

A STUDY OF HEATING WOOD BY
HIGH FREQUENCY ELECTRICITY

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THESIS

A Study of Heating Wood by High
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THESIS

1

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CONTENTS

Introduction	Page 1
A Different Age	2
Uses and Advantages in Aircraft	3
Dry Bending	5
Methods of Heating	6
Electrical Method	6
Hot Plate Method	9
The Advantages of High Frequency Heating	13
Explanation of Computations Necessary	20
Calculation of Power Required	30
Estimated Initial Operating Costs	31
Equipment and Results	37

FIGURES

1.	Bending	Page 7
2.	Heat Penetration	11
3.	Glue Setting Time	12
4.	Temperature Gradients- Steam Plates	14
5.	Temperature Gradients- Electrical Heating	15
6.	Fundamental Circuit	21
7.	(a) Current Distribution	21
	(b) Current Distribution	21
8.	(a) Schematic & Vector Diagrams of Simple Circuit	23
	(b) Schematic & Vector Diagrams of Simple Circuit	23
9.	(a) Schematic & Vector Diagrams of Circuit with Wood Added	23
	(b) Schematic & Vector Diagrams of Circuit with Wood Added	23
10.	Power Factor Variation with Moisture Control	26
11.	Power Factor Variation with Frequency	26
12.	Variation, with Frequency, of Reactance, Equivalent Resistance and Voltage	29
13 & 14	Power Concentration for a Given Time Interval	32 & 33
15.	Initial Cost- Equipment & Cost per Kilowatt	35
16.	Tube Cost, Power Cost, and Overall Operating Cost Versus Power Delivered	36

17&18.	Photographs of Equipment	39-40
19.	Variation of Dielectric Constant with Moisture Content	48

Heating Wood by High Frequency Electricity

INTRODUCTION:

This research was undertaken to determine a possible method of dry bending of wood. The necessity for this work was brought about by the shortage of materials, caused by the war. Wood has replaced metals in many places in the last few years, and due to additional research, it is still entering many new fields.

This new use of wood is very likely to continue even after the shortage of materials is at an end. This is because the raw material is much cheaper. All metals are necessarily hard to mine and the supplies are exhaustable. The more metals that are used up, the more costly they will become since lower content ores will be used. The lumber supply of our country, if properly husbanded, as is our present government policy, is inexhaustable, as it is constantly being replaced. Then, too, the type of wood most suitable for our uses can be grown, and thereby improve the raw material source.

In fabricating products of wood, the labor required does not need to be as skilled as in other fields. As wood began to replace metals in some aircraft parts, piano manufacturers and other wood working agencies, which figured they were outside the realm of war work, were surprised to obtain

war contracts. Unskilled labor was rapidly trained and put to work.

Many people express amazement when they learn that wood is replacing metals in aircraft parts, but they forget that the original airplanes were constructed of wood almost entirely. The use of wood in aircraft parts was brought to a rapid stop by the crash of the airliner that cost Knute Rockne his life in 1931. This crash brought about so much unfavorable publicity concerning this wooden winged plane that wooden parts were outlawed.

A. DIFFERENT AGE:

Since that time a new era in glues has come to pass. In the old glues, their animal origin supported mold growth and encouraged termites. It was a common saying that, "That plane will keep on flying as long as the termites hold hands". The new glues are of chemical origin and discourage both mold and termites. These glues are of a type called "ir-reversible." That is, they are thermosetting. Once a high temperature is applied and the glue sets, the joint cannot be destroyed. Samples of wood have been soaked in wated until the wood started to rot away, but the glue joint remained.

Coupled with all these other factors, indicating the continued use of wood, is the fact that, for many of its new uses, it is actually doing a better job than was its predecessor. On this point aircraft use is by far the most

spectacular.

USE AND ADVANTAGES IN AIRCRAFT:

The facts, from actual planes constructed, show that any plane made of wooden parts will show at least a ten mile an hour increase in speed over a metal model. The reason for this is very clearly seen from tests by the National Advisory Committee for Aeronautics. These tests revealed that one row of normal, roundhead rivets, placed spanwise, a third of the distance from the leading edge of a wing, results in a 27% increase in drag. Nine rows of rivets increase this startling loss to slightly over 30%. Even the flush riveted wing is inferior to the wooden wing. The complexity of the thousands of parts required for a metal wing is overcome by its wooden counterpart, thus simplifying and speeding production.

Strangely enough, the amazing advantages of woods, result from what appear to be the very weak points of the material. To achieve an equal strength/weight ratio, wood must be thicker than metal- this is a blessing in disguise. Metal being very thin is therefore very flexible and must be reinforced with many stiffeners. Regardless of the number of stiffeners used, inside practical limitations, the metal will ripple in flight and cause a flutter or tremor to run through the ship at high speeds. However minute are these ripples, loss of lift and added drag result. Increased

" skin friction " is brought about and the boundry layer of air, that clings close to the surface of the wing, is apt to break away from the upper surface of the wing much further forward of the trailing edge than would ordinarily be expected.

Another weakness of wood proves to be an advantage under shell fire. Because wood shears more easily, it offers less resistance than metal to the passage of a bullet. This means that the bullet will not be flattened or badly distorted. Consequently, bullets and shell fragments leave much cleaner exit holes when they rip through the far side of a wooden structure. Not only does metal distort the bullet, but it frequently " tumbles " the projectile in flight so that it rips great exit holes. The metal blossoms or " flowers " around the exit point.

The wood, being thicker, possesses a greater modulus of rigidity and has, consequently, what is known as a greater local strength. Because of this, the amount of reinforcing may be a minimum.

This plywood is actually very resistant to fire. Every glue layer will retard the advance of fire. As strange as it may seem, a piece of plastic bonded plywood of equal strength/weight ratio takes many times as long as either duraluminum or stainless steel to hole through under the flame of an acetylene torch.

Builders of all metal planes are daily amazed as they discover different uses for wood. Starting with little items like trim tabs, plastic plywood is being used for an ever increasing number of parts; bomb-bay doors, air ducts, and scoops, flaps, pilot seats, ammunition chutes, and wing tips. It seems that numerous metal items can be replaced by this processed wood, even to gasoline tanks.

DRY BENDING:

The purpose of dry bending is to overcome many of the difficulties met in old methods of bending wood. For generations wood has been bent by soaking it until it became thoroughly wet and then clamping it to a form until dry. This required hours of soaking and also hours of drying. Many forms were required if any number of pieces were to be made.

Another old method of bending wood is to steam it. This raises the moisture content and the temperature. In this method of bending the same result is obtainable as above, but more rapidly. All these methods of adding moisture necessarily add hours of waiting for drying out. It was therefore planned to overcome this difficulty by bending the wood dry.

The proof is very simple. If a piece of very thin wood, 1/16th of an inch or less, is held above an open flame, far enough away so that it is not burnt, it may be

slowly bent downwards at the ends. The underlying theory of this is fairly simple. The fibers of wood, when heated, lose their ability to withstand a compressive force, and the ability to withstand tension is still present. This causes the neutral axis of the wood to move toward the tension side of the specimen. As the specimen is bent, the fibers telescope into one another, and, if the wood is held in this position until it cools, these fibers will still resist tension but will be more dense from being compressed. Thus the piece will retain its new shape.

METHODS OF HEATING:

These facts established, the problem becomes one of choosing a method of heating the wood. In choosing a method of heating the wood, three methods were considered. Two of these methods were steam or gas heated plates, or rolls. The other method of heating considered was the use of high frequency current. The first two methods will be considered as one because of their similarity. In order to compare the different methods of heating, an elementary explanation of the electrical method will be given here, while the formulas and computations will be given further on.

ELECTRICAL METHOD:

Elementary physics teaches that energy is the force of nature that is utilized to do work. Energy occurs in a number of forms, but it cannot be created or destroyed. It can, however, be converted from one form to another. The

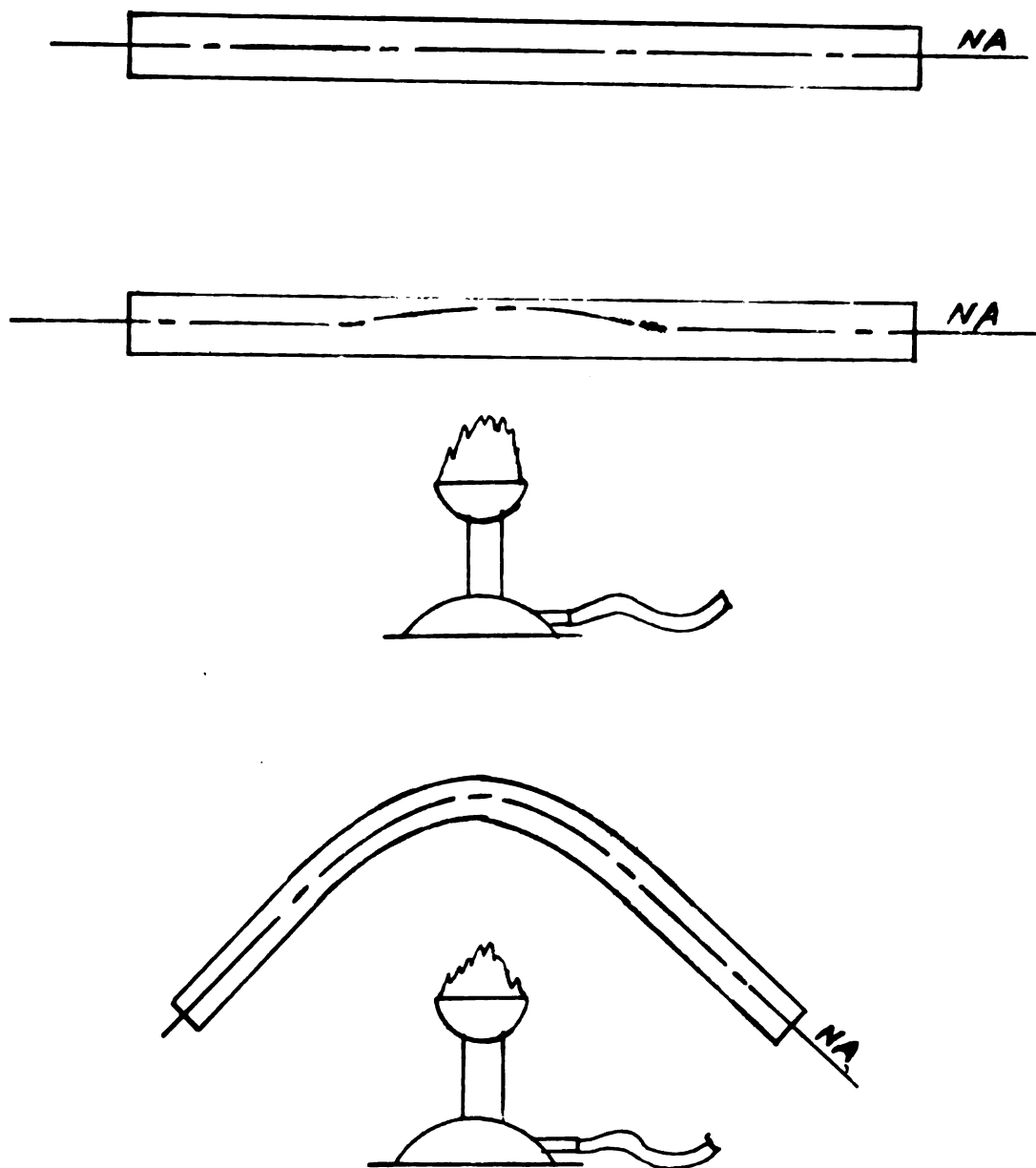


Fig. 1

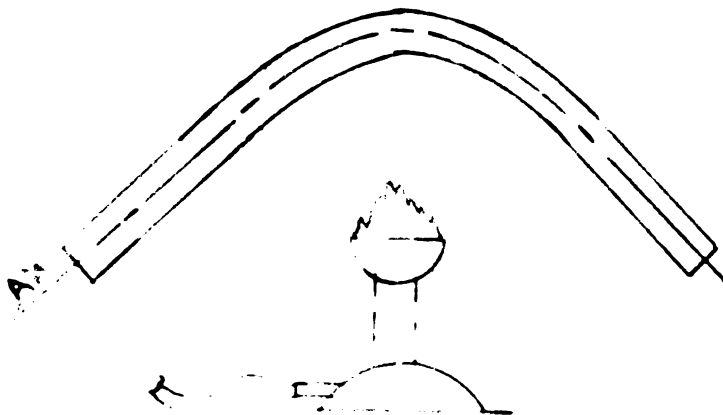
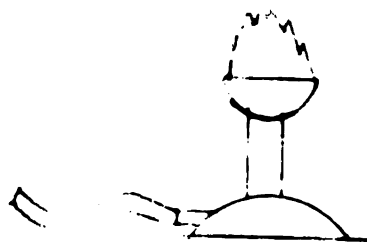
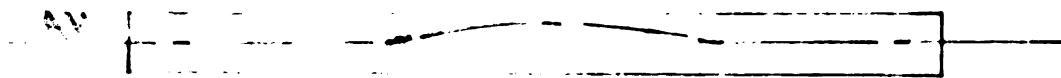


Fig 1

total amount of energy will remain the same and will be recoverable in its new form, except for losses.

Science has developed the atomic theory of matter. That is, that all matter is made up of molecules. These molecules are in turn made of atoms. The atoms are grouped in various geometric arrangements. This difference in arrangement of atoms is what makes the different substances.

If these molecules are disturbed, for instance rubbed together, heat is produced by the friction, just as a fire may be kindled by the heat generated by rubbing two sticks together. Everyone is familiar with the conversion of one form of energy into another. If a wire is bent back and forth rapidly, the wire will become heated where the bending occurs. Actually this heat was generated by the molecular friction caused by deforming the wire. This is an example of mechanical energy being converted into heat.

All forms of energy have standards of measurements. Mechanical energy is expressed in foot pounds; heat energy in B.T.U's (British Thermal Units); and electricity in watts. One kilowatt is 1,000 watts. This quantity of electricity operating for one hour (one kilowatt hour) will produce 3, 413 B.T.U's.

High frequency electrostatic heating is merely taking electricity and converting it to a form that will cause molecules in a substance to distort and rub together, thus setting up friction which results in heat.

This distortion of the molecules occurs with each reversal of the current, or twice in each cycle. When radio frequency current is applied to the wood at a frequency in the millions, there is rapid distortion of the molecules. As they are pulled one way and another, several million times per second, the wood is rapidly heated.

HOT PLATE METHOD:

For years hot plates have been used in making plywood and veneering furniture. Their temperature must be high enough to drive the heat by conduction from the contact surface to the glue line, or point where heat is desired. The application of heat reduced the setting time of the glue. Until the heat was used, all parts had to be held in clamps for four hours or more until the chemical reaction in the glue could take place. When heat was applied on thin veneers, the same job could be done in two minutes where it took hours before. Every wood fabrication involving the use of glue would use heat if it could, but the thickness of the wood definitely limits its use.

Wood is not a good conductor of heat as evidenced in the table shown on Page 10.

Calories transmitted per second through a plate 1 Cm. thick over an area of 1 square Cm. when the temperature difference between the faces of the plate is 1 degree C.

<u>Substance</u>	<u>Conductivity</u>
Copper	1.00
Aluminum	0.50
Brass	0.26
Steel	0.15
Brick, common red	0.0015
Asbestos paper	0.0006
Cardboard	0.0005
Wood (Fir)	0.0001

The fact that wood is a poor conductor of heat is the reason for its utility for insulating purposes. However, for transmitting heat to glue between two pieces of wood, it is such a poor conductor that only thin plies can be handled rapidly with heat applied to the surface. If too high a temperature is applied to the surface, it is a well known fact that the surface may be checked, hardened, or scorched. If plywood is not carefully handled, its structure may be exploded, or its surface steam blistered by the high surface temperature of the hot plates.

Figure 2 shows how slowly heat penetrates wood as the thickness of the wood between the hot plate and the measured point increases.

Figure 3 shows how much more rapidly a typical glue sets at higher temperature. The time that could be saved if the temperature could be raised throughout the wood uniformly is obvious.

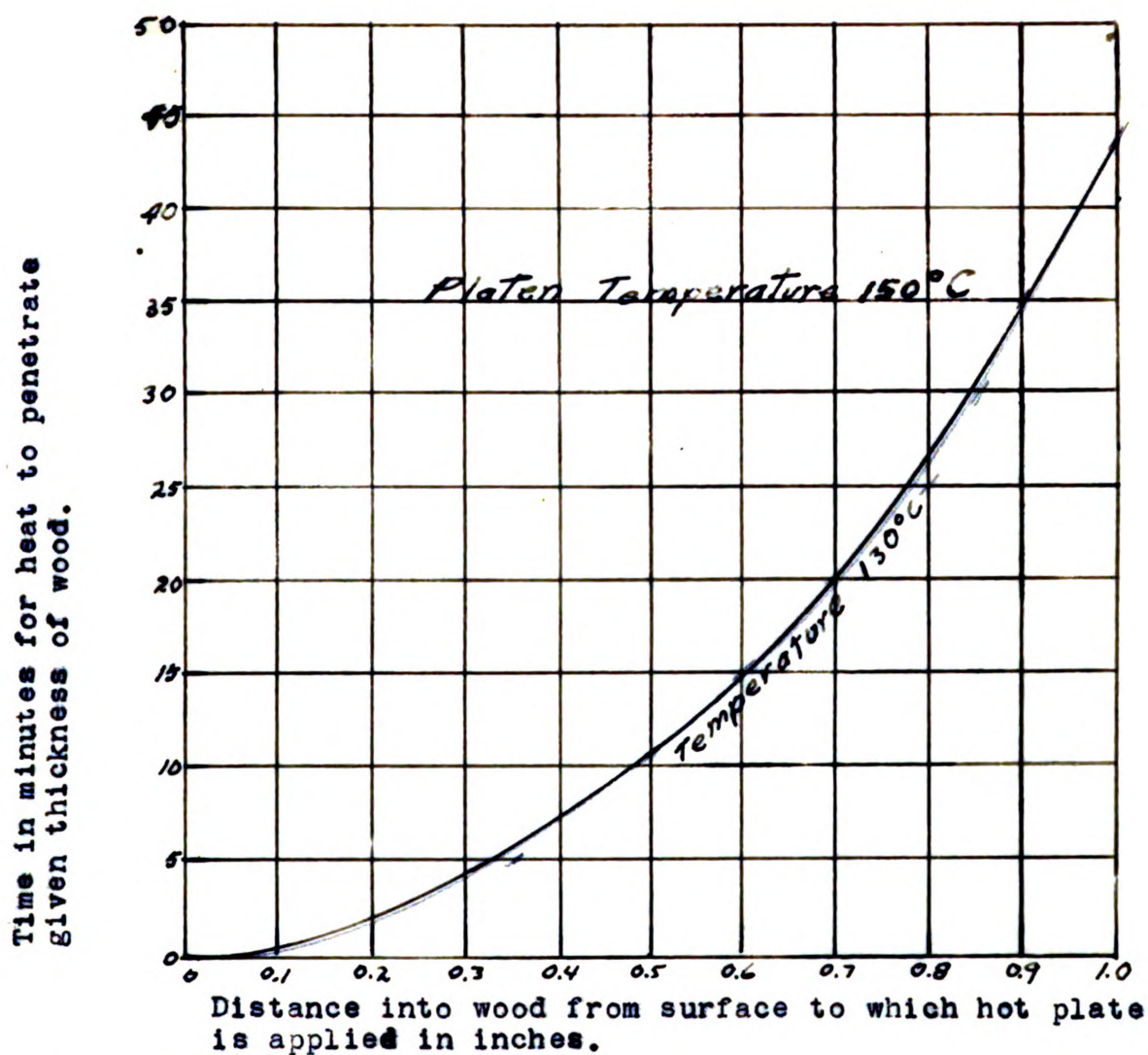


Figure 2. Curve showing time that must elapse before temperature reaches 130 ° C at various distances from a hot plate whose temperature is 150 ° C.

started at 120 °C. Time in minutes to reach 130 °C at various distances from surface of wood.

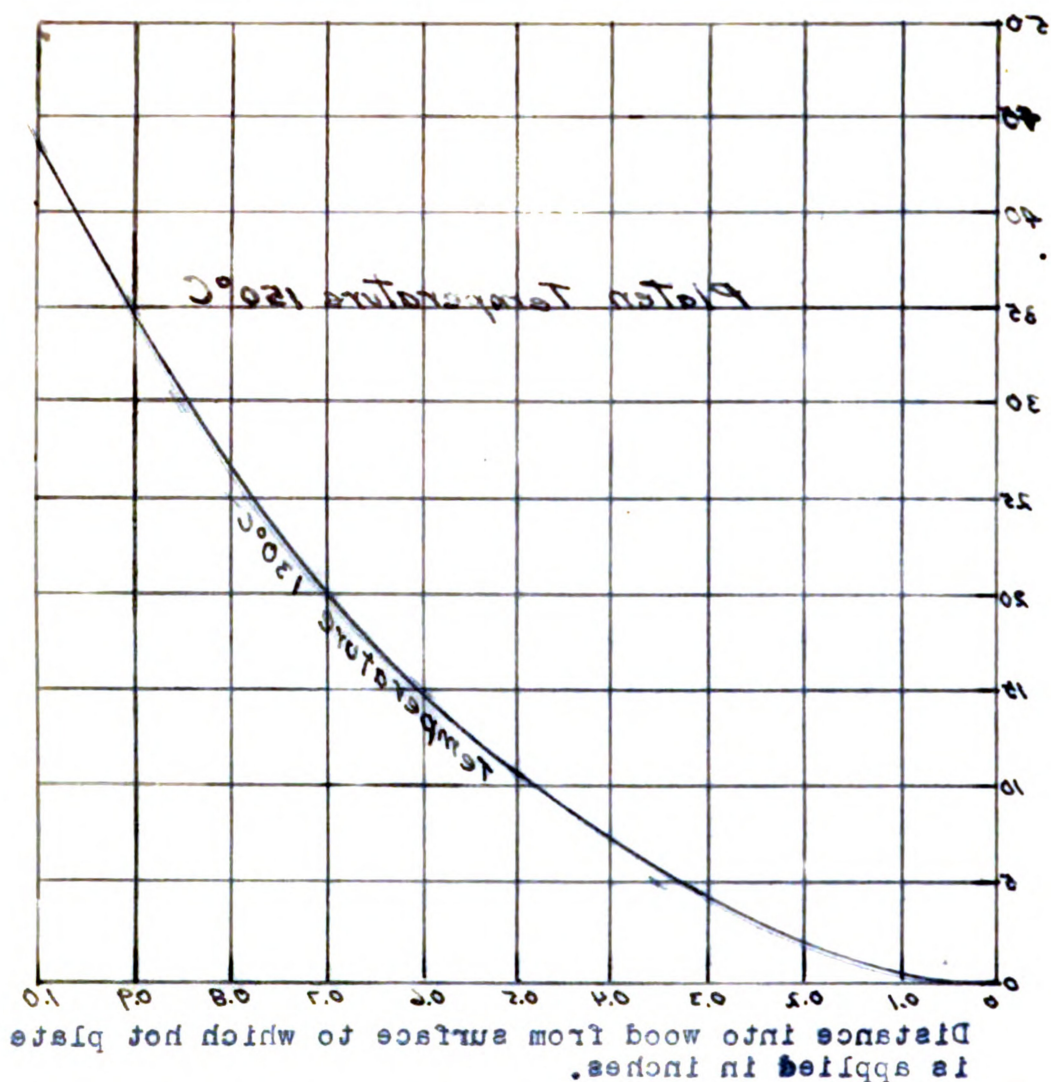


Figure 2. Curve showing time that must elapse before temperature reaches 130 °C at various distances from a hot plate whose temperature is 120 °C.

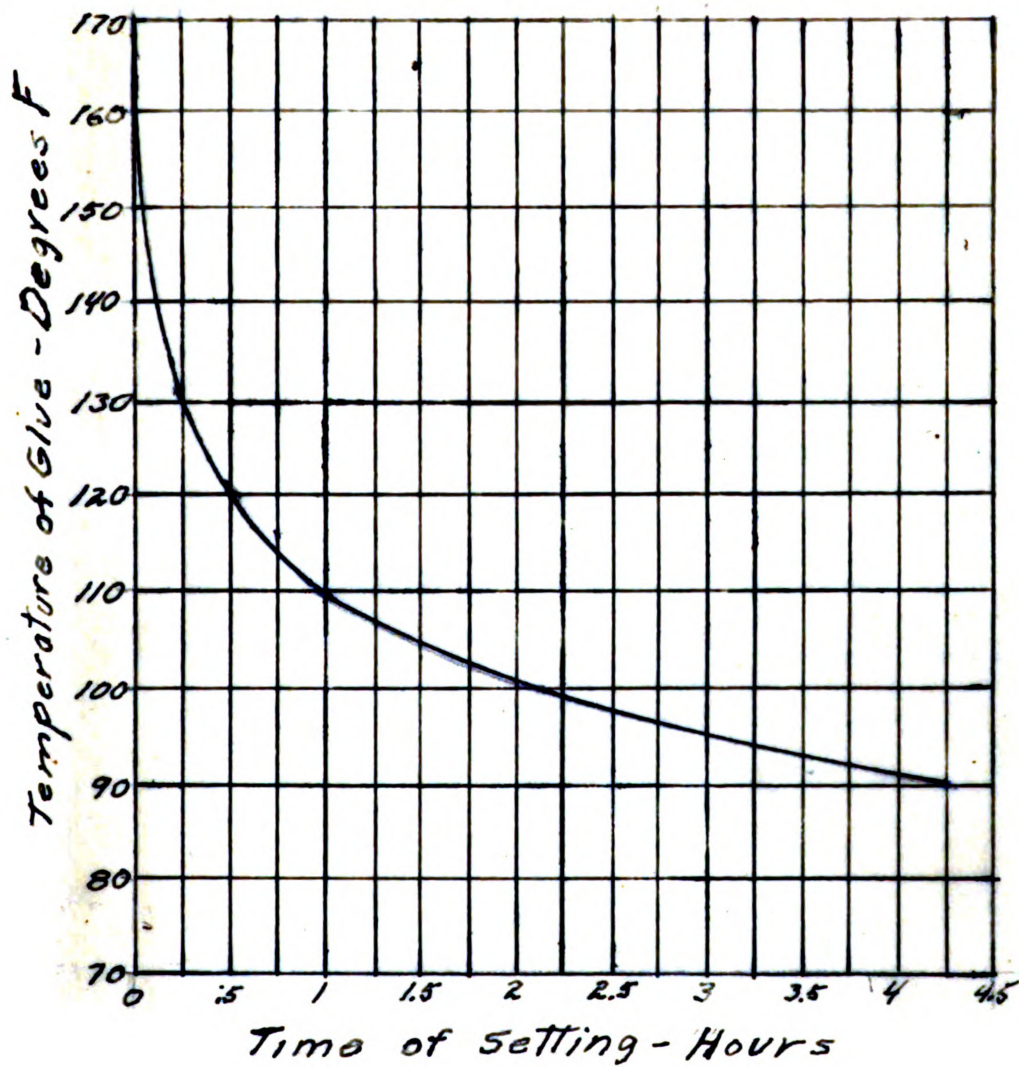


Fig. 3

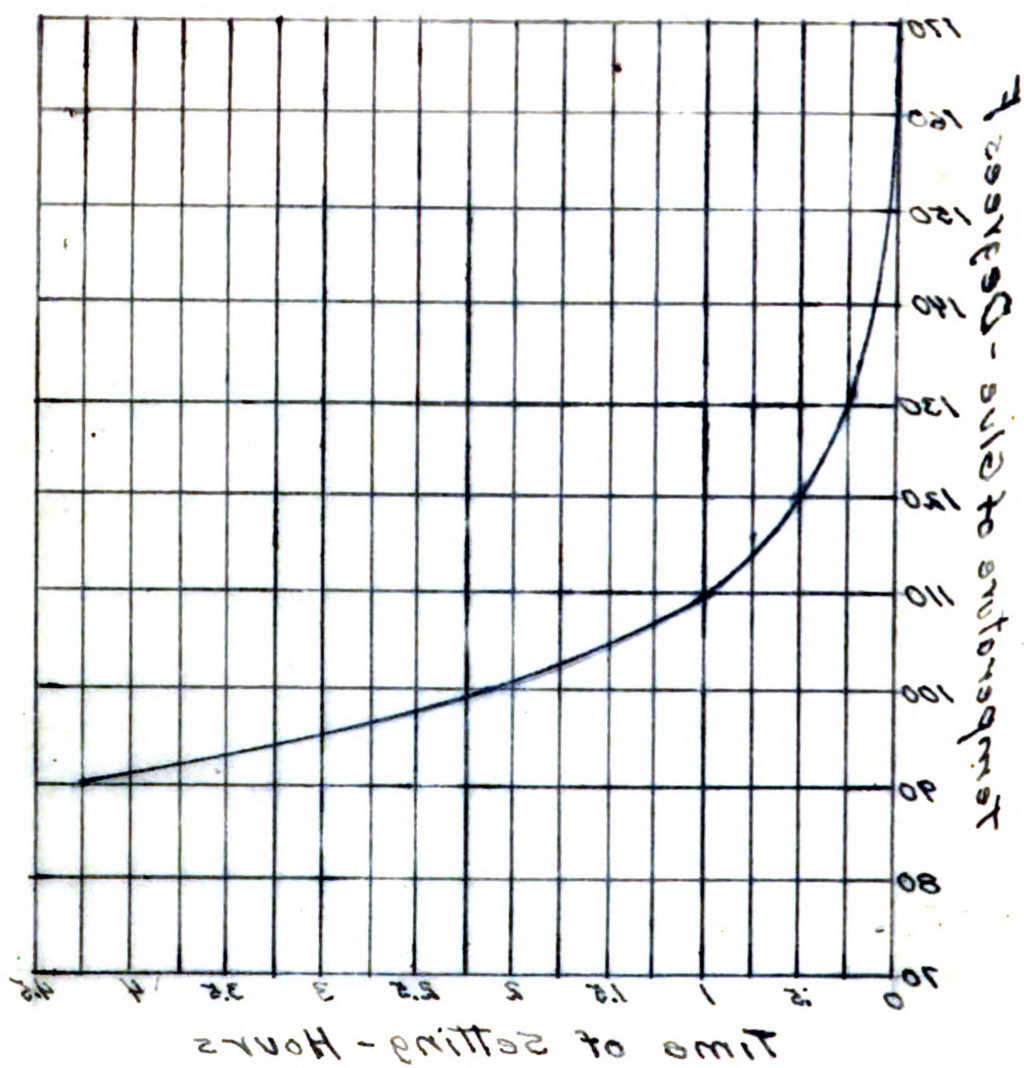


Fig. 3

THE ADVANTAGE OF HIGH FREQUENCY HEATING:

The advantage of the high frequency method follows from the fact that this method of heating actually does cause the heat to be generated simultaneously and uniformly throughout the whole body of the wood. This means that neglecting losses, the whole block of wood comes up to temperature evenly. It means that the time required, for a given increase in temperature is independent of the thickness of the wood. These effects are in marked contrast to the hot plate method where the outer layers come up to temperature much more quickly than the interior.

In order to obtain a more detailed picture of the temperature gradients in the two systems the time-temperature curves have been computed for several typical cases. These are shown in Figures 4 and 5. The values from which the steam plate curves of Figure 4 were plotted, were calculated from the formula:

$$\theta = \theta_s - (\theta_s - \theta_0) F\left(\frac{\alpha t}{d^2}, \frac{x}{d}\right)$$

where:

θ - is the temperature at point x and time t

θ_s - is the plate temperature

θ_0 - is the original temperature of the wood

α - is the thermal diffusivity of the wood

d - is the thickness of the wood

Values of the function $\left(\frac{\alpha t}{d^2}, \frac{x}{d}\right)$ are given by Brown

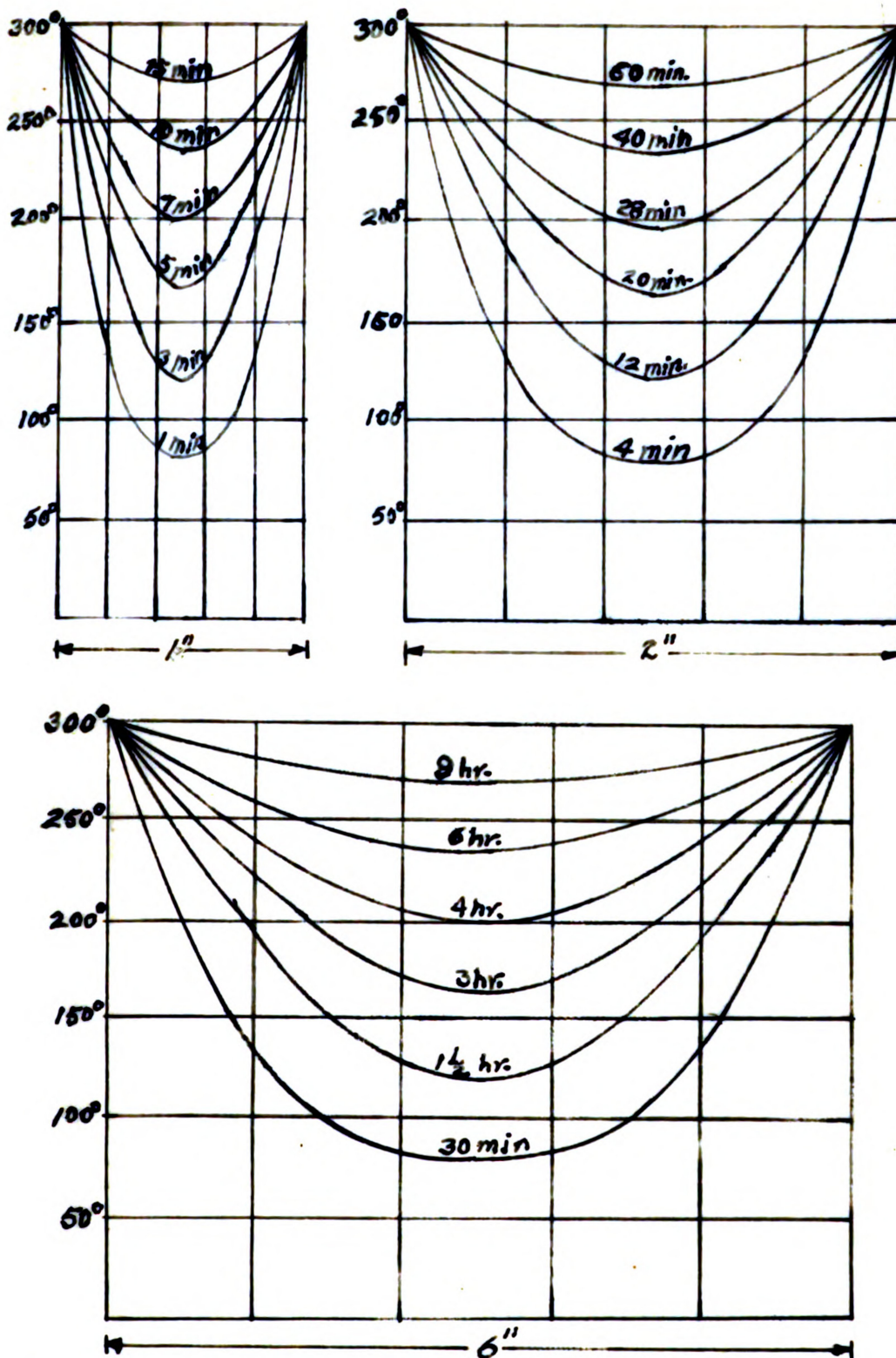


Fig 4. Time-temperature distribution curves for 1", 2", and 6" thicknesses of wood heated by external means- such as steam plattens, heat tunnel, etc. Curves are calculated for a thermal diffusivity of .0063 for spruce at 8-10% moisture content.

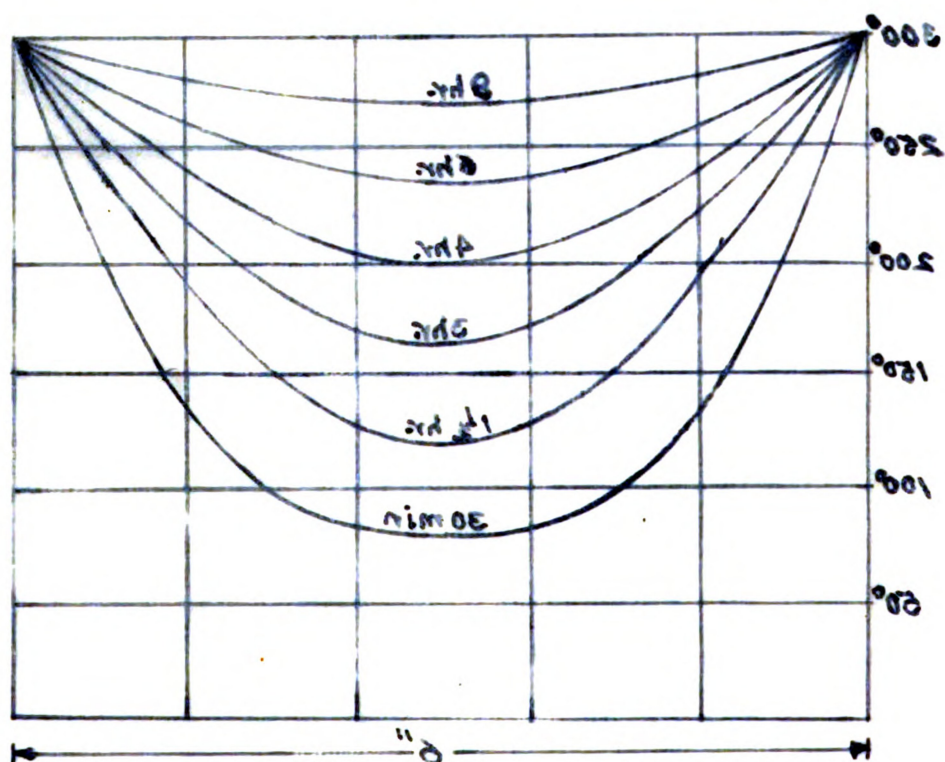
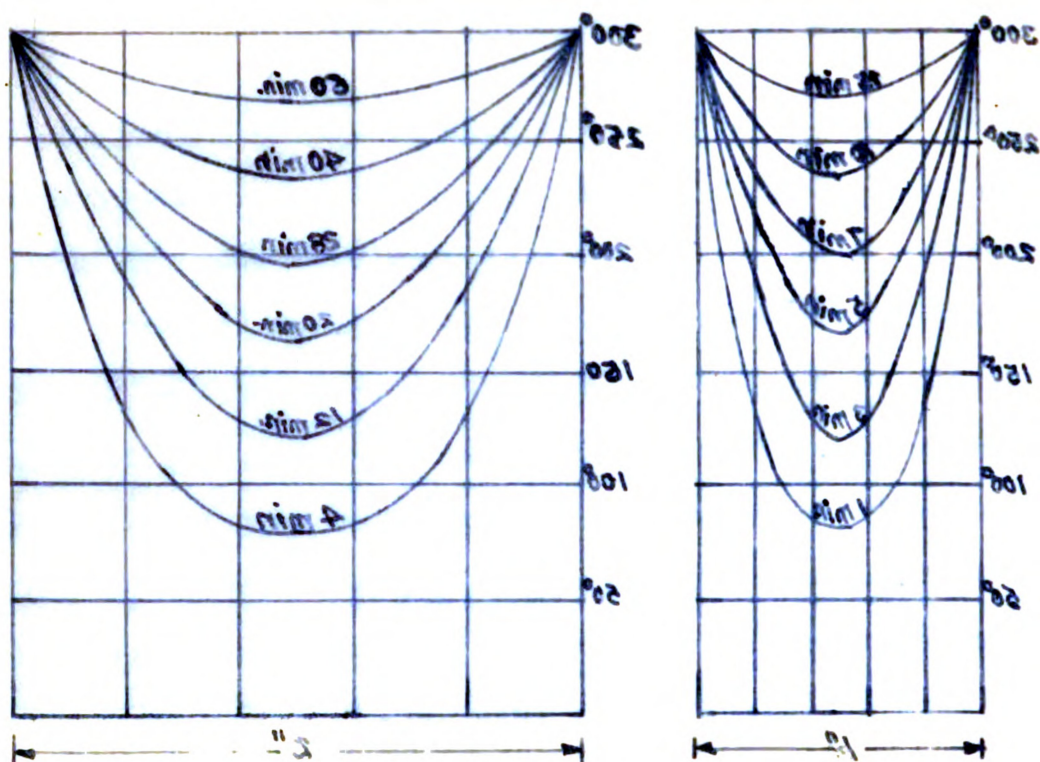


Fig. 4. Time-temperature distribution curves for 1", 2", and 6" thicknesses of wood heated by external means - such as steam platens, heat tunnel, etc. Curves are calculated for a thermal diffusivity of .0063 for spruce at 8-10% moisture content.

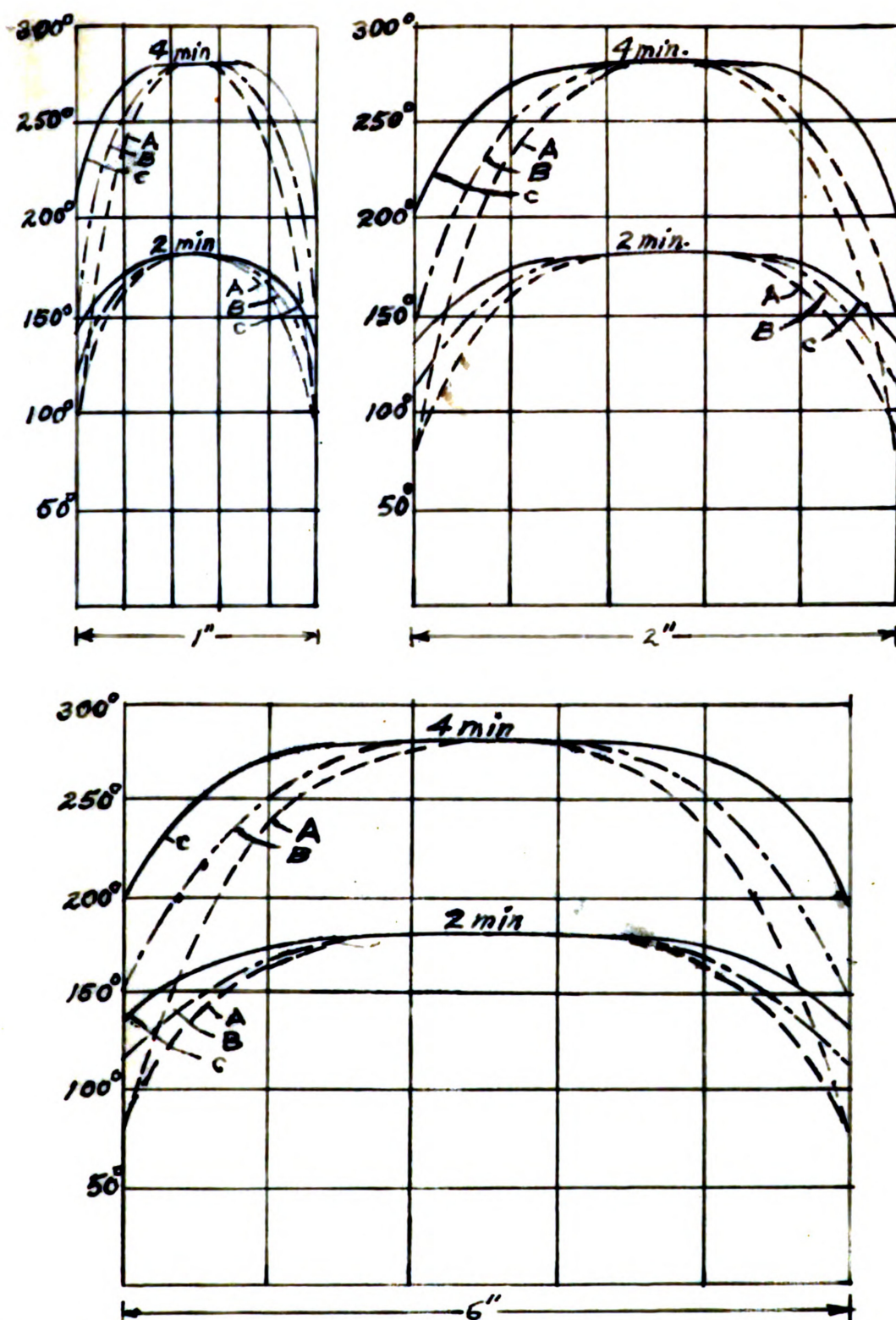


Fig 5. Time-temperature distribution curves for 1", 2" and 6" thickness of spruce heated by radio frequency (5 watts/cu.in.). Curve A is for the wood directly against cold plates; Curve B for wood against thin metal electrodes; Curve C for a thin insulating material between wood and press platens.

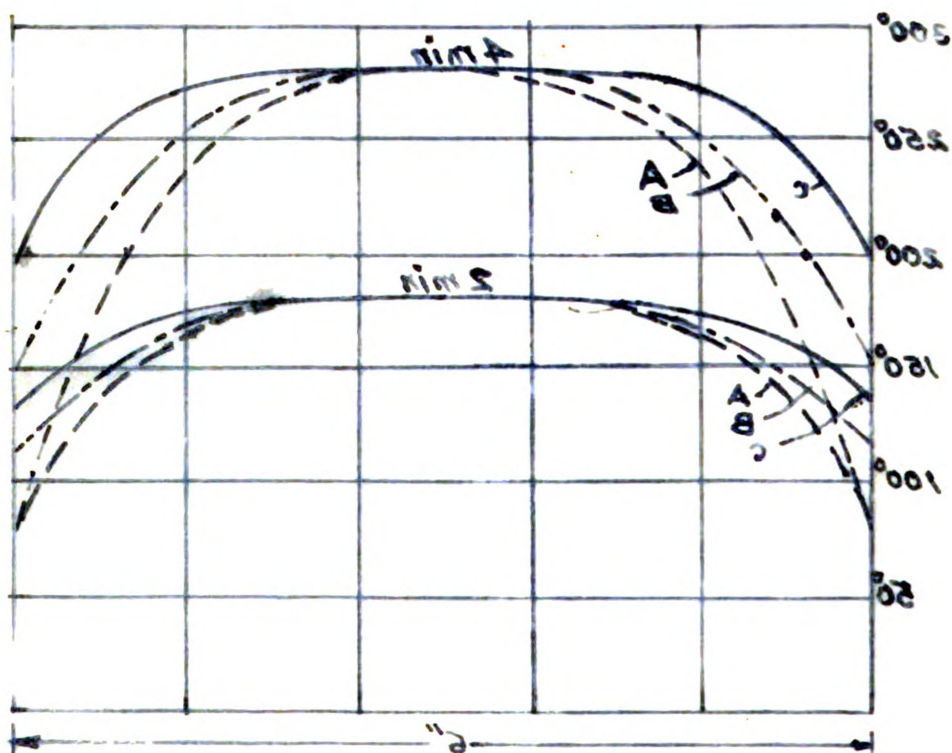
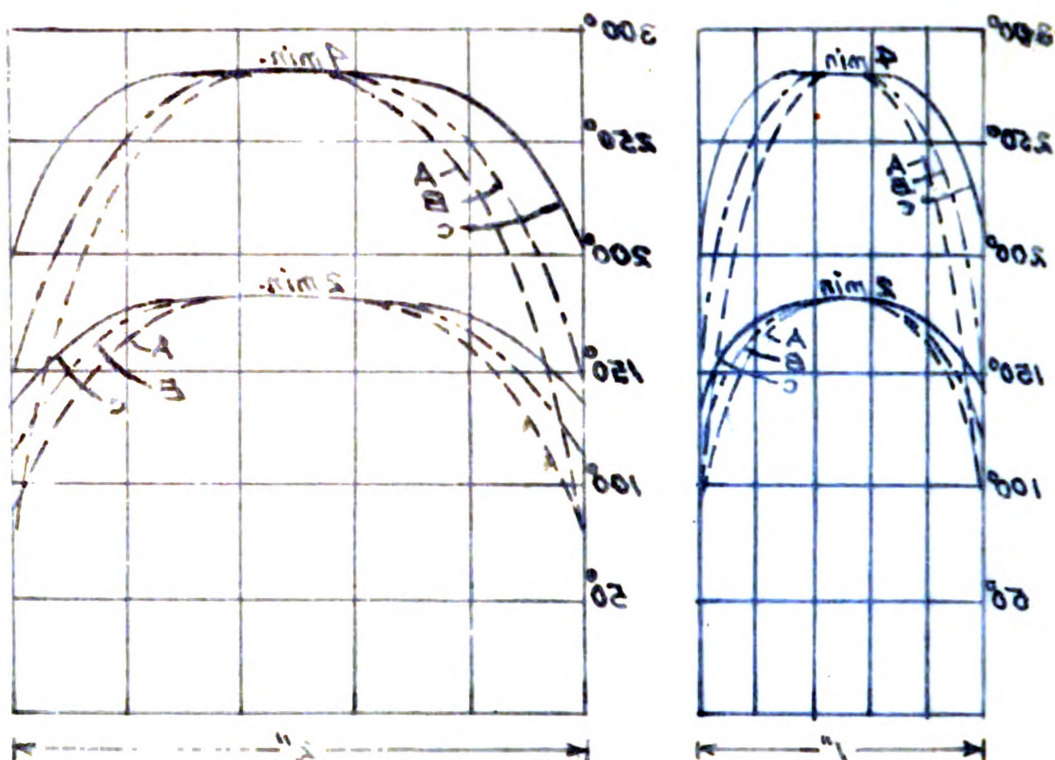


Fig. 2. Time-temperature distribution curves for 1", 2", and 4" thickness of spruce heated by radio frequency (5 watts/cm.in.). Curve A is for the wood directly against cold plates; Curve B for wood against thin metal electrodes; Curve C for a thin insulating material between wood and press platens.

Marco. They are also given by the McAdams and other sources, but the first reference is the most usable in this case. A value of .0063 for the thermal diffusivity of spruce at 8 to 10% moisture content was used.

The curves shown in Figure 5 are based mainly on experimental measurements made on various sections of wood heated by the high frequency method. For each time-thickness relation a set of three curves is given. This is necessary because the temperature gradient in wood heated by this method depends on the conduction losses. These losses depend to a certain extent on the equipment used. The three typical set-ups that are illustrated in these curves are as follows:

1 - the case where the material is directly against the faces of a large cold press.

2 - where the material is clamped between relatively thin metal plates which are exposed to the air.

3 - where a thin layer of heat-insulating material (such as press board) is placed between the material and the press, or between the electrodes and the press.

The curves for the cold press set-up are shown dotted. The large mass of metal tends to absorb the heat and consequently the outer surface of the wood never rises above the ambient temperature. The curves for the thin electrodes are shown broken. In this case the surface temperature rises to some extent and the gradient is less sharp.

The curves for the set-up where heat insulation is used are shown solid. These are purely indicative since in this case the gradient depends on the amount of heat insulating material. The curves shown are for measurements made with heat insulating sheets having $1/8$ th. the thickness of the wood itself.

In comparing the curves for the different methods, the most striking feature is the fact that for a 1" thickness the high frequency process gives a time-cycle of four minutes (to 280°), where the steam plate method requires some fifteen minutes to bring the center to the same temperature. Further increases in the thickness of the wood causes even greater discrepancy since, as the above formula shows, the time required for heat to penetrate increases as the square of the thickness. Moreover, the steam plate time-cycles are fixed and there is no way of appreciably shortening them. On the other hand, the time-cycles required for high frequency heating depend entirely on the power used. The curves of Figure 5 were calculated on the basis of a power to give five watts per cubic inch of material. If this power were doubled to ten watts per cubic inch, it would decrease the time required by half. The temperature would then be raised to 280° in two minutes.

When the comparative time-cycles for thicknesses greater than 1" are considered, it is immediately evident that the advantages of high frequency are enormous. As

indicated in Figure 5, the time to heat thicker sections by high frequency is the same as the time for the one inch section. This statement is true, of course, only if the power per cubic inch is kept constant. In other words, the total power is increased as the thickness increases. If the total power is held constant, then the time varies directly as the thickness. In the steam plate method, on the other hand, the time varies as the square of the thickness. This leads to one of the main advantages which is that the wood may be treated with heat throughout regardless of its section. Yet another advantage is evident when the shape of the curves of Figures 4 and 5 are considered. In the hot plate method the outer layers of wood are at a high temperature for a very considerable length of time. As a result these tend to dry out and a degree of "case hardening" sets in. In critical sections such as aircraft parts, this is very objectionable. Sometimes the wood must be conditioned after glueing by being wet on the outside to increase the moisture content of the outside layers. With high frequency this drying out does not occur, even when the cycle is fairly long, because the temperature gradient has a slope the reverse of that which would cause such an effect.

Too much moisture may cause steam from near the surface or close to the hot plate. Hence ordinary hot plate practice has been to use almost dry wood of 2 or 3% moisture content to prevent damage due to steam blisters. Then, after glueing, the recommended practice is to raise the

moisture content back up to 8 or 12%, or about its normal outdoor operating moisture content. Moisture content can be high when high frequency heating is used, without likelihood of damage to the piece. This makes it unnecessary to dry airplane wood to such a low moisture content.

The high frequency method of heating is a great saver. By doing the job quicker, a great saving of time is affected and therefore a saving of labor. Due to the fact that a press outfitted with high frequency does work so much more rapidly, it greatly reduces the number of presses required, and therefore the floor space necessary. The power used for a certain job would be less because the power is only on while the unit is in use. Between loadings, the unit is turned off, thereby eliminating the loss experienced in maintaining a continuous head of steam.

There is also the matter of work comfort and safety of the operators to be considered. There is not the heat ordinarily surrounding steam plates, and since there are not hot plates to burn the operator, and the electricity is turned off for loading and unloading, the operator is in much more pleasant and safe surroundings.

An advantage of less importance in this case is the fact that once this wood has been subject to the field of high frequency current all infestation then present will be destroyed.

An important consideration, when new press installations are considered, is the fact that the presses themselves can be made of much cheaper design, since the massiveness associated with steam plates and multiple openings are done away with. The capacity of two 300 kilowatt units is at least equivalent to three fifteen opening hot presses with automatic loaders.

EXPLANATION OF COMPUTATIONS NECESSARY:

Heating wood with electrical power, aside from the difficult application problems which invariably arise, is a relatively simple operation. Theoretically, at least, it is only necessary to have a generator of suitable characteristics and to connect the same by means of wires or other conductors to the wood which it is desired to heat.

An arrangement of this sort is shown in Figure 6. The piece of wood to be heated is placed between two electrodes, each of which is coupled to one side of the line from the generator. The area of these plates with respect to the area of wood determines the distribution of current and therefore the area and volume heated, as shown in Figures 7a and 7b.

In some cases such an arrangement as 7a would be useful, but for simplicity and ease of calculation the following discussion will be limited to the set-up in 7b, where the plate area is equal to the area of the wood. With

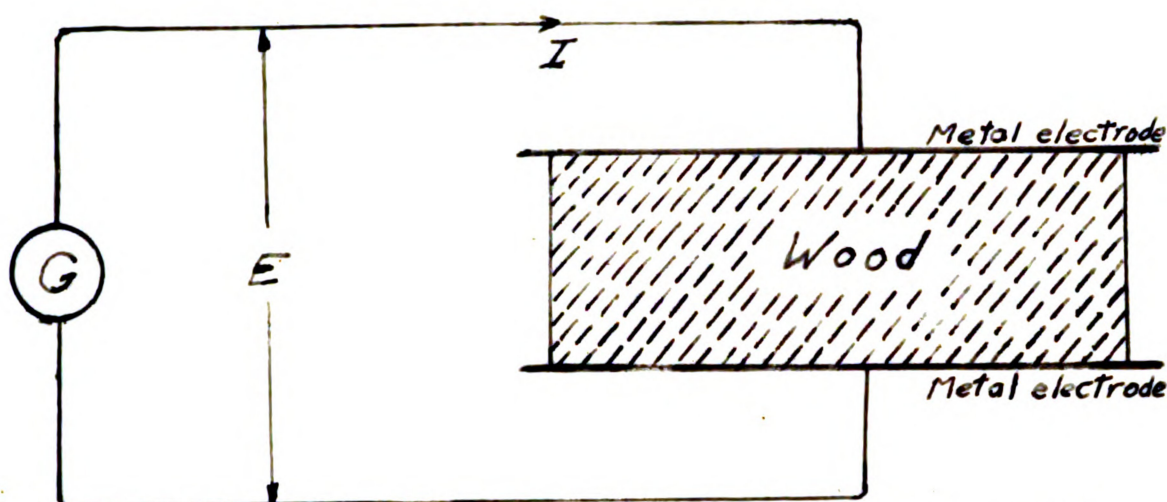


Fig. 6. Fundamental circuit used in heating wood with radio frequency power. The wood is placed between metal electrodes which are connected to a generator.G. Resistance to passage of the current I causes the wood to heat.

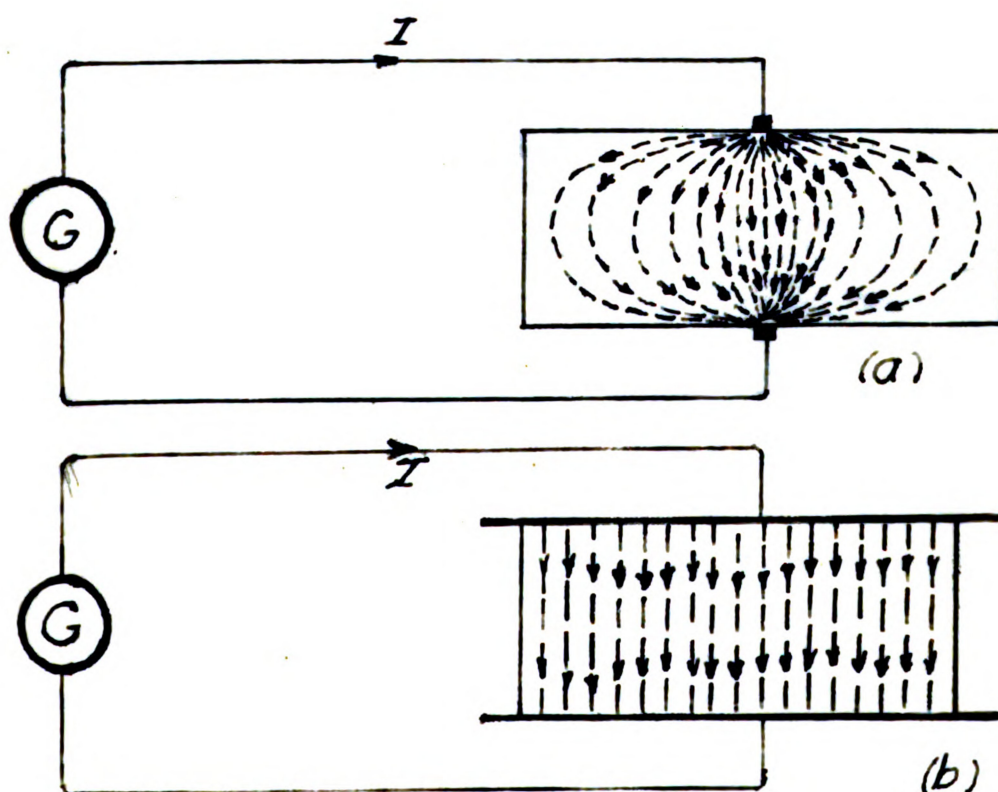


Fig 7. The distribution of current paths through the wood(a) when only small contact points are used; (b) when large metal plates, called "electrodes" are used.

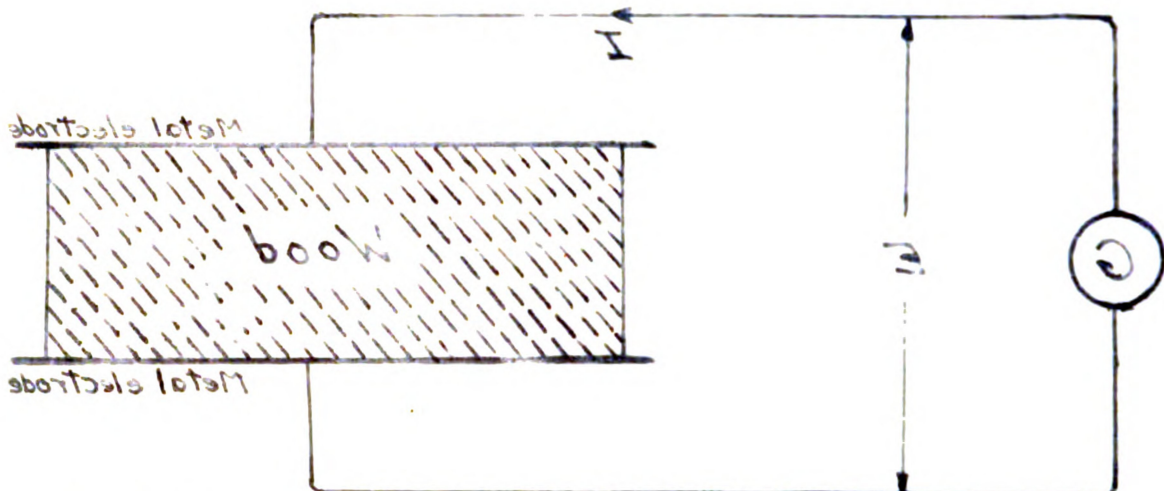


Fig. 6. Fundamental circuit used in heating wood with radio frequency power. The wood is placed between metal electrodes which are connected to a generator. G. Res-istance to passage of the current I causes the wood to heat.

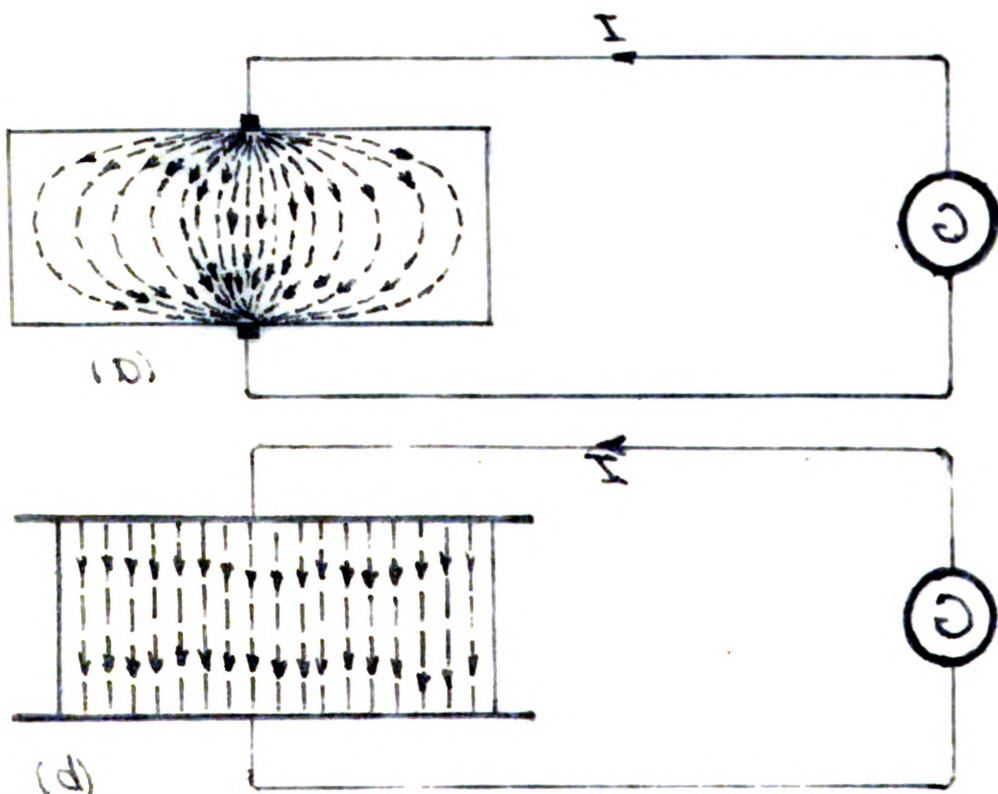


Fig. 7. The distribution of current paths through the wood (a) when only small contact points are used; (b) when large metal plates, called "electrodes" are used.

such an arrangement, the voltage generated by generator G causes a current to flow around the circuit, through the wood, and back to the generator as shown. The magnitude of this current will be determined by the voltage supplied by the generator and the resistance the wood offers to the passage of the current.

If the size of the wood to be heated is known, it is easy enough to calculate the voltage required to produce a certain heating effect. The metal plates used for electrodes constitute a condenser. If there were not wood between the plates, they would be a perfect condenser and would be represented schematically as in Figure 8a, while current flowing would lead the impressed voltage by 90° , and the vector diagram would be as shown in Figure 8b. The power consumed would be zero.

Since there is wood between the plates, there is no longer a perfect condenser, as the wood presents a leakage path; that is, dielectric constant is greater than 1. The circuit now formed can be represented by a schematic diagram as in 9a, with a perfect condenser paralalled by a resistance equivalent to the wood. This value of R_p is merely a representative value, as the resistance is dependent on the frequency of the impressed voltage. The vector diagram may be drawn as in Figure 9b. The capacity C of the plates remains the same, and the current I_c still leads the voltage by 90° , but a new current, I_r , is now included and is in phase with the voltage. The line current is made up of these

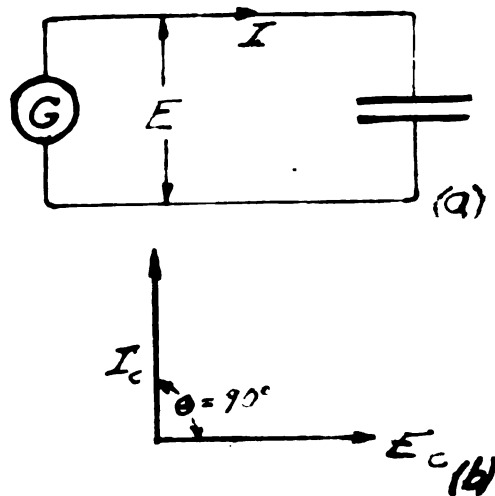


Fig. 8. Schematic (a) and vector (b) diagrams for a circuit in which a generator is connected to a " perfect " condenser. The current and voltage are 90° out of phase; hence, no power is consumed.

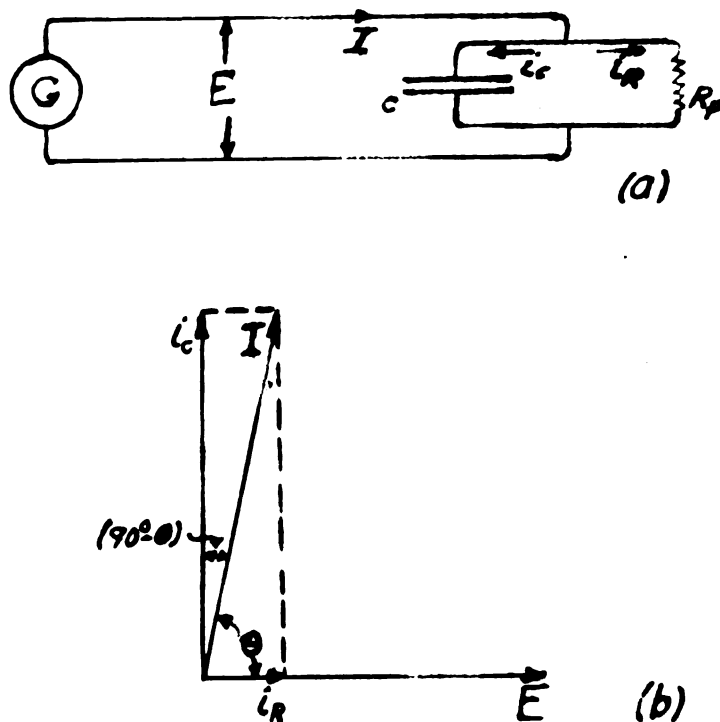


Fig 9. Schematic (a) and vector (b) diagrams for a similar circuit in which the condenser has a poor dielectric such as wood. The current i_r flowing through the equivalent resistance R_p represents the power which is expended in heating wood.

Fig. 8. Schematic (a) and vector (b) diagrams for a circuit in which a generator is connected to a "perfect" condenser. The current and voltage are 90° out of phase; hence, no power is consumed.

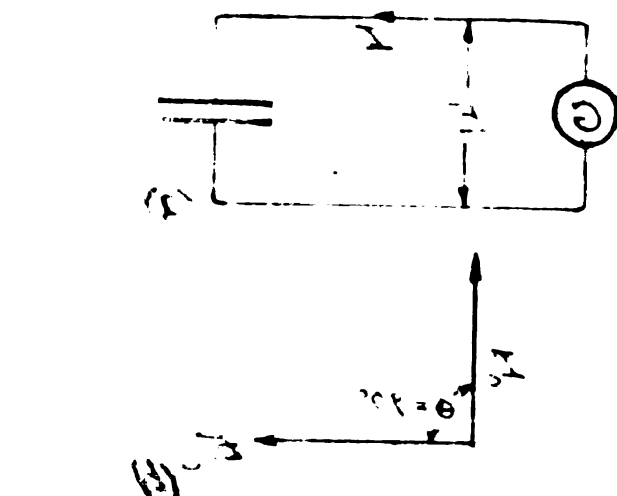
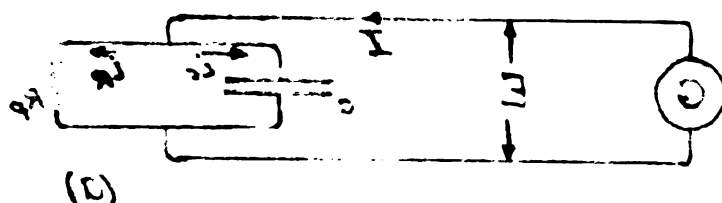
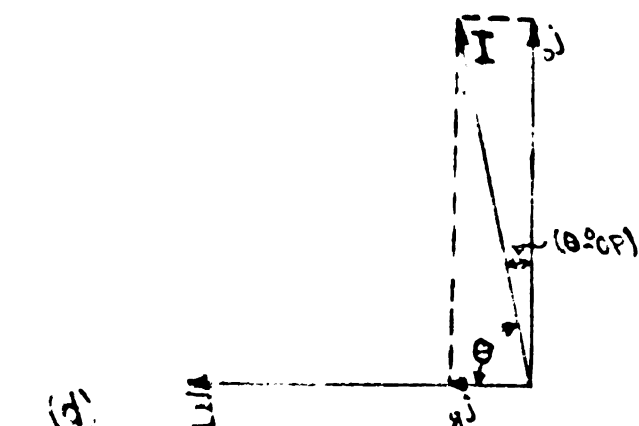


Fig. 9. Schematic (a) and vector (b) diagrams for a circuit in which the condenser has a poor dielectric such as wood. The current flowing through the equivalent resistor R_p represents the power which is expended in heating



wood.

components and therefore it leads the voltage by an angle less than 10° and there is power dissipated by the current. Since i_r is the only current causing a use of power, it is the only one which matters. In order to calculate R_p , it is found that :

$$\text{Power factor} = \cos \theta = \sin(90^\circ - \theta)$$

for small angles

$$\sin(90^\circ - \theta) = \tan(90^\circ - \theta)$$

Therefore :

$$\text{P.F.} \approx \tan(90^\circ - \theta) \approx \frac{i_r}{i_c}$$

$$i_r = \frac{E}{R_p} \qquad i_c = \frac{E}{X_c}$$

$$\text{P.F.} = \frac{X_c}{R_p}$$

$$R_p = \frac{X_c}{\text{P.F.}} \qquad (1)$$

The value of X_c (the capacitive) can be calculated from:

$$X_c = \frac{1}{2\pi f c} \qquad (2)$$

f - is the frequency

c - is the capacitance and may be figured from the equation:

$$C \text{ (in farads)} = \frac{KA}{4\pi d}$$

K - the dielectric constant; A - the area of the plates in square centimeter ; D - is the distance between the plates in centimeters.

The value of the power factor P.F. can easily be measured by means of a radio frequency bridge or Q-meter. The power factor of a material is usually thought of as a constant. However, recent measurements (see Figures 10 and 11) show that P.F. varies considerably with frequency , moisture, and impregnation. For the calculation here an approximate value will suffice.

Now that R_p has been found, it remains to determine the power delivered to the circuit as heat from the following formulas:

$$P = i_r^2 R_p \quad (3)$$

If the amount of power required to heat the material is calculated, as described below, P is known and from equation (3) i_r can be calculated. Since:

$$E = i_r R_p \quad (4)$$

the value of E (the voltage) which is required to force through the wood the current necessary to heat it the desired amount, can be calculated.

If substitution of some actual values are made in the above calculations, the reason for the use of high frequencies will be clearly preceptible.

The following calculations are taken from information used in making compregnated propellor blocks by the Camfield Manufacturing at Grand Haven, Michigan.

Example (1)- It is desired to use 60-cycle

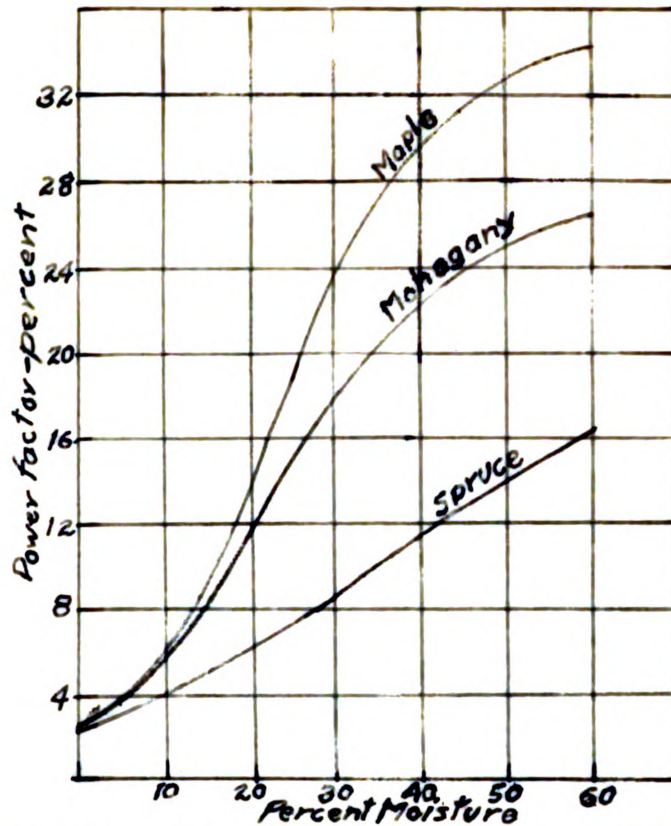


Fig 10. Variation of power factor with percent moisture for three species. Measured values for one specie vary considerably; hence, these curves should be used only as a first approximation.

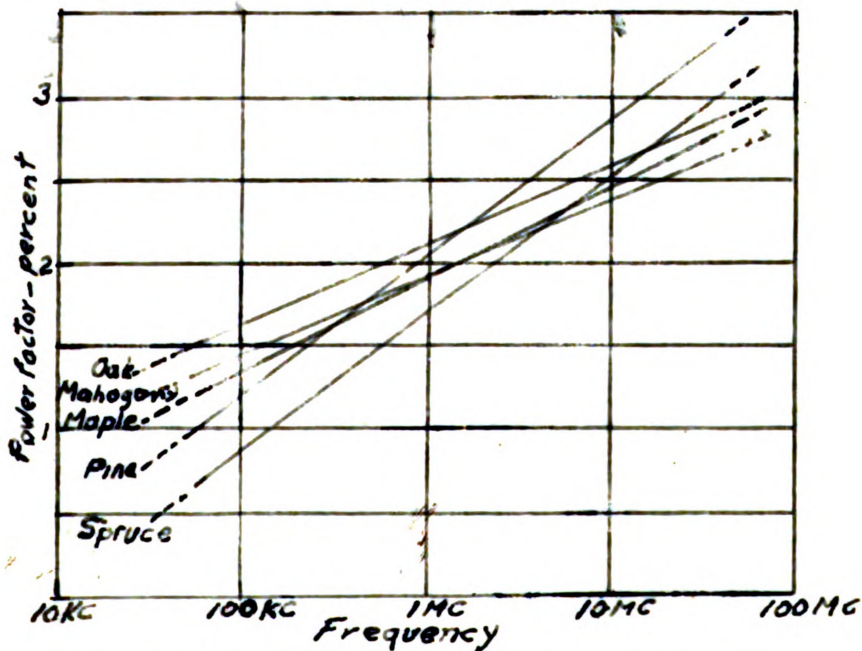


Fig. 11. Variation of power factor with frequency. At lower frequencies these curves tend to flatten out.

Fig. 10. Variation of power factor with percent moisture for three species. Measured values for one species vary considerably; hence, these curves should be used only as a first approximation.

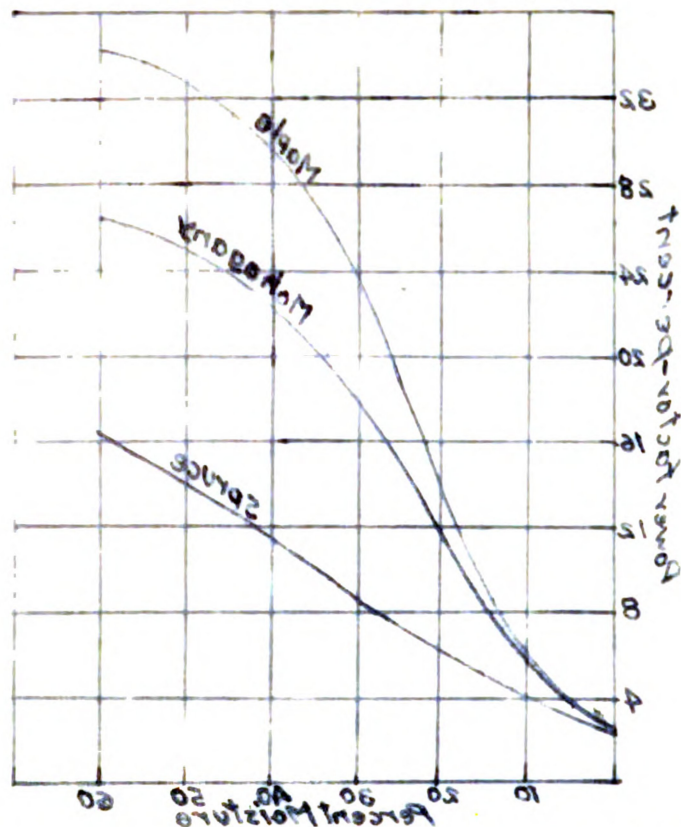
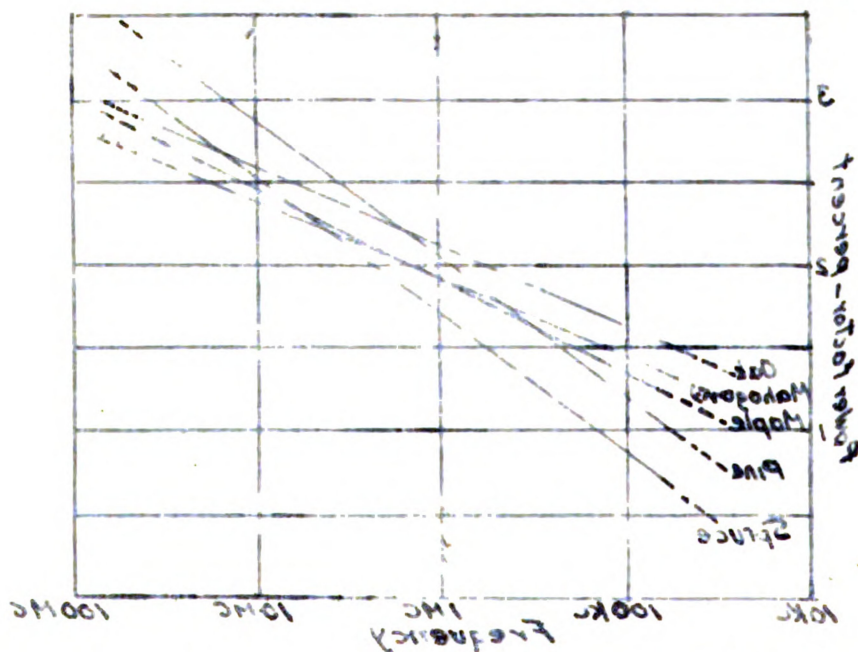


Fig. 11. Variation of power factor with frequency. At lower frequencies these curves tend to flatten out.



current to heat a test propeller to 240° . By the method shown below it has been calculated that a power of 6,000 watts is required to do this in a time of eight minutes. By calculation C was found to be 150 microfarads; hence, from equation (2):

$$X_c = \frac{1}{2\pi f c} = \frac{1}{6.28 \times 60 \times 150 \times 10^{-12}} = 12$$

and from (1):

$$R_p = \frac{17,700,000}{.05} = 354,000,000 \text{ ohms} \quad (\text{taking P.F.} = .05)$$

from (3) :

$$P = i_r^2 R_p$$

$$P = 6000, R_p = 354,000,000$$

$$i_r^2 = \frac{6000}{354,000,000}$$

$$i_r = 4.13 \times 10^{-3} \text{ amperes}$$

$$\begin{aligned} \text{from (4): } E &= i_r R_p = 4.13 \times 10^{-3} \times 354 \times 10^6 \\ &= 1,460,000 \text{ volts} \end{aligned}$$

In other words, the desired heating could be accomplished with 60-cycle current only by the use of an entirely impractical voltage.

Example (2) -Now assume that the same block is to be heated with current at a frequency of one million cycles:

$$\text{from (2)} \quad X_c = \frac{1}{2 f c} = \frac{1}{6.28 \times 10^6 \times 150 \times 10^{-12}} = \frac{10^6}{943}$$

$$X_c = 1010 \text{ ohms}$$

$$\text{from (1): } R_p = \frac{1010}{.05} = 20,200 \text{ ohms}$$

from (3):

$$P = i_r^2 R_p = 6000$$
$$i_r^2 = \frac{6000}{20,200} = .297$$
$$i_r = .545 \text{ amp.}$$

from (4):

$$E = i_r R_p = .545 \times 20,200$$

$$E = 11,000 \text{ volts}$$

If one megacycle current is used, the unit can be operated with only 11,000 volts across the load. If the frequency is increased still higher to ten megacycles the required voltage would drop to 3480 volts. In order to show this effect of frequency graphically, the values of X_c , R_p , and E for a large range of frequencies have been plotted in Figure 12.

As can be seen from Figure 12, the voltage required for a given power input (that is, a given heating effect) is inversely proportional to the square root of the frequency. This means that, generally speaking, the higher the frequency the better, although a practical limitation is encountered due to the fact that the efficiencies of some types of tubes fall off at the higher frequencies.

The actual maximum voltage used will depend on the thickness of the load. For very thin sections only a few hundred volts can be used before arc-over occurs. In thicker sections the voltage can go as high as 15,000 volts. It is unsatisfactory to go beyond this limit, as the corona effect takes place; that is the plates will begin discharging into the air.

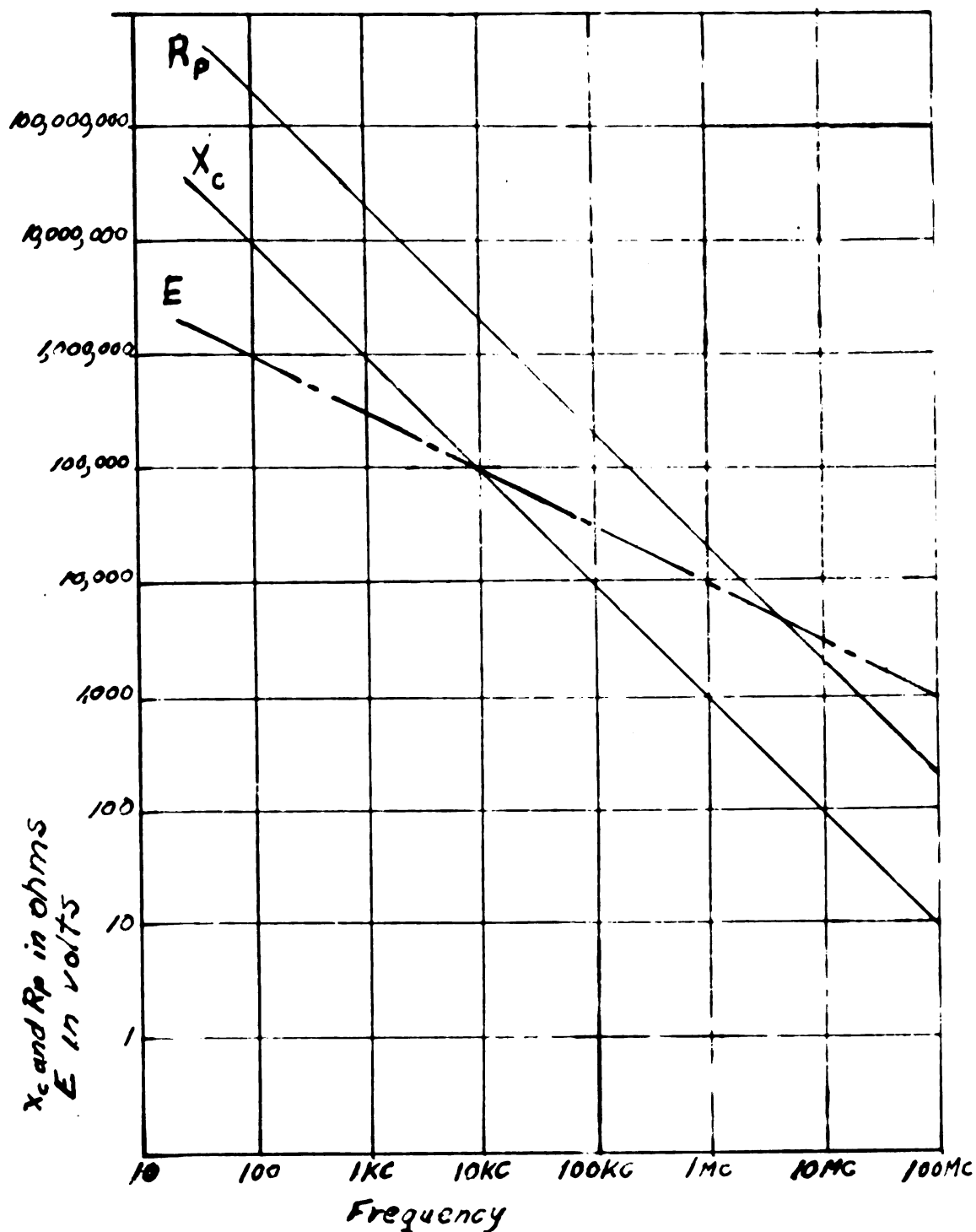
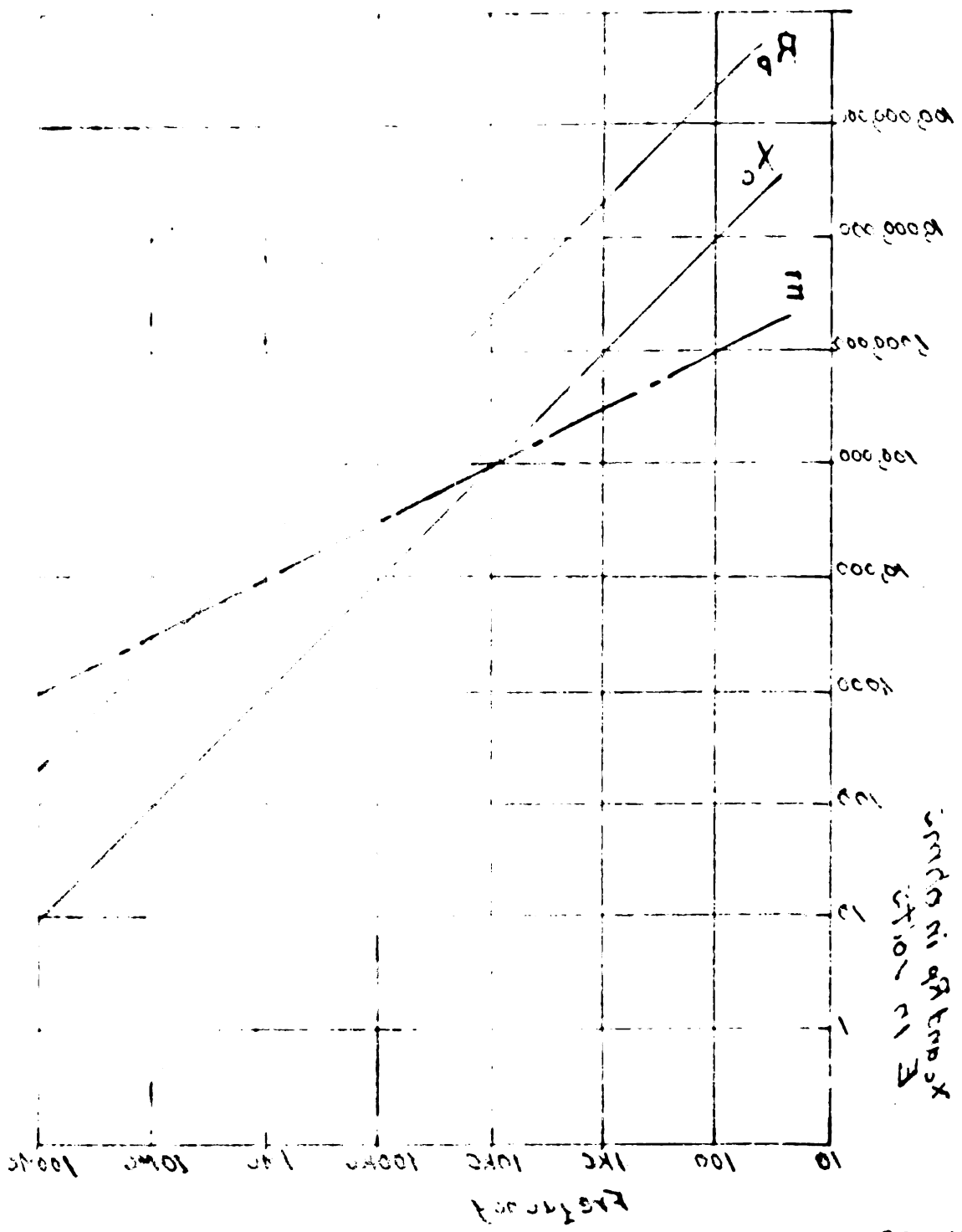


Fig 12. Variation with frequency of the reactance X_c , the equivalent resistance R_p and the voltage E across the load

for a typical radio frequency heating set-up. Note that the voltage E varies inversely as the frequency; hence, higher frequencies mean less danger of voltage flash-over.

phenomena mean less danger of voltage flash-over. voltage E varies inversely as the frequency; hence, higher frequencies for a typical radio frequency heating set-up. Note that the

Fig 12. Variation with frequency of the resistance X , the equivalent resistance R_p and the voltage E across the load



CALCULATION OF THE POWER REQUIRED:

The amount of heat (in gram calories) required to raise the temperature of a certain quantity of wood, or any material, a certain number of degrees can be calculated from the relation:

$$H = p \ c \ \Delta t \ x \ \text{Volume}$$

where: p - specific heat (cal. per gram per degree C.)

c - density (gram per cubic centimeter)

Δt - change in temperature (degrees C)

v - volume (cubic centimeters)

The power required to produce this amount of heat in a given time is:

$$\begin{aligned} P(\text{watts}) &= \frac{4.187H}{\text{time in seconds}} \\ &= \frac{4.187 \ x \ (\ pc \ x \ \Delta t \ x \ \text{volume})}{\text{time in seconds}} \end{aligned}$$

If the following substitutions are made:

cubic inches for cubic centimeters

degrees fahrenheit for degrees centigrade

time in minutes for time in seconds

the following equation is obtained:

$$P \ \text{watts} = \frac{.637 \ x \ p \ c \ x \ T \ x \ \text{volume (cu. in.)}}{\text{time in minutes}}$$

where : T = degrees F

In some cases it is more convenient to express this in terms of required power concentration; that is:

$$\text{Power concentration (watts / cu. in.)} = \frac{.637 \ pc \ t}{\text{time (min)}}$$

In other cases where a limited amount of power is available,

it may be desired to know the time required to raise the material so many degrees. This is simply:

$$\text{time (min)} = \frac{.637 \text{ p c } \Delta t}{\text{Watts/ cu. in.}}$$

In order to give an idea of the power required in typical instances, two sets of curves have been drawn (Fig. 13 and 14) showing the relation of power concentration to time interval, for several different temperature increments. These curves are based on values of pc .25 , and pc .35. Most woods give values lying between these two curves. Where accurate data is available, the curves may be used for other values of pc.

It should be noted that the power requirements, as indicated in the figures, are the power which must be used up in the wood itself. In other words, if there is any loss of power, it will have to be supplied in addition to the above. This power loss, while a small percentage if large sections are used, is a large and important factor on thin sections.

ESTIMATED INITIAL OPERATING COSTS:

* The cost of radio frequency power per kilowatt is not uniform but rather decreases gradually as the power of the installation increases. This is illustrated by the curve of Figure 15, which has been drawn on the basis of such information as is available on installations made to date. Unfortunately, varying applic-

50 40 30 20 10 9 8 7 6 5 4 3 2

Time - Minutes

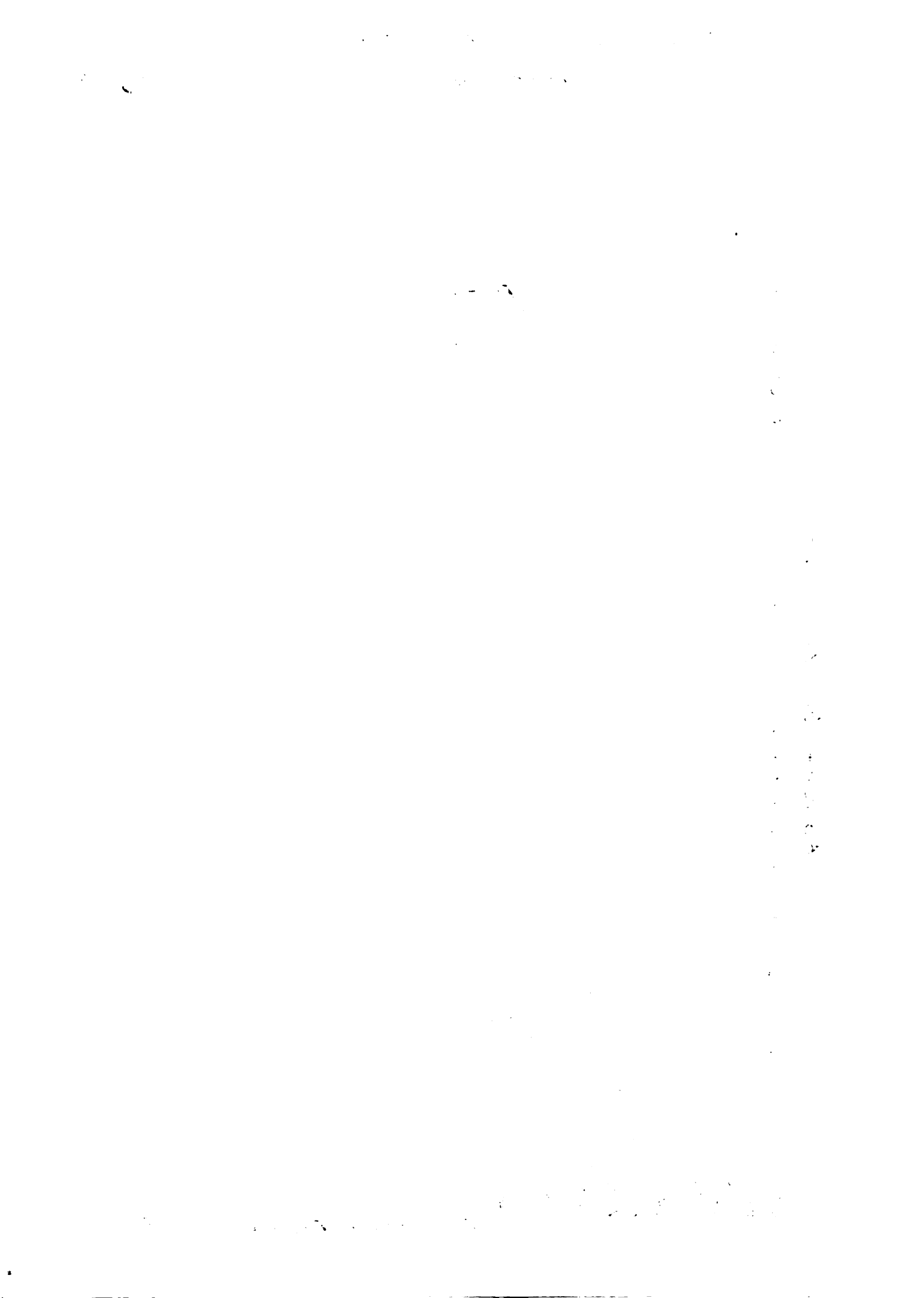
Fig. 13

Power - Watts Per Cu. In.

$pc = 25$

320 300 280 260 240 220 200 180 160 140 120 100 80 60

Temperature Increase - deg. F

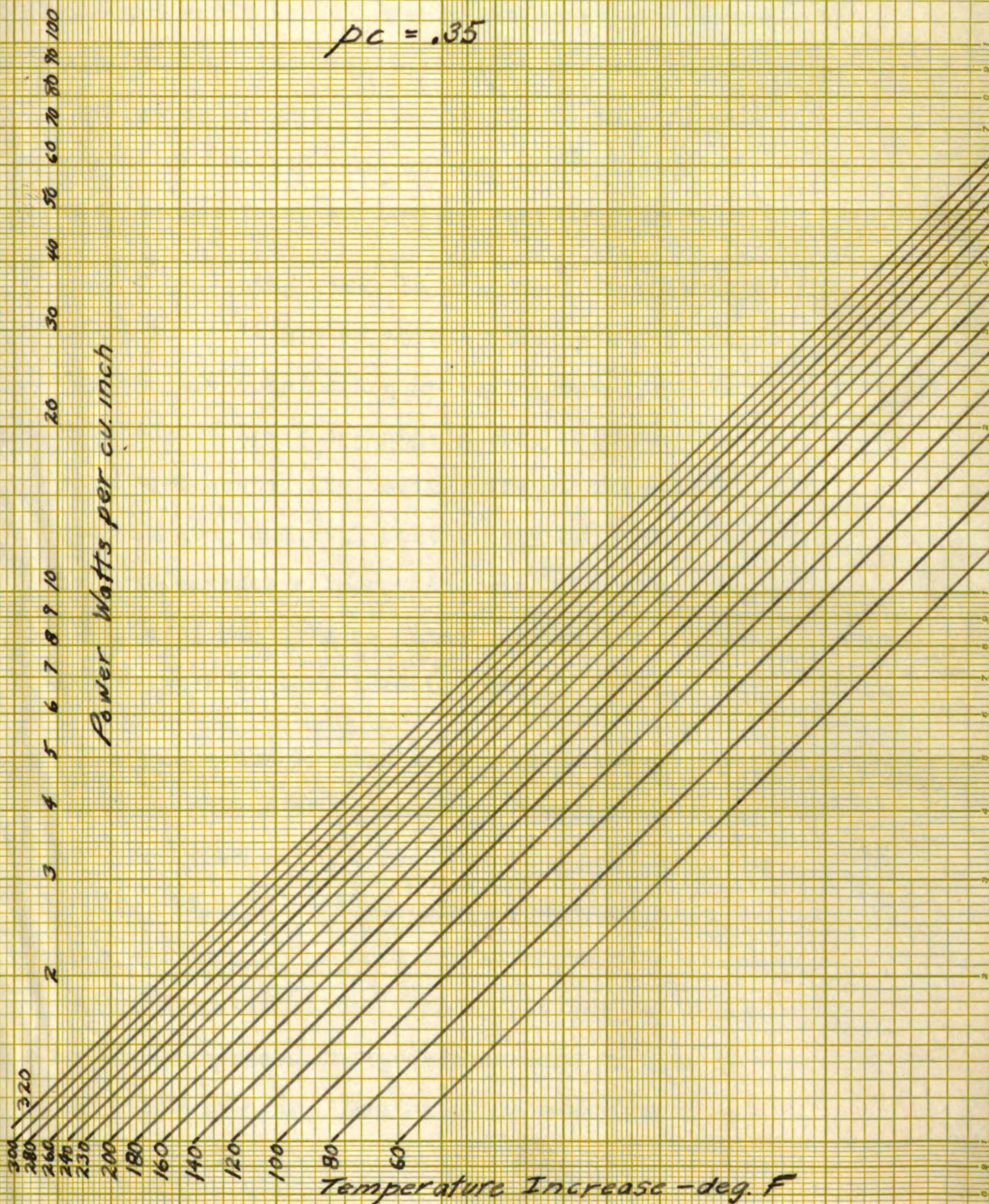


50 40 30 20 10 9 8 7 6 5 4 3 2

Time - Minutes

Fig. 14

$$pc = .35$$



ations and engineering costs were necessarily involved in these. Also, there was some difference in cost of equipments of different manufacture. For this reason all available information was plotted and a broad curve drawn so as to include all points. The result at least gives a quick indication of what installations to date have cost. The dotted line on this graph indicates the average "cost per KW" at various powers.

Operating costs in equipment of this type are made up mainly of tube replacement and power costs. Since there are no moving parts, other maintenance costs are negligible. Contrary to some statements, the useful life of the equipment is long and will most likely be terminated by obsolescence rather than wear. Depreciation, therefore, can only be based on some arbitrary figure such as that used for tax purposes.

In order to gain some idea of operating costs, a number of equipments of various powers were analyzed and the results shown as the curves of Fig. 15. In this calculation average tube life was assumed as 5000 hours(which is a reasonable estimate of the life of present day tubes in this service). Power was assumed to cost 1¢ per kilowatt hour. Depreciation was figured on

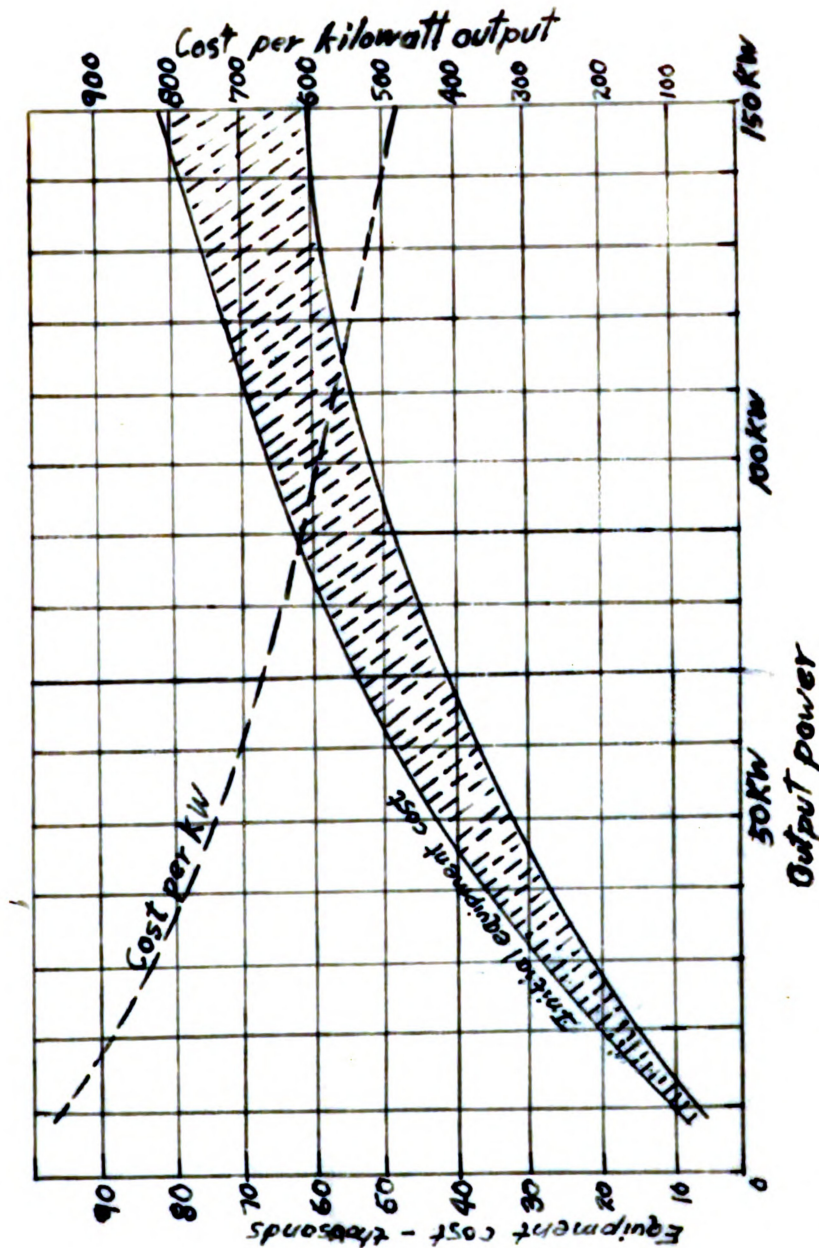
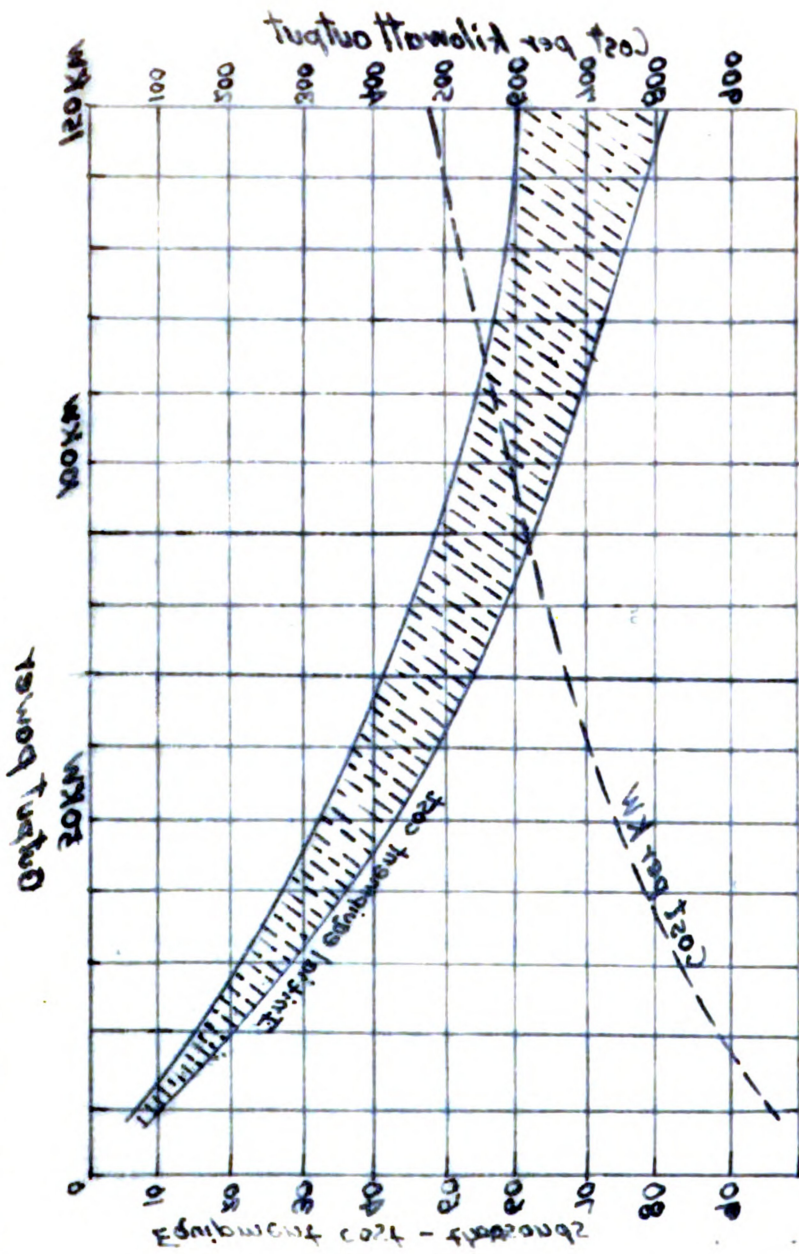


Fig. 15. Initial cost of radio frequency equipment and cost per KW based on a number of installations made by different manufacturers.

manifester.
 bel KM pssed on a number of installations made by different
 Fig. 12. Initial cost of radio frequency equipment and cost



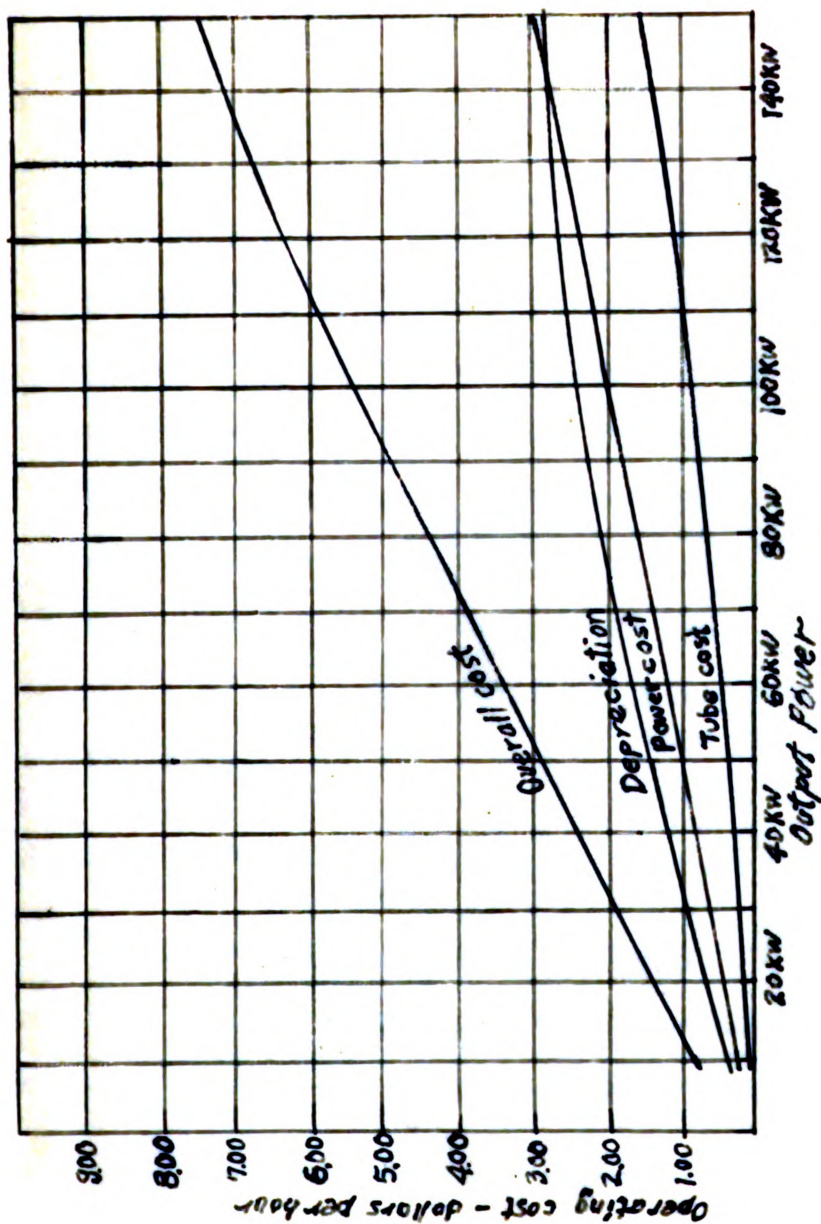


Fig. 16. Approximate tube cost, power cost and overall operating cost of radio frequency equipment versus power delivered to the load. See text for basis of calculations.

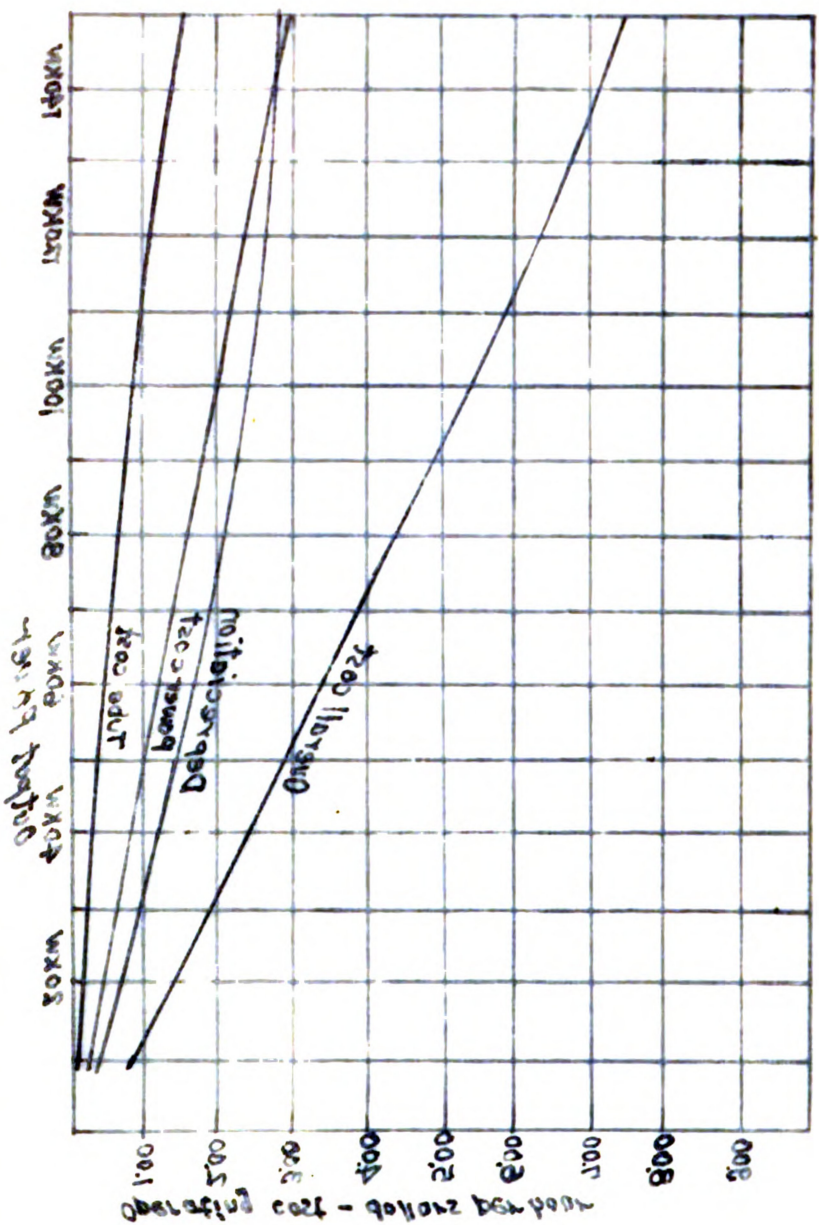


Fig. 10. The curves show the relationship between energy cost and total cost. The fuel cost is the most significant component of the total cost.

the basis of 25,000 hours of operating life (approximately three years at 24 hours a day, or nine years at 8 hours a day.). The overall cost, of course, is simply the total of depreciation, tube and power costs.

It is worth noting that these costs can only be assumed to hold for the present period. Simplifications in design, improvements in tube construction and other factors which can be quite clearly foreseen will undoubtedly lead to lower first cost and lower operating cost. However, it is apparent that even on the basis of the costs indicated in Fig. 15, there are many present day jobs on which this type of equipment can easily be justified from the cost standpoint.

EQUIPMENT AND RESULTS:

In choosing the source of power, there are two possibilities. The first was a straight oscillator circuit. The objection to this type of power supply was that the frequency

* This estimated cost section is from information supplied by the R.C.A. Manufacturing Company, Inc. This firm is one of the major companies supplying such equipment.

would vary with every change in load. While this type of circuit required the least equipment, it would give only around 30% efficiency.

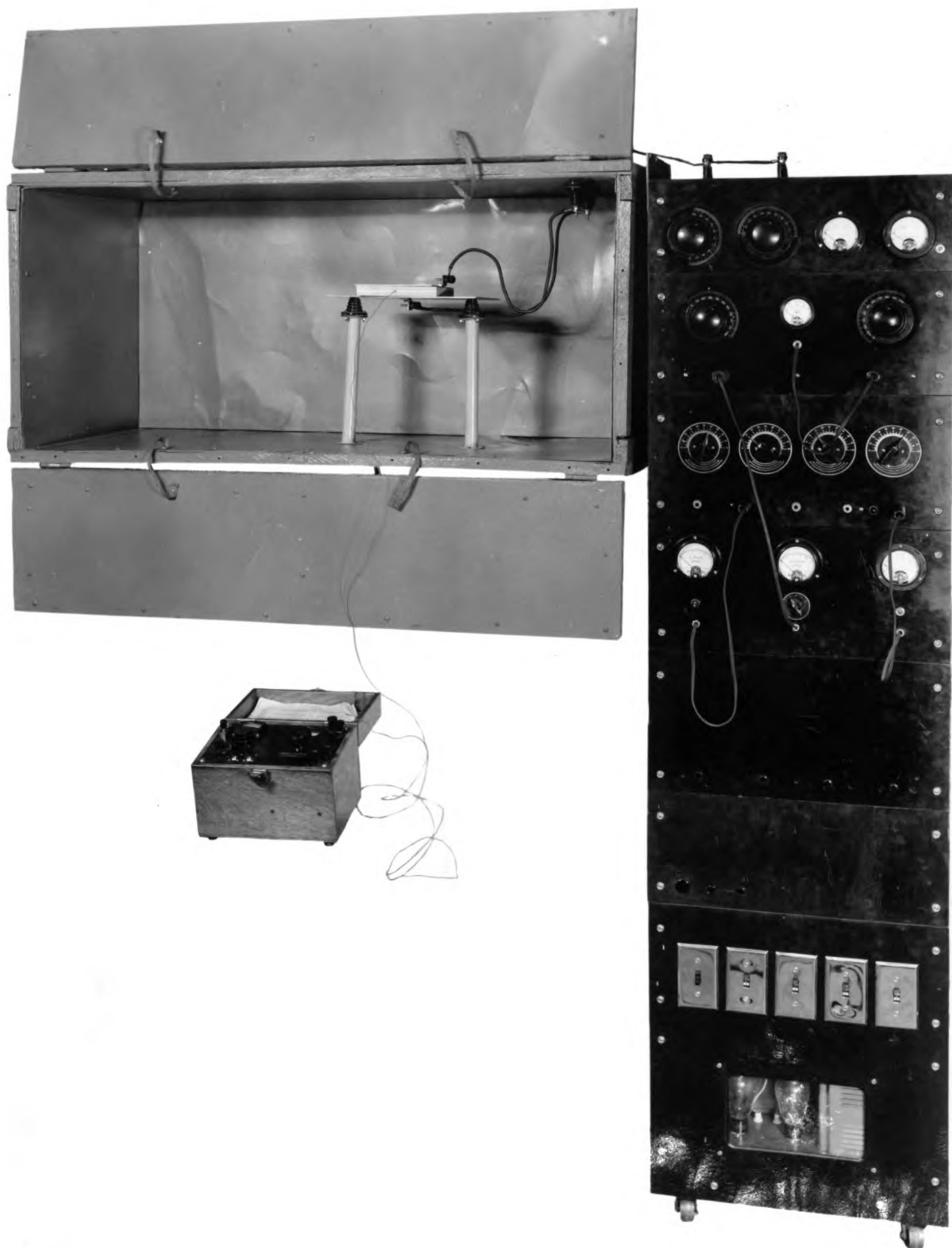
The other possibility was a crystal controlled amplifier circuit. In this system the frequency would remain constant and simple. This system also offered the advantage of having from 75 to 80% efficiency.

The equipment described in the following is shown in the photographs of Figures 17 and 18.

The original equipment consisted of a "Ham" transmitter. All the tubes and necessary parts were on this set. The problem of getting the equipment in shape for testing amounted to rewiring and altering about half the stages.

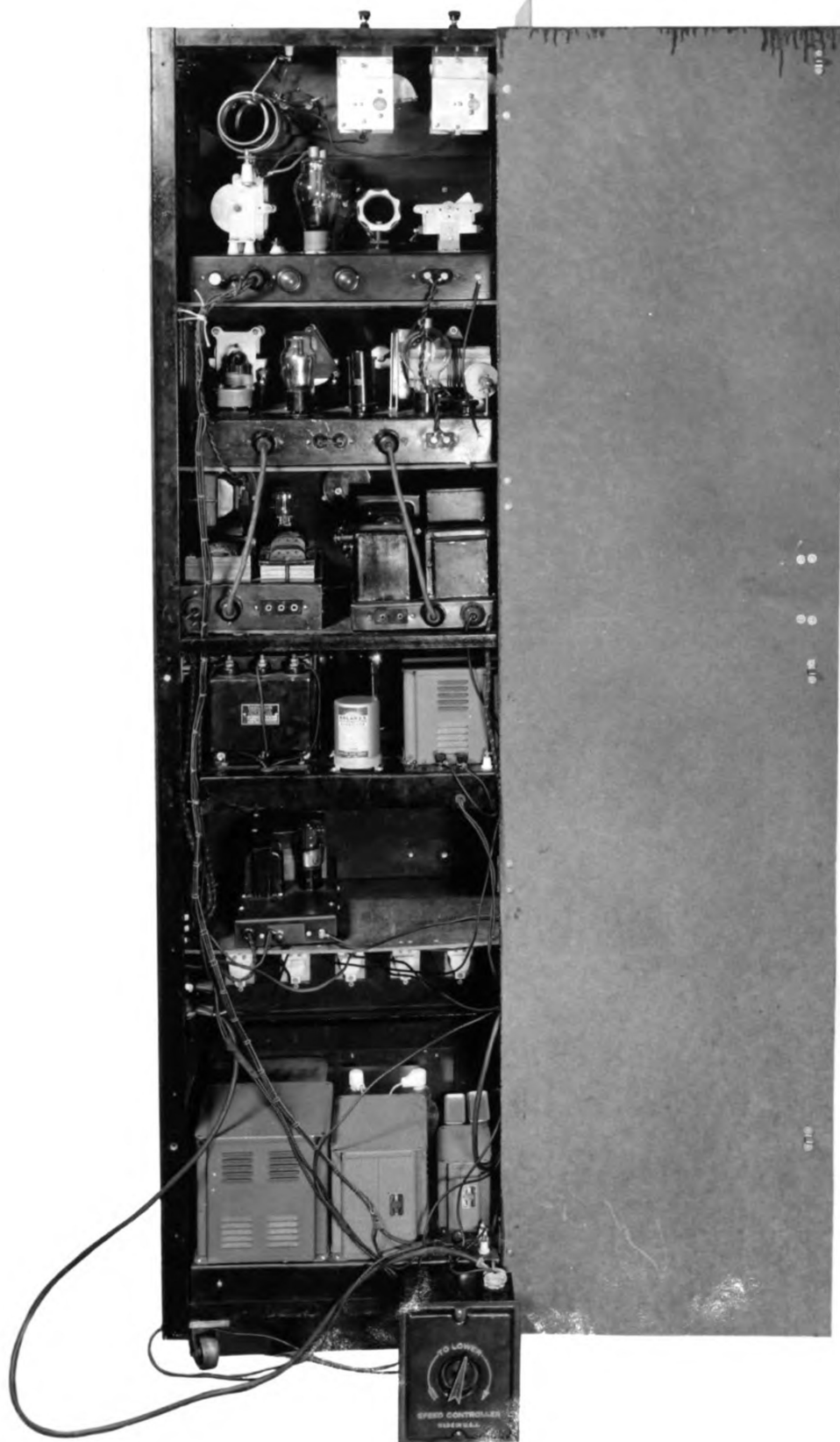
When the first tests were run, the main power supply was the original one from the transmitter. After a short time this supply blew out and another one had to be built. This supply was tested, but it was found that the plate voltage on the second buffer stage (see blue print in pocket) was too low. This necessitated the building of a separate power supply for the second buffer stage.

The transmitter being in shape for actual coupling to the load, the rest of the equipment was built. Since this high frequency current is identical to that used in radio broadcasting , it was necessary to take unusual precautions to see that the unit did not get on the air. This was espec-



13779-2

Fig. 17.



13779-1

Fig 18

ially necessary because of the war and the action taken by the Federal Communications Commission in ruling all private transmitters off the air. The unit was not complete as to the stage for voice pickup, but the remaining mechanism was capable of emitting waves that might have caused "jamming" of certain wave bands.

A shielded room was built of fine mesh screen wire. This wire was all electrically connected together and connected to a pipe driven into the ground. This was to prevent any possible escape of radio waves from the equipment.

A large box was built for holding the electrodes. This box was completely lined with sheet metal as a precautionary measure. This would not only keep the radio waves in, but would protect anyone working around it being burned by the high frequency current. There was usually around 3,000 watts on the plates, and anyone contacting them would undoubtedly be injured.

The original plates used were made of $\frac{1}{4}$ " aluminum and were 6" wide by 24" long. The lower plate was mounted on beehive insulators about 2" from the bottom of the box. In testing with these plates, it was found that they were too large for the capacity of the transmitter, and, also, that the capacity effect of the plates with the metal side of the box was too great.

Smaller plates were made from $1/16$ " thick aluminum. These were 6" wide and from 3" to 12" long. The lower plate

this time was mounted nearly in the middle of the box on long tubes with beehive insulators on top. This set-up was as shown in the photograph of the equipment, Figure 17.

The equipment being complete, the problem was one of coupling the power to the load. The first attempt was made by direct contact to the tank coil in the final stage of the transmitter. From there each side of the line was fed through a variable condenser and then to one of the plates.

This arrangement was not satisfactory, as the desired control could not be obtained, so an inductive coupling to the tank coil was arranged, as shown in the schematic diagram included in the pocket of this thesis. With this set-up the desired coupling could be arranged by shifting the pick-up coils with respect to the tank coil. The line was fed from each pick-up coil through the condensers and then to the plates.

The purpose of the pick-up coils and the condensers is to allow tuning of the circuit. This tuning consists of varying the capacitive and inductive effects in the circuit so that a resonant condition can be established. Resonance is a balance between the capacitive and inductive characteristics such that maximum power and efficiency can be obtained.

The transmitter was attached to the board and tuned, and a test was started when there occurred a dead short across the condensers. When the equipment was turned off, it was found that the bakelite strips supporting the plates of the

variable condensers had been "cooked". The large amount of power being drawn by the load was so great that the current had sufficient power to arid through this insulation, burning it, and causing it to swell. Because of this a new and better type of insulation had to be used.

There was another difficulty noted in this trial. The equipment was found to be very sensitive to its surroundings. When it was attempted to tune the circuit, the effect of capacity between the human hand and the condenser plates was too great. The circuit would apparently be in resonance, but when the hand was removed from the dials it would no longer be tuned. Also, the front panel of the transmitter was found to be heating, evidently from the passage of current between the ~~two~~ condensers by way of the fiberboard panel.

To correct the above conditions it was necessary to move the condensers 6" back from the front panel and the dials. Additional insulation was put in between the condensers and the supporting panels. The new plastic, Lucite, was used to make the extension rods from the dials to the condensers and to support the condensers from the fiber panels. The bakelite strips for supporting the condenser plates were also replaced by Lucite. These strips lasted until an unusually large load was drawn, when they too were "cooked".

Since Lucite would not work, an even better insulation had to be used. "Styron", a trade name for polystyrene, was used and found to be able to withstand the load.

During the course of the tests it was found that, contrary to expectations, the plates, between which the wood was placed, were heating. This was contrary to the supposed theory, and the cause has not been determined. After a run of perhaps 10 minutes, the wood would be hot but the plates would be far hotter. Since these plates were aluminum it would seem unlikely that they would draw more heat from the wood than they would lose to the air. Then too, the old principal of thermodynamics that heat will not flow up hill; that is, from a lower temperature area to a higher temperature area, would deny this to be possible. To check this, a test was run with a sheet of thin plastic between the plates and the wood. It was found that the same condition prevailed; that is that the plates were still hotter than the wood.

Just as a matter of interest, a piece of Styron was placed between the plates- by itself. When the power was turned on it was found that some power was being drawn. When the power was turned off, it was found that neither the plates nor the Styron showed any sign of heat. Just where the power used was dissipated is a matter for speculation. So far no explanation for the heating of the plates could be found.

Since the sections of the wood tested were necessarily small, it was felt that undoubtedly a large part of the opposition to the flow of current was from the air gap between the plates. This gap was caused by the nonconformity of the plates to the surface of the wood. To correct this, and also to re-

duce the radiation losses from the plates, heavy sections of wood were clamped over the plates to hold them tightly against the wood charge.

The matter of obtaining temperatures presented some difficulty at first. A thermometer was impractical because of its size. A thermocouple would fit between the plys of wood all right, but nothing was known about what effect the high frequency field would have on it. It was feared that the thermocouple might pick up the high frequency current and fire back through the potentiometer, ruining it. A thermocouple was inserted between the plys but not connected, and a test run was made.

The thermocouple was checked for the presence of the high frequency current and was found to be all right. It was then connected to potentiometer and found to operate all right.

Using the set-up outlined above several tests were run and temperatures noted by use of the potentiometer. In heating just two plys of Douglas fir it was found this equipment would raise the charge to 365°F. before radiation losses reached the point that no further appreciable temperature gain was noted in five minutes.

Further tests were run with "tego resin film" glue between the sheets of wood. This glue is made of a paper sheet impregnated with phenol formaldehyde glue solution. The sheet of glue consists of 1/3 rd. paper and 2/3 rds. phenol-formaldehyde. The tests run on this wood showed that sufficient

pressure could not be maintained to form a satisfactory joint.

These tests proved that the possibilities of using this system for dry bending wood. Tests run at the same time in the power laboratory of Michigan State College gave indications of what temperatures would be required to do this bending. The tests consisted of forming 1/16" sheets of the wood on pipes carrying high pressure steam. The smallest pipe the wood could be formed to was 5½" diameter. The wood was formed by clamping it to the pipe by a block cut to conform to its periphery. The inner side of the strips of wood being bent came to a temperature of 350°F. while the exterior surface was from 75° to 100° lower, due to the loss of heat to the air. The strips bent under these conditions maintained their rounded shape.

One difficulty was found in that the exterior surface of the wood tended to splinter because the heat loss left the surface temperature too low. It is felt that if the electrical method is used, the uniform temperature will eliminate this difficulty.

The power available from the transmitter used was too small to heat, but limited sections and to remove the wood so heated for bending allowed it to cool so rapidly that nothing could be done with it.

Several conclusions can be drawn from the results of this work. The first is that more power should be available for further tests. The second is that if bending is to be

accomplished the electric power should be applied to some sort of rolls. Using a set-up such as this would permit forming the wood as it is heated. This would present some difficulty as the wood is bound to vary somewhat in thickness, and that would cause a variation in spacing between the rolls as the wood traveled through.

Another difficulty would be that the moisture content of wood is not uniform. The variation of moisture content causes a variation in the dielectric constant as may be seen in Figure 19.

The two problems mentioned above will cause a variation in the capacitance of the rolls and make the tuning of the circuit a continuous and difficult problem.

One other system might be considered, and that is using an electrical system to bring the wood up to temperature and then forming it in gas heated rolls. The whole subject will require much further study before a satisfactory answer can be found.

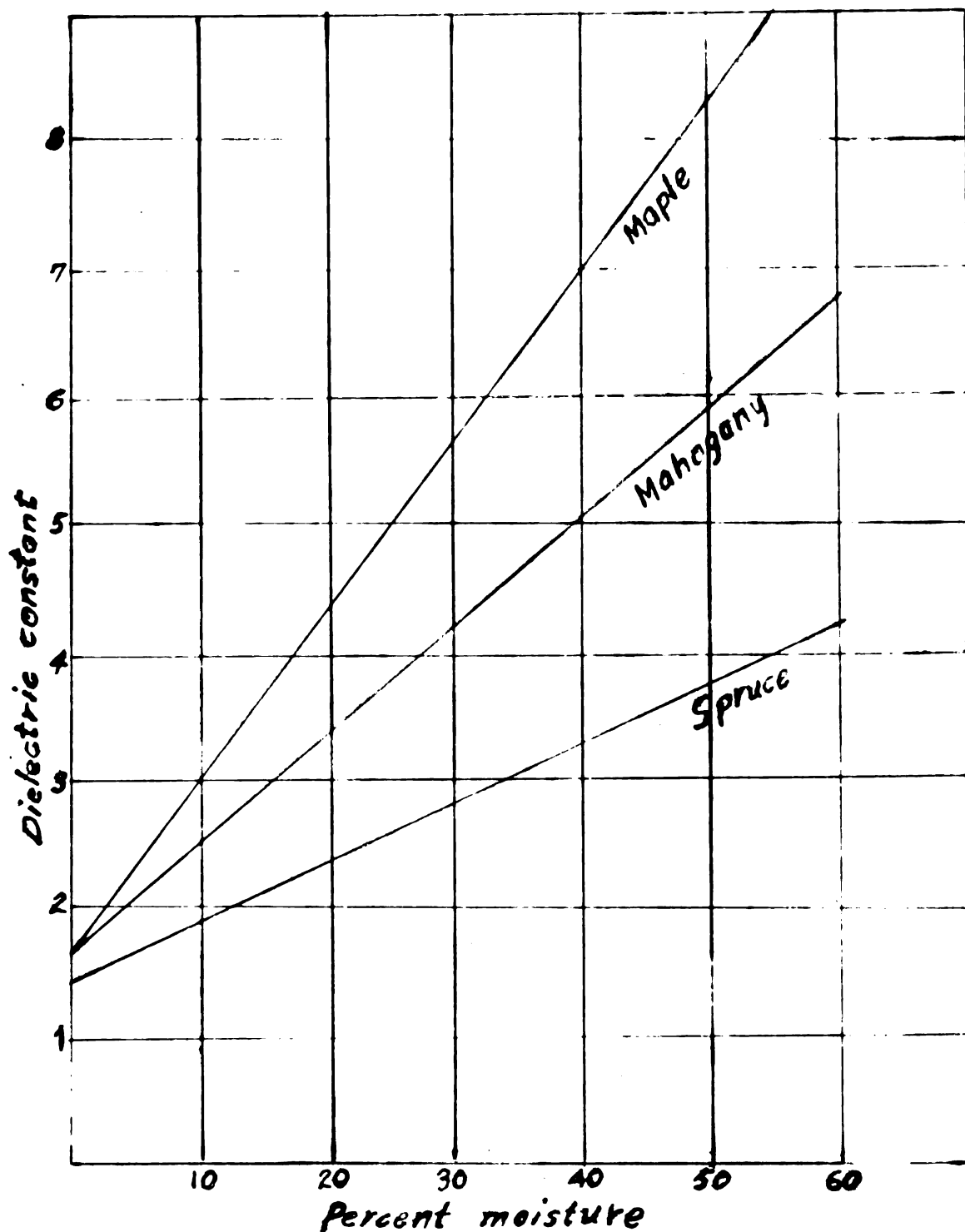
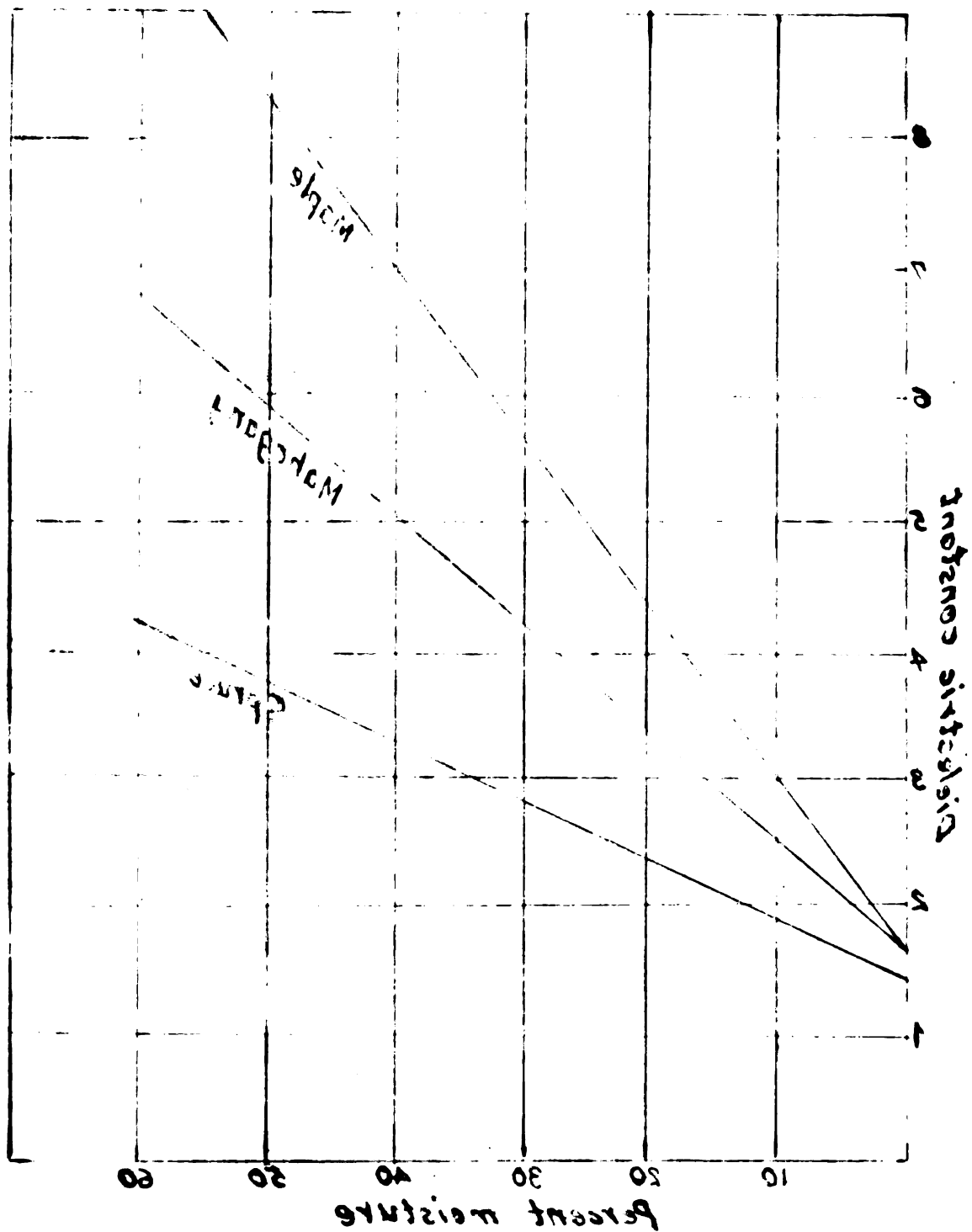


Fig. 19. Variation of dielectric constant with percent moisture content for three species.

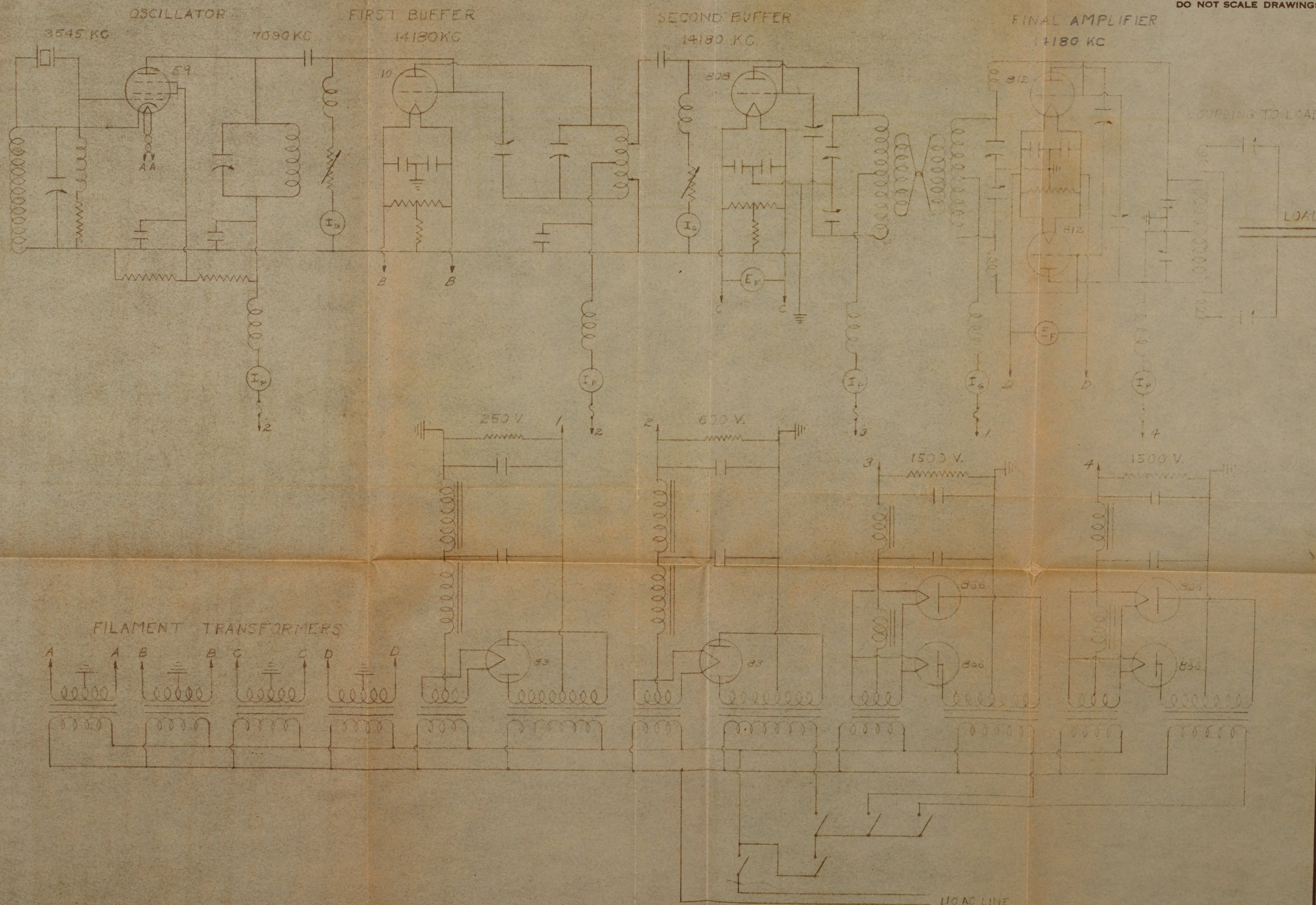
Fig. 19. Variation of dielectric constant with percent moisture content for three species.



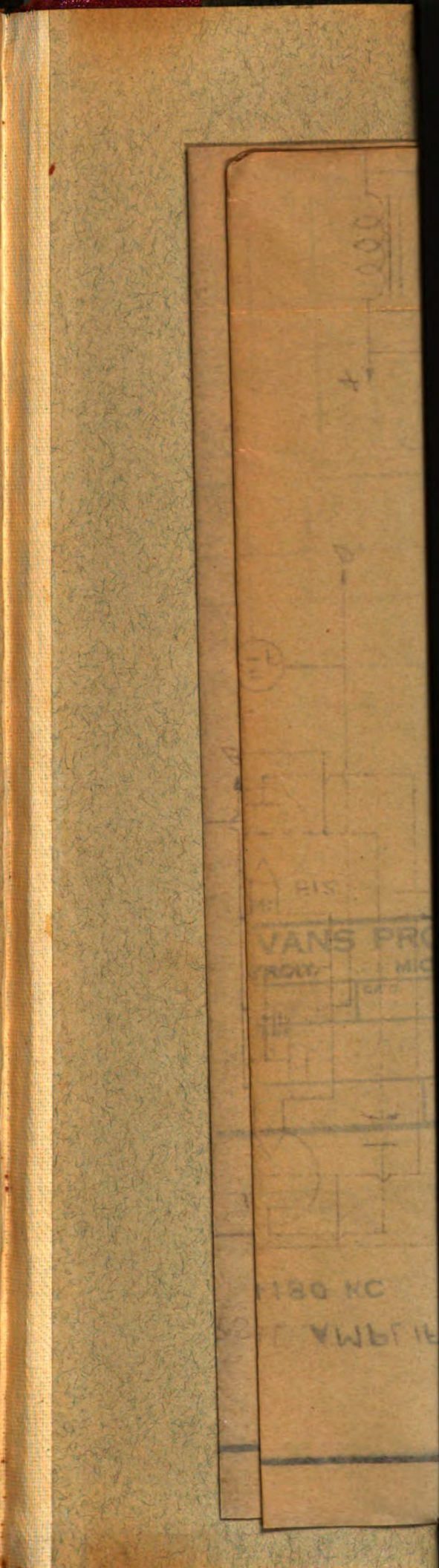
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DO NOT SCALE DRAWINGS



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