacitance from C_o to $C_o + \Delta C_s$. By decreasing the oscillator output, the resonance voltage without sample is adjusted to the old value V_r and again lowered by detuning to V. The width of the resonance curve between A' and B' measured on C_m now has the smaller value ΔC_o. By measuring ΔC_i, ΔC_o, the frequency ω of the oscillator, the ratio V_r/V, and the capacitance of the condenser without sample C_o and with sample $C_o + \Delta C_s$, the dielectric constant and loss of the sample can be calculated.

The dielectric constant is simply given by the ratio of the capacitance of the sample holder with and without sample

$$\epsilon' = \frac{C_o + \Delta C_s}{C_o} = 1 + \frac{\Delta C_s}{C_o} \tag{9}$$

The conductance G_s produced by the sample follows from a discussion of the circuit impedances

$$G_s = \frac{\omega(\Delta C_i - \Delta C_o)}{2\sqrt{\left(\frac{V_r}{V}\right)^2 - 1}} \tag{10}$$

The loss tangent of the sample, according to figure 5 and equation (6), determine ϵ'' by

$$\tan\theta = \frac{\epsilon''}{\epsilon'} = \frac{G_s}{\omega(C_o + \Delta C_s)} \tag{11}$$

Only capacitance changes need be made when the method of reference 1 is used. The errors produced by lead impedances are thus reduced to a minimum and the correction factors for stray capacitances can be calculated.

APPARATUS AND MATERIALS

Sample Holder with Thermostatic Control

In order ~~to~~ draw conclusions as to the efficiency of high-frequency heating, it was necessary to investigate the dielectric response of the sample at several temperatures. A sample holder was therefore constructed which made it possible to heat the material and to keep it at a prescribed temperature level.

Figure 6 gives a cross section of the apparatus. The plate condenser $P_1 - P_2$ is surrounded by a brass jacket H, through which a heated liquid is pumped from a thermostated bath. The liquid circulates directly over the rear of the condenser plate P_1, which is fastened to a bellows B and can be set to the desired distance from P_2 by the micrometer screw M. The electrode P_2 is kept insulated and in fixed position by specially ground quartz insulators Q. Plate P_1 can be accurately set parallel to P_2 by adjustment of three springs S. If the faces of a sample are not exactly parallel, this spring arrangement allows P_1 to come to a full contact. The micrometer head is not fastened to P but pushes only against the surface with a spherical contact. Backlash is avoided by the counteracting spring S.

A sample holder of this kind, besides being a plate condenser, acts at higher frequencies as a network of distributed capacitances and inductances. In figure 7, the equivalent network is indicated. For each frequency the values of the distributed parameters C_{d1} and L_d are different; but, after finding them for a given frequency, a correction curve for that frequency, which allows the true capacitance for every setting of the sample condenser C_s to be found, can be drawn.

With this sample holder, temperature runs were made up to about 100° C, which is the upper temperature limit of the thermostated bath. This series of runs was sufficient to indicate the behavior of wood and resin with changes in temperature.

Wood

Five types of wood: sap and red birch (Betula spp.), yellow poplar (Liriodendron tulipifera), "African mahogany" (Khaya spp.), and Mexican mahogany (Swietenia spp.), commonly used in aircraft manufacture, were investigated unimpregnated to gain a reliable starting point for the research. For simplicity, these species are hereinafter referred to as "sap birch," "red birch," "poplar," and "mahogany." In its "dry" state, the material had been heated for 24 hours at 125° C, then cooled in a desiccator and weighed immediately. Any percentage of moisture content reported refers to the increase in weight in comparison with the dry state. The wood was used in disks 2 inches in diameter and about 1/8 inch thick; the samples were flat to about 2/1000 inch and their surfaces were covered with a thin layer of vaseline to insure good electrical contact with the electrodes. The vaseline coating also helped simultaneously to stabilize the moisture content over longer periods.

Resins

Seven commercial thermosetting phenolic-type resins were employed in the investigation: Five were essentially impregnants; one, a resin usually employed as an adhesive; and one, a film consisting of porous paper impregnated with resin. They are referred to by type, as follows:

Type A, B, C } impregnant, medium polymer

D, E } impregnant, low polymer

F impregnant and adhesive, medium polymer

G adhesive, film

RESULTS AND DISCUSSION

Dielectric Constant and Loss of Wood as Function of Frequency, Moisture Content, and Temperature

In most of the graphs presented, only dielectric constant ϵ' and dielectric conductivity σ have been plotted; in figure 8, however, a complete example is given for all four parameters, dielectric constant ϵ' (equation (5)), loss factor ϵ'' (equation (5)), loss tangent $\tan\theta$ (equation (6)), and conductivity σ (equation (7)). Figure 8 shows the response of dry sap birch between 1 and 100 megacycles; the dielectric constant is about 2.2 over the whole range; ϵ'' has a flat maximum at 20 megacycles; but σ increases continuously because of its proportionality with ω.

A comparison of sap birch, red birch, mahogany, and poplar in figure 9 shows that sap birch has a value slightly higher than the values of the other woods. Water absorption causes the values of ϵ' and σ to increase rapidly; the values for sap birch are again higher than the values for the other woods. (See figs. 10 and 11.)

While the preceding measurements give the impression of smooth characteristics without modulation, a survey on a more extended frequency scale (fig. 12) shows the existence of two pronounced regions of dielectric response: an absorption at very low frequencies disappearing at about 10,000 cycles and a second one with its maximum between 10 million and 100 million cycles. The low-frequency region must probably be ascribed to "interfacial" polarization: Ions migrate through the fiber layers, are stopped at the boundaries, and pile up as space charges. With increasing frequency the traveling distance of the charge carriers shortens, the interior boundaries become unimportant, the space charge effect disappears. The high-frequency maximum in the ϵ'' curve is produced by polar materials like water dipoles, tending to orient themselves in field direction but lagging behind the driving field strength.

Figure 13 summarizes the data for the conductivity as function of moisture content and shows again the advantage of using higher frequencies.

If the dielectric response is measured as a function of temperature, a very interesting effect appears: In dry woods, the dielectric constant and conductivity increase with temperature (figs. 14 and 15); in moist wood a very marked decrease is observed (figs. 14 to 16). Apparently the water dipoles suffer less friction at higher temperature and the loss produced by them moves to shorter wave lengths. The losses in dry wood, however, may be produced by polar groups coming at higher temperature to free rotation.

The Dielectric Behavior of Resins

Except for the dry film, the resins are all used as aqueous solutions or suspensions. Typical of the medium polymers is type A, for which the dielectric constant and conductivity in the dry solid form are shown in figure 17 as functions of the frequency. The losses are low. The effect of temperature on the characteristics of a medium polymer (type F) is shown in figure 18. The small decrease in dielectric constant with increased temperature is accompanied by an increase in conductivity (fig. 18). In the film adhesive (type G) the situation is more complex, as the crossing of the characteristics indicates (fig. 19). The paper base of the film may be responsible for the complication.

Impregnated Woods

Uncured.- A study of the curves of wood and resin characteristics would not indicate much of an effect if wood were impregnated with resin. Figure 20 shows, however, that a remarkable increase of dielectric constant takes place when sap birch is treated with type A impregnant. The water content (max. of 10 percent) left by the impregnation process (commercial process: wood bone-dry; then soaked in impregnating solution at room temperature for 48 hr and air-dried for 24 hr) cannot account for the change, as a comparison between figures 16 and 20 indicates. The effects of wood, moisture, and resin are apparently not additive.

In the following table are listed the percentages of resin impregnant (solids) retained in the wood after soaking. Percentages are based upon the dry weight of the wood before impregnation, that is, wood at six percent moisture content.

Table I

Resin Contents of Impregnated Wood, Percent

Resin	Species		
Type	Birch	Yellow poplar	Mahogany
A	23.3	28.1	22.4
B	25.9	32.5	23.2
C	25.6	29.0	25.7
D	30.2		
E	33.0		

Figure 21 shows the effect of impregnation of types A and D on poplar; figures 22 and 23 compare the effect of types A, C, and D on African and Mexican mahogany at room temperature. A temperature increase on impregnated woods raises dielectric constant and loss (figs. 21, 22, and 24);

whereas, in moist wood without impregnation, the opposite effect is observed (figs. 14 to 16). The individual effects of wood and resin upon the dielectric properties are clearly visible; the combination of sap birch and type A resin produces the highest values, but the general effect is the same in every case.

The state of polymerization of the resin in general has little effect upon the characteristics of the impregnated wood, as a comparison of figures 20 to 24 shows. The one apparent exception to this rule seems to be sap birch—tested with type A impregnant. Figure 25 shows how closely a medium polymer (type B) and low polymer (type E) may coincide. The exceptional type A is included to show the extreme deviation from the usual condition. The effect of temperature on a low polymer (type E) is shown in figure 26, with the extreme case again plotted for comparison.

Dielectric measurements apparently yield a very sensitive measure of the state of polymerization, as figure 27 indicates. At room temperature the samples age, their dielectric constant and loss decrease, and seemingly approach after a month the same final value that can be reached quickly by moderate heating.

All measurements given so far refer to material impregnated in a commonly employed cycle. This cycle consists in first drying the veneers, then soaking them in the impregnating bath, and subsequently air-drying or force-drying to the desired final moisture content. It seemed possible that a suggested alternative process, presoaking of the wood in water or using it completely green instead of predrying, might speed up the impregnation process and affect the final characteristics. Some experimental runs (fig. 28), presoaking 24 hours in water at room temperature and then impregnating for 12 or 24 hours in the resin solution, yielded material of lower dielectric constant and conductivity. In tensile strength tests, these presoaked panels showed slightly better results.

Before curing, the panels are sometimes prepressed at about 70° C to reduce the thickness of the material some 20 percent. The resulting increase in density produces an increase in dielectric constant and loss (fig. 29), as is to be expected.

Cured.- The dielectric properties of the cured, impregnated, and compressed material (specific gravity 13) are given in figures 30 to 32. The combination of sap birch and type A resin is again used for determining the curves. Figures 30 and 31 refer to two sets from the same group of closely matched impregnated panels, the one set being cured in a factory, the other in the laboratory. In both cases the material shows high dielectric constant and loss, but the order is somewhat reversed, indicating that the method of handling is of some importance. The longer the time internal between impregnating and curing and the older the cured sample, the lower are, normally, dielectric constant and loss. The freshly cured material apparently contains appreciable quantities of moisture released by the polymerization reaction, and the loss of this moisture with time makes itself felt (fig. 28). The temperature coefficient remains positive (fig. 30) for a sample three months old. Such panels again increase slightly in dielectric constant and conductivity in very moist weather.

Some Experiments with Special Impregnants

After the wood is cured, the exterior pressure cannot normally be released until the pressure of the water vapor in the wood has been lowered sufficiently by cooling to avoid rupture of the sample. Other factors being equal, it is therefore desirable to use resins of low setting temperature. A lowering of the phenol in the phenol-formaldehyde resins may be effected by substitution of phenolic compounds like cresol or resorcinol. Consequently, a few resin solutions were made up containing 1 molecule of phenolic compound to $1\frac{1}{2}$ molecules of formaldehyde.

Figure 33 gives the dielectric measurements on sap birch impregnated with these solutions; the percentage refers to the amount of phenol replaced by the other compound. The cresol content is apparently especially effective.

Qualitative measurements of the setting temperature established the following tentative sequence, arranged in the order of fastest to slowest setting time: aminophenol, resorcinol, phenol, cresol, nitrophenol.

Summary of Information Gained from Dielectric Measurements

Figures 8 to 33 give the basic facts about the dielectric properties of woods, resins, and their combinations, which can be summarized as follows:

1. Large dielectric conductivity is desirable for high-frequency heating. It can be achieved by a proper combination of wood and impregnating solution; it increases with frequency.

2. An impregnated sample does not represent in its dielectric response the effect of wood plus water plus resin, but a new entity with appreciably higher losses.

3. For the combination of sap birch and type A resin a dielectric conductivity of 10^{-5} ohm^{-1} cm^{-1} at 50 megacycles (6 m) can be easily reached. This value represents (equation (8)) for a field strength of 1000 volts per centimeter an input of 10 watts or 2.4 calories per second. The same order of magnitude holds for other wood-resin combinations. If the specific heat of the wood and resin compressed to twice normal density is 0.8, its temperature can be raised 3° C per second or to 150° C in about 45 seconds. This condition will be about true for the center of the wood; the outer layers will lag somewhat behind on account of the heat loss to the electrodes and surroundings.

4. The characteristics of the impregnated and even of the cured sample change as function of time. Dielectric constant and conductivity decrease as time passes, probably indicating a slow polymerization in the uncured material and a loss of reaction moisture in the cured.

5. Presoaking of the wood instead of predrying and the development of resins of lower setting temperature might be considered. Some preliminary experiments in this direction are reported.

6. Dielectric constant and loss provide a sensitive indicator of moisture content and state of impregnation of the material.

7. The temperature coefficient of dielectric constant and loss are indicative of the condition of a

sample: In dry wood it is found to be positive, in moist wood negative, in impregnated and in cured wood it is again positive.

Oscillator and Sample Holder for Dielectric Heating

The foregoing measurements and calculations indicated that high-frequency treatments should measurably reduce the heating period of wood-resin combinations. To verify this conclusion and to establish a few principles, a 500-watt high-frequency oscillator-amplifier of a simple and flexible design was developed (fig. 34).

The driver consists of one double-tetrode 815 used as a push-pull oscillator and coupled directly into the grids of two power pentodes 8001. These tubes, again in push-pull arrangement, were selected because they require relatively low input power and allow high frequencies to be reached. Different coil and condenser combinations were made to cover the whole frequency range between 1 and 100 megacycles.

The output circuit was coupled to the amplifier stage by fixed inductive coupling. An inductance-capacitance network, serving as impedance transformer, transmitted the power from the oscillator to the sample through a coaxial line. A coil across the sample condenser compensated for a part of the capacitance.

The sample electrodes were circular disks cut from thin copper sheets. With the sample between them they were inserted into a press made from a 30-ton automobile jack. Porcelain tiles backed by asbestos provided the necessary electrical and heat insulation between condenser and press.

The temperature of the sample was controlled by a thermocouple inserted between layers of the veneer. The voltage across the sample was measured with a vacuum voltmeter.

Results of the High-Frequency Tests

Samples of sap birch and type A resin $3\frac{3}{4}$ inches in diameter and 3/8 inch thick subjected to a field of 600 volts per centimeter at 35 megacycles could be heated from room temperature to 150° C in about 1 minute. During the heating the impedance changes and the impedance transforming network had to be regulated to keep a purely resistive load. This regulation was also necessary if the pressure on the sample changed. The use of pressure during the preliminary heating period does not seem advisable because the wood easily becomes overheated in local regions and chars. If the pressure is applied after the heating period, no difficulties are encountered.

After a temperature of 150° C was reached, about 6 minutes were required at this temperature under pressure for curing and 3 minutes more under pressure without energy input for cooling to 80° C. The total time required for a curing cycle in the high-frequency field amounted thus to about 10 minutes. Heating and curing in the normal commercial cycle for material originally 1 inch thick takes about 40 minutes as compared with 7 minutes in the high-frequency field. Thickness is immaterial in the high-frequency process.

Figure 35 compares the dielectric properties of the "high-frequency cured" wood with those of the oven-cured material and of the impregnated panel before curing. The high-frequency process produced a cured material of much lower dielectric constant and loss than the normal heating cycle. This result seems readily understandable, for during the normal heating process the outside is hotter than the inner parts; consequently, the resin in the outside layers polymerizes first and traps the water developing in the interior during the setting process. In the high-frequency case the situation is just reversed and the moisture has a chance to evaporate. On large panels the effect may not be so pronounced.

Tensile-strength tests of samples of sap birch and type A resin cured by high frequency and by the standard hot-press cycle showed no essential difference between the two curing processes.

In addition to high-frequency curing, a number of gluing experiments have been successfully carried out. Wood samples several inches thick were glued together in 15 minutes; the glue layer itself (type F or type G) could be brought to 150° C in 30 seconds by selective heating but required additional time for setting.

SUGGESTIONS FOR FUTURE RESEARCH

The data obtained in the present investigation certainly should be supplemented by more extensive measurements under accurate control of time and temperature after impregnation. The facts available, however, are sufficient to proceed with practical applications. Experiments should be undertaken for curing and molding of odd-shape parts like propeller blades. The variation in thickness and density of the wood presents difficulties to the high-frequency process, which may be overcome by the proper reaction of the impregnating material – its losses should diminish while the curing proceeds. In addition, molds of the proper shape should be developed, if necessary, to equilibrize the field strength.

The increase of dielectric conductivity with frequency observed makes one further development feasible – it should be possible to construct an ultra-high-frequency gun, portable and operated like a hand drill, which would allow curing, gluing, and repairing on airplanes in the field.

CONCLUSIONS

Basic information about curing of resin-wood combinations by high-frequency heating indicates that the process is feasible, flexible, and timesaving. An energy input of about 10 watts per cubic centimeter of the material is desirable and can be produced with a field strength of about 600 volts per centimeter at about 50 megacycles. The value of dielectric measurements for investigating and controlling the properties of woods, resins, and their combinations is established.

Laboratory for Insulation Research,
Massachusetts Institute of Technology,
Cambridge, Mass., July 26, 1942.

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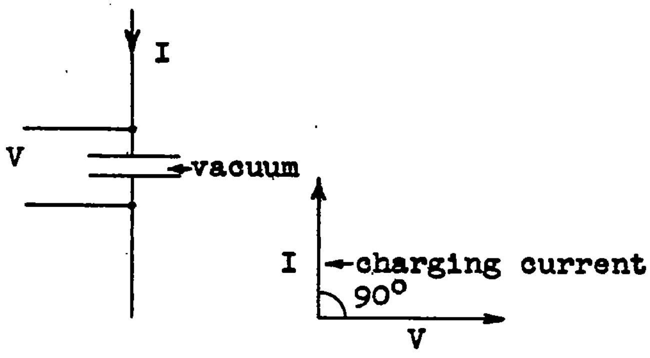


fig. 1a.

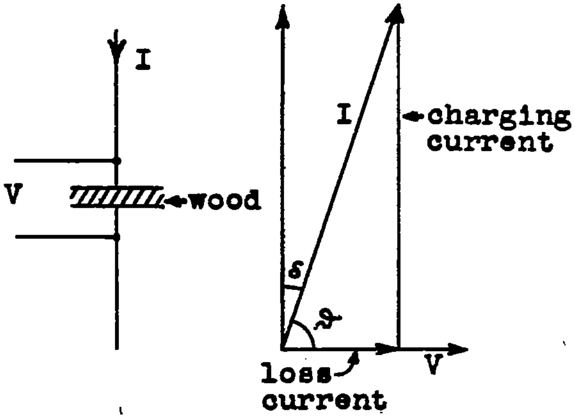


fig. 1b.

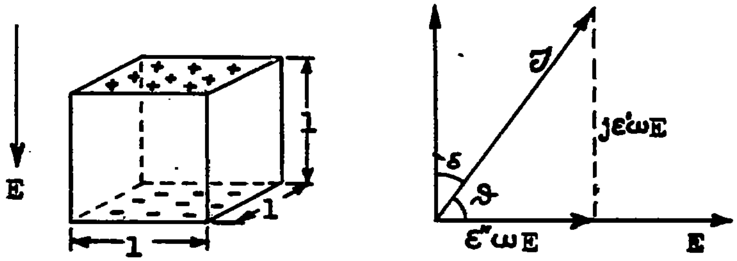


fig. 2.

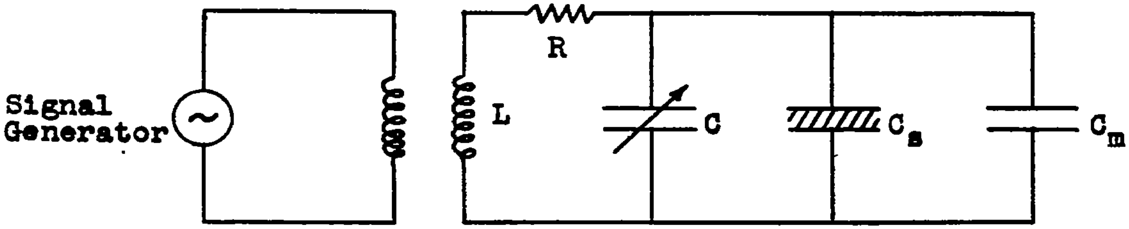
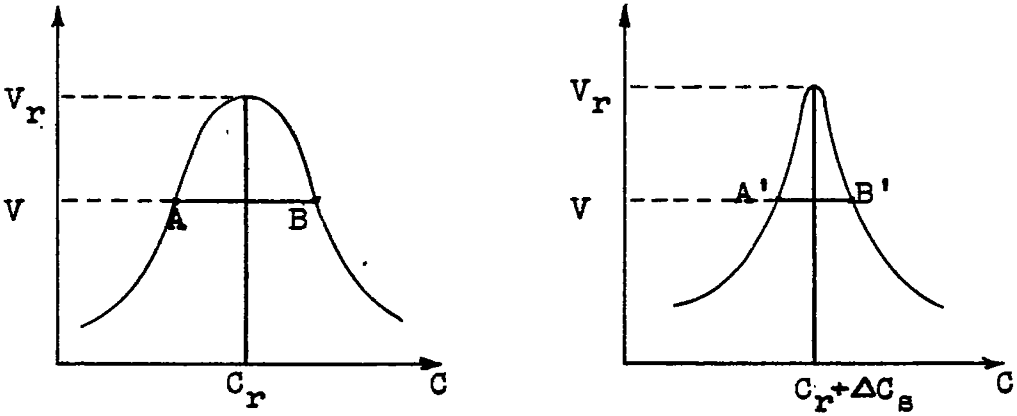


fig. 3.



with sample without sample

fig. 4.

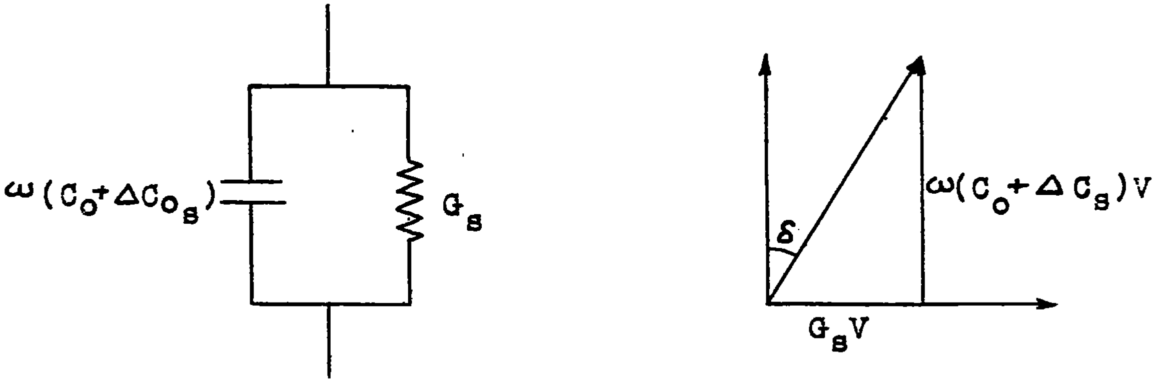


fig. 5.

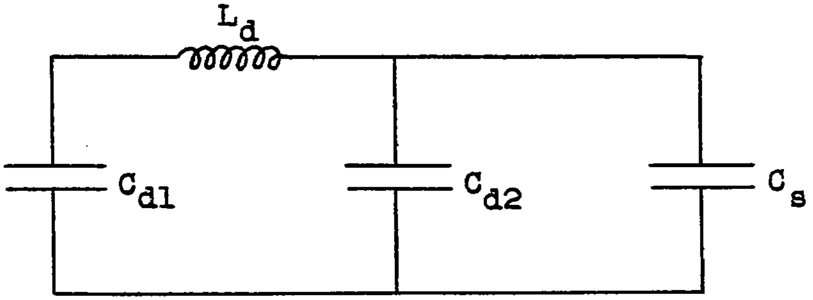
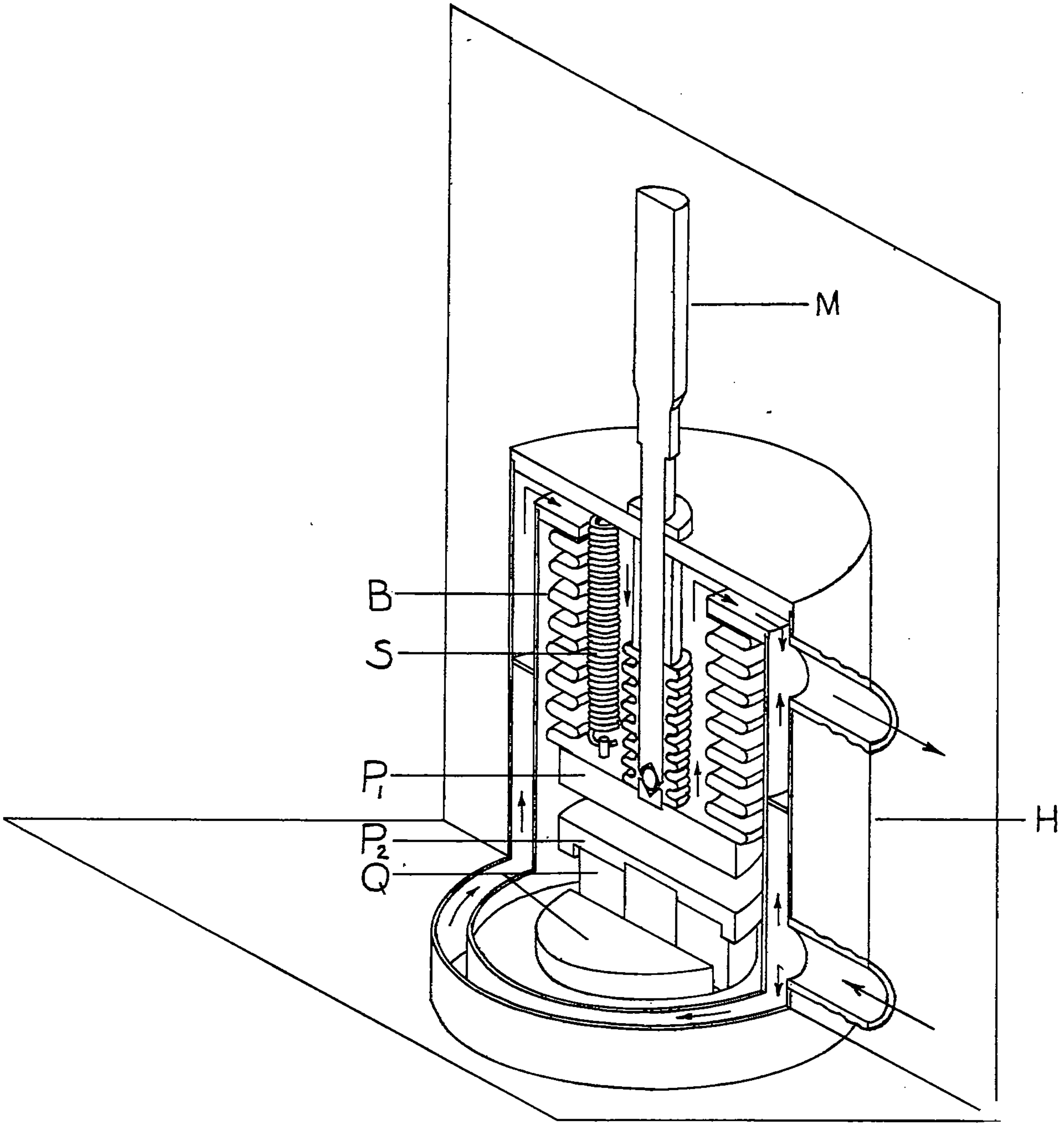


fig. 7



SAMPLE HOLDER

FIG. 6

Fig. 8

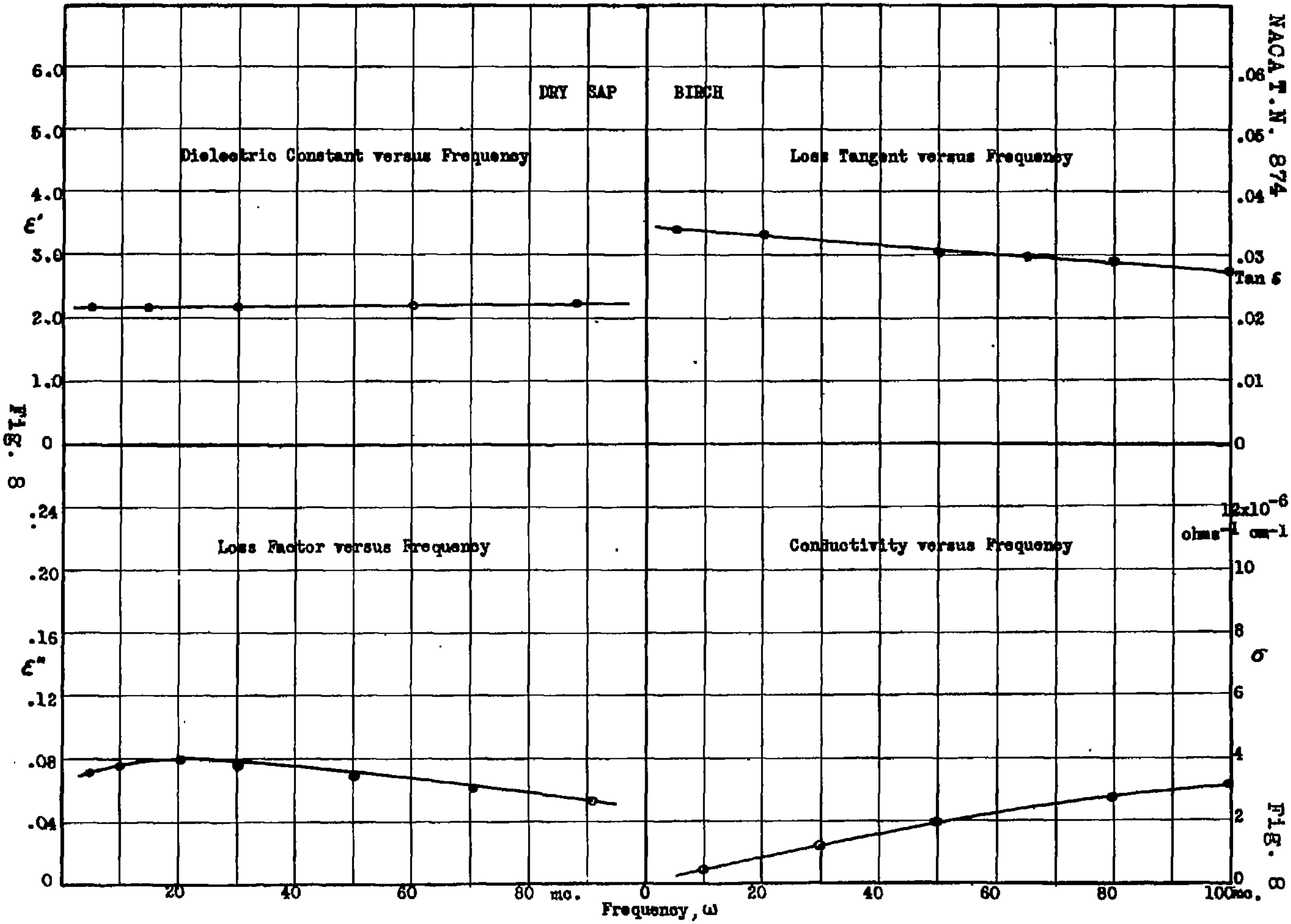

DRY SAP BIRCH
Dielectric Constant versus Frequency
Loss Tangent versus Frequency
Loss Factor versus Frequency
Conductivity versus Frequency
ε'
6.0
5.0
4.0
3.0
2.0
1.0
0
ε"
.24
.20
.16
.12
.08
.04
0
.06
.05
.04
.03
Tan δ
.02
.01
0
12x10⁻⁶
ohms⁻¹ cm⁻¹
10
8
σ
6
4
2
0
20
40
60
80 mc.
0
20
40
60
80
100 mc.
Frequency, ω

Fig. 8

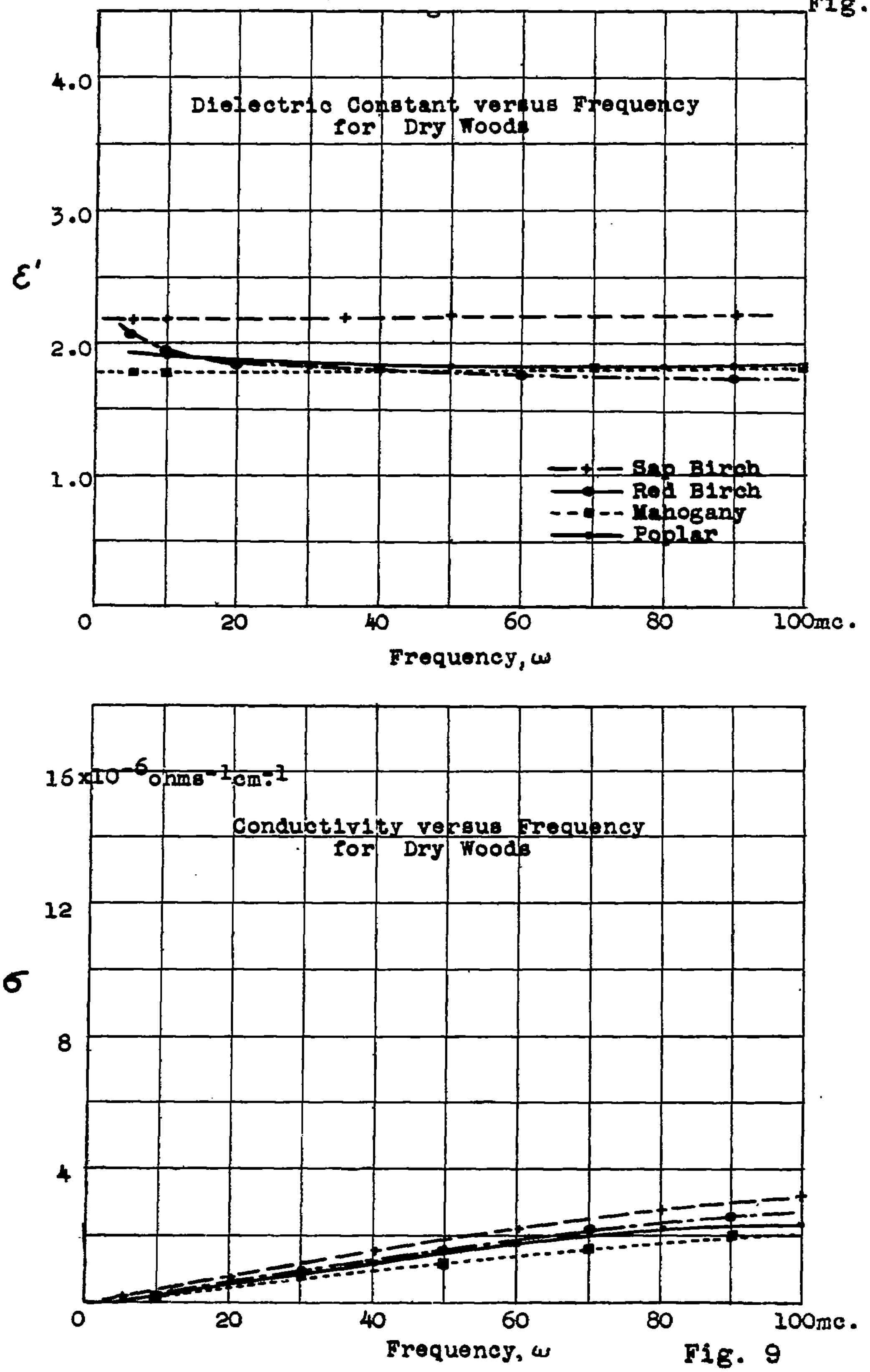

4.0
3.0
2.0
1.0
ε′
Dielectric Constant versus Frequency for Dry Woods
Sap Birch
Red Birch
Mahogany
Poplar
0
20
40
60
80
100mc.
Frequency, ω
16x10^{-6}ohms^{-1}cm.$^{-1}$
12
8
4
σ
Conductivity versus Frequency for Dry Woods
0
20
40
60
80
100mc.
Frequency, ω

Fig. 9

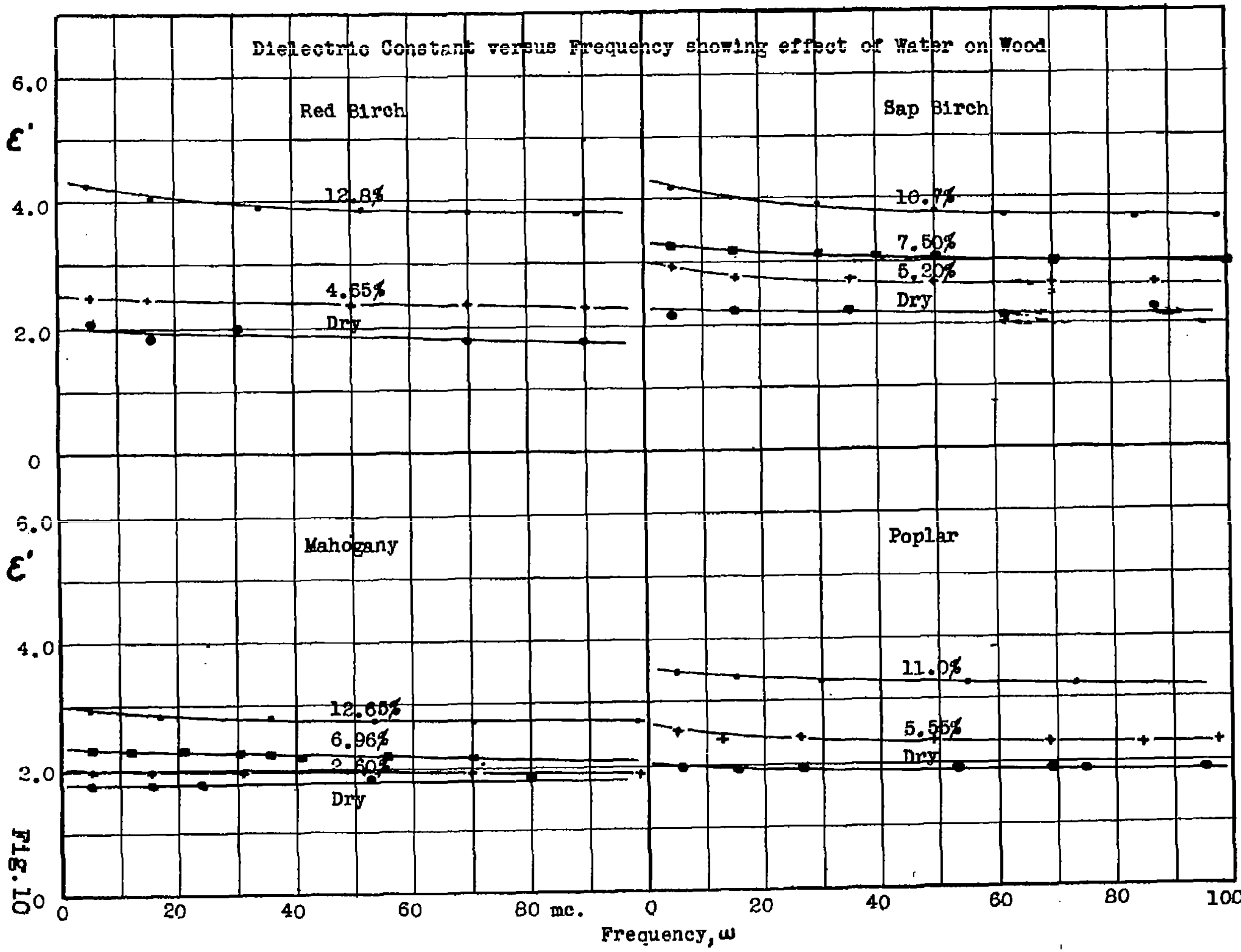

Dielectric Constant versus Frequency showing effect of Water on Wood
Red Birch
Sap Birch
Mahogany
Poplar
ε'
ε'
6.0
4.0
2.0
0
6.0
4.0
2.0
0
12.8%
4.65%
Dry
10.7%
7.50%
5.20%
Dry
12.65%
6.96%
2.60%
Dry
11.0%
5.55%
Dry
0
20
40
60
80 mc.
0
20
40
60
80
100mc.
Frequency, ω

Fig. 10

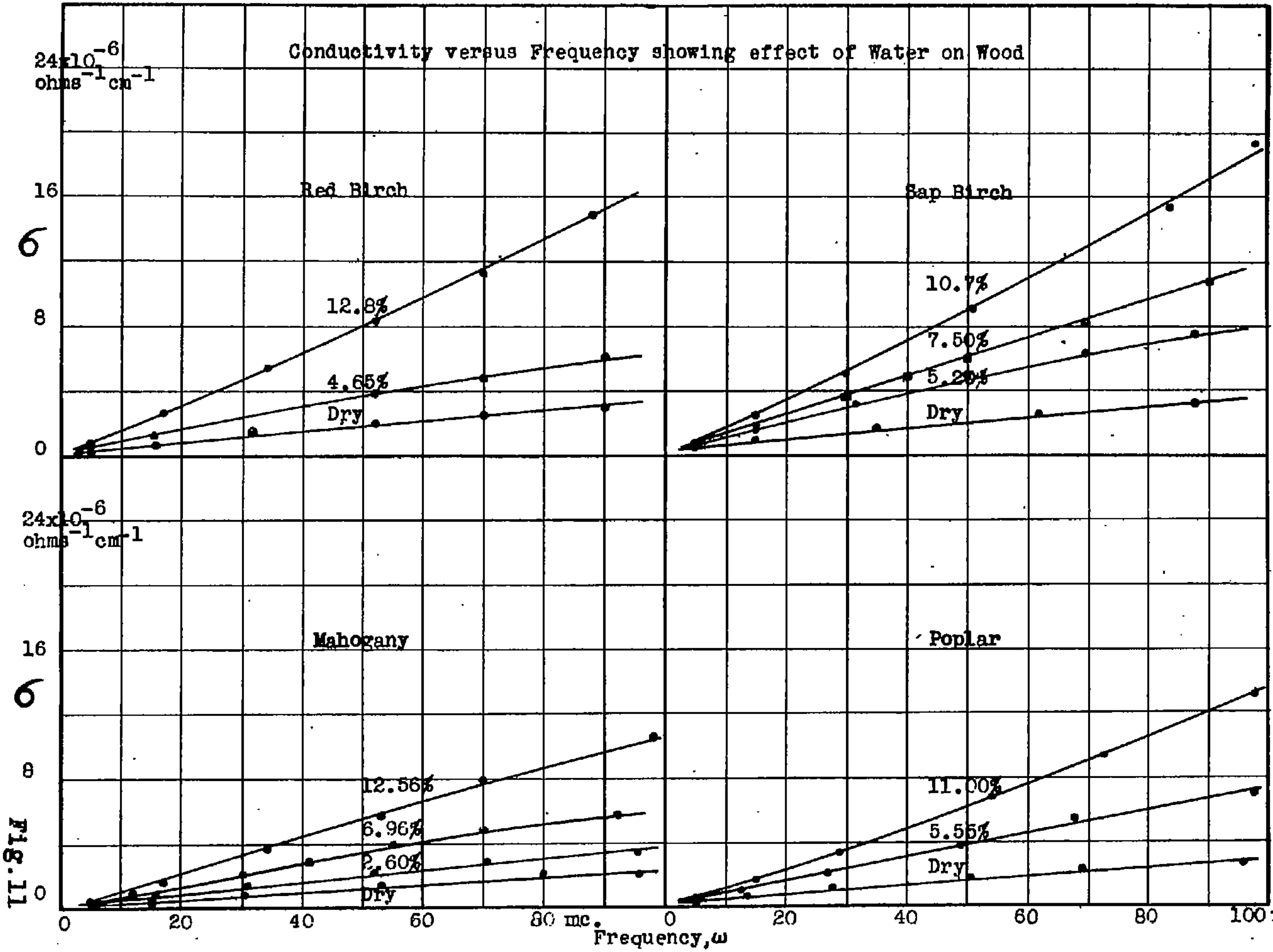
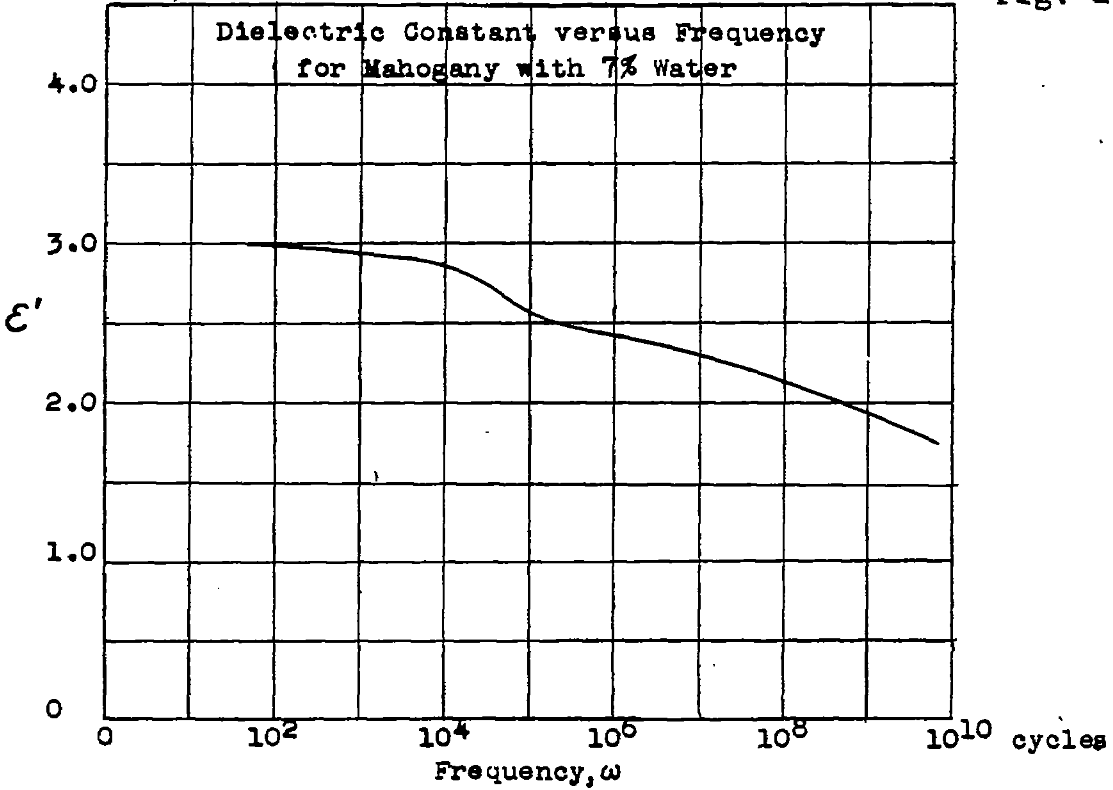

Conductivity versus Frequency showing effect of Water on Wood
24x10^{-6} ohms^{-1}cm^{-1}
16
6
8
0
Red Birch
12.8%
4.65%
Dry
Sap Birch
10.7%
7.50%
5.20%
Dry
24x10^{-6} ohms^{-1}cm^{-1}
16
6
8
0
Mahogany
12.56%
6.96%
2.60%
Dry
Poplar
11.00%
5.55%
Dry
0
20
40
60
80 mc.
0
20
40
60
80
100 mc.
Frequency,ω

Fig. 11


Dielectric Constant versus Frequency
for Mahogany with 7% Water
4.0
3.0
2.0
1.0
0
ε'
0
10²
10⁴
10⁶
10⁸
10¹⁰
cycles
Frequency, ω

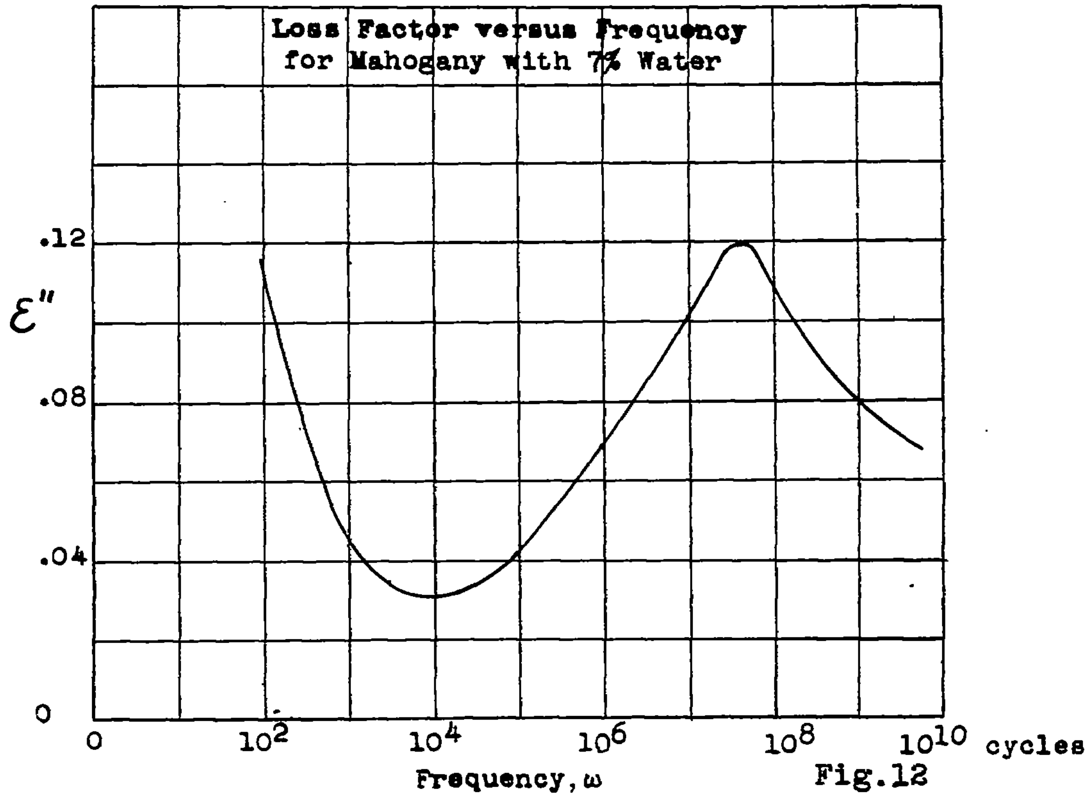

Loss Factor versus Frequency
for Mahogany with 7% Water
.12
.08
.04
0
ε"
0
10²
10⁴
10⁶
10⁸
10¹⁰
cycles
Frequency, ω

Fig.12

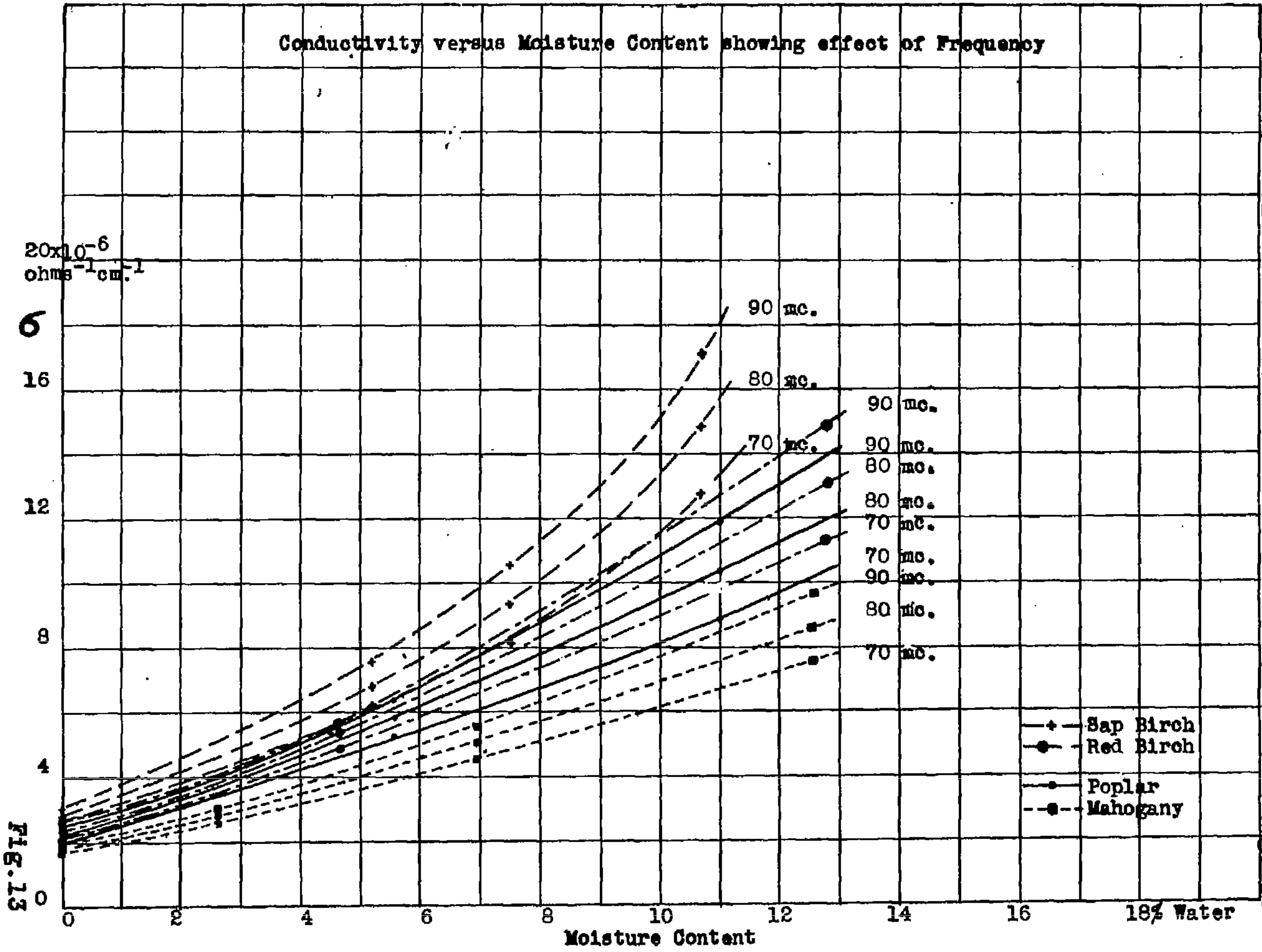

Conductivity versus Moisture Content showing effect of Frequency
20x10^{-6} ohms^{-1}cm.$^{-1}$
σ
16
12
8
4
0
0
2
4
6
8
10
12
14
16
18% Water
Moisture Content
90 mc.
80 mc.
70 mc.
90 mc.
90 mc.
80 mc.
80 mc.
70 mc.
70 mc.
90 mc.
80 mc.
70 mc.
Sap Birch
Red Birch
Poplar
Mahogany

Fig. 13

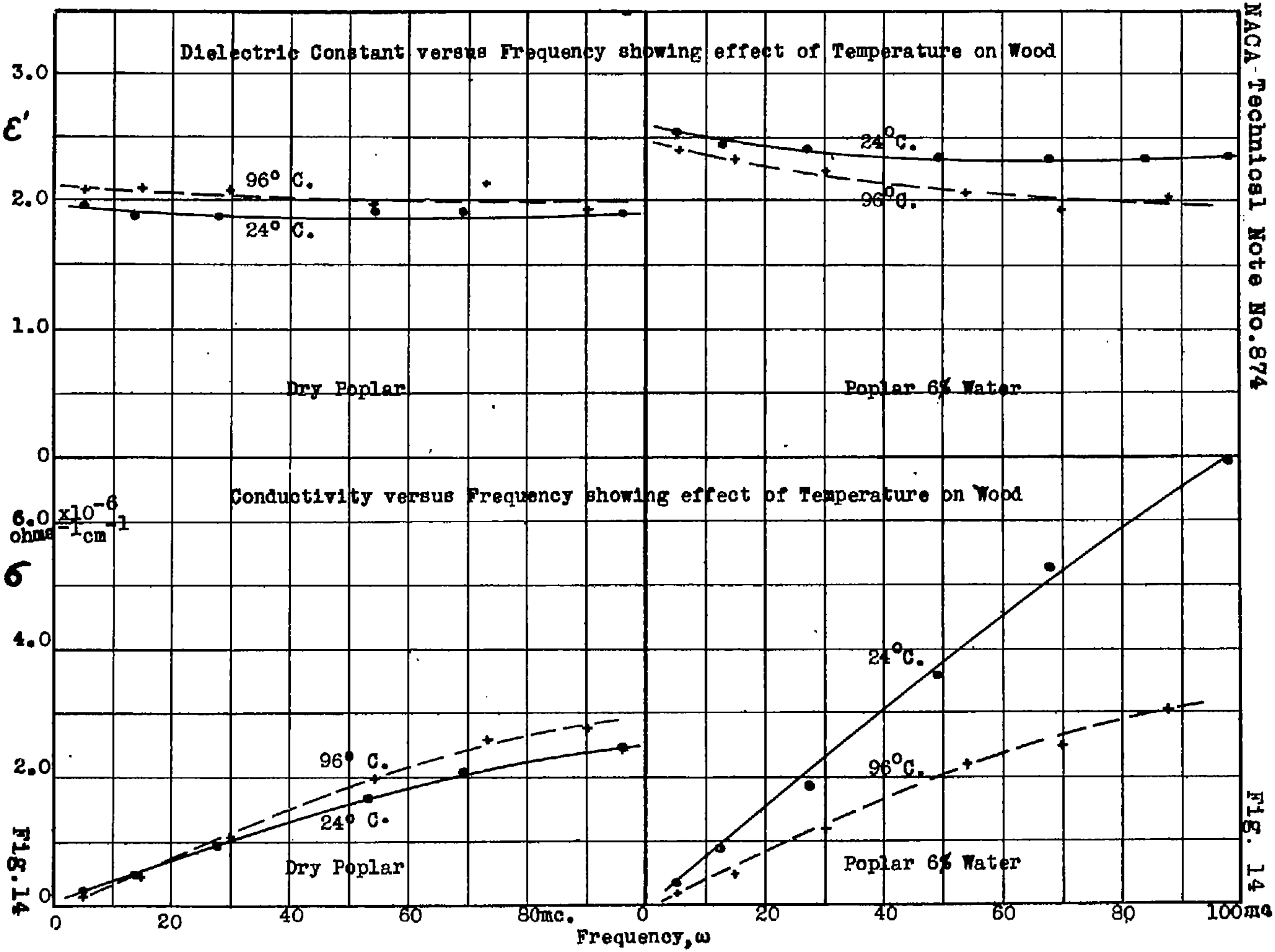

Dielectric Constant versus Frequency showing effect of Temperature on Wood
ε'
3.0
2.0
1.0
0
96° C.
24° C.
24°C.
96°C.
Dry Poplar
Poplar 6% Water
Conductivity versus Frequency showing effect of Temperature on Wood
σ
6.0 x10^{-6} ohms^{-1}cm^{-1}
4.0
2.0
0
96° C.
24° C.
24°C.
96°C.
Dry Poplar
Poplar 6% Water
0
20
40
60
80mc.
0
20
40
60
80
100mc
Frequency, ω

Fig. 14

Fig. 14

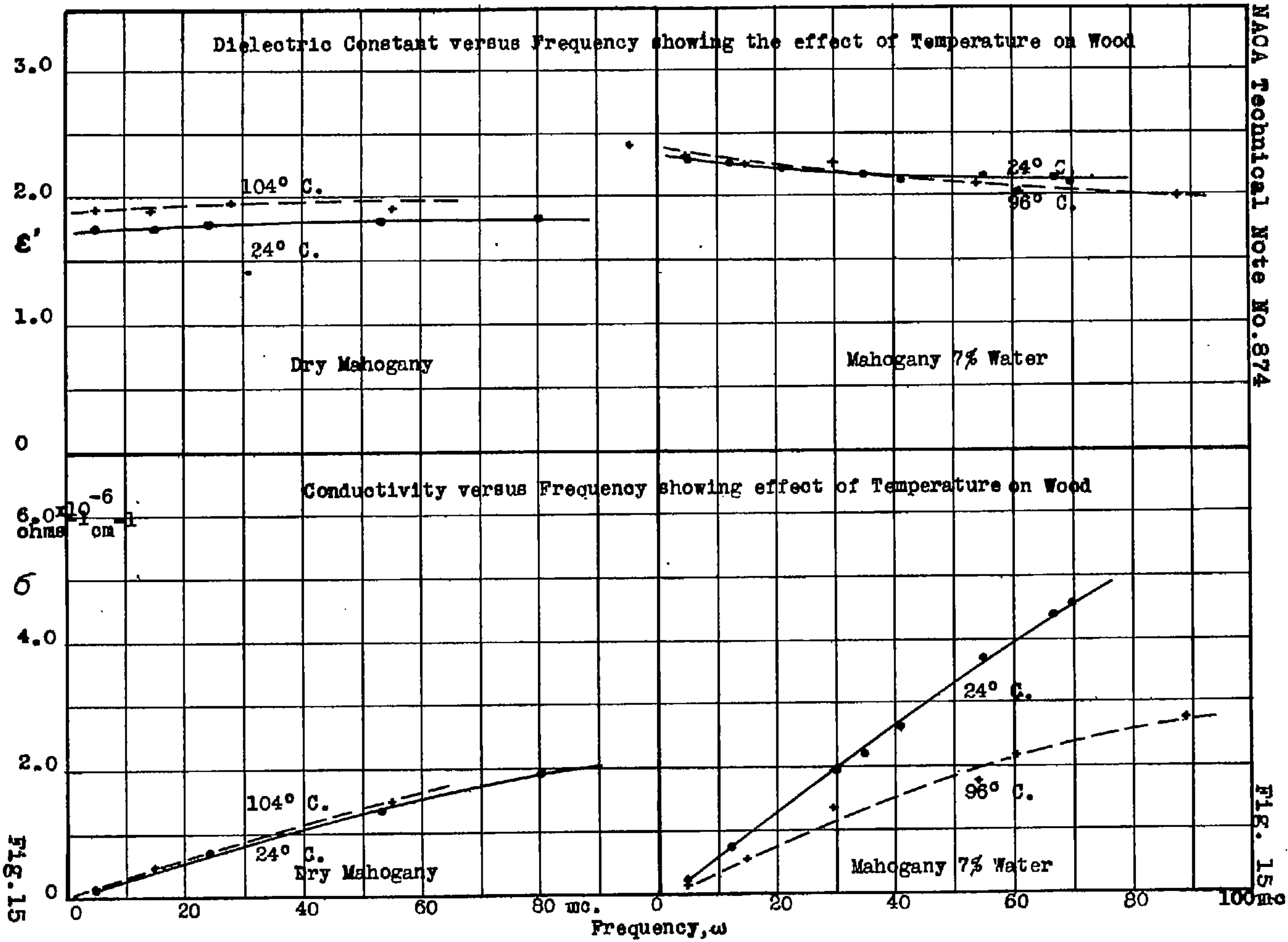

Dielectric Constant versus Frequency showing the effect of Temperature on Wood
3.0
2.0
1.0
0
ε'
104° C.
24° C.
Dry Mahogany
24° C.
96° C.
Mahogany 7% Water
Conductivity versus Frequency showing effect of Temperature on Wood
6.0x10^-6 ohms^-1 cm^-1
σ
4.0
2.0
0
104° C.
24° C.
Dry Mahogany
24° C.
96° C.
Mahogany 7% Water
0
20
40
60
80 mc.
0
20
40
60
80
100mc
Frequency, ω

Fig. 15

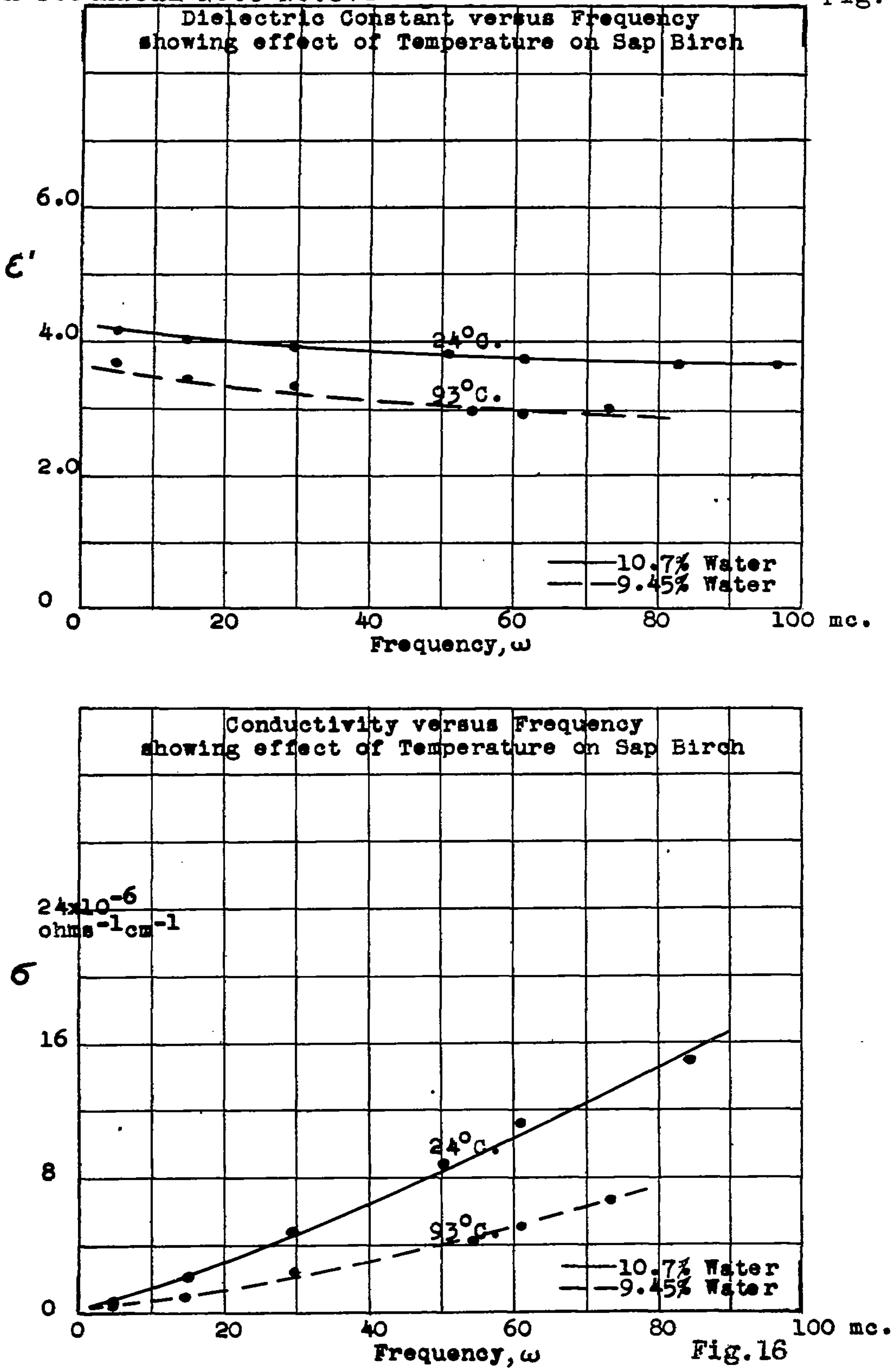
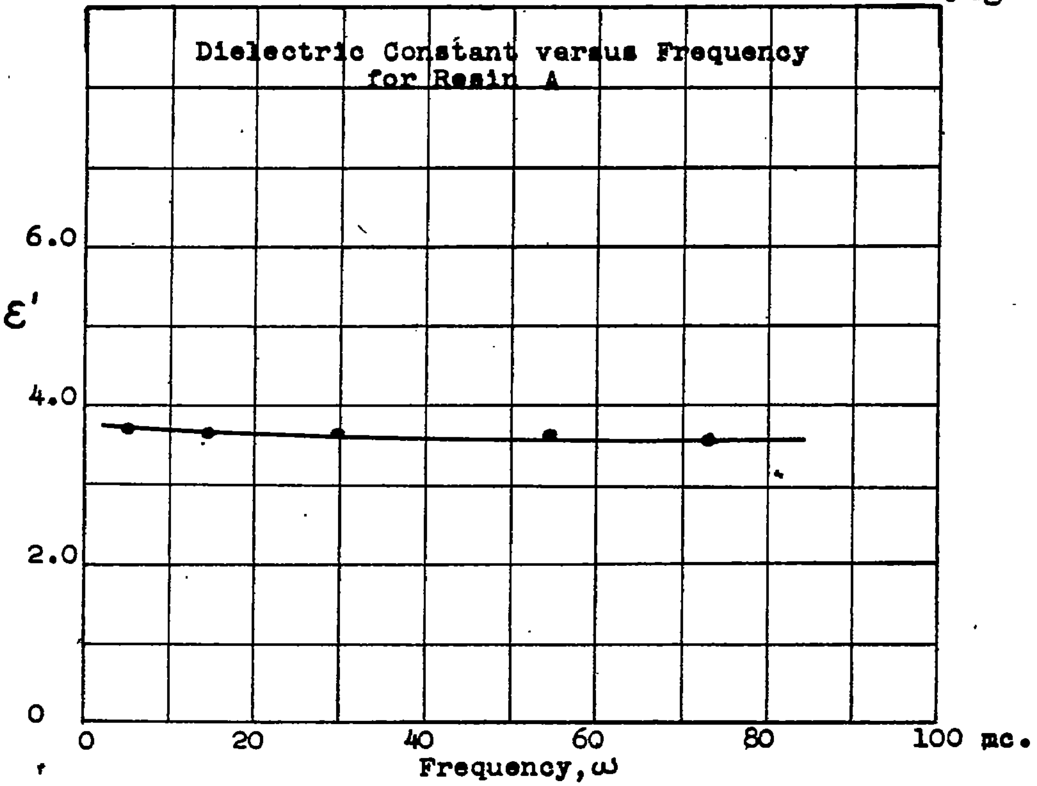

Dielectric Constant versus Frequency
showing effect of Temperature on Sap Birch
ε'
6.0
4.0
2.0
0
0
20
40
60
80
100 mc.
Frequency, ω
24°C.
93°C.
10.7% Water
9.45% Water
Conductivity versus Frequency
showing effect of Temperature on Sap Birch
σ
24x10⁻⁶ ohms⁻¹cm⁻¹
16
8
0
0
20
40
60
80
100 mc.
Frequency, ω
24°C.
93°C.
10.7% Water
9.45% Water

Fig.16


Dielectric Constant versus Frequency
for Resin A
6.0
ε'
4.0
2.0
0
0
20
40
60
80
100 mc.
Frequency, ω

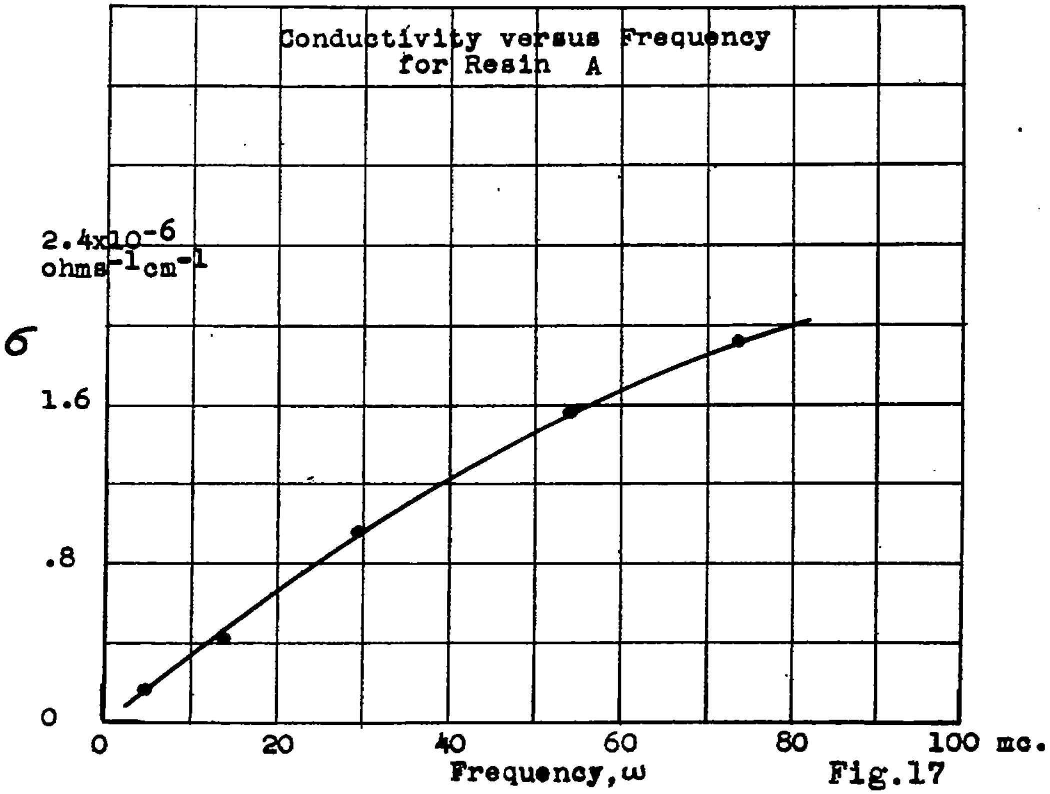
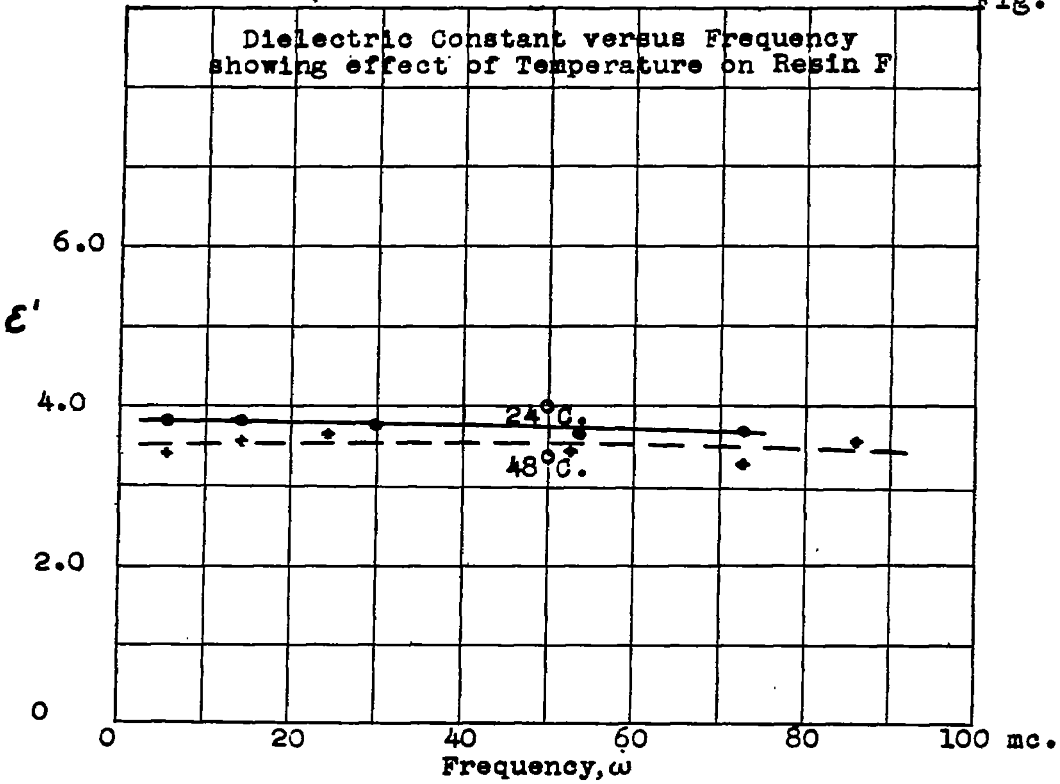

Conductivity versus Frequency
for Resin A
2.4x10-6
ohms-1cm-1
σ
1.6
.8
0
0
20
40
60
80
100 mc.
Frequency, ω

Fig.17


Dielectric Constant versus Frequency
showing effect of Temperature on Resin F
ε'
6.0
4.0
2.0
0
24°C.
48°C.
0
20
40
60
80
100 mc.
Frequency, ω

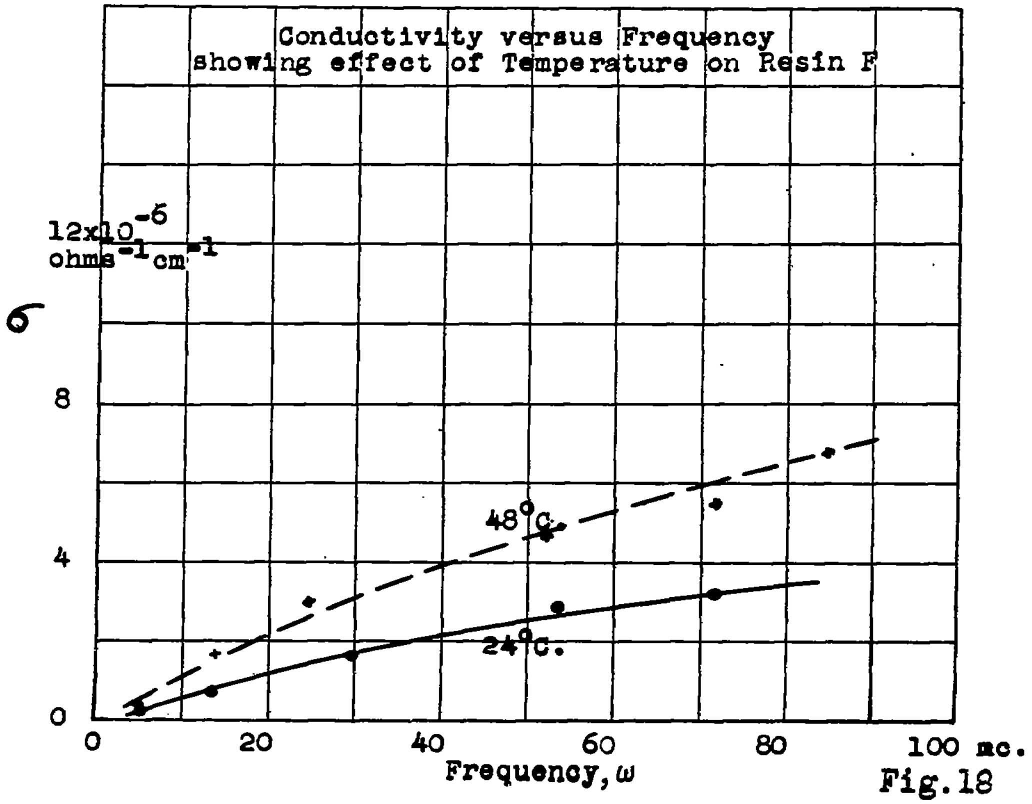
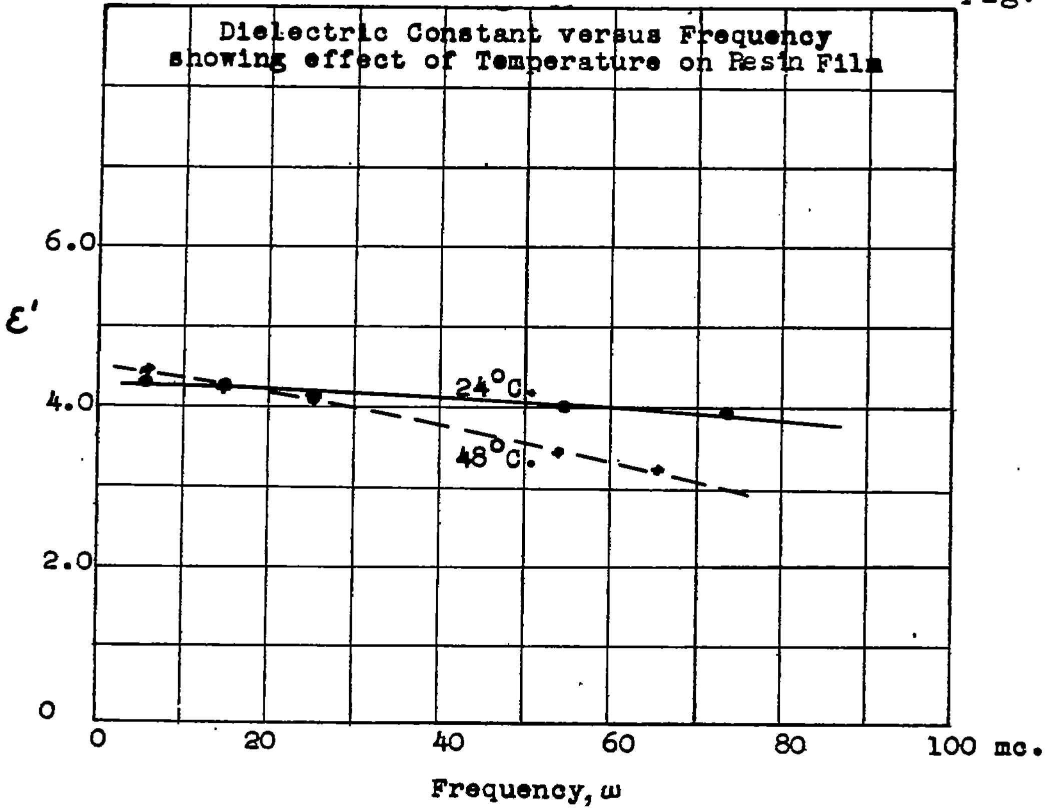

Conductivity versus Frequency
showing effect of Temperature on Resin F
12x10^-6 ohms^-1 cm^-1
σ
8
4
0
48°C.
24°C.
0
20
40
60
80
100 mc.
Frequency, ω

Fig.18


Dielectric Constant versus Frequency
showing effect of Temperature on Resin Film
ε'
6.0
4.0
2.0
0
24°C.
48°C.
0
20
40
60
80
100 mc.
Frequency, ω

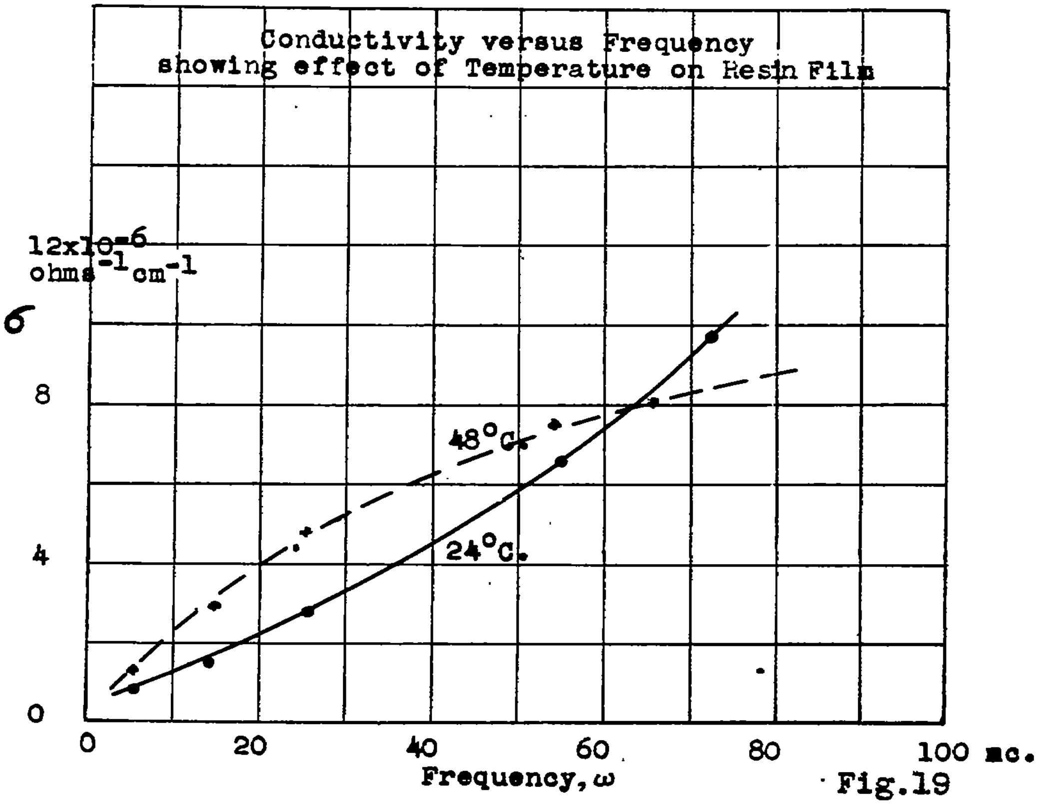
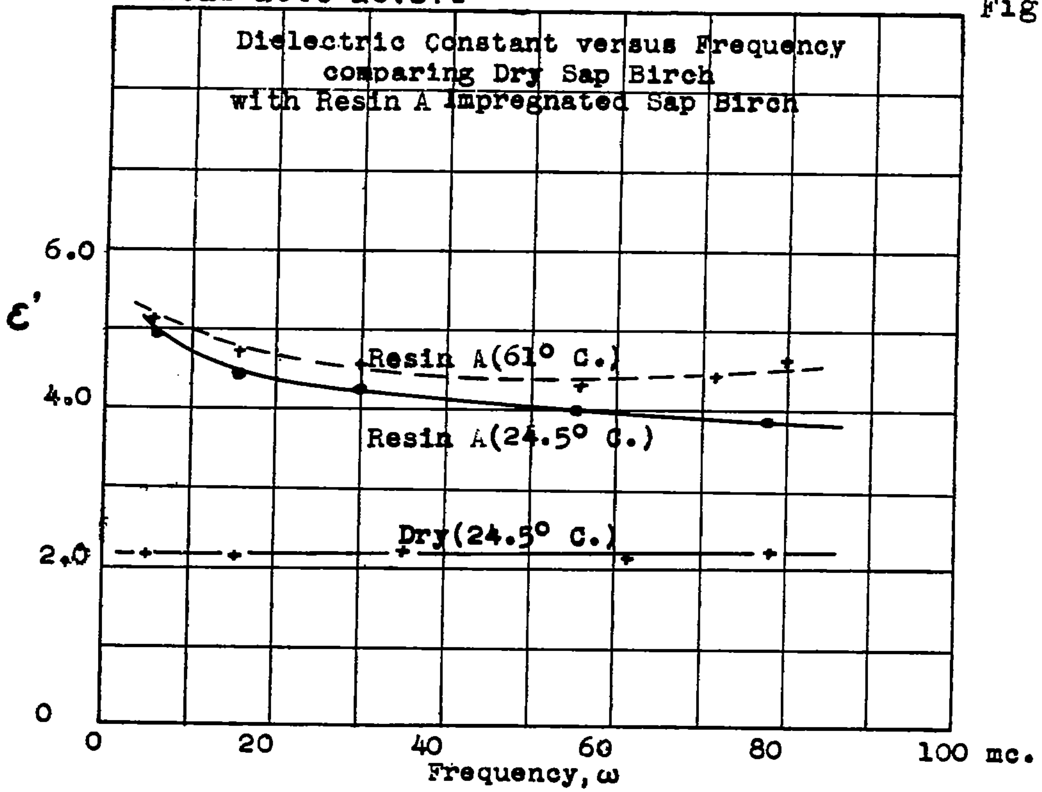

Conductivity versus Frequency
showing effect of Temperature on Resin Film
12x10^{-6}
ohms^{-1}cm^{-1}
σ
8
4
0
48°C.
24°C.
0
20
40
60
80
100 mc.
Frequency, ω

Fig.19


Dielectric Constant versus Frequency
comparing Dry Sap Birch
with Resin A Impregnated Sap Birch
ε'
6.0
4.0
2.0
0
Resin A(61° C.)
Resin A(24.5° C.)
Dry(24.5° C.)
0
20
40
60
80
100 mc.
Frequency, ω

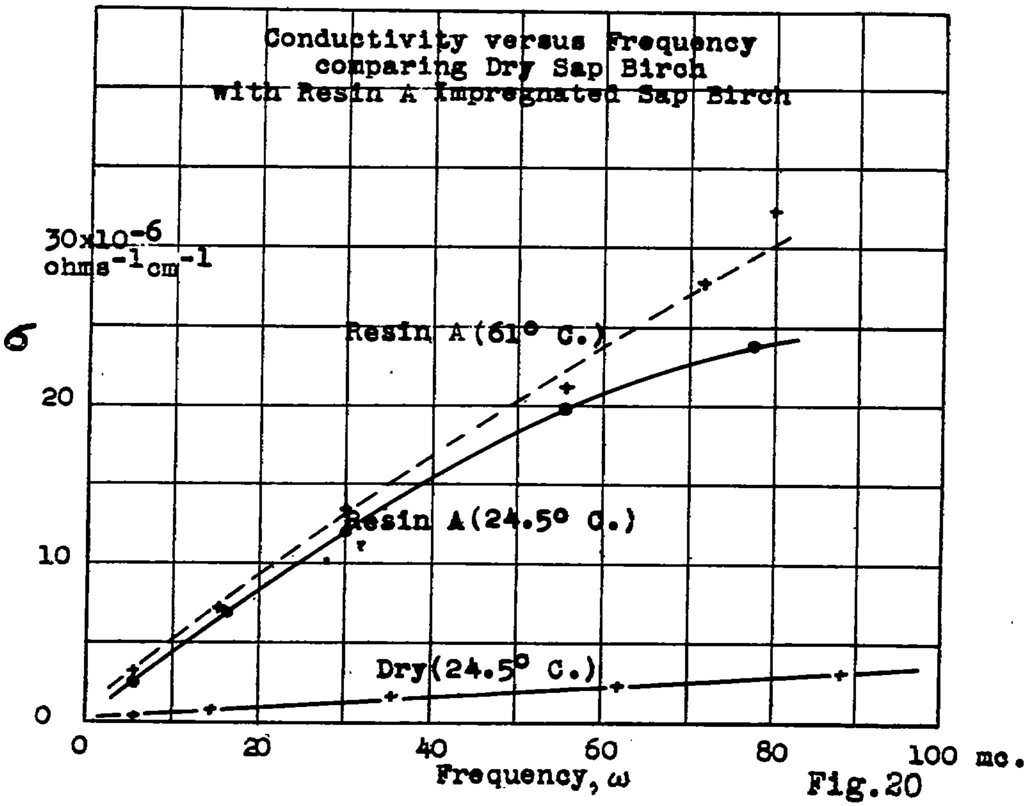
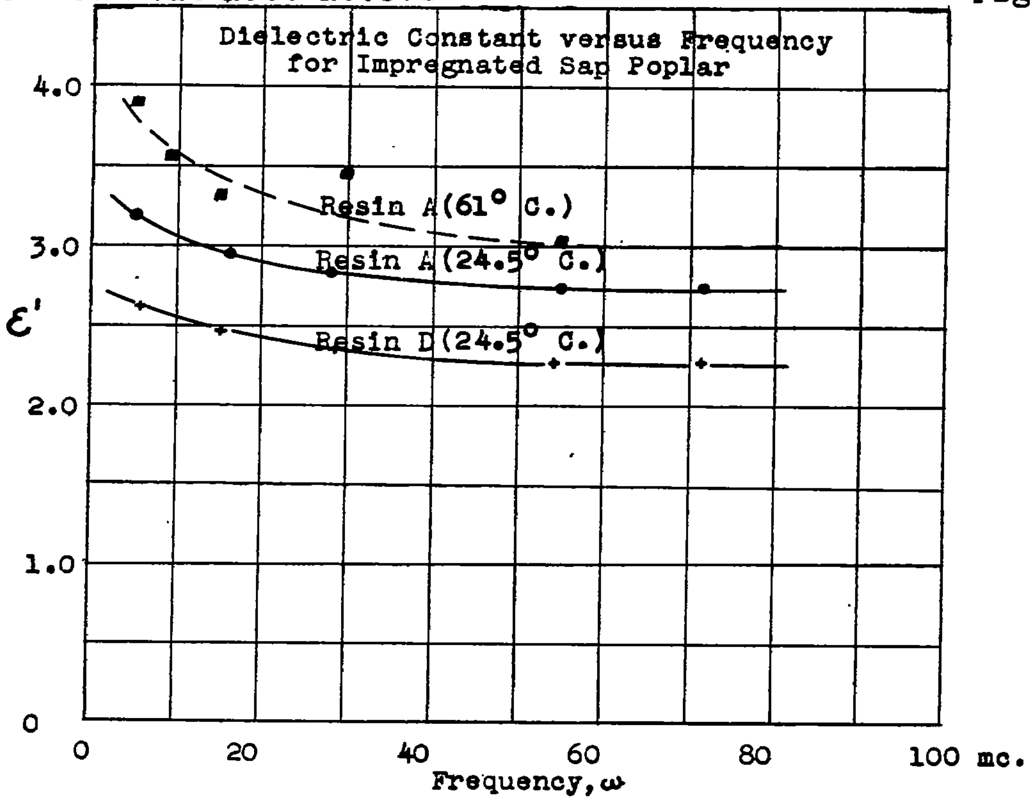

Conductivity versus Frequency
comparing Dry Sap Birch
with Resin A Impregnated Sap Birch
σ
30x10^-6 ohms^-1cm^-1
20
10
0
Resin A (61° C.)
Resin A (24.5° C.)
Dry(24.5° C.)
0
20
40
60
80
100 mc.
Frequency, ω

Fig.20


Dielectric Constant versus Frequency
for Impregnated Sap Poplar
Resin A(61° C.)
Resin A(24.5° C.)
Resin D(24.5° C.)
ε'
4.0
3.0
2.0
1.0
0
0
20
40
60
80
100 mc.
Frequency, ω

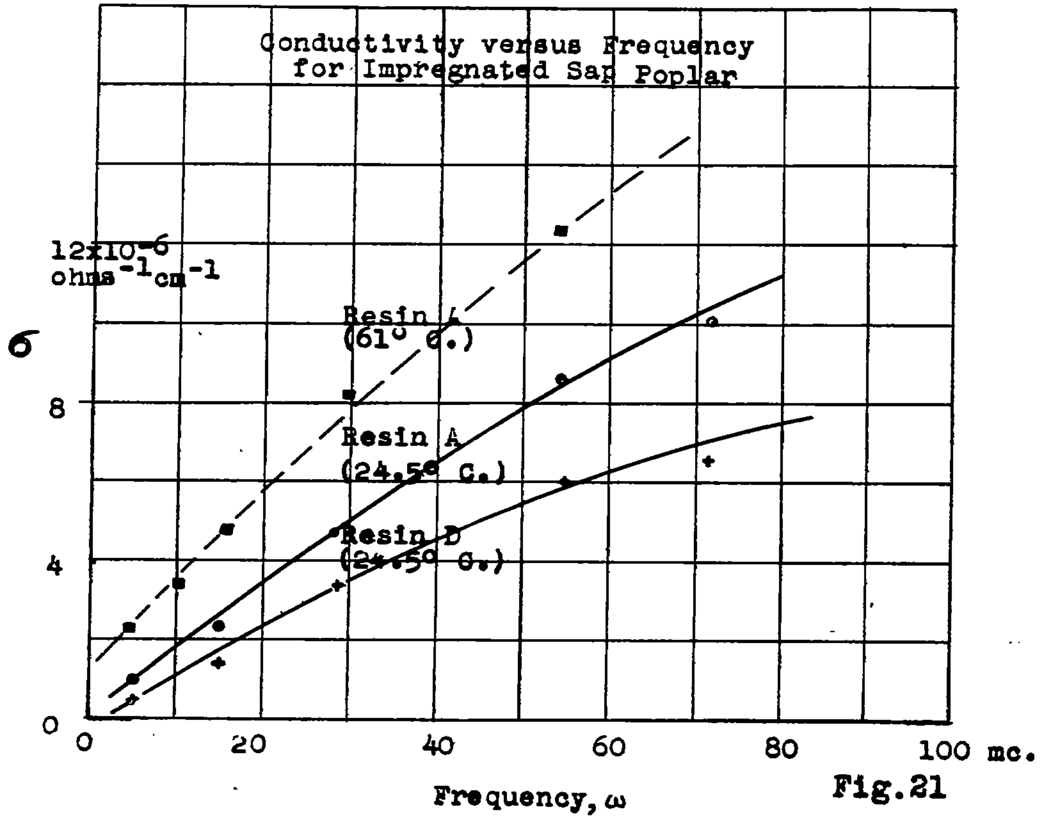
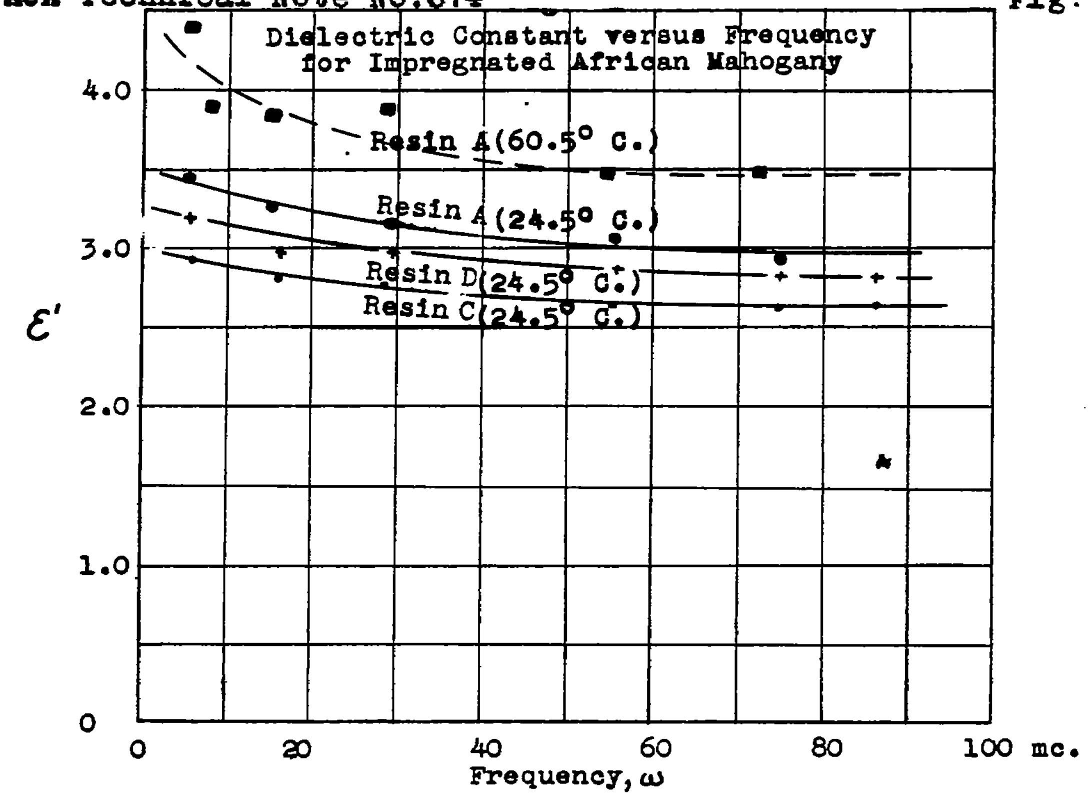

Conductivity versus Frequency
for Impregnated Sap Poplar
12x10^{-6}
ohms^{-1}cm^{-1}
σ
Resin A
(61° C.)
Resin A
(24.5° C.)
Resin D
(24.5° C.)
8
4
0
0
20
40
60
80
100 mc.
Frequency, ω

Fig.21


Dielectric Constant versus Frequency
for Impregnated African Mahogany
Resin A(60.5° C.)
Resin A (24.5° C.)
Resin D(24.5° C.)
Resin C(24.5° C.)
ε'
4.0
3.0
2.0
1.0
0
0
20
40
60
80
100 mc.
Frequency, ω

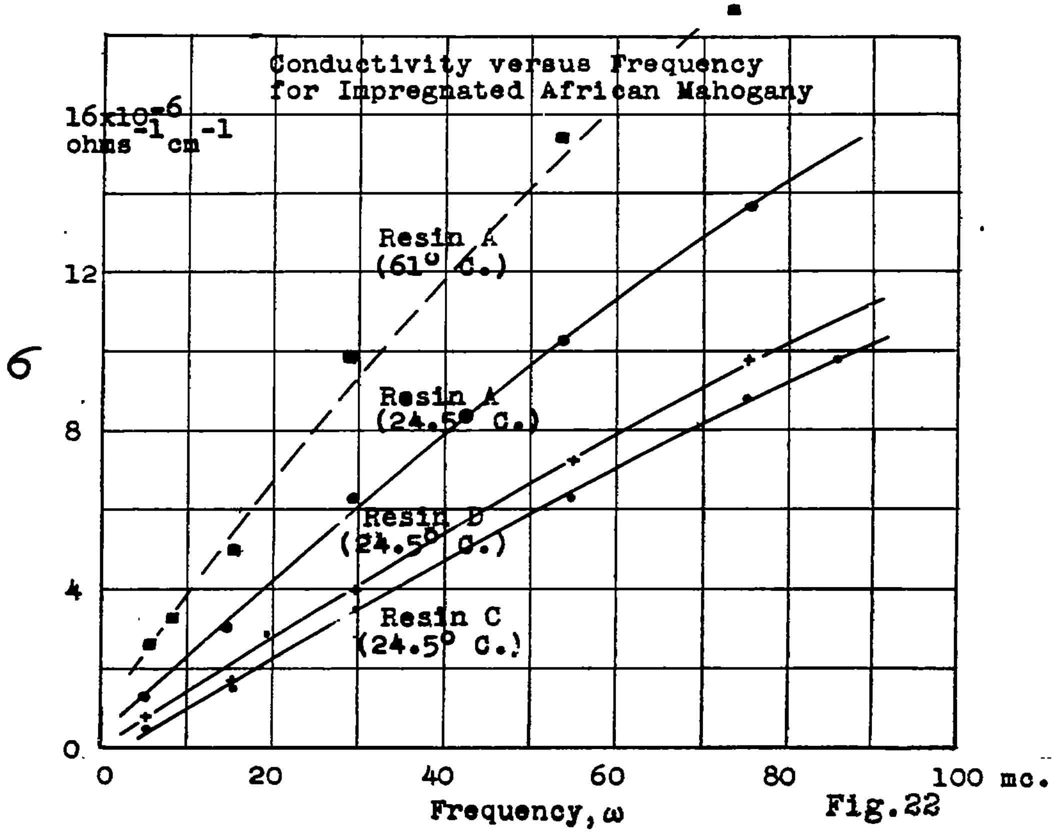
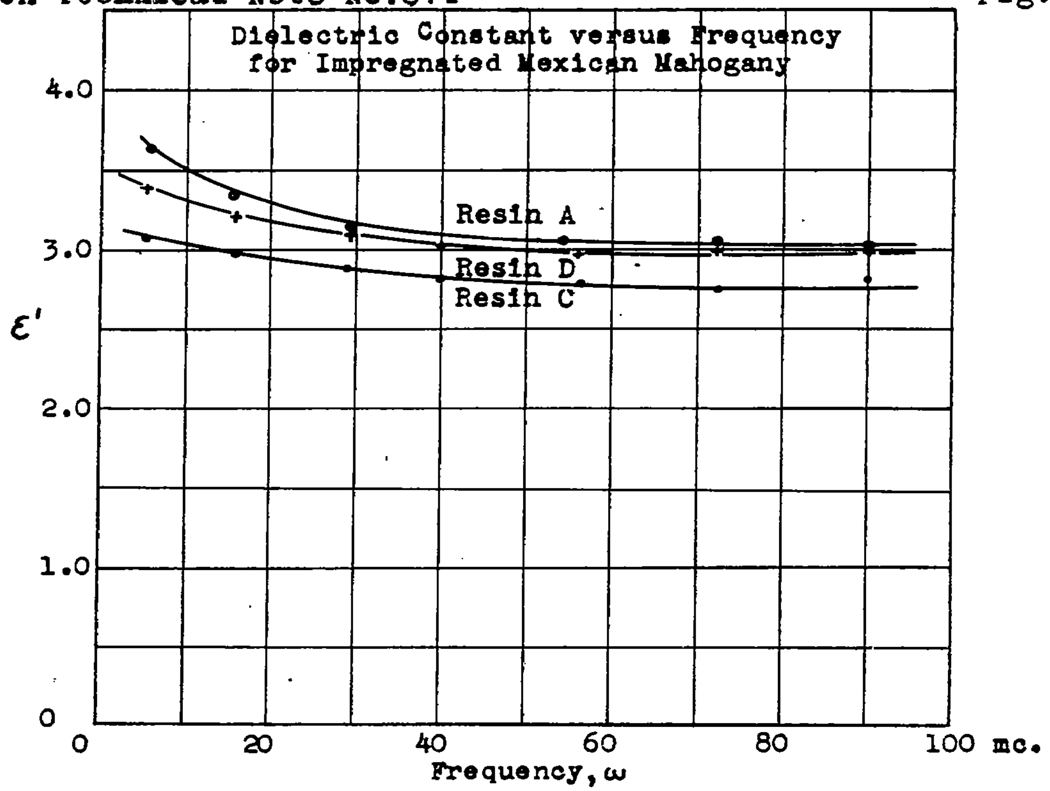

Conductivity versus Frequency
for Impregnated African Mahogany
16x10⁻⁶ ohms⁻¹ cm⁻¹
Resin A (61° C.)
Resin A (24.5° C.)
Resin D (24.5° C.)
Resin C (24.5° C.)
σ
12
8
4
0
0
20
40
60
80
100 mc.
Frequency, ω

Fig.22


Dielectric Constant versus Frequency
for Impregnated Mexican Mahogany
4.0
3.0
2.0
1.0
0
ε'
Resin A
Resin D
Resin C
0
20
40
60
80
100 mc.
Frequency, ω

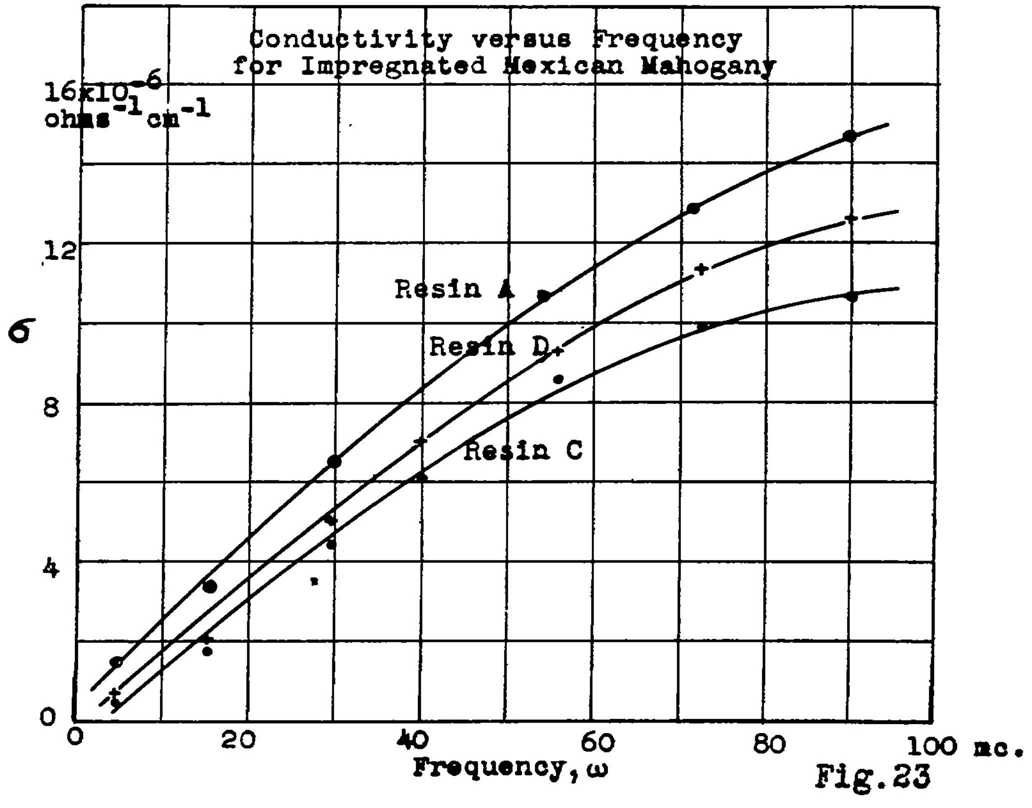
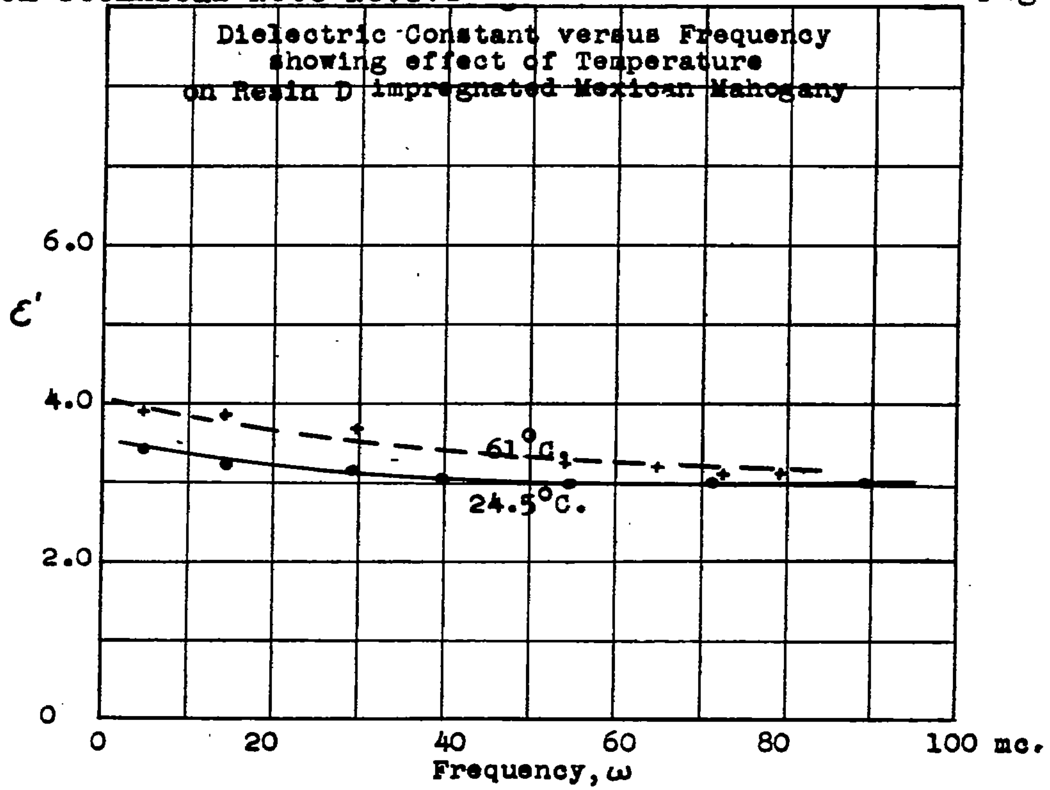
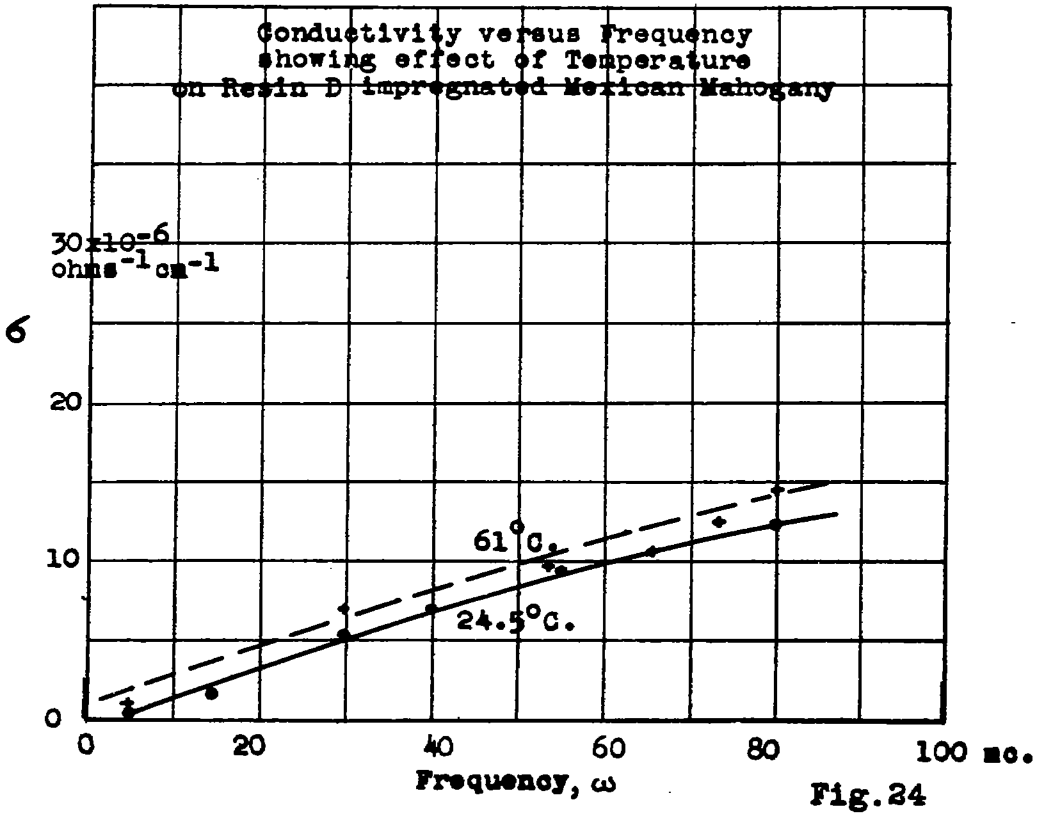

Conductivity versus Frequency
for Impregnated Mexican Mahogany
16x10^{-6}
ohms^{-1} cm^{-1}
12
8
4
0
σ
Resin A
Resin D
Resin C
0
20
40
60
80
100 mc.
Frequency, ω

Fig.23

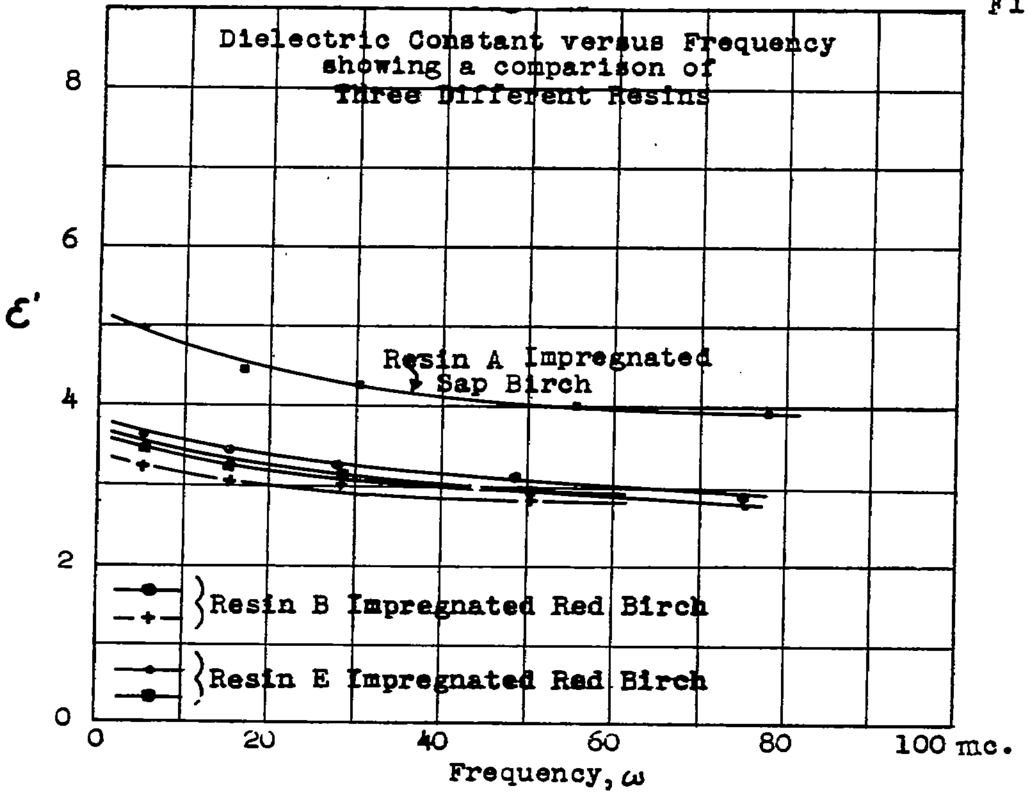


Dielectric Constant versus Frequency showing effect of Temperature on Resin D impregnated Mexican Mahogany



Conductivity versus Frequency showing effect of Temperature on Resin D impregnated Mexican Mahogany

Fig.24


Dielectric Constant versus Frequency
showing a comparison of
Three Different Resins
ε'
0
2
4
6
8
Resin A Impregnated Sap Birch
Resin B Impregnated Red Birch
Resin E Impregnated Red Birch
0
20
40
60
80
100 mc.
Frequency, ω

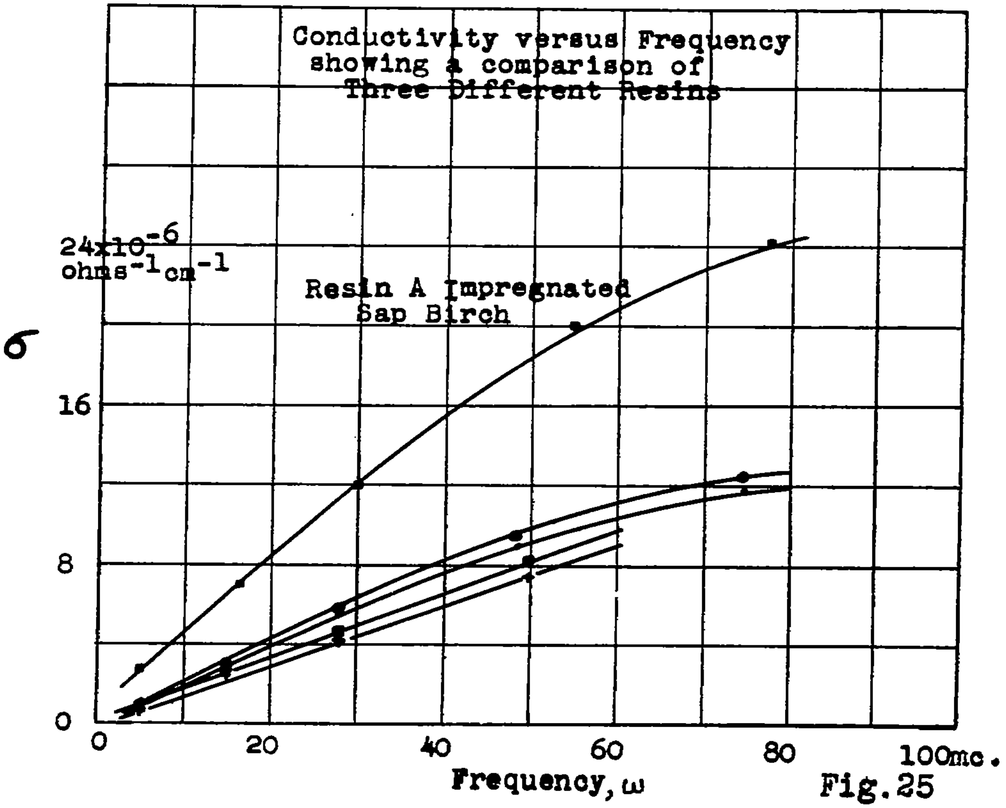
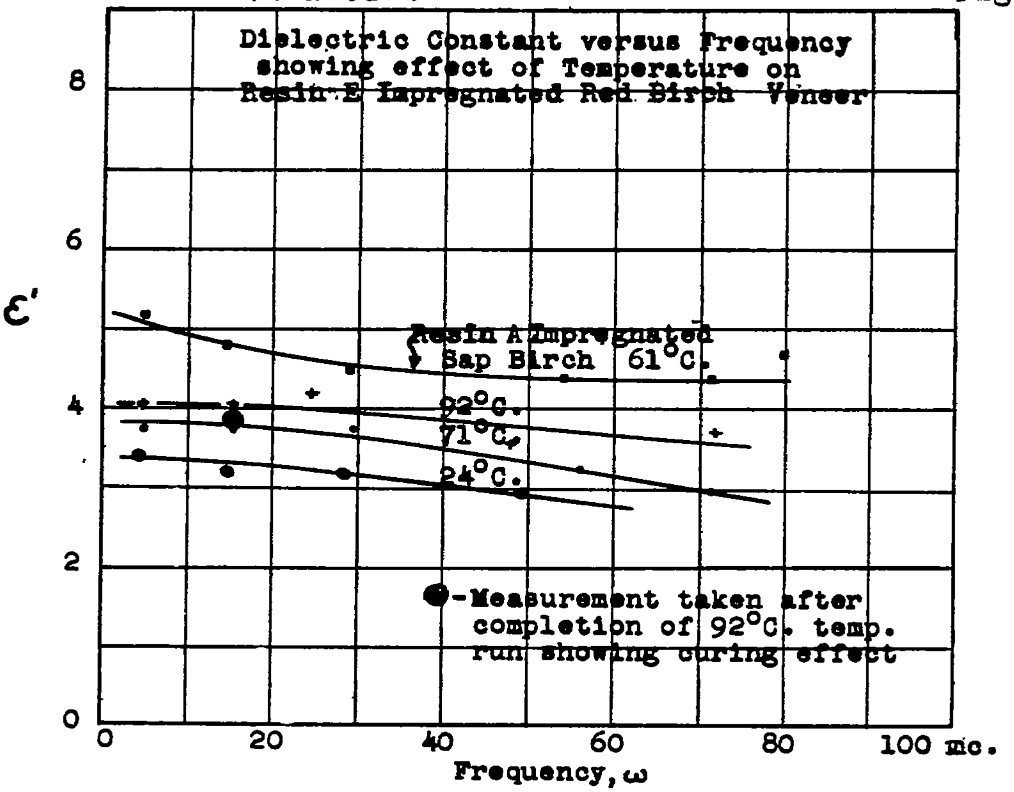

Conductivity versus Frequency
showing a comparison of
Three Different Resins
σ
24x10^-6 ohms^-1 cm^-1
16
8
0
Resin A Impregnated Sap Birch
0
20
40
60
80
100mc.
Frequency, ω

Fig.25


Dielectric Constant versus Frequency
showing effect of Temperature on
Resin E Impregnated Red Birch Veneer
Resin A Impregnated
Sap Birch 61°C.
92°C.
71°C.
24°C.
● -Measurement taken after
completion of 92°C. temp.
run showing curing effect
ε'
0
2
4
6
8
0
20
40
60
80
100 mc.
Frequency, ω

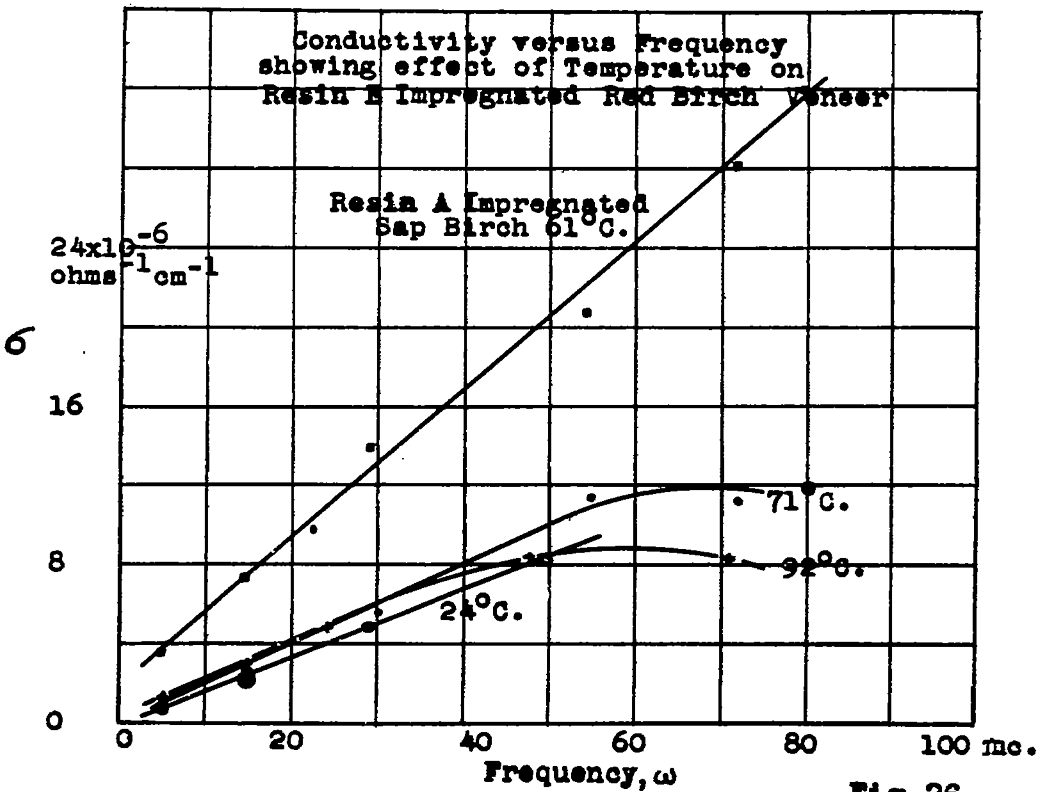
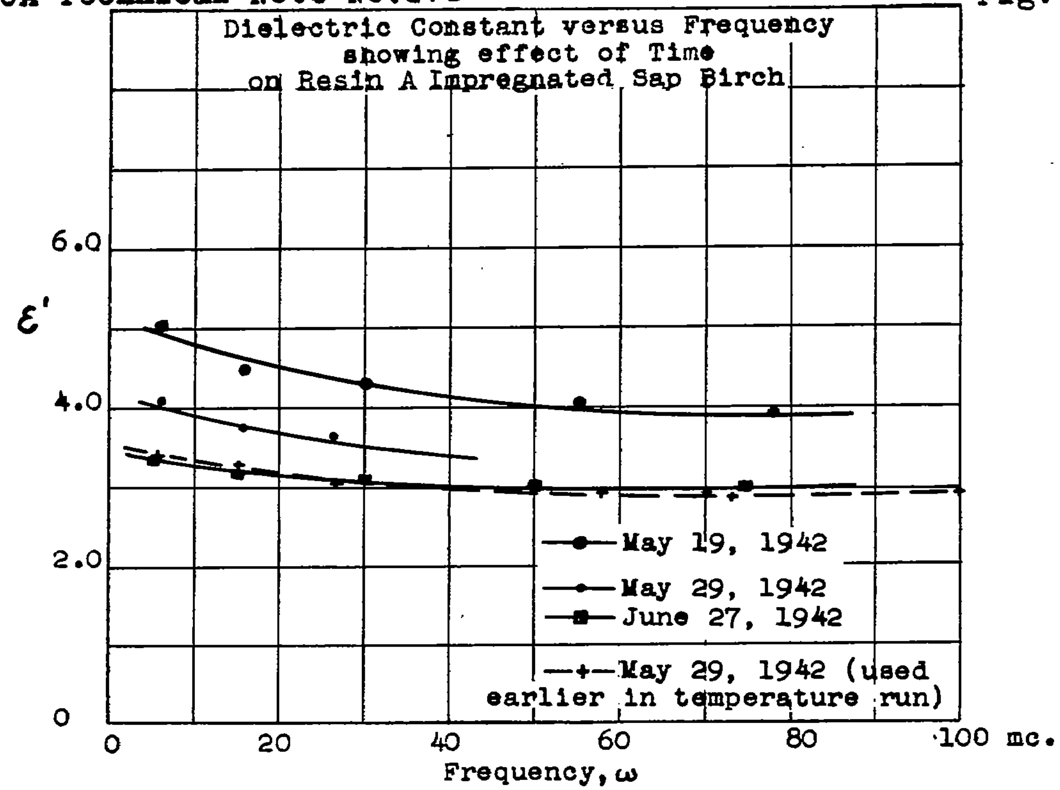

Conductivity versus Frequency
showing effect of Temperature on
Resin E Impregnated Red Birch Veneer
Resin A Impregnated
Sap Birch 61°C.
71°C.
92°C.
24°C.
σ
24x10⁻⁶ ohms⁻¹cm⁻¹
16
8
0
0
20
40
60
80
100 mc.
Frequency, ω

Fig.26


Dielectric Constant versus Frequency
showing effect of Time
on Resin A Impregnated Sap Birch
ε'
6.0
4.0
2.0
0
0
20
40
60
80
100 mc.
Frequency, ω
May 19, 1942
May 29, 1942
June 27, 1942
May 29, 1942 (used earlier in temperature run)

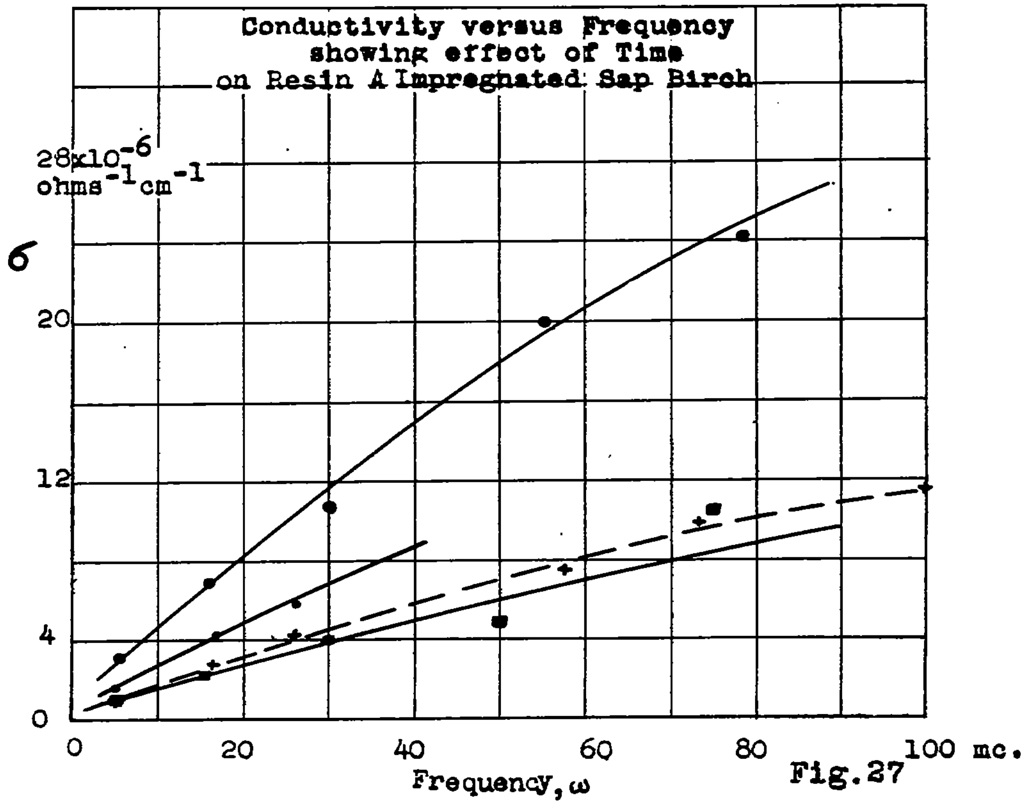
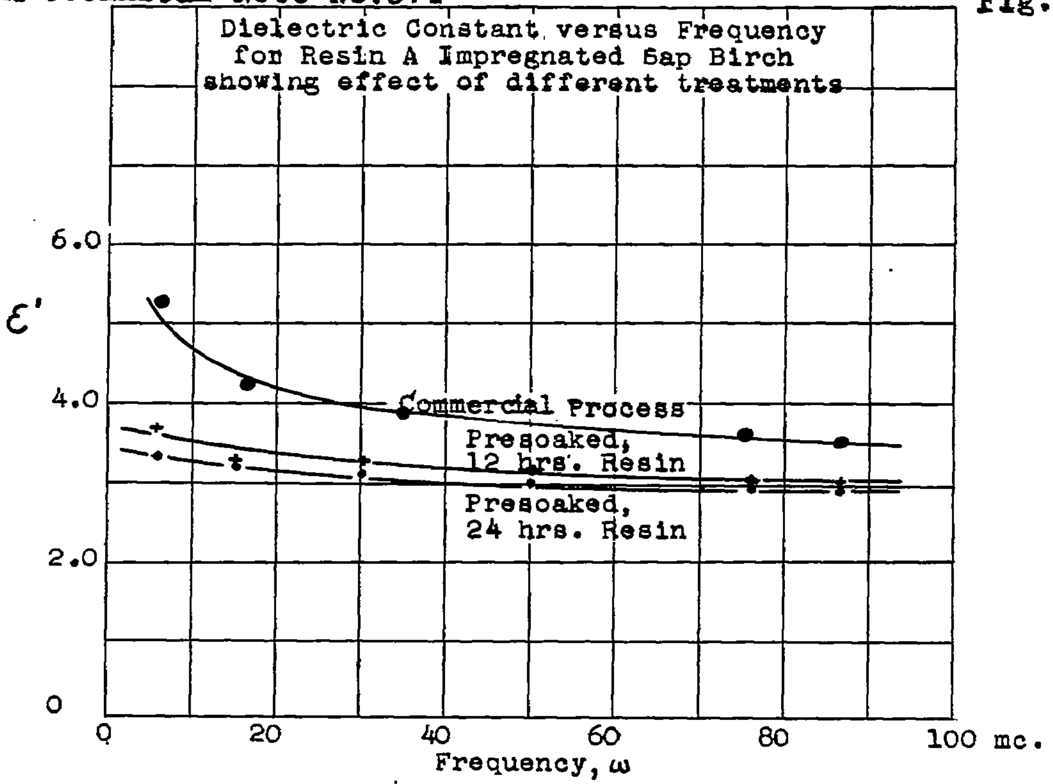

Conductivity versus Frequency
showing effect of Time
on Resin A Impregnated Sap Birch
28x10^{-6}
ohms^{-1}cm^{-1}
σ
20
12
4
0
0
20
40
60
80
100 mc.
Frequency, ω

Fig.27


Dielectric Constant versus Frequency
for Resin A Impregnated Sap Birch
showing effect of different treatments
ε'
6.0
4.0
2.0
0
Commercial Process
Presoaked,
12 hrs. Resin
Presoaked,
24 hrs. Resin
0
20
40
60
80
100 mc.
Frequency, ω

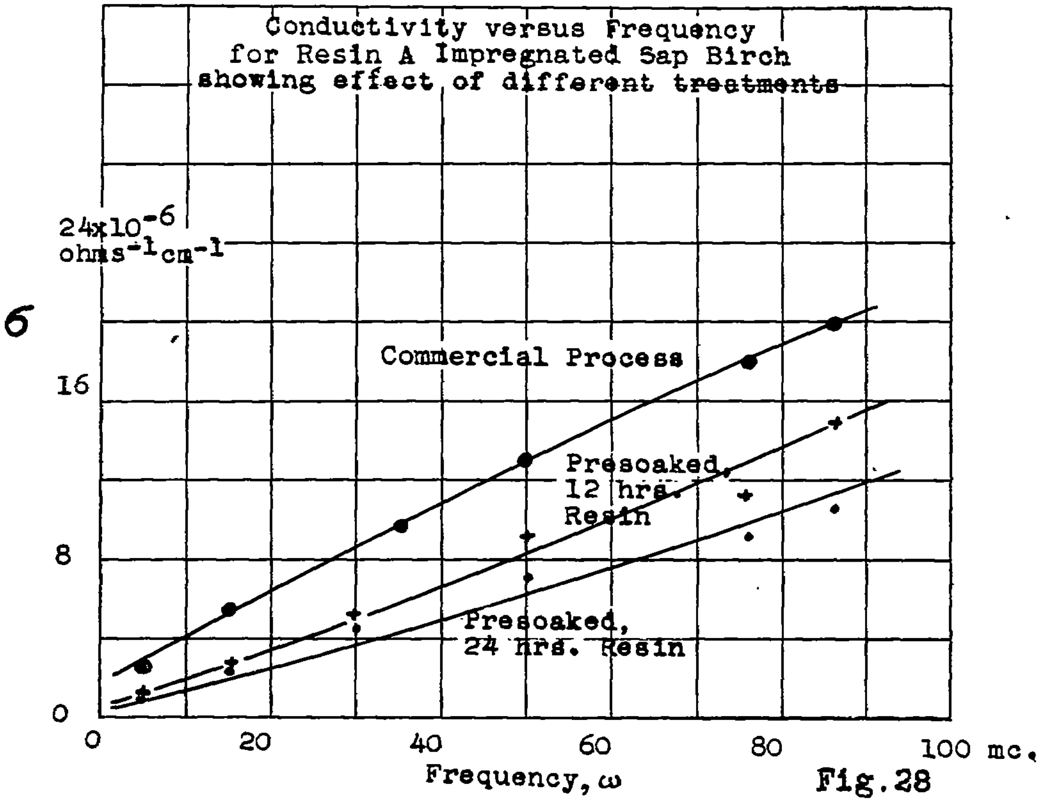
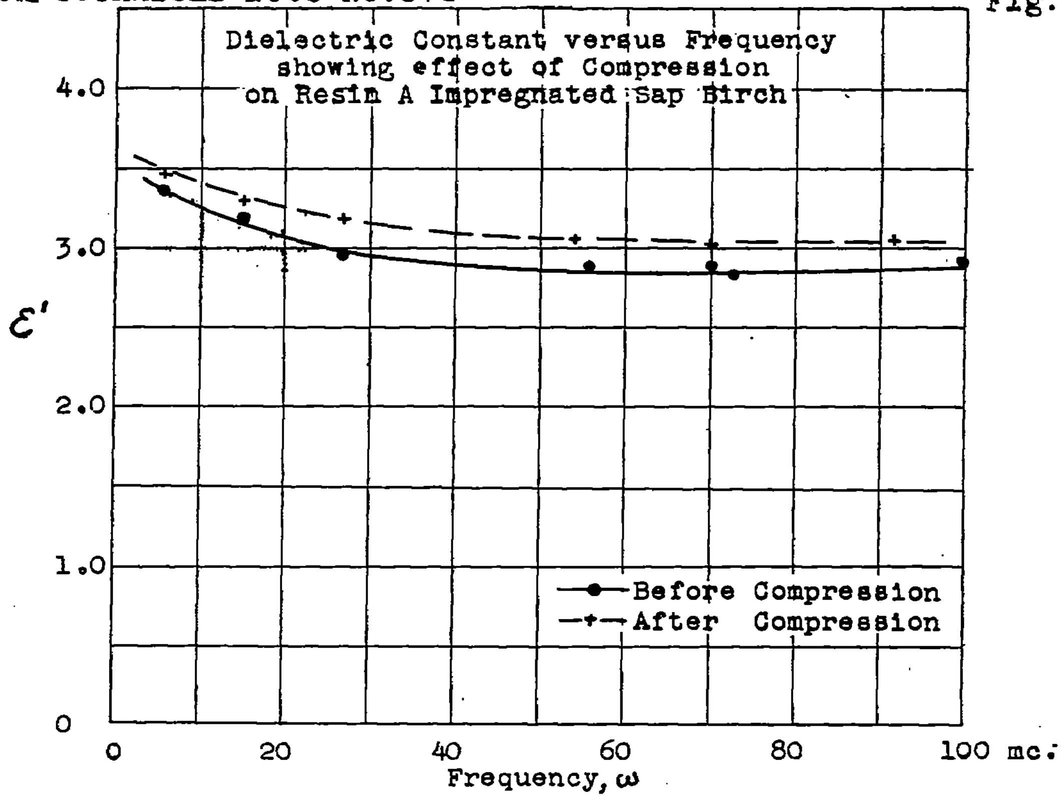

Conductivity versus Frequency
for Resin A Impregnated Sap Birch
showing effect of different treatments
24x10^{-6}
ohms^{-1}cm^{-1}
σ
16
8
0
Commercial Process
Presoaked,
12 hrs.
Resin
Presoaked,
24 hrs. Resin
0
20
40
60
80
100 mc.
Frequency, ω

Fig.28


Dielectric Constant versus Frequency showing effect of Compression on Resin A Impregnated Sap Birch
4.0
3.0
2.0
1.0
0
ε'
0
20
40
60
80
100 mc.
Frequency, ω
Before Compression
After Compression

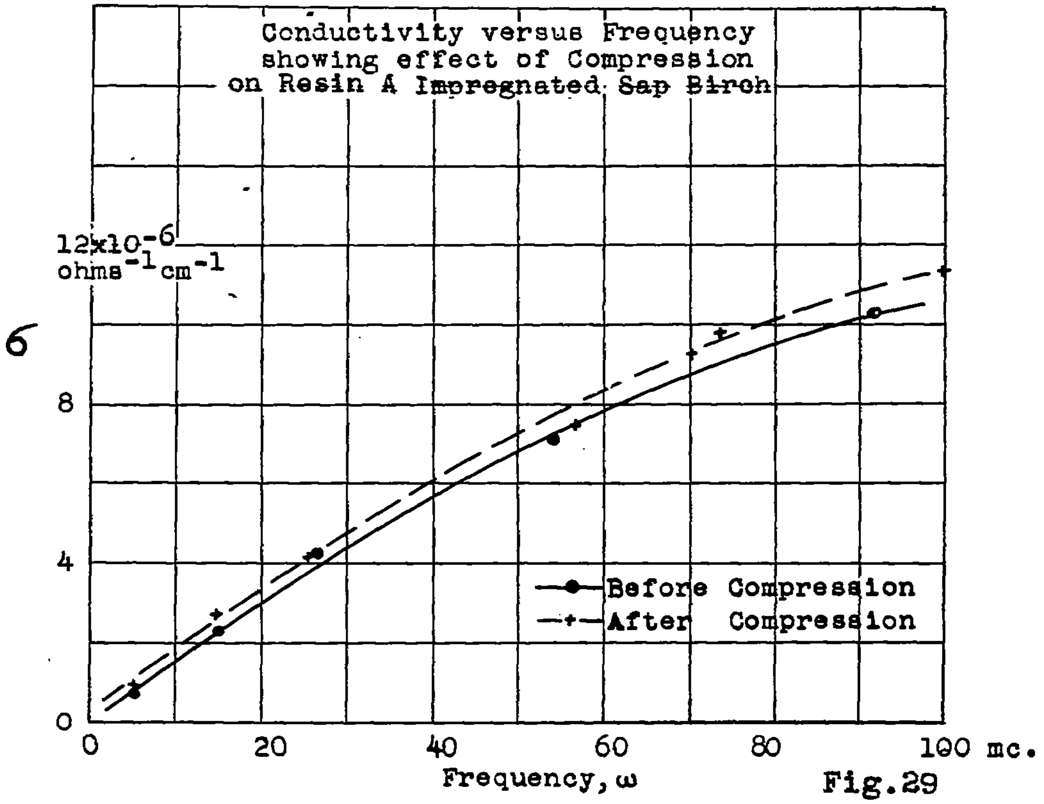
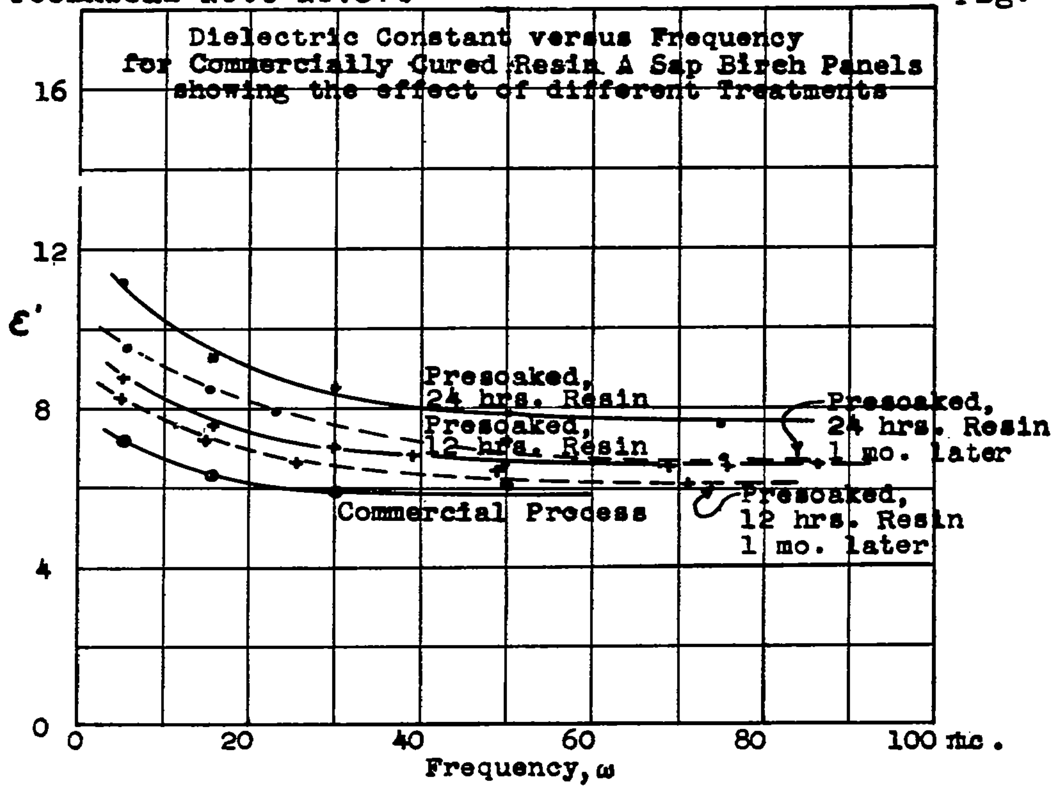
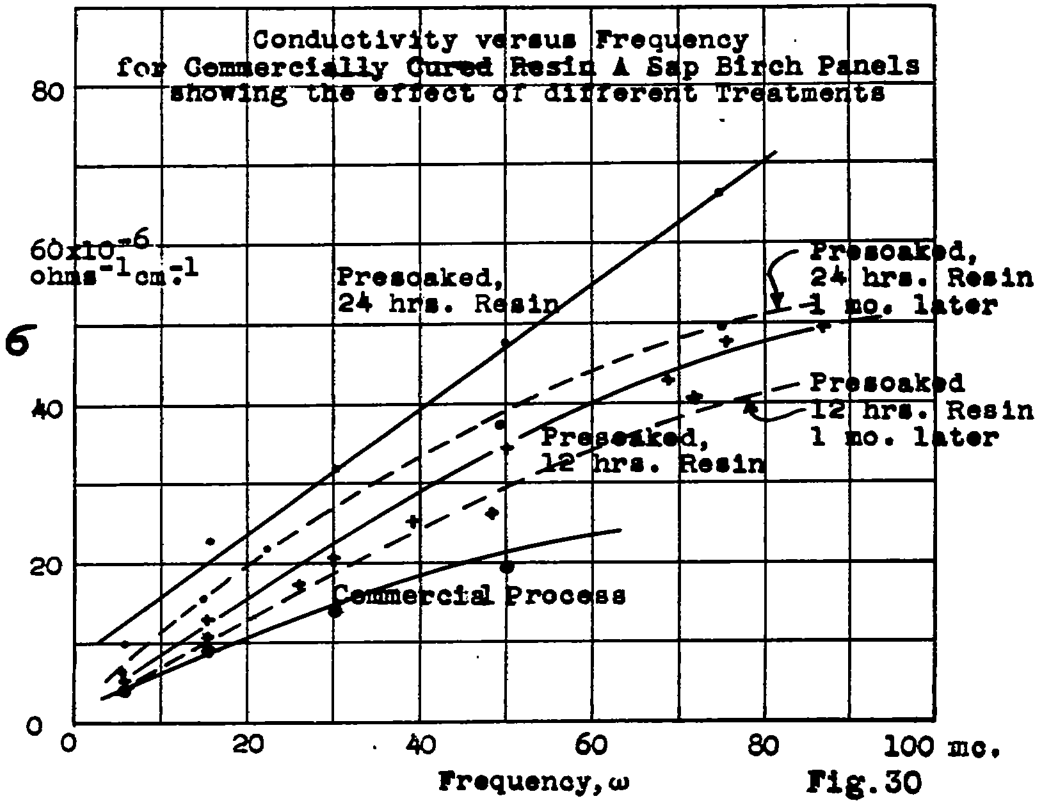

Conductivity versus Frequency showing effect of Compression on Resin A Impregnated Sap Birch
12x10^-6 ohms^-1 cm^-1
σ
8
4
0
0
20
40
60
80
100 mc.
Frequency, ω
Before Compression
After Compression

Fig.29

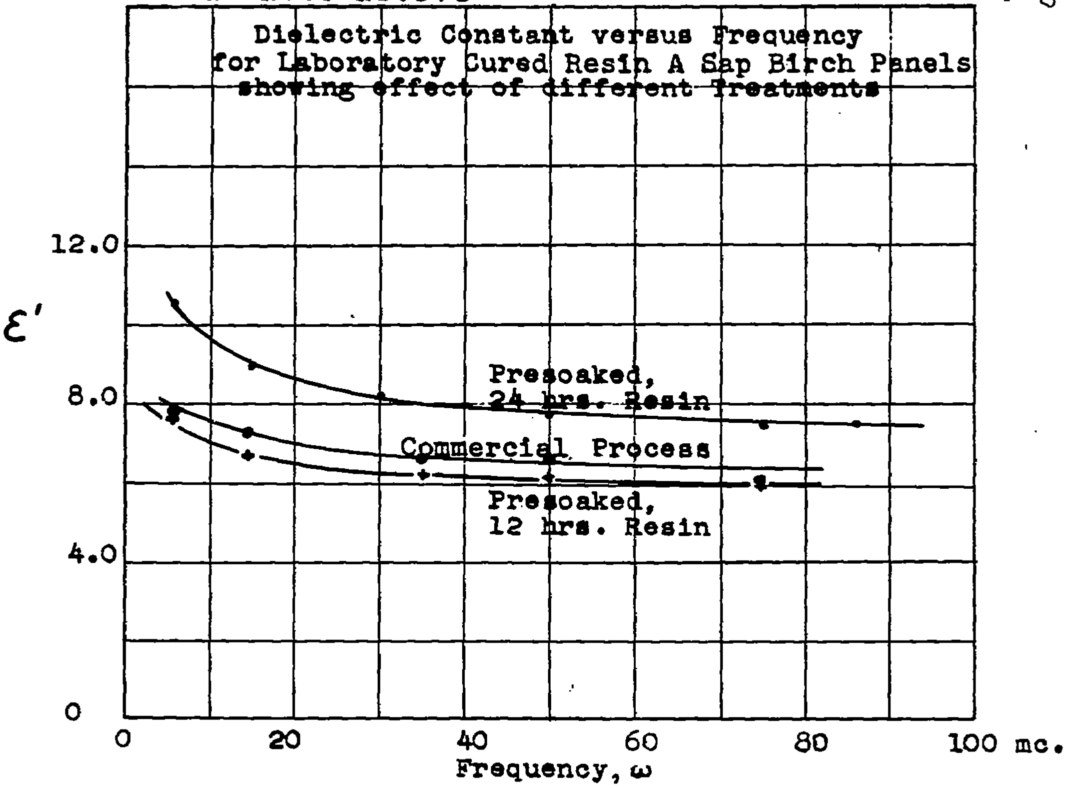


Dielectric Constant versus Frequency for Commercially Cured Resin A Sap Birch Panels showing the effect of different Treatments



Conductivity versus Frequency for Commercially Cured Resin A Sap Birch Panels showing the effect of different Treatments

Fig.30


Dielectric Constant versus Frequency
for Laboratory Cured Resin A Sap Birch Panels
showing effect of different Treatments
ε'
12.0
8.0
4.0
0
Presoaked,
24 hrs. Resin
Commercial Process
Presoaked,
12 hrs. Resin
0
20
40
60
80
100 mc.
Frequency, ω

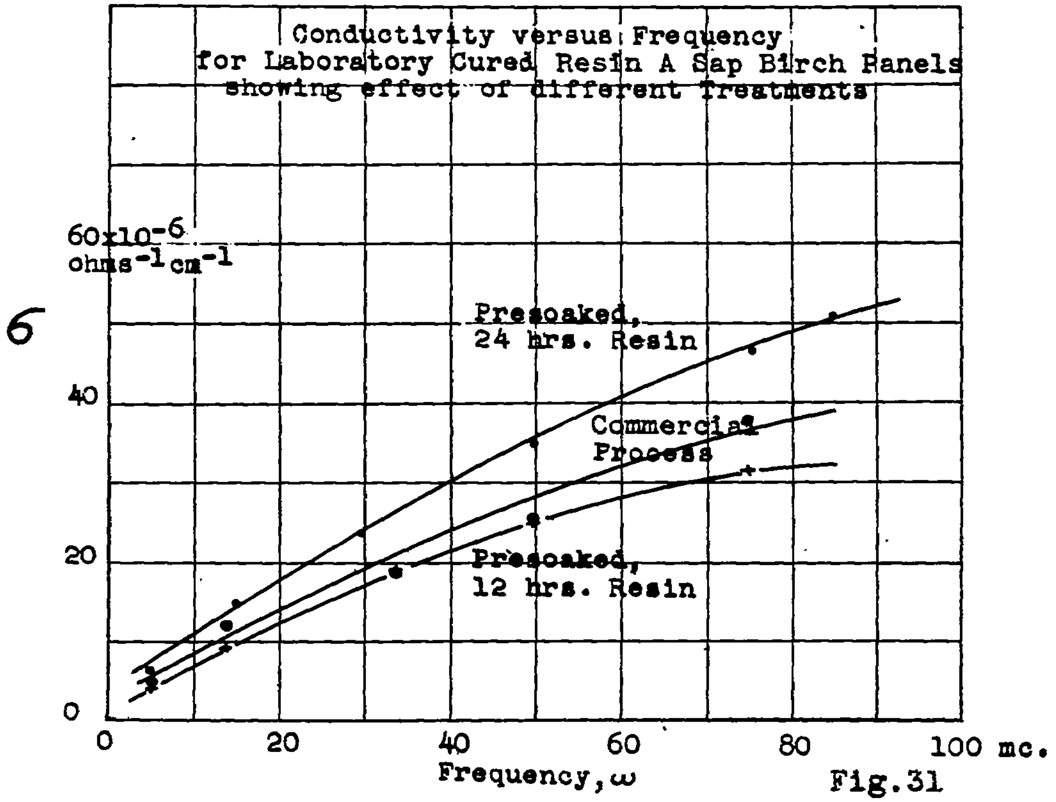
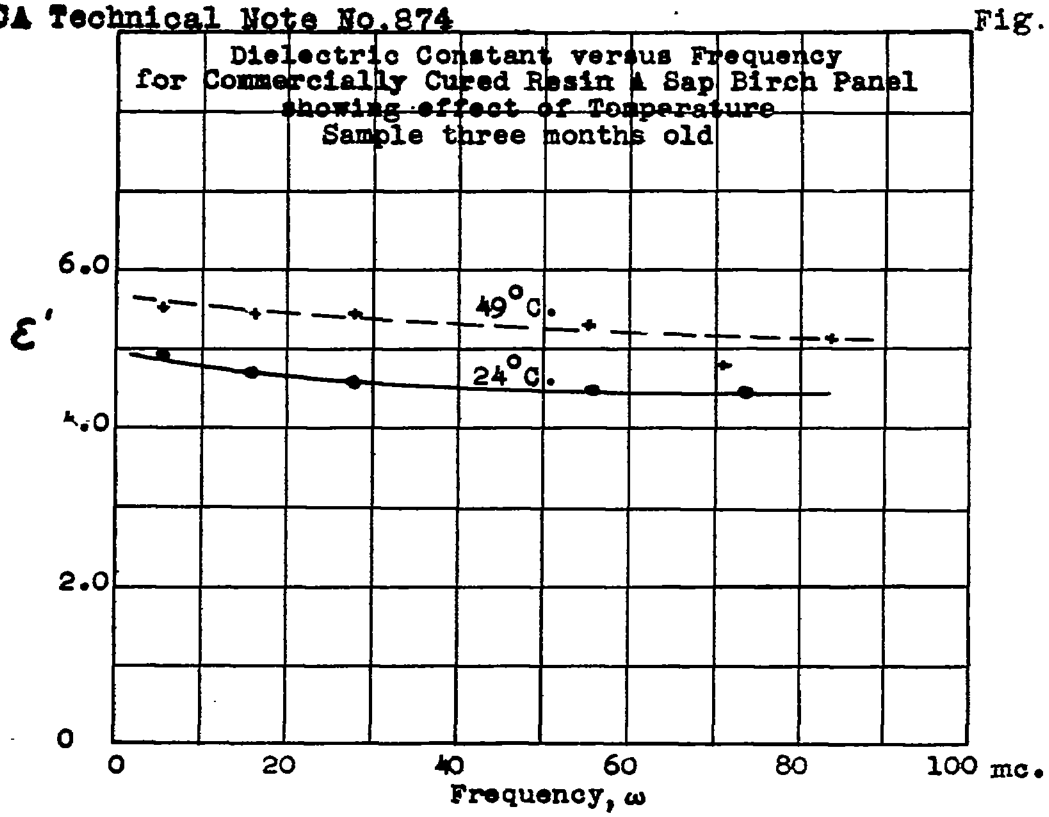
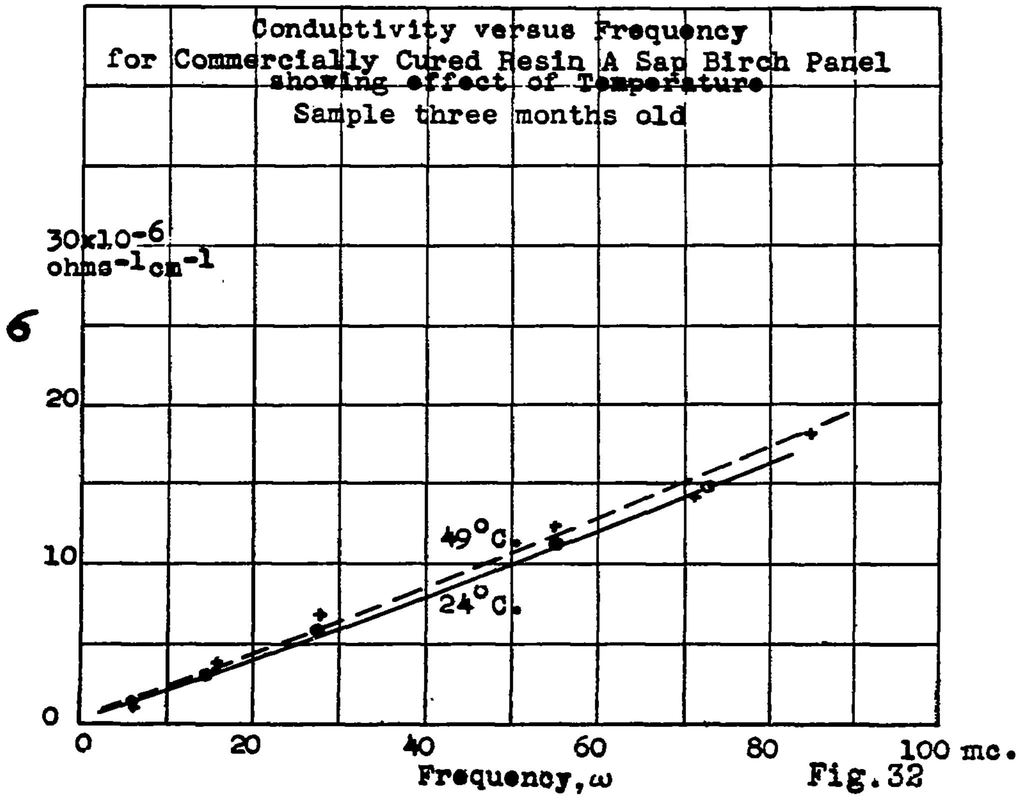

Conductivity versus Frequency
for Laboratory Cured Resin A Sap Birch Panels
showing effect of different Treatments
σ
60x10⁻⁶
ohms⁻¹ cm⁻¹
40
20
0
Presoaked,
24 hrs. Resin
Commercial
Process
Presoaked,
12 hrs. Resin
0
20
40
60
80
100 mc.
Frequency, ω

Fig.31



Dielectric Constant versus Frequency
for Commercially Cured Resin A Sap Birch Panel
showing effect of Temperature
Sample three months old



Conductivity versus Frequency
for Commercially Cured Resin A Sap Birch Panel
showing effect of Temperature
Sample three months old

Fig.32

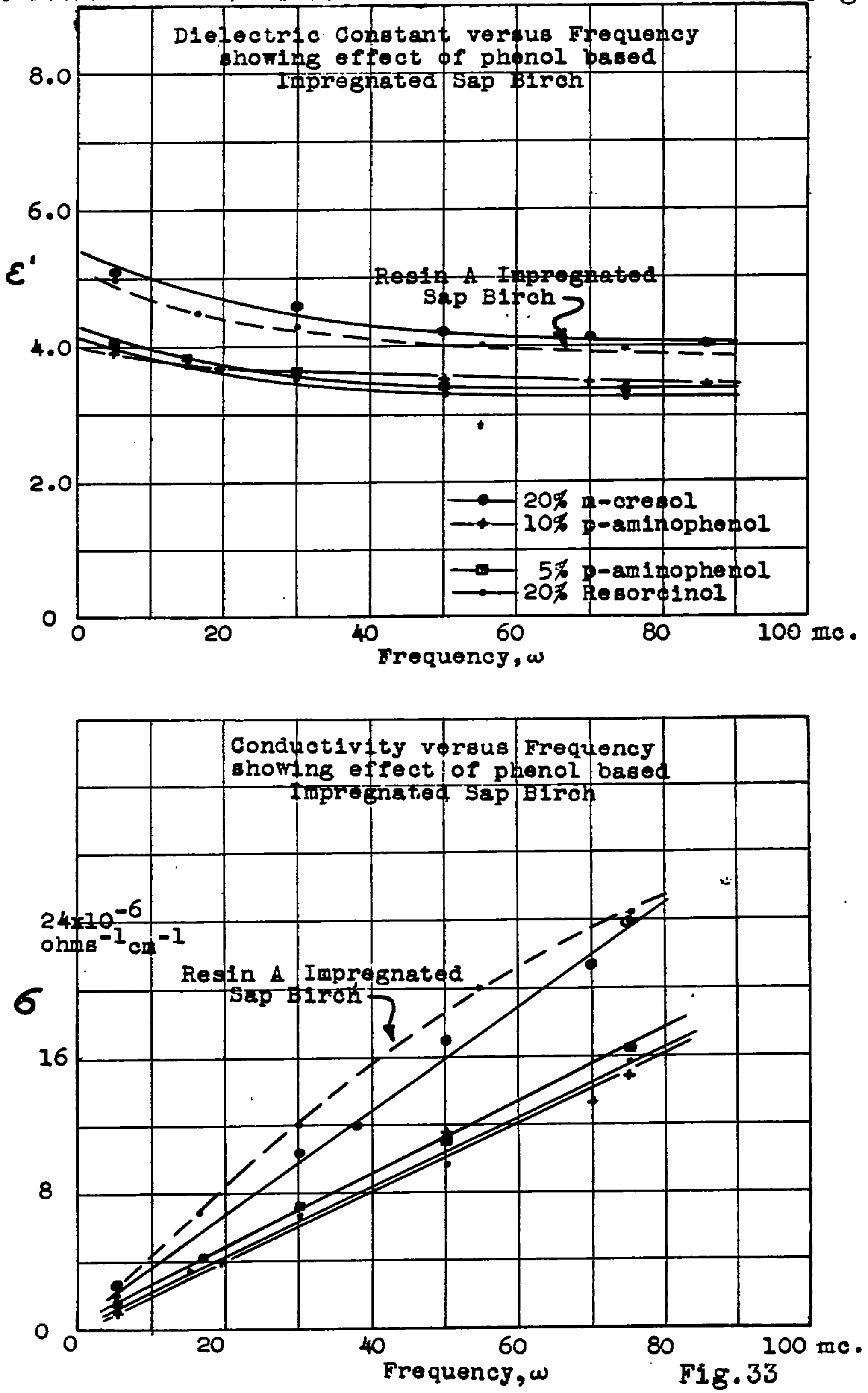
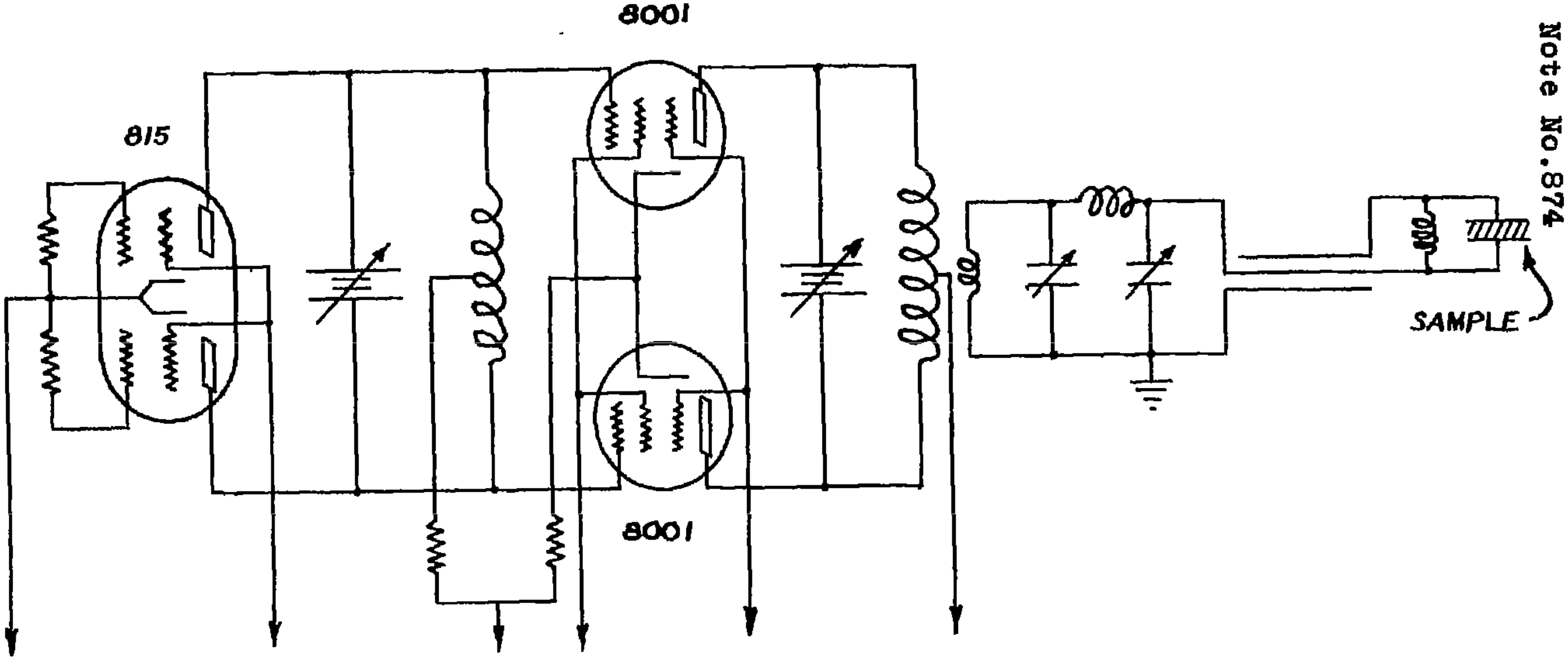

Dielectric Constant versus Frequency
showing effect of phenol based
Impregnated Sap Birch
8.0
6.0
4.0
2.0
0
ε'
Resin A Impregnated
Sap Birch
20% m-cresol
10% p-aminophenol
5% p-aminophenol
20% Resorcinol
0
20
40
60
80
100 mc.
Frequency, ω
Conductivity versus Frequency
showing effect of phenol based
Impregnated Sap Birch
24x10^{-6}
ohms^{-1}cm^{-1}
σ
16
8
0
Resin A Impregnated
Sap Birch
0
20
40
60
80
100 mc.
Frequency, ω

Fig.33

HIGH FREQUENCY OSCILLATOR-AMPLIFIER



TO POWER SUPPLIES

2500 V.

FIG. 34

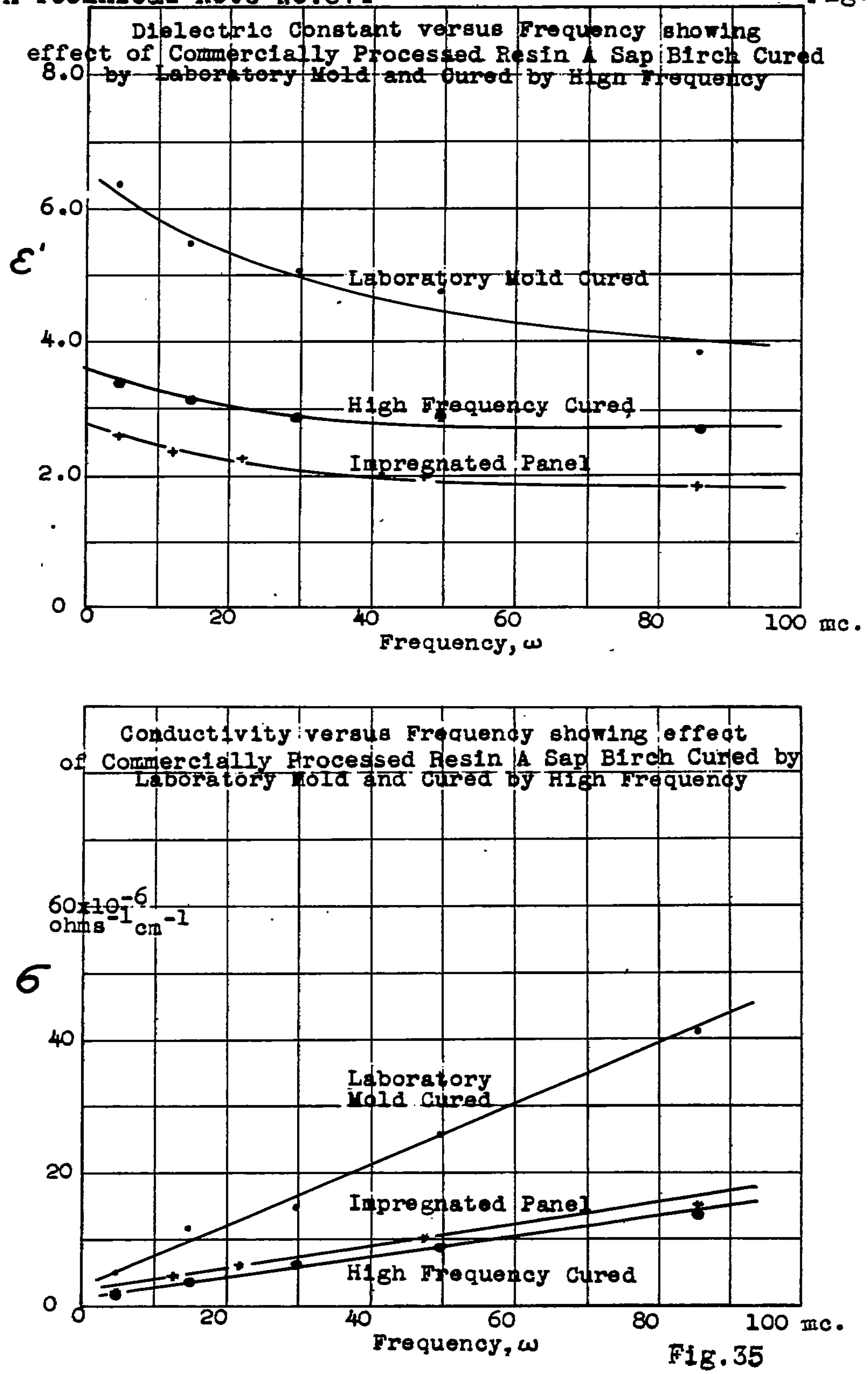

Dielectric Constant versus Frequency showing effect of Commercially Processed Resin A Sap Birch Cured by Laboratory Mold and Cured by High Frequency
ε'
8.0
6.0
4.0
2.0
0
Laboratory Mold Cured
High Frequency Cured
Impregnated Panel
0
20
40
60
80
100 mc.
Frequency, ω
Conductivity versus Frequency showing effect of Commercially Processed Resin A Sap Birch Cured by Laboratory Mold and Cured by High Frequency
σ
60x10⁻⁶ ohms⁻¹cm⁻¹
40
20
0
Laboratory Mold Cured
Impregnated Panel
High Frequency Cured
0
20
40
60
80
100 mc.
Frequency, ω

Fig.35

TSDIN FORM 60 A (13 MAR 47)

Osgood, W. R.

R20/11

AUTHOR(S)

P-7-4-12

DIVISION: Stress Analysis and Structures (7)
SECTION: Structural Testing (4)
CROSS REFERENCES: Tubing, Structural - Strength (95267); Steel alloys - Strength (90408)

ATI- 8647

ORIG. AGENCY NUMBER
TN-896

REVISION

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FORG'N. TITLE: Axial Loads, Tubes, Steel

ORIGINATING AGENCY: National Advisory Committee for Aeronautics, Washington, D. C.

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COUNTRY	LANGUAGE	FORG'N.CLASS	U. S.CLASS.	DATE	PAGES	ILLUS.	FEATURES
U. S.	Eng.		Restr.	Jul'43	55	26	photos, tables, graphs

ABSTRACT

Round heat-treated Cr-Mo-Steel tubing was tested under axial load, bending load, torsional load, combined bending-axial load, combined bending-torsional load, and combined axial-bending-torsional load. Properties of material were determined by tensile and compressive tests. Practical example is solved showing procedure in designing tubular cantilever member to carry combined loads. Formulas are derived for evaluation of maximum strength of steel tubing under individual or combined loads.

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[illegible] 1945

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SECTION: Structural Testing (4)
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