A DIRECT-READING RADIO FREQUENCY WATTMETER

by

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INTRODUCTION

In many applications at radio frequencies, it would be desirable to have a direct reading wattmeter by means of which power could be measured without any knowledge of the value of load impedance. Most of the methods now available to measure radio frequency power require that the load impedance be known. However, in many cases the load impedance may change, thus making the calibration of the instrument incorrect.

In this thesis, a study is made of the possibility of constructing a direct reading radio frequency wattmeter that will correctly indicate power regardless of the magnitude of load impedance. Use is made of the fact that power delivered to a load over a transmission line can be obtained from the difference between the power contained in the incident traveling wave and the power contained in the reflected traveling wave.

An experimental model of a wattmeter constructed on this principle is described and an experimental analysis is made to demonstrate that power may be accurately determined by this method.

The limitations and range of the instrument are discussed and suggestions are made for improvements in future applications of this principle.

POWER MEASUREMENTS AT RADIO FREQUENCIES

In sixty cycle power systems, the science of measuring power has reached a high state of development. Portable wattmeters are available to cover a wide range of conditions. These wattmeters may be easily connected in almost any circuit with a minimum effect on the circuit itself. One of the desirable features of wattmeters available at power frequencies is the fact that the same instrument may be used with relatively low leading or lagging power factor. Also, they are direct reading instruments and it is not necessary to know the value of load impedance to measure the power.

Contrasted with power measurements at sixty cycles, the measurement of radio frequency power is not in such a high state of development. In the available instruments, most of features listed above are absent. At present, for each specific case a special type of circuit must be used. Care must be taken that the measuring device does not influence the circuit under test. With most radio frequency wattmeters the load impedance must be known and the power then calculated. This means that if the load impedance varies for any reason, the exact manner of this variation must be known before the power may be measured. Therefore, these instruments may not be considered as direct reading. The following is a discussion of a few of the methods now used to measure power at radio frequencies.

The Ammeter Method--Ammeters are available that will correctly indicate the value of radio frequency current over a wide range of frequencies. These instruments are of the thermocouple type and respond to the root mean square value of current. An ammeter of this type may be used to measure power if the series resistance component of the load impedance is known. The power is then given by the familiar equation:

$$P = I_{rms}^2 R_s \tag{1}$$

The ammeter scale is then calibrated in terms of power for a given value of resistance.

The disadvantages of this method are apparent. The wattmeter may not be transferred from one circuit to another unless the series resistance component of the load is the same in every case. Also, the resistance of a particular load must not change or the calibration of the ammeter scale will not be correct.

However, this method is simple and quite accurate provided that the series resistance of the load does not change. For these reasons, it is used frequently in such applications as measuring the power delivered to an antenna system. Here, the radiation resistance of the antenna may be measured by means of an impedance bridge and this resistance will not change greatly. Periodic checks can be made and scale corrections applied when it is found necessary.

Voltmeter Method--Voltmeters are also available to accurately measure radio frequency voltages. These instruments have a very high impedance so that they have a very small effect on the circuit under test. Vacuum tube voltmeters are the most commonly used for this application, although electrostatic voltmeters may be used in some cases.

If the voltage across the load is known, and the parallel component of resistance can be determined, the power may be readily calculated from the equation:

$$P = \frac{E_{rms}^2}{R_p} \tag{2}$$

This method is very similar in nature to the ammeter method. However, this method is not used commercially to the same extent as the ammeter method.

<u>The Three Ammeter Method</u>--A method has been described by J.L. Hollis (1, pp. 142-143), for measuring radio frequency power by means of three simultaneous ammeter readings. The way in which these ammeters are connected in the circuit is shown in Figure 1.

In this circuit, A_2 measures the current through the load Z_L, and A_3, in series with a known capacitive reactance X_c, determines the voltage across the load. The third ammeter is used in conjunction with the other two to determine the phase angle of the load. The magnitude and phase angle of the load can be calculated from these three ammeter readings. Therefore, the power may also be determined. For greatest accuracy, X_c should have somewhere near the same magnitude as Z_L.

This method has the advantage that the power may be measured without previously knowing the exact value of Z_L. However, it has two distinct disadvantages which limit its use as a general purpose

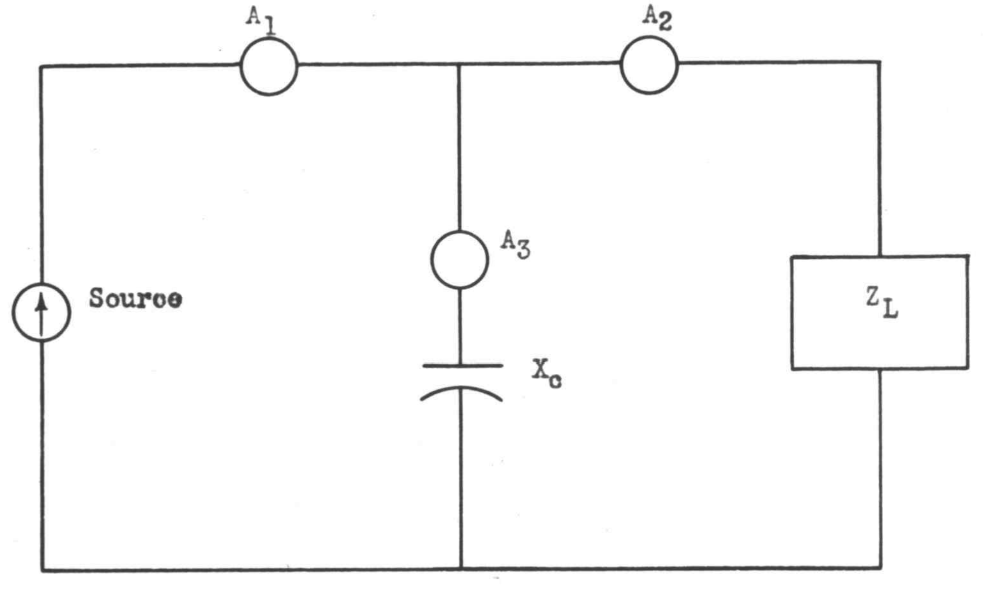


FIGURE 1

Three ammeter method for measuring R-F power and load impedance.

instrument. First, it is not direct reading; that is, three simultaneous readings must be made and the power then determined by calculation or by graphical solution. The other disadvantage arises from the fact that for greatest accuracy X_c should be nearly equal to Z_L. Therefore, the magnitude and phase angle of the load impedance as seen from the generator is greatly altered. This may not be permissible in many applications. The method has been used, however, and has proven quite satisfactory on specific applications.

Other Methods--Other methods have been tried with varying degrees of success. Several methods have been presented using vacuum tube circuits (3, pp.937-938). One of these combines two square law vacuum tube voltmeters in such a way as to give an indication proportional to the product of the current and voltage and the cosine of the angle between them.

In the microwave region the usual procedure is to convert the microwave power into heat and then use this heat to alter the resistance of some element such as a thermistor. Then by means of bridge measurements the change in resistance is calibrated in terms of power.

All of the methods described so far have definite limitations. The following is an investigation to determine if there is some different method of approach whereby an instrument could be developed which would more nearly approach the versatility of the wattmeters employed at power system frequencies.

AN ANALYSIS OF THE PROBLEM

General Considerations--In analyzing the problem of making measurements of power, the basic concept of power in an electric circuit should first be studied. Consider the circuit of Figure 2.

If in this circuit, the quantities e and i represent the instantaneous magnitudes of the voltage across the load and the current through the load, then the instantaneous power developed in the load will be the product of the two.

$$\text{Instantaneous power} = ei \qquad (3)$$

However, the quantity that is usually desired is the average power rather than the instantaneous power. The average power can be determined by integrating equation (3) over one complete cycle, and dividing by the period. That is:

$$\text{Average power} = \frac{1}{T}\int_0^T ei\ dt \qquad (4)$$

The electrodynamometer type wattmeter responds to the average value of the product of the currents in the stationary coil and the moving coil.

$$\text{Deflection} = \frac{k}{T}\int_0^T i_s i_m\ dt \qquad (5)$$

In this equation k is a constant. Therefore, if the current in the stationary coil is proportional to the current in the load, and the current in the moving coil is proportional to the voltage across the load, the deflection will be directly proportional to the average power delivered to the load. This has been done at

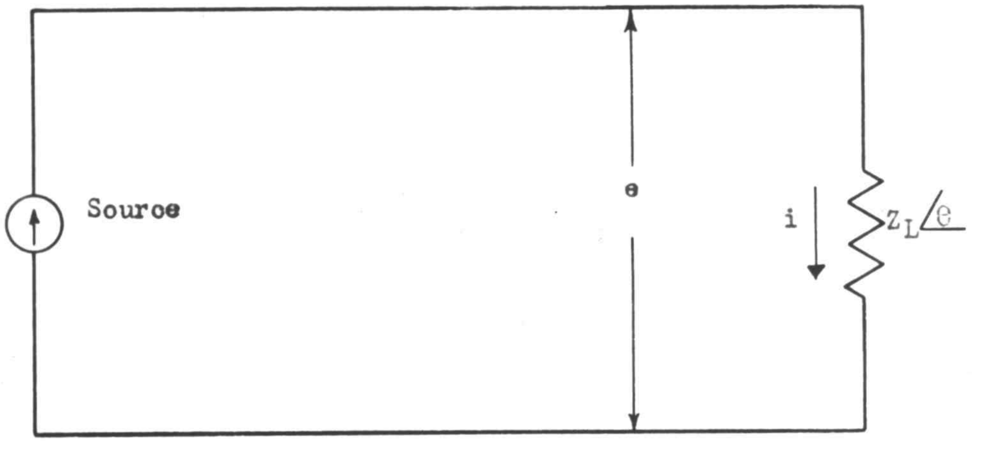


FIGURE 2

Source of power connected to a load impedance, Z_L.

power frequencies which results in instruments that will accurately indicate power regardless of waveshape or value of load impedance.

If the current and voltage in equation (4) are both sinusoidal functions, then the equation can be written

$$P_{ave} = \frac{1}{2\pi}\int_0^{2\pi} (E_m \sin nwt) I_m \sin(wt + \theta)\, d(wt) \tag{6}$$

where E_m and I_m are the maximum values of the functions, and θ is the phase angle between them. If this integral is evaluated, the expression for power becomes

$$P_{ave} = \frac{E_m I_m}{2} \cos\theta \tag{7}$$

Since the voltage is the product of the current and the load impedance, the power can also be obtained from the equations

$$P = I_{rms}^2 Z_L \cos\theta \tag{8}$$

and

$$P = \frac{E_{rms}^2}{Z_L} \cos\theta \tag{9}$$

These equations are representative of the ammeter method and the voltmeter method of measuring power.

In radio frequency power measurements, the difficulty arises from the fact that an instrument of the dynamometer type that will operate at these frequencies cannot readily be constructed.

<u>An Analysis of the Power Transferred over a Transmission Line</u>--Consider the case of a high frequency transmission line with no power losses in the line itself, such as that shown in Figure 3.

With the symbols defined as shown, the incremental voltage drop across an elementary length of line, dx, will be

$$dv = iZ\,dx \tag{10}$$

The decrease in current through the element of length will be

$$di = vy\,dx \tag{11}$$

From these equations, the equations for voltage and current at any point on the line may be determined as follows:

$$\frac{dv}{dx} = iZ \tag{12}$$

and

$$\frac{di}{dx} = vy \tag{13}$$

differentiating:

$$\frac{d^2v}{dx^2} = Z\,\frac{di}{dx} \tag{14}$$

and

$$\frac{d^2i}{dx^2} = y\,\frac{dv}{dx} \tag{15}$$

Substituting the value of $\frac{di}{dx}$ from equation (13) into equation (14):

$$\frac{d^2v}{dx^2} = Zyv \tag{16}$$

Similarly, the second derivative of current with respect to distance becomes:

$$\frac{d^2i}{dx^2} = Zyi \tag{17}$$

These equations are straightforward, linear, second order

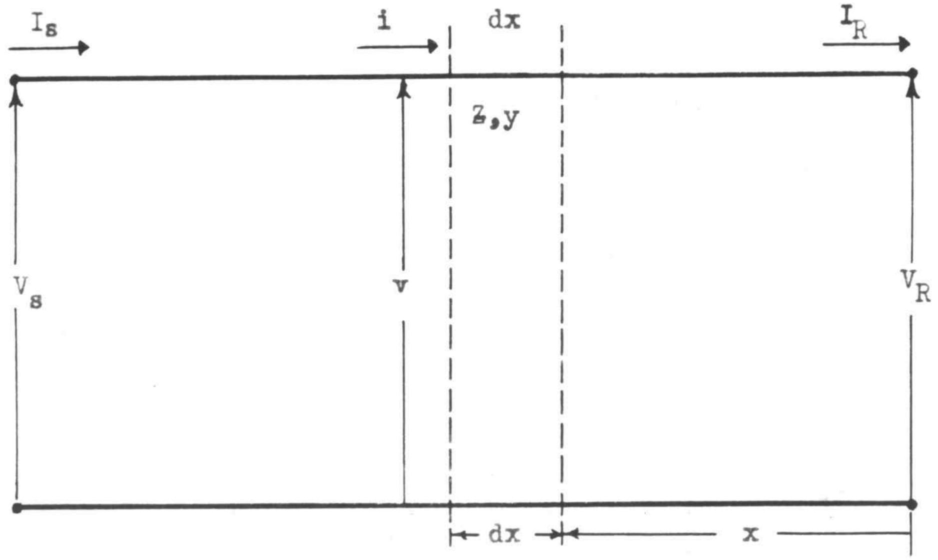


FIGURE 3

The general transmission line.

SYMBOLS: V_s = instantaneous sending end voltage.
I_s = instantaneous sending end current.
v = instantaneous voltage at any point, x.
i = instantaneous current at x.
I_R = instantaneous current at receiving end.
V_R = instantaneous voltage at receiving end.
z = series impedance per unit length of line.
y = shunt admittance per unit length of line.

differential equations with constant coefficients and the solutions are

$$v = Ae^{x\sqrt{Zy}} + Be^{-x\sqrt{Zy}} \tag{18}$$

$$i = \frac{1}{Z}\frac{dv}{dx} = A\sqrt{\frac{y}{Z}}\,e^{x\sqrt{Zy}} - B\sqrt{\frac{y}{Z}}\,e^{-x\sqrt{Zy}} \tag{19}$$

In these equations, the quantity $\sqrt{Zy}$ is called the propagation constant, and with no losses in the transmission line, will be an imaginary quantity denoted by the symbol $j\beta$. The quantity $\sqrt{\frac{Z}{y}}$ is the characteristic impedance of the transmission line, and will be resistive for a lossless line. The usual symbol for this quantity is Z_o. The constants A and B may be evaluated from the Boundary conditions. When this is done, equations (18) and (19) become:

$$v = \left[\frac{v_R}{2} + \frac{i_R Z_o}{2}\right] e^{j\beta x} + \left[\frac{v_R}{2} - \frac{i_R Z_o}{2}\right] e^{-j\beta x} \tag{20}$$

$$i = \left[\frac{v_R}{2Z_o} + \frac{i_R}{2}\right] e^{j\beta x} - \left[\frac{v_R}{2Z_o} - \frac{i_R}{2}\right] e^{-j\beta x} \tag{21}$$

The quantities on the right of equations (20) and (21) represent traveling waves, one traveling in the positive x direction and one traveling in the negative x direction. The combination of these two components will give the usual standing wave on the transmission line. The quantity in each of the brackets represents a function varying sinusoidally with time.

$$\left[\frac{v_R}{2} + \frac{i_R Z_o}{2}\right] = V_{i(max)} \sin wt \tag{22}$$

$$\left[\frac{v_R}{2} - \frac{i_R Z_o}{2}\right] = V_{r(max)} \sin(wt + \theta) \tag{23}$$

In these equations, $V_{i(max)}$ is the maximum value of the incident traveling wave, $V_{r(max)}$ is the maximum value of the traveling wave that is reflected from the load, and θ is the phase angle between these two voltage waves at the load. The magnitude and sign of θ are determined from the relationship between the characteristic impedance of the line and the load impedance. The quantities $e^{j\beta x}$ and $e^{-j\beta x}$ represent a phase shift of the sinusoidal quantities as a function of distance. Therefore, the components of current and voltage can be expressed in terms of sinusoidal functions as follows:

$$\begin{aligned} v &= V_{i_{max}} \sin wt \; e^{j\beta x} + V_{r_{max}} \sin(wt + \theta) \; e^{-j\beta x} \\ &= V_{i_{max}} \sin(wt + \beta x) + V_{r_{max}} \sin(wt - \beta x + \theta) \end{aligned} \tag{24}$$

$$i = \frac{V_{i_{max}}}{Z_o} \sin(wt + \beta x) - \frac{V_{r_{max}}}{Z_o} \sin(wt - \beta x + \theta) \tag{25}$$

These equations can also be stated in a different form by expressing the exponential quantities in equations (20) and (21) in terms of hyperbolic functions.

$$v = V_R \cosh j\beta x + I_R Z_o \sinh j\beta x \tag{26}$$

$$i = I_R \cosh j\beta x + \frac{V_R}{Z_o} \sinh j\beta x \tag{27}$$

The power delivered to the load over the transmission line is equal to

$$P_{ave} = \frac{V_{R_{max}} I_{R_{max}}}{2} \cos \phi \tag{28}$$

if it is assumed that V_R and I_R are sinusoidal quantities. The phase angle between V_R and I_R is ϕ.

However, from equations (24) and (25) a different expression for power can be obtained.

$$P_{ave} = \frac{1}{2\pi}\int_0^{2\pi} vi \; d(wt) \tag{29}$$

where from equations (24) and (25):

$$vi = \frac{V_{i_m}^2}{Z_o}\sin^2(wt + \beta x) - \frac{V_{r_m}^2}{Z_o}\sin^2(wt - \beta x + \theta)$$

Therefore:

$$P_{ave} = \frac{V_{i_m}^2}{2\pi Z_o}\int_0^{2\pi}\sin^2(wt + \beta x)d(wt) - \frac{V_{r_m}^2}{2\pi Z_o}\int_0^{2\pi}\sin^2(wt - \beta x + \theta)d(wt) \tag{30}$$

When these integrals are evaluated between the limits specified, the expression reduces to

$$P_{ave} = \frac{V_{i_m}^2 - V_{r_m}^2}{2Z_o} = \frac{V_{i(rms)}^2 - V_{r(rms)}^2}{Z_o} \tag{31}$$

Equation (31) is the familiar expression which represents the power delivered to the load as the difference between the power contained in the incident traveling wave and the power contained in the reflected traveling wave. It will be noticed from this equation that if some method could be found to measure the magnitude of the incident voltage wave and the reflected voltage wave, then the power could be determined without any further knowledge of the load impedance. Of course, the magnitude and phase of the load impedance will determine the relationship between the incident voltage and the reflected voltage. Further examination of the equation reveals that frequency does not enter into the relationship.

It will be remembered that the chief difficulties of the present methods of measuring radio frequency power arise from the fact that an exact knowledge of the value of load impedance is often required. Therefore, if a wattmeter can be constructed that operates on the principle set forth in equation (31), it will represent a considerable improvement over present methods. This will be particularly true in the case of experimental studies where the load impedance may be variable.

A DEVICE FOR MEASURING POWER BASED ON TRANSMISSION LINE ANALYSIS

The first problem in measuring power by means of equation (31) is to find a means to measure the incident voltage and the reflected voltage separately. At first glance this may seem to be a difficult task, since the voltage at any point on the line is a somewhat complicated function of both of these quantities.

However, there is a simple circuit available by means of which a voltage proportional to either of these quantities may be obtained. Consider the circuit of Figure 4, (2, p. 15-20).

This circuit represents a transmission line with characteristic impedance Z_o, and terminated in a load impedance Z_L. The quantities v and i represent the instantaneous magnitude of the voltage and current at the point indicated. It is assumed that the resistor, R, is physically small compared to the wave length of the supply voltage. Then v and i can be expressed as in equations (24) and (25).

$$v = V_{i_m} \sin(wt + \beta x) + V_{r_m} \sin(wt - \beta x + \theta) \qquad (24)$$

$$i = \frac{V_{i_m}}{Z_o} \sin(wt + \beta x) - \frac{V_{r_m}}{Z_o} \sin(wt - \beta x + \theta) \qquad (25)$$

With assumed positive directions as shown, the unknown voltage, V, can be expressed as the difference between the voltage, E_R, across the resistor, R, and the voltage, E_{c_1}, across the capacitor, C_1. The voltage E_R will be equal to the current times the resistance.

$$E_R = Ri = \frac{R}{Z_o} \left[V_{i_m} \sin(wt + \beta x) - V_{r_m} \sin(wt - \beta x + \theta) \right] \qquad (32)$$

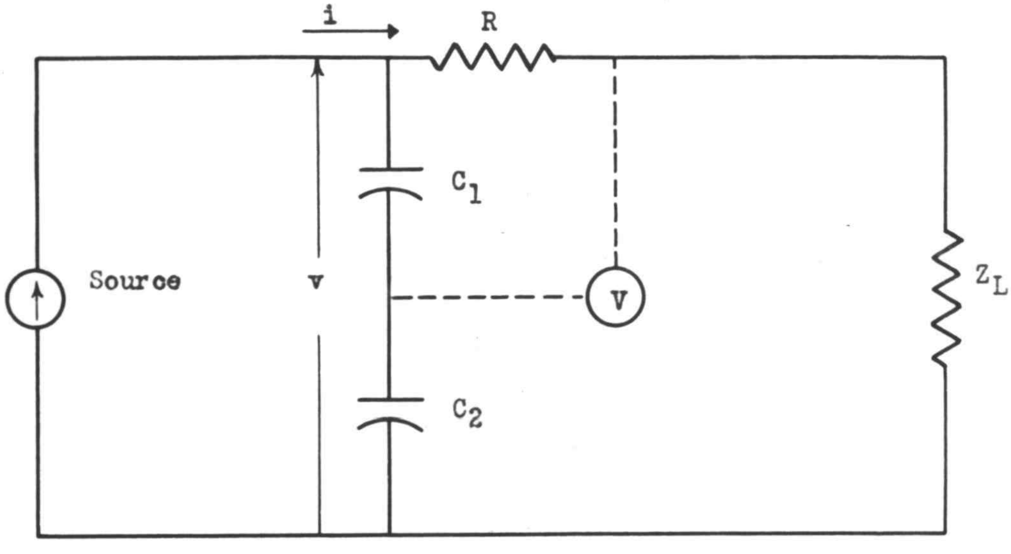


FIGURE 4

Circuit for measuring reflected component of voltage.

The voltage across the capacitors will divide in proportion to the reactance:

$$E_{c_1} = v \frac{X_{c_1}}{X_{c_1} + X_{c_2}} = v \left(\frac{C_2}{C_1 + C_2}\right) \tag{33}$$

If the values of C_1 and C_2 are chosen so that C_1 is much larger than C_2, equation (33) becomes:

$$E_{c_1} = \frac{C_2}{C_1} v = \frac{C_2}{C_1} \left[V_{i_m} \sin(wt + \beta x) + V_{r_m} \sin(wt - \beta x + \theta) \right] \tag{34}$$

The voltage, V, can now be obtained by subtracting equation (34) from equation (32)

$$V = E_R - E_{c_1} = \left(\frac{R}{Z_o} - \frac{C_2}{C_1}\right) V_{i_m} \sin(wt + \beta x) - \left(\frac{R}{Z_o} + \frac{C_2}{C_1}\right) V_{r_m} \sin(wt - \beta x + \theta) \tag{35}$$

If the values of R and $\frac{C_2}{C_1}$ are chosen so that $\frac{R}{Z_o}$ is equal to $\frac{C_2}{C_1}$ it is evident that equation (35) reduces to:

$$V = -\left(\frac{R}{Z_o} + \frac{C_2}{C_1}\right) V_{r_m} \sin(wt - \beta x + \theta)$$

or

$$V_{(rms)} = \left(\frac{R}{Z_o} + \frac{C_2}{C_1}\right) V_{r(rms)} = KV_{r(rms)} \tag{36}$$

Thus, by means of this circuit, with the values of R, C_1, and C_2 chosen as stated above, a voltage may be obtained that is proportional only to the reflected component of the total voltage. The value of R should be small so as not to dissipate any more power than necessary. Also, the combined reactance of C_1 and C_2 should be large so as not to draw any more current than necessary.

A voltage proportional to the incident component of voltage may also be obtained by placing the capacitors C_1 and C_2 on the other side of the resistor R as shown in Figure 5.

With this circuit, the unknown voltage, V, is equal to the sum of the voltage drops across R and C_1. Therefore, the voltage, V, can be obtained by adding equations (32) and (34)

$$V = E_R + E_{c1} = \left(\frac{R}{Z_o} + \frac{C_2}{C_1}\right) V_{i_m} \sin(wt + \beta x) - \left(\frac{R}{Z_o} - \frac{C_2}{C_1}\right) V_{r_m} \sin(wt - \beta x + \theta) \qquad (37)$$

If the values of R, C_1, and C_2 are chosen as before, equation (36) becomes:

$$V = \left(\frac{R}{Z_o} + \frac{C_2}{C_1}\right) V_{i_m} \sin(wt + \beta x)$$

or

$$V_{(rms)} = \left(\frac{R}{Z_o} + \frac{C_2}{C_1}\right) V_{i_{(rms)}} = KV_{i_{(rms)}} \qquad (38)$$

The circuits of Figures 4 and 5 may be combined so that V_i and V_r may be measured simultaneously. How this may be done is demonstrated in Figure 6.

In this circuit, the resistor, R, is common to both measuring circuits. This will not introduce error if the combined reactance of C_1 and C_2 is large compared to the load impedance.

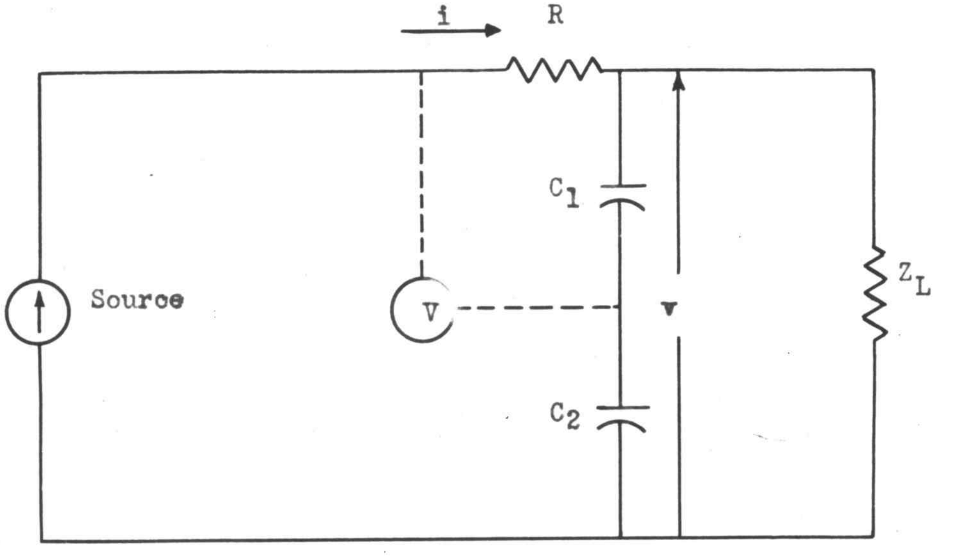


FIGURE 5

Circuit for measuring incident component of voltage

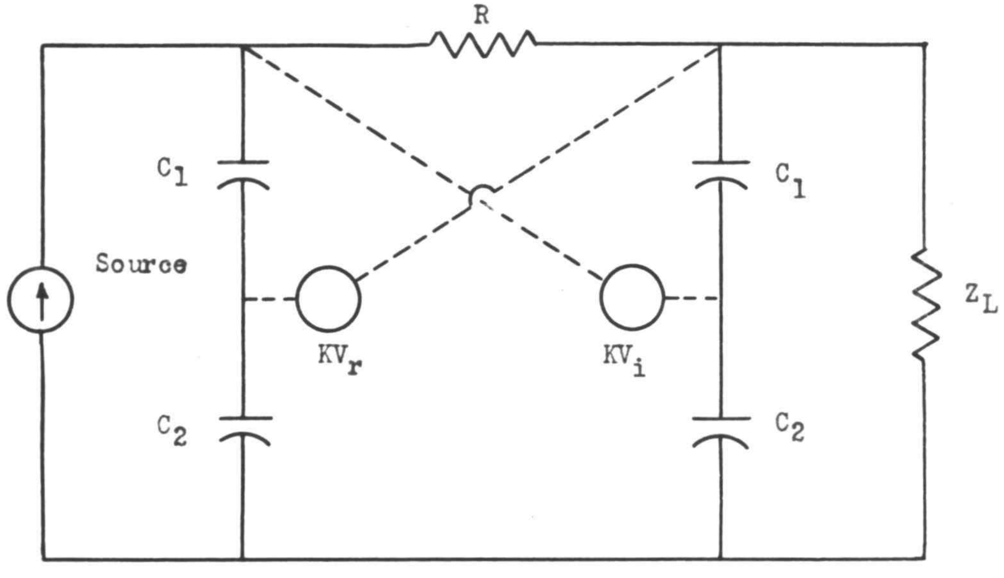


FIGURE 6

Circuit for simultaneously measuring V_i and V_r.

From these two simultaneous readings, the power could be readily calculated. However, it is the purpose of this study to develop a direct-reading wattmeter with no calculations required. To do this, it will be necessary to devise a means to obtain the squares of the incident and reflected components of voltage and obtain a deflection on an instrument proportional to the difference of these squares. That deflection could then be calibrated directly in terms of power.

A Square Law Device--Since it is desired to obtain readings proportional to ${V_i}^2$ and ${V_r}^2$, a square law type of detector must be used. There are several types of vacuum tube circuits that could be used for this purpose, but these circuits are usually complex and must have associated power supplies to make them operative. Reference to Figure 6 will show that the detector will have to operate at essentially full line voltage above ground. Therefore, the detector should be of simple construction and physically small to prevent excessive capacitive currents from flowing through the detector to ground.

Probably the simplest type of square law device available for this purpose is the vacuum thermocouple. The thermocouple consists of a heater element in close proximity with a thermo-junction. When current is passed through the heater element, a voltage is developed in the thermo-junction that will be proportional to the square of the effective value of current flowing in the heater element. If the thermo-junction, or couple circuit, is closed through an external circuit, the relationship between the heater current and the couple current can be expressed as follows:

$$I_c = KI_H^2 \tag{39}$$

In this equation, I_c represents the couple circuit current, and I_H represents the heater circuit current. The couple current will be direct current, but the heater current may be either direct or alternating.

Thermocouples are available for radio frequency use with heater elements that remain essentially resistive over a wide range of frequencies. Physically they are quite small, being not much larger than an ordinary thimble. Such a device as this lends itself very well to the present application.

<u>The Complete Circuit</u>--If thermocouples such as those described above are used as the detector elements in Figure 6, a microammeter connected to each one would indicate a direct current proportional to the square of the effective value of either V_i or V_r. The final step necessary to obtain a direct reading wattmeter is to obtain a deflection proportional to the difference between these two quantities. Since a direct voltage of definite polarity is developed in the couple circuit, this may be done rather easily. By connecting the couple circuits of the two thermocouples in series opposition and using a single microammeter to indicate the resultant current, the required relationship is obtained.

$$I_{TC_1} = K V_i^2 \tag{40}$$

$$I_{TC_2} = K V_r^2 \tag{41}$$

$$I_{TC_1} - I_{TC_2} = K(V_i^2 - V_r^2) = K' P_{ave} \tag{42}$$

In order to connect the two couple circuits together, it is necessary that the couple be electrically isolated from the heater in each of the thermocouples. If this were not true, there would be an undesired connection between the two independent measuring circuits. Thermocouples are available in which the heater and the couple are not physically connected and there is only one micro-microfarad of capacitance between them.

Figure 7 represents the completed circuit for a direct reading wattmeter based on the expression for power in equation (31).

The circuit of Figure 7 has been drawn for the case where the transmission line is a coaxial cable. The resistor, R, is then built into the center conductor.

Theoretically, the circuit of Figure 7 should function properly without any further modifications. However, it was found that due to certain practical considerations some additions had to be made. In the next section, the construction and operation of an experimental model of this basic wattmeter circuit will be described.

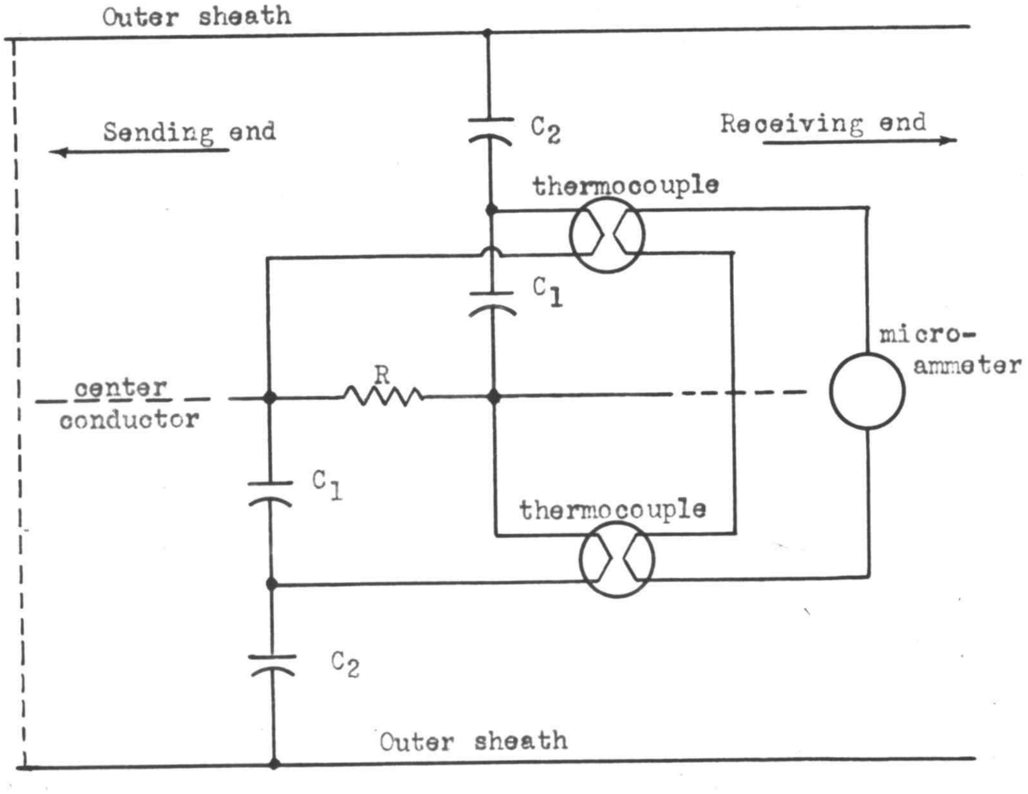


FIGURE 7

The complete circuit for a direct-reading wattmeter.

AN EXPERIMENTAL RADIO FREQUENCY WATTMETER

Construction--An experimental wattmeter similar to that shown in Figure 7 was constructed to verify the theoretical discussion. The wattmeter was constructed for use with RG-8U coaxial cable which has a characteristic impedance of fifty three ohms.

It was found that with the thermocouples connected directly in the circuit as shown in Figure 7, there was still excessive radio frequency current flowing through the heater of the thermocouple to ground through the capacitance to ground of the thermocouple. This caused an undesired deflection of the microammeter.

To correct this, it was found necessary to first rectify the voltage to be measured by means of a 1N34 crystal diode. The rectified voltage was then applied to the thermocouple through a suitable filter. The heater of the thermocouple was shunted by a capacitor so that any current that flowed through the capacitance to ground of the thermocouple would not pass through the heater. The complete experimental circuit diagram is shown in Figure 8.

It was mentioned before that there is only one micro-microfarad of capacitance between the heater and the couple of the thermocouples used. Experimentally it was found that there is considerable more capacitance than this between the couple circuit and ground. Therefore, a considerable portion of the full line voltage appears between the heater and the couple. The insulation between the heater and the couple is designed to withstand approximately one hundred

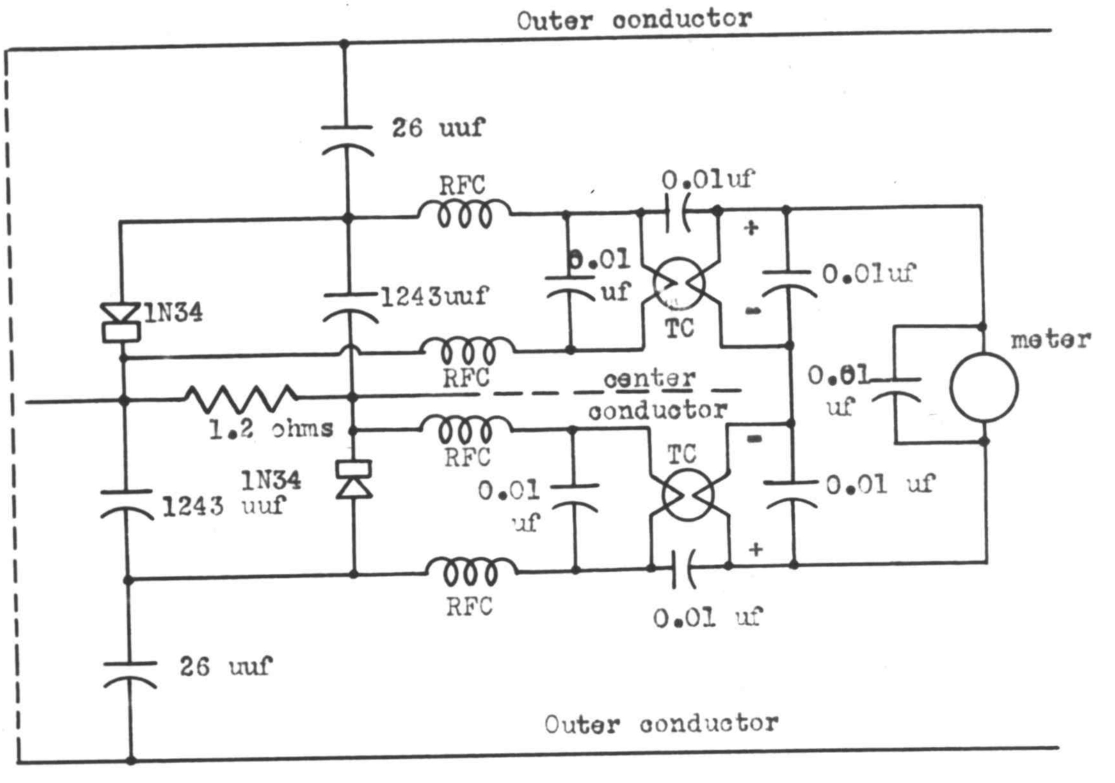


FIGURE 8

Complete circuit for experimental wattmeter.

volts, so there is danger of a breakdown of the insulation unless something is done to reduce the voltage between the heater and the couple. This was accomplished by connecting a large capacitor between the heater and the couple as shown in Figure 8. In the final circuit, the only purpose of having the heater and couple insulated from each other is to provide direct current isolation between the two measuring circuits. Radio frequency isolation is effectively provided by the radio frequency choke coils in the filter circuits.

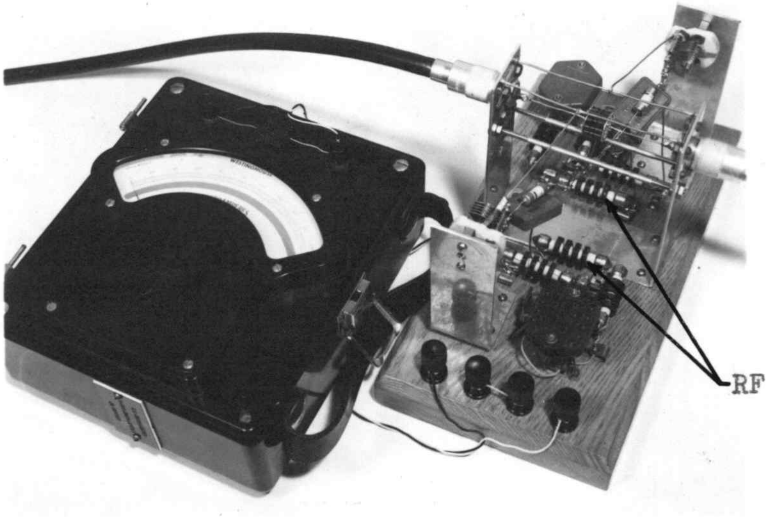
The capacitors, C_1, are variable air capacitors that may be adjusted to the exact value necessary to give the proper balance between the two circuits.

The 1N34 crystals should be selected to have as nearly identical characteristics as possible. The same is true of the two thermocouples.

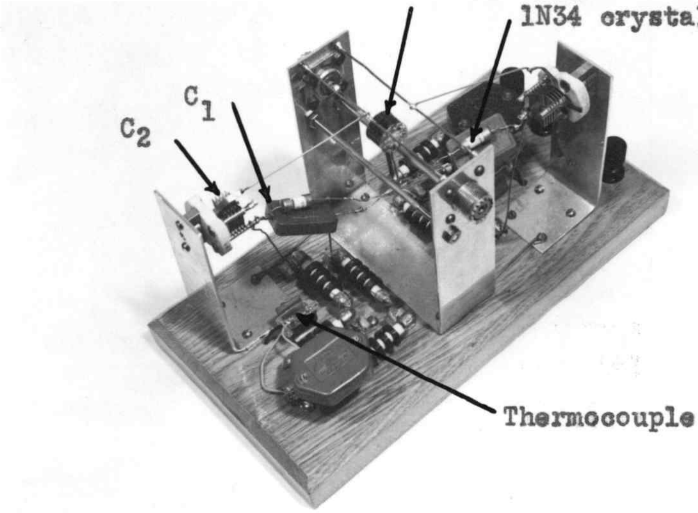
Figure 9 is a photograph of the final experimental model showing the details of the physical arrangement of the component parts.

One of the interesting and critical features of this wattmeter is the construction of the one ohm resistor that must be placed in the center conductor of the coaxial cable. In order for the circuit to perform properly, this resistor must be nearly pure resistance at the frequency of operation. Also, the resistor must be able to carry the full line current with no appreciable change in resistance. The construction of this resistor is shown in Figure 10.

Nine one quarter watt composition resistors were mounted in a



Front View



Rear View

FIGURE 9

Experimental radio frequency wattmeter

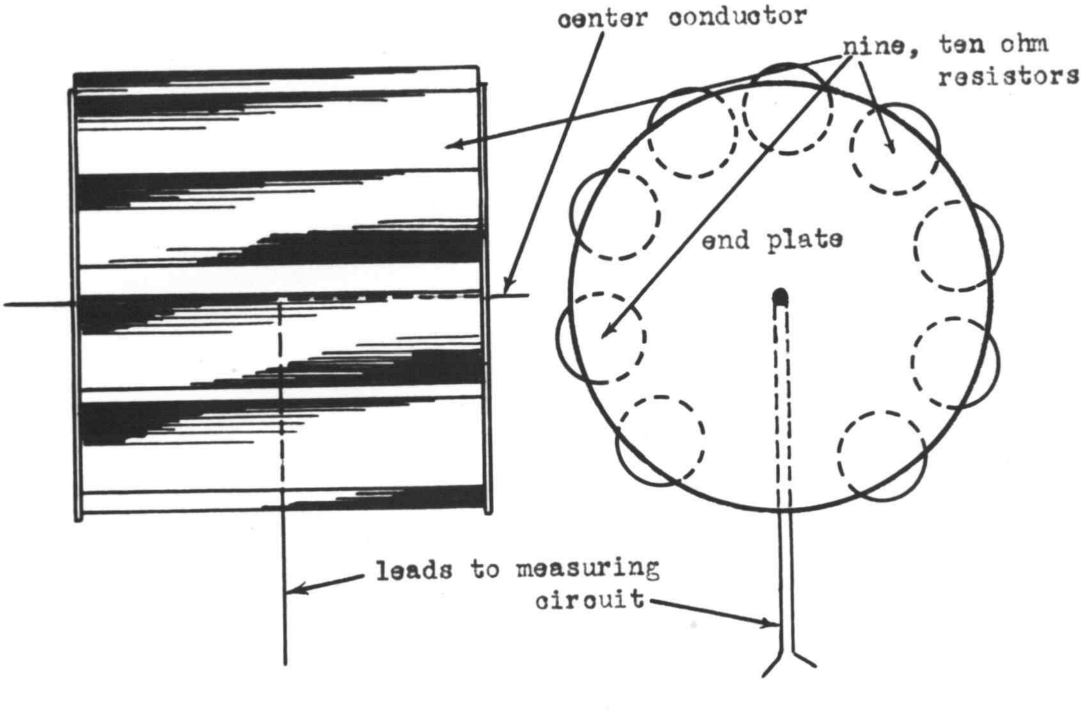


FIGURE 10

Construction of non-inductive resistor.

cylindrical configuration as shown in the Figure. To measure the voltage drop across the resistor, the leads are brought down the center of the cylinder and out the middle in a plane at right angles to the direction of current flow. This method keeps the loop area of the measuring leads at a minimum, and therefore the voltage induced in these leads will be very small. The resistor constructed in this manner has a resistance of 1.2 ohms and an inductive reactance of 0.14 ohms at two megacycles.

It is absolutely necessary that the reactance of this resistor be of the order of one tenth or less the magnitude of the resistance component. The reason for this can be seen if the circuit is analyzed, taking into account the reactance of this resistor. Consider the circuit of Figure 11.

In this circuit, the reactance of the resistor is assumed to be 0.3 ohms at two megacycles. This circuit was analyzed first with a load having a leading power factor, and then with a load of the same magnitude but with a lagging power factor. For the case shown, $(KV_i)^2 - (KV_r)^2$ was equal to 3.48 with the lagging power factor load, and only 1.92 with the leading power factor load. The power delivered to the load was 34 watts in both cases. If the reactance of the resistor were zero, $(KV_i)^2 - (KV_r)^2$ would be 2.73.

Thus, the presence of the reactance causes a phase error to be present in the calibration of the wattmeter. This phase error will be a limiting factor in determining the useful frequency range of the wattmeter.

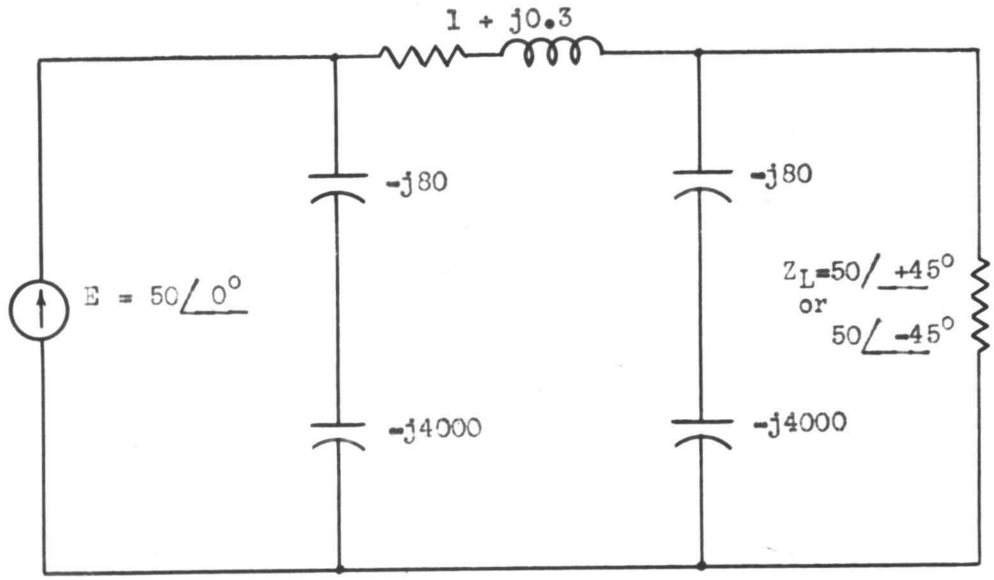


FIGURE 11

Circuit of wattmeter at two megacycles with additional reactance added to the series non-inductive resistor.

Referring again to Figure 9, it will be noticed that there are four terminals available to connect to the microammeter. The output of each thermocouple is brought out separately so that either V_i^2 or V_r^2 may be measured independently if desired. By doing this, the magnitude of the voltage standing wave ratio may be obtained from the equation

$$\text{VSWR} = \frac{V_i + V_r}{V_i - V_r} \tag{43}$$

The terminals are so arranged that it is only necessary to connect the two inner terminals together and the two outer terminals to the microammeter to measure power.

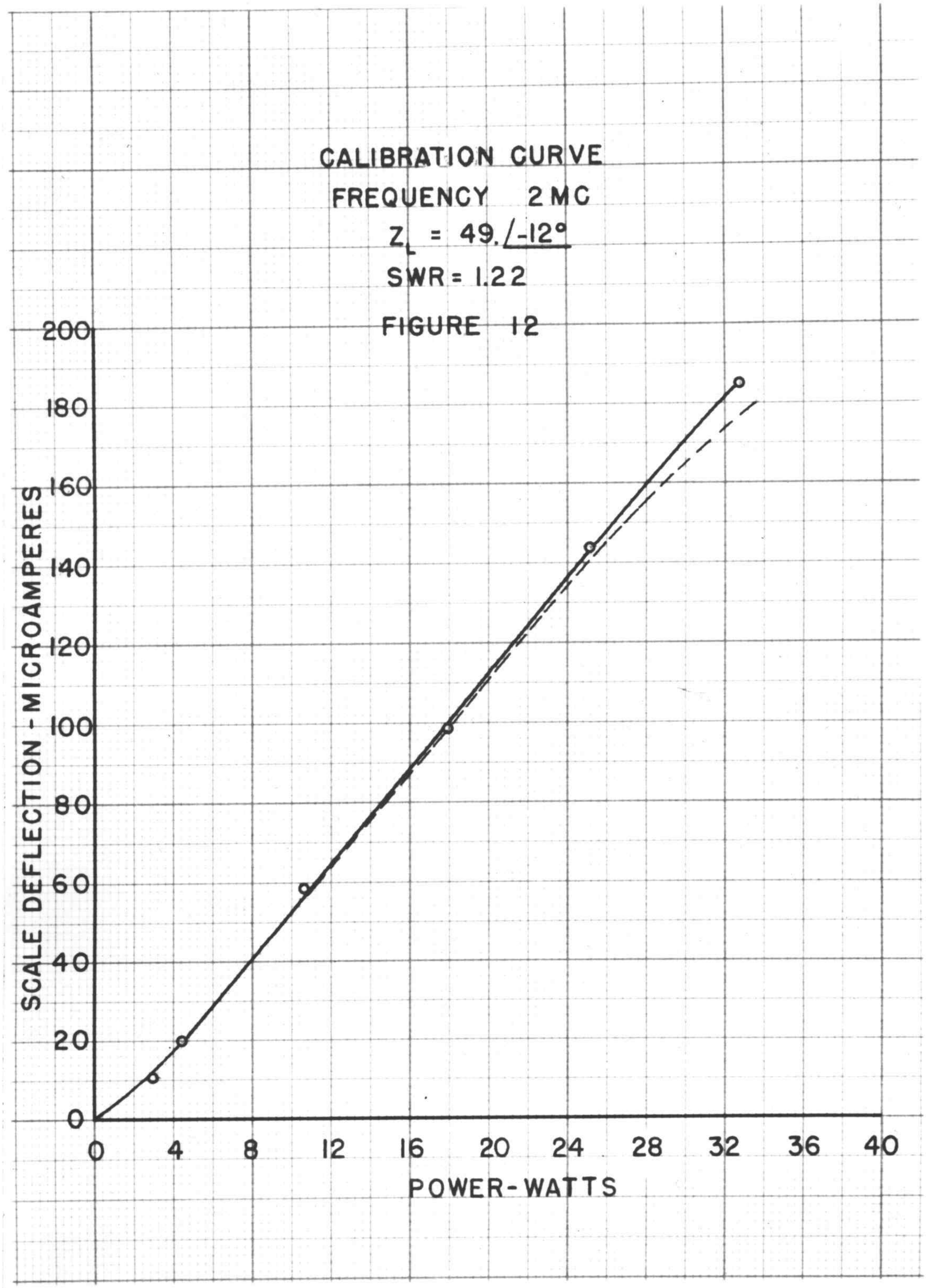
<u>Calibration</u>--The wattmeter was calibrated by measuring the power delivered to a known load impedance. The voltage across the load impedance was measured by means of a vacuum tube voltmeter and the actual power delivered to the load was then calculated by means of equation (9). The deflection of the microammeter was recorded for different values of power and this deflection was then plotted as a function of the actual power. If all of the component parts used in the construction of the wattmeter were ideal, this function would be a straight line.

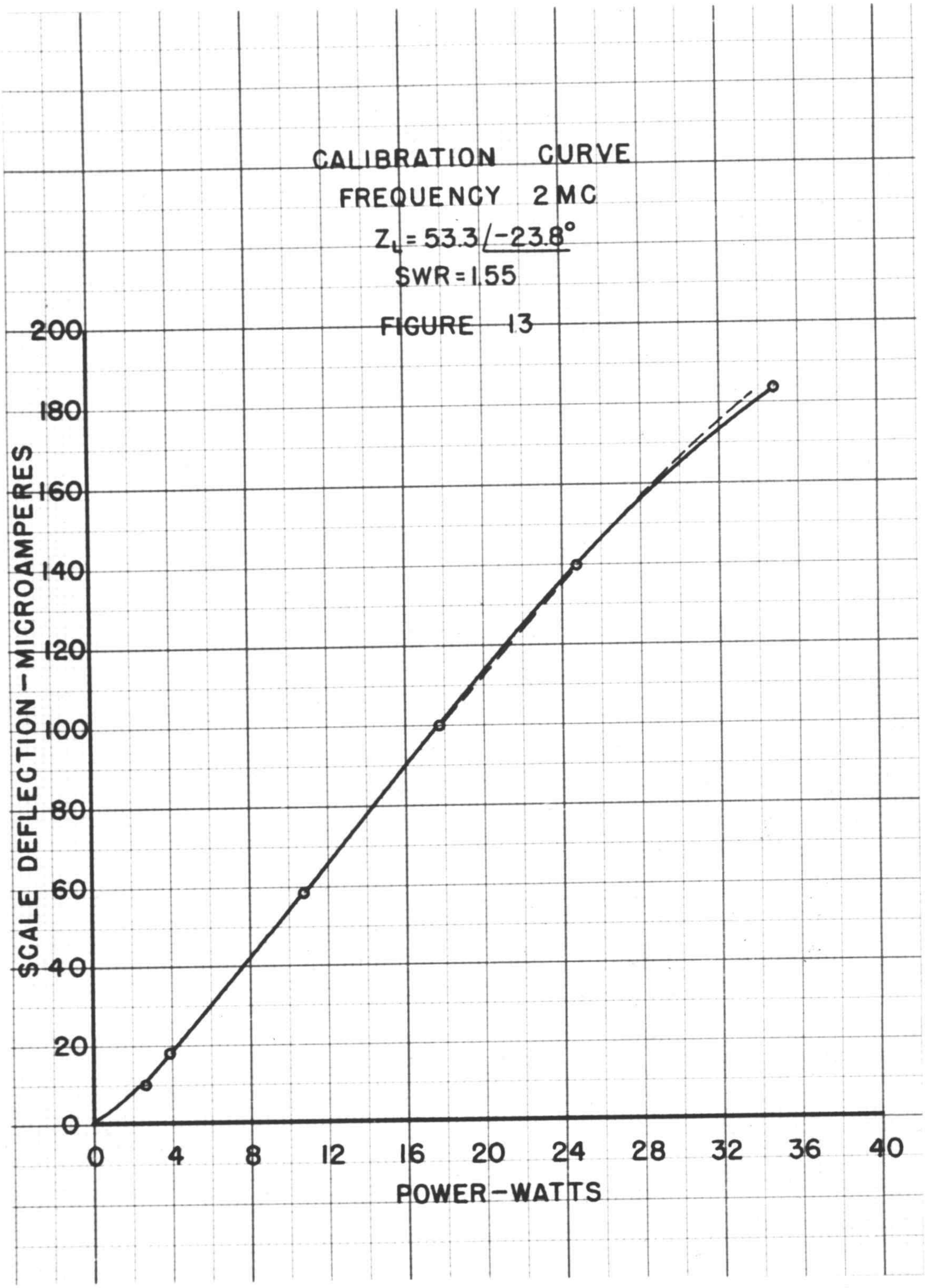
For the initial calibration attempt, the value of C_2 was adjusted by means of a radio frequency bridge to make $\frac{e_1}{e_2}$ equal to $\frac{R}{Z_o}$. It was later found necessary to readjust the value of C_1 slightly to make the calibration hold true for a wide range of load impedances.

For the final calibration, load impedances were chosen with magnitudes both much larger and much smaller than the characteristic impedance. Also, load impedances with both leading and lagging power factors were used. The results of this calibration, together with the actual values of load impedances used, are shown graphically in Figures 12 through 21.

An examination of these calibration curves shows that the scale deflection is very nearly a linear function of the actual power for a wide range of load impedances. On each one of the calibration curves, a dotted curve is also present which indicates the average calibration curve for the wattmeter. It will be noticed that most of the calibration curves follow the average curve extremely closely over the region tested. Most of the deviation comes at the upper end of the scale. Some possible reasons for this deviation will be discussed in a later section.

Response of Wattmeter With Modulation Present--The calibration of the wattmeter was obtained with a sinusoidal two megacycle source. It was also desired to determine the response of the wattmeter to waves of a complex nature. To do this, the two megacycle carrier was modulated with a sinusoidal audio signal. When this is done, the output consists of the carrier plus the upper and lower side frequencies. The complete expression for the output voltage with modulation present is given by equation (44).


CALIBRATION CURVE
FREQUENCY 2 MC
Z_L = 49. /-12°
SWR = 1.22
FIGURE 12
SCALE DEFLECTION - MICROAMPERES
0
20
40
60
80
100
120
140
160
180
200
0
4
8
12
16
20
24
28
32
36
40
POWER-WATTS


CALIBRATION CURVE
FREQUENCY 2 MC
$Z_L = 53.3\angle -23.8^\circ$
SWR = 1.55
FIGURE 13
SCALE DEFLECTION - MICROAMPERES
0
20
40
60
80
100
120
140
160
180
200
0
4
8
12
16
20
24
28
32
36
40
POWER-WATTS

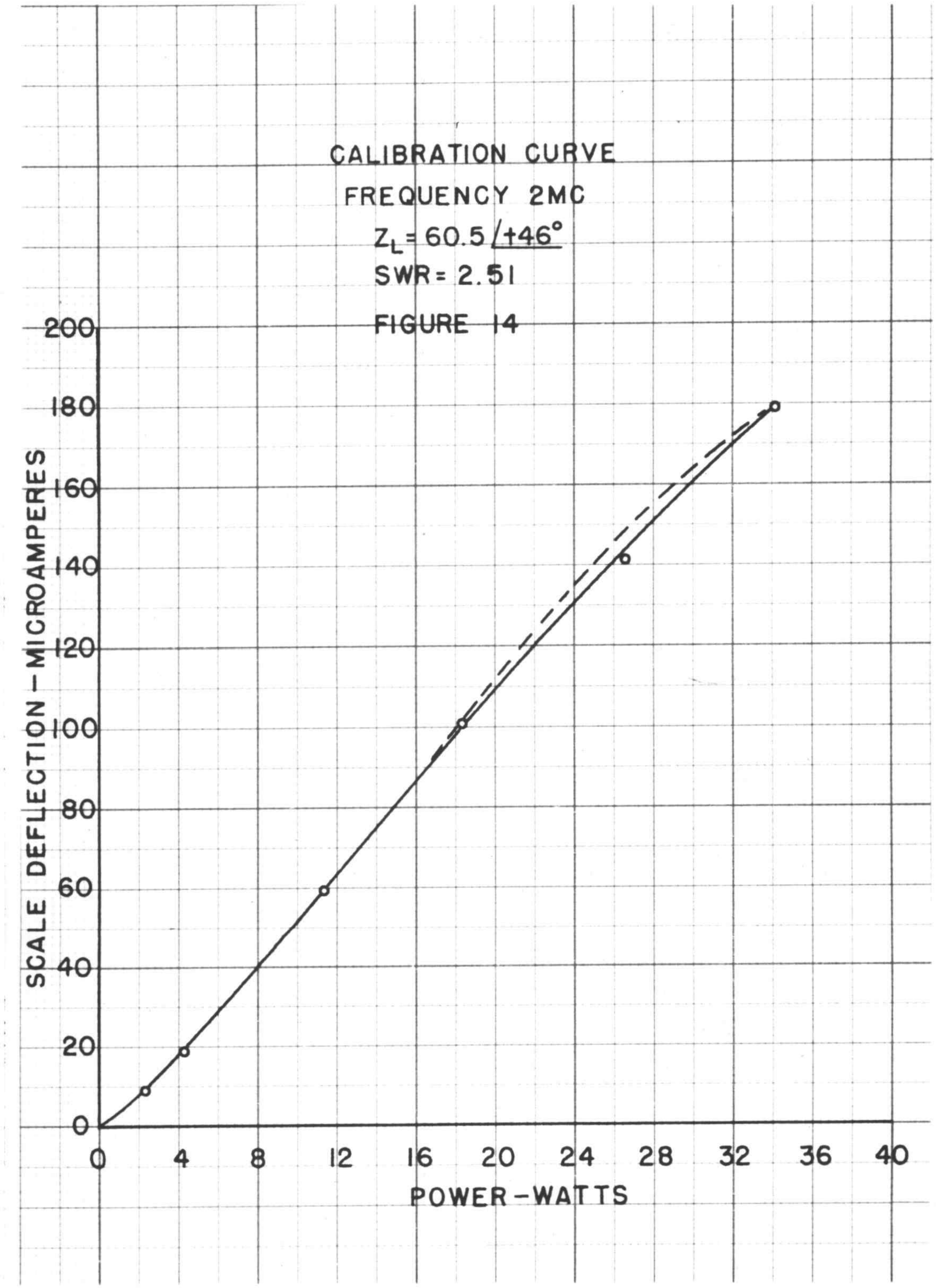
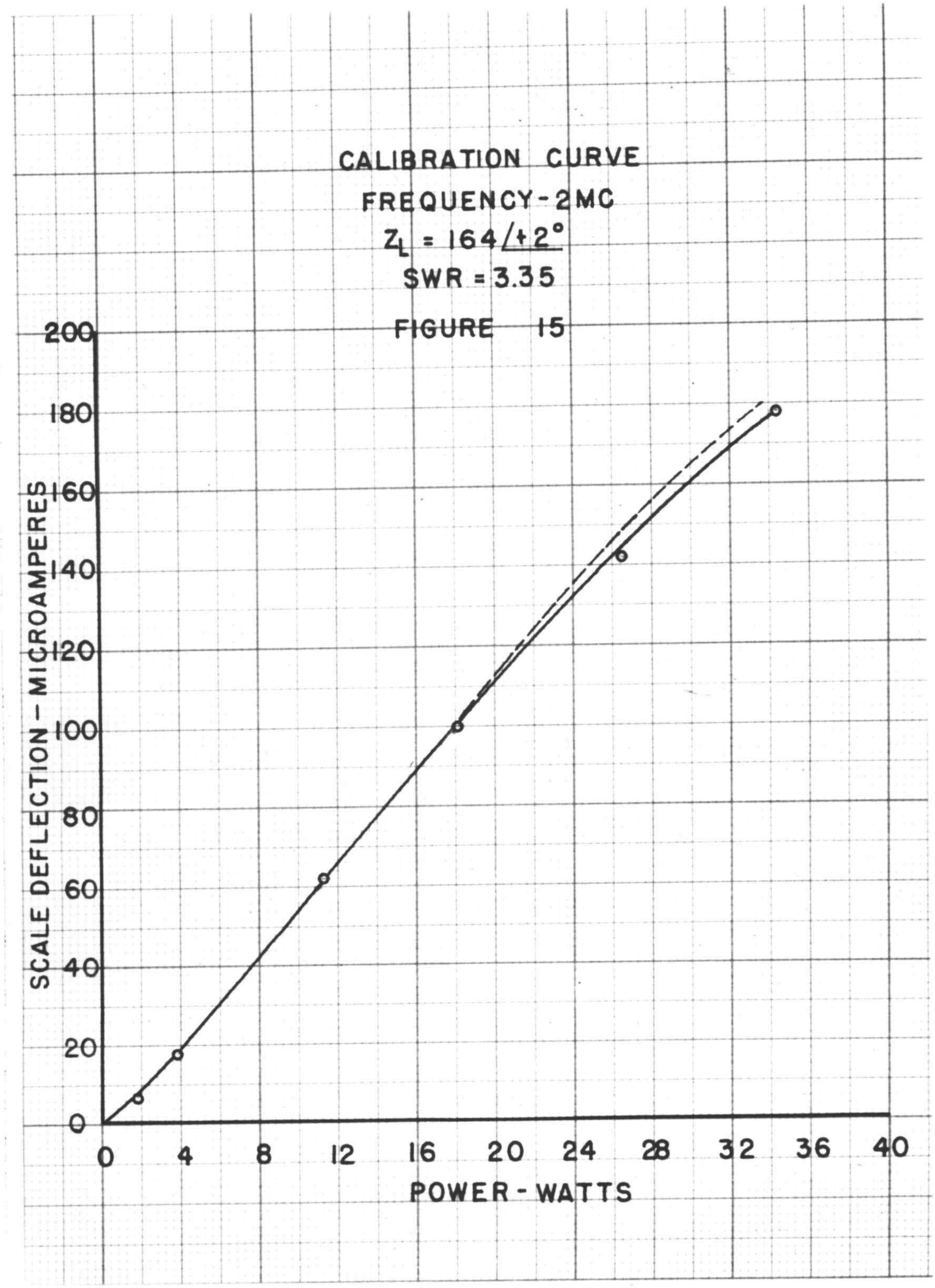
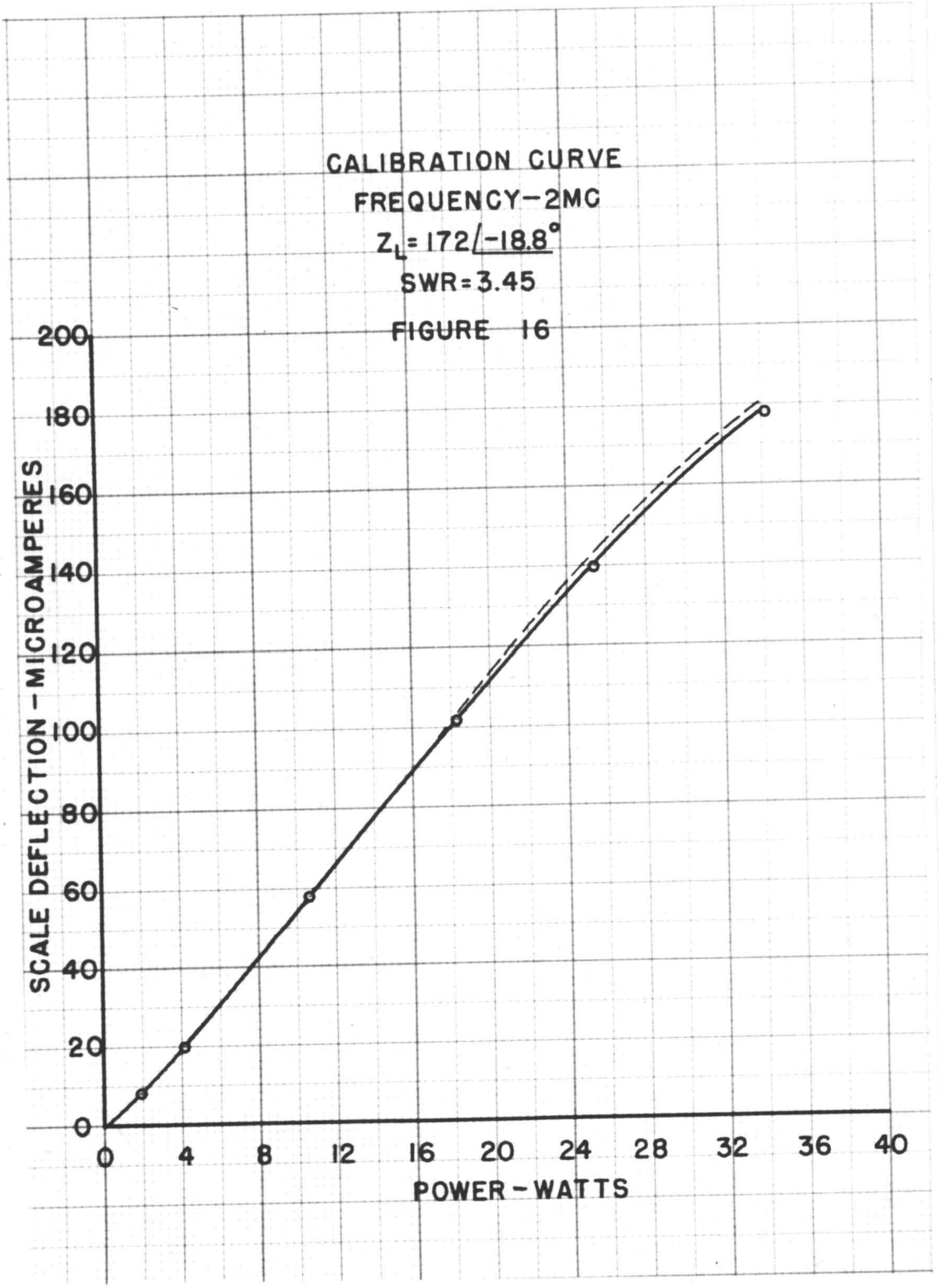
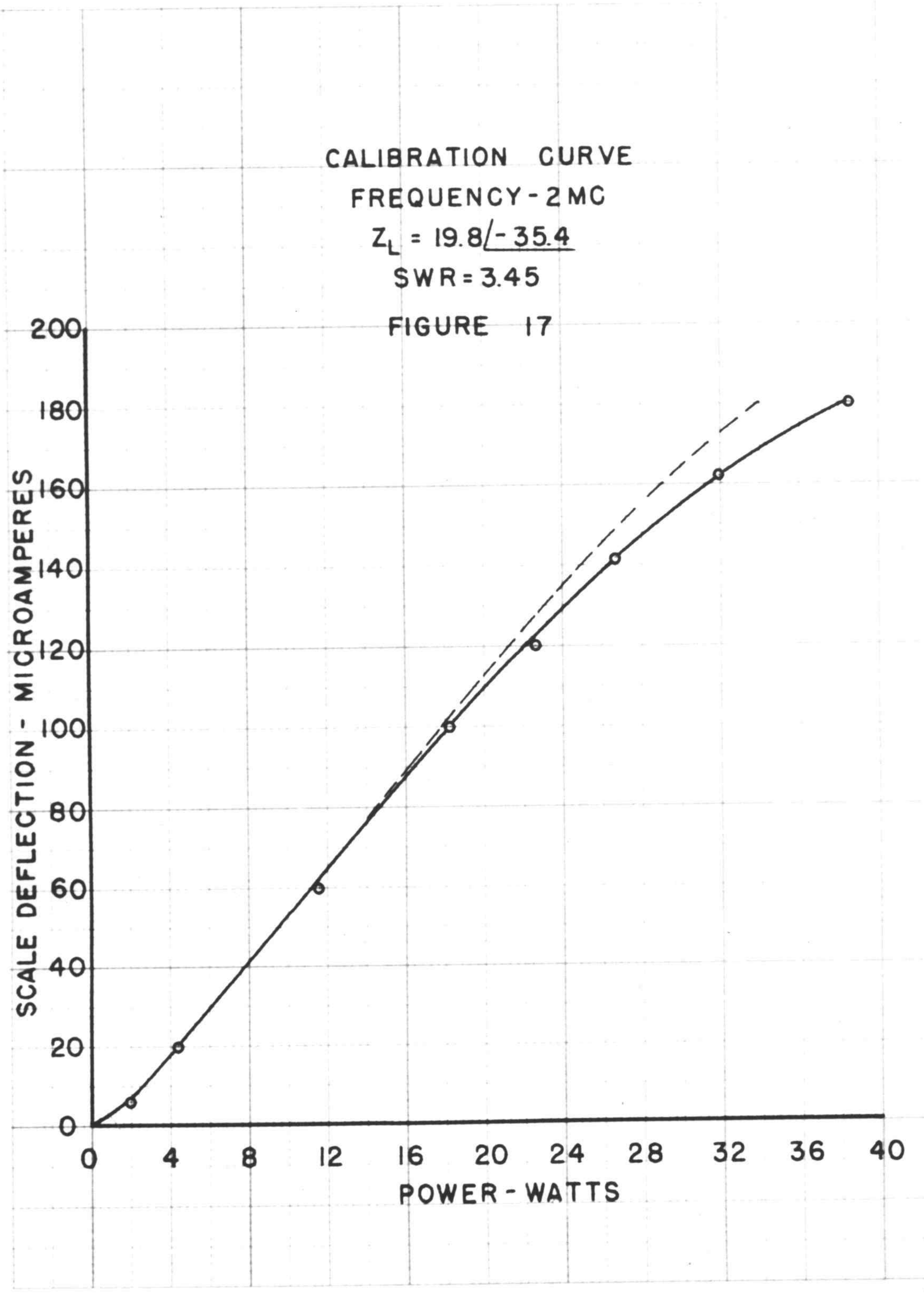
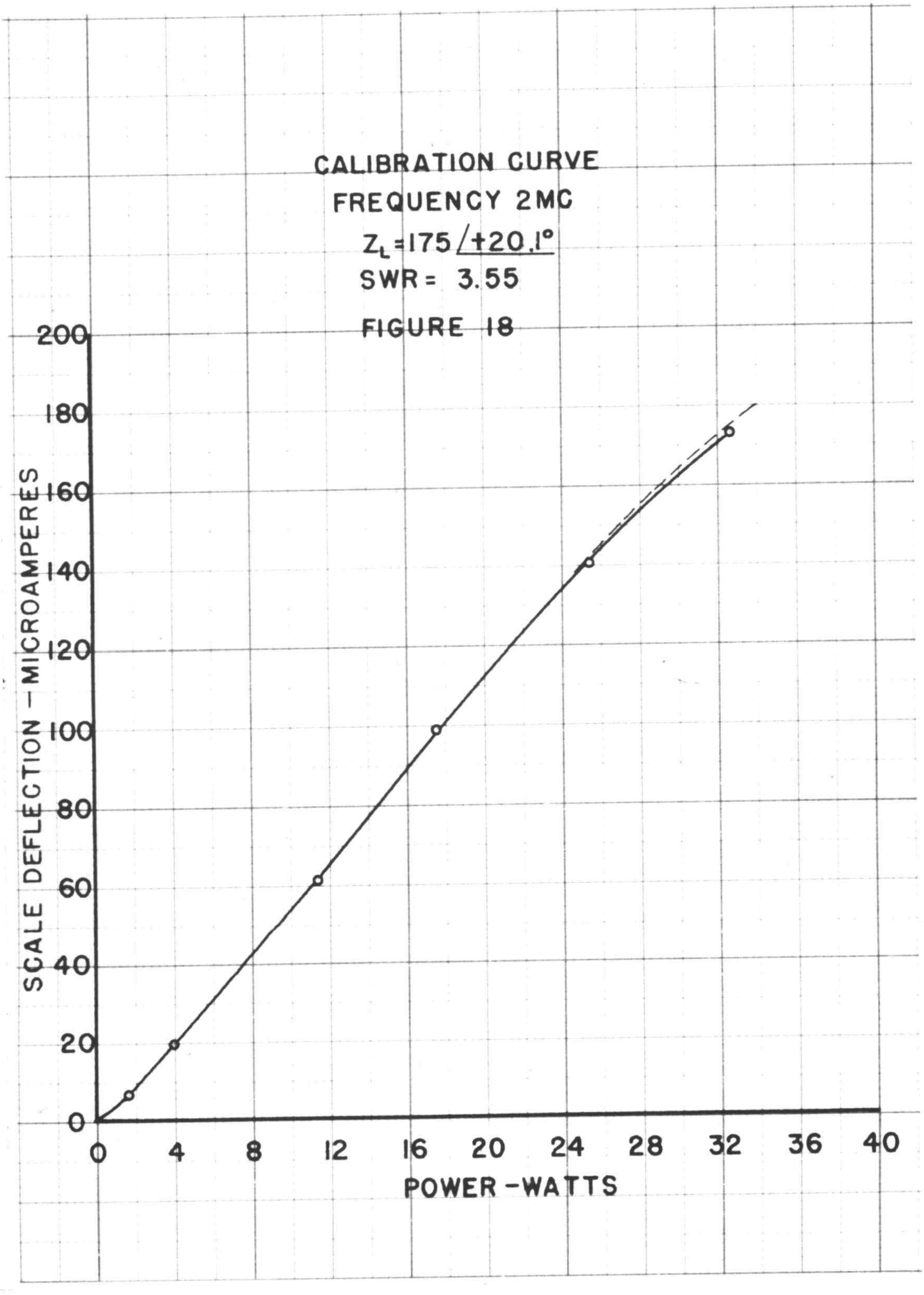

CALIBRATION CURVE
FREQUENCY 2MC
$Z_L = 60.5 \angle +46°$
SWR = 2.51
200
180
160
140
120
100
80
60
40
20
0
SCALE DEFLECTION - MICROAMPERES
0
4
8
12
16
20
24
28
32
36
40
POWER-WATTS

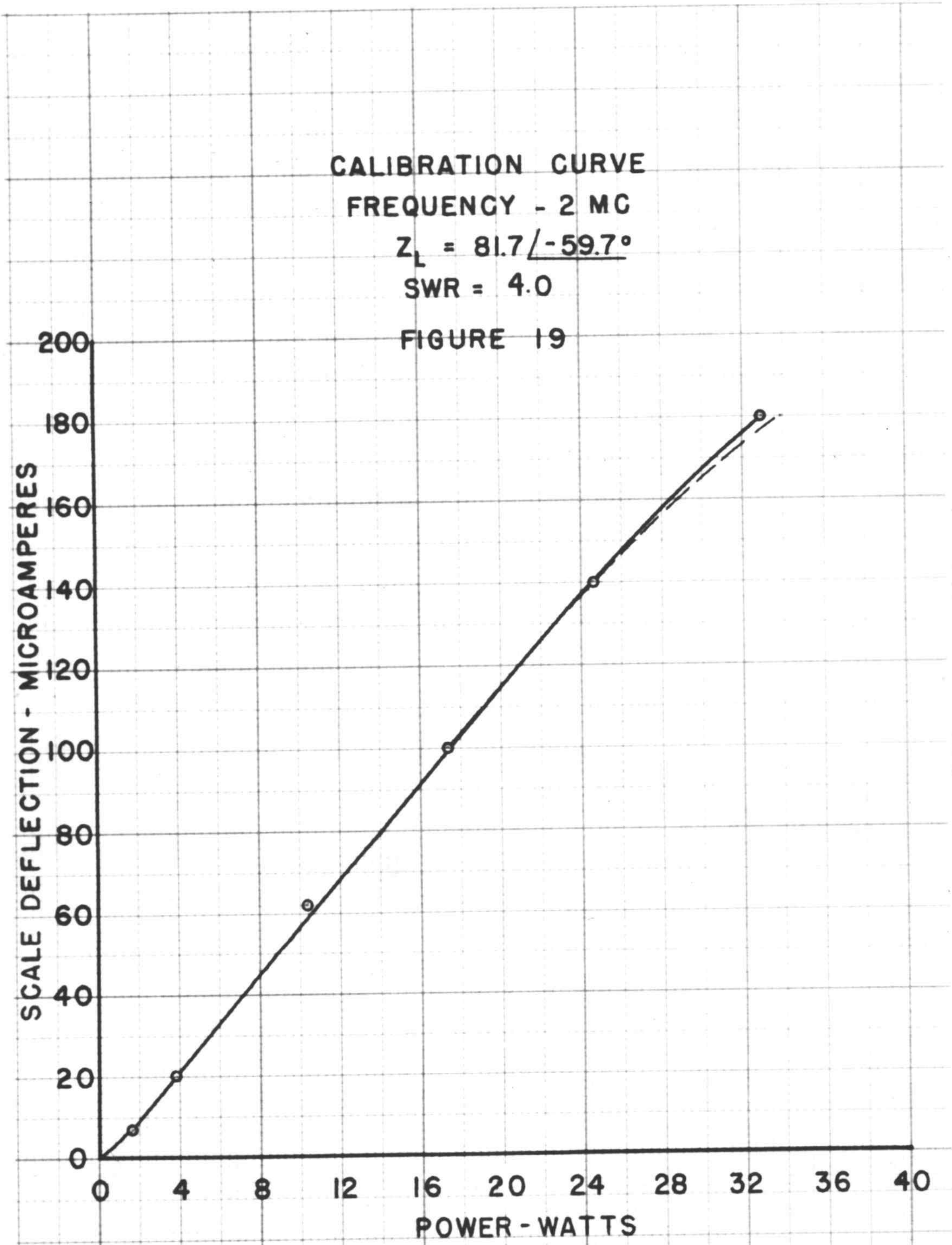
FIGURE 14

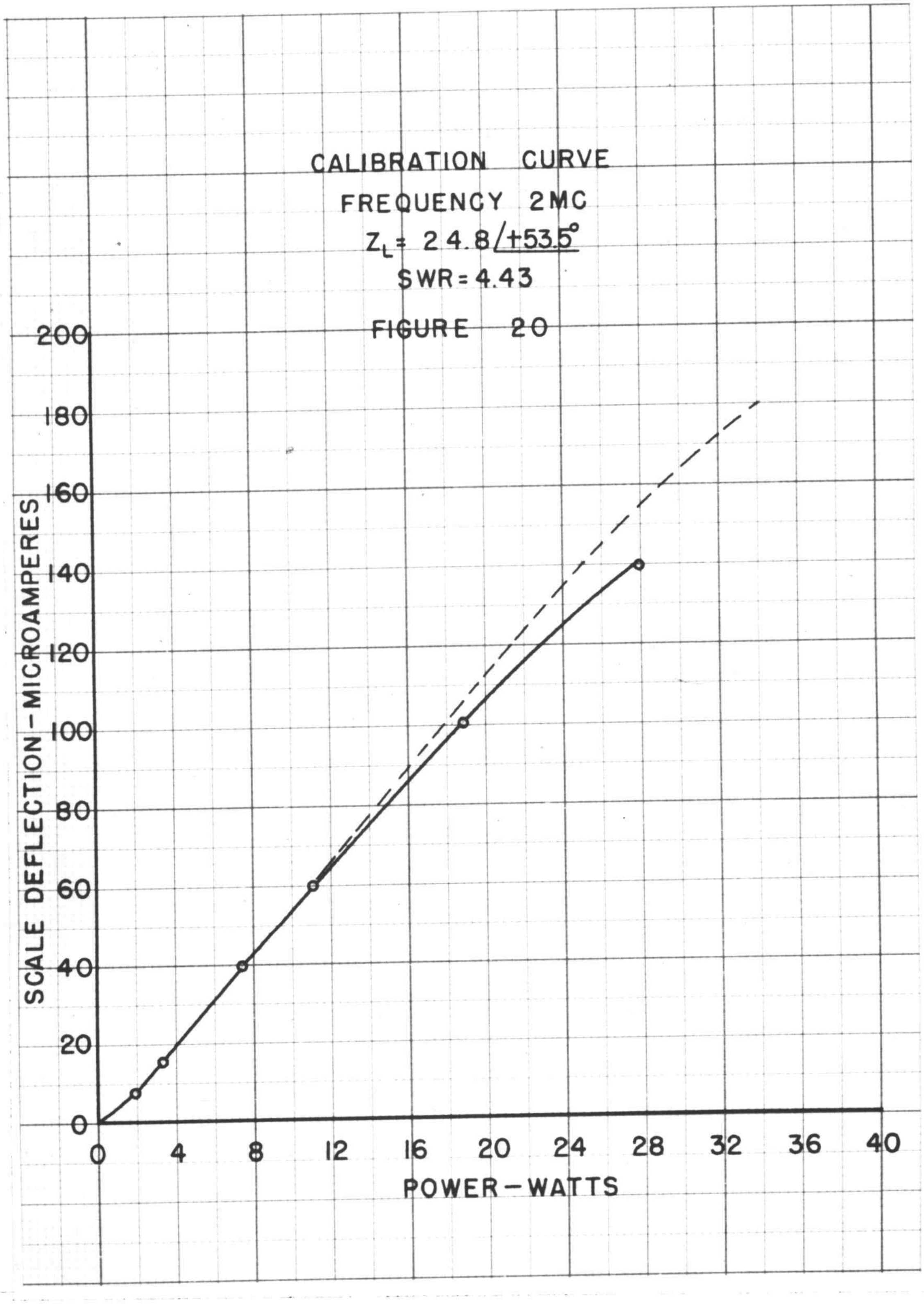

CALIBRATION CURVE
FREQUENCY - 2MC
$Z_L = 164\angle{+2°}$
SWR = 3.35
FIGURE 15
SCALE DEFLECTION - MICROAMPERES
0
20
40
60
80
100
120
140
160
180
200
POWER - WATTS
0
4
8
12
16
20
24
28
32
36
40

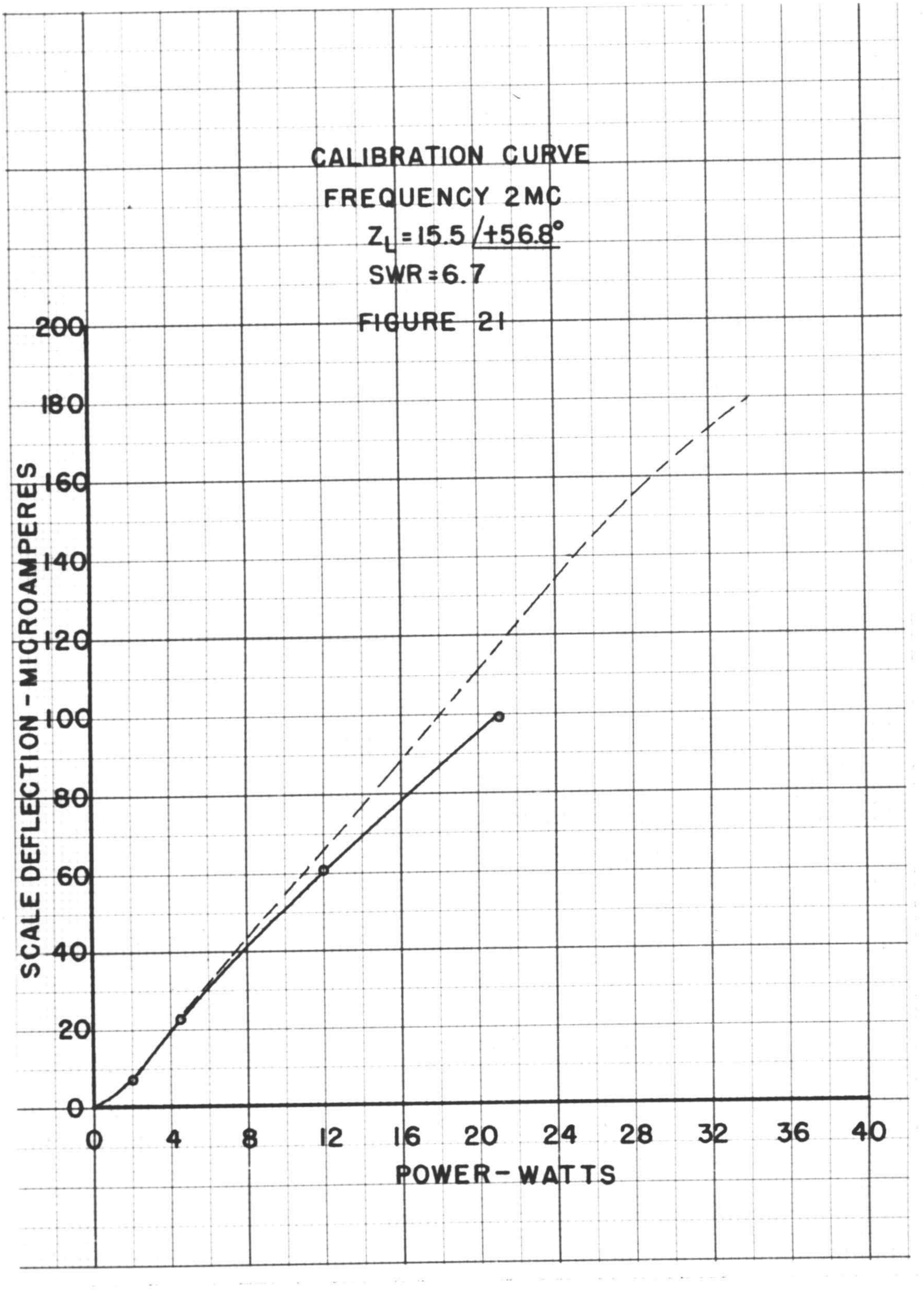

CALIBRATION CURVE
FREQUENCY-2MC
$Z_L = 172\angle{-18.8^\circ}$
SWR=3.45
FIGURE 16
SCALE DEFLECTION - MICROAMPERES
0
20
40
60
80
100
120
140
160
180
200
0 4 8 12 16 20 24 28 32 36 40
POWER-WATTS


CALIBRATION CURVE
FREQUENCY - 2 MC
$Z_L = 19.8\underline{/-35.4}$
SWR = 3.45
FIGURE 17
SCALE DEFLECTION - MICROAMPERES
0
20
40
60
80
100
120
140
160
180
200
0
4
8
12
16
20
24
28
32
36
40
POWER - WATTS


CALIBRATION CURVE
FREQUENCY 2MC
$Z_L = 175 \angle +20.1°$
SWR = 3.55
FIGURE 18
SCALE DEFLECTION - MICROAMPERES
0
20
40
60
80
100
120
140
160
180
200
0
4
8
12
16
20
24
28
32
36
40
POWER-WATTS


CALIBRATION CURVE
FREQUENCY - 2 MC
$Z_L = 81.7\angle{-59.7°}$
SWR = 4.0
FIGURE 19
SCALE DEFLECTION - MICROAMPERES
0
20
40
60
80
100
120
140
160
180
200
0
4
8
12
16
20
24
28
32
36
40
POWER - WATTS


CALIBRATION CURVE
FREQUENCY 2MC
$Z_L = 24.8 \angle +53.5^\circ$
SWR = 4.43
FIGURE 20
SCALE DEFLECTION - MICROAMPERES
200
180
160
140
120
100
80
60
40
20
0
0
4
8
12
16
20
24
28
32
36
40
POWER - WATTS


CALIBRATION CURVE
FREQUENCY 2MC
$Z_L = 15.5 \angle +56.8^{\circ}$
SWR = 6.7
FIGURE 21
SCALE DEFLECTION - MICROAMPERES
200
180
160
140
120
100
80
60
40
20
0
0
4
8
12
16
20
24
28
32
36
40
POWER - WATTS

$$e = E_c \sin w_c t + \frac{m}{2} E_c \sin(w_c + w_m)t$$
$$+ \frac{m}{2} E_c \sin(w_c - w_m)t \qquad (44)$$

In this equation, w_m is the frequency of the modulating wave, E_c and w_c are the magnitude and frequency of the carrier, and m is the modulation factor. If the magnitude of the unmodulated carrier and the modulation factor are known, the total power delivered to the load can be calculated by superposition. If the modulating frequency is small compared to the carrier frequency, the impedance of the load will be the same for the three components of output voltage.

$$P_{ave} = \left[E^2_{c_{rms}} + \left(\frac{m}{2} E_{c_{rms}} \right)^2 + \left(\frac{m}{2} E_{c_{rms}} \right)^2 \right] \frac{\cos\theta}{Z_L}$$
$$= E^2_{c_{rms}} \left(1 + \frac{m^2}{2} \right) \frac{\cos\theta}{Z_L} \qquad (45)$$

The modulation factor, or percentage of modulation, can readily be determined by means of a cathode ray oscilloscope.

The response of the wattmeter to a modulated wave is presented graphically in Figures 22 and 23. Starting from some convenient initial scale deflection with no modulation present, the carrier was modulated progressively from zero to one hundred per cent. The actual power output was calculated from equation (45). Both the calculated and indicated power were then plotted as a function of the per cent modulation. For the upper set of curves on Figures 22 and 23, the initial deflection of the microammeter was 100 microamperes.

For the lower set of curves, the initial deflection was 80 microamperes. The modulation frequency for Figure 22 was four hundred cycles per second, while that for Figure 23 was four thousand cycles per second.

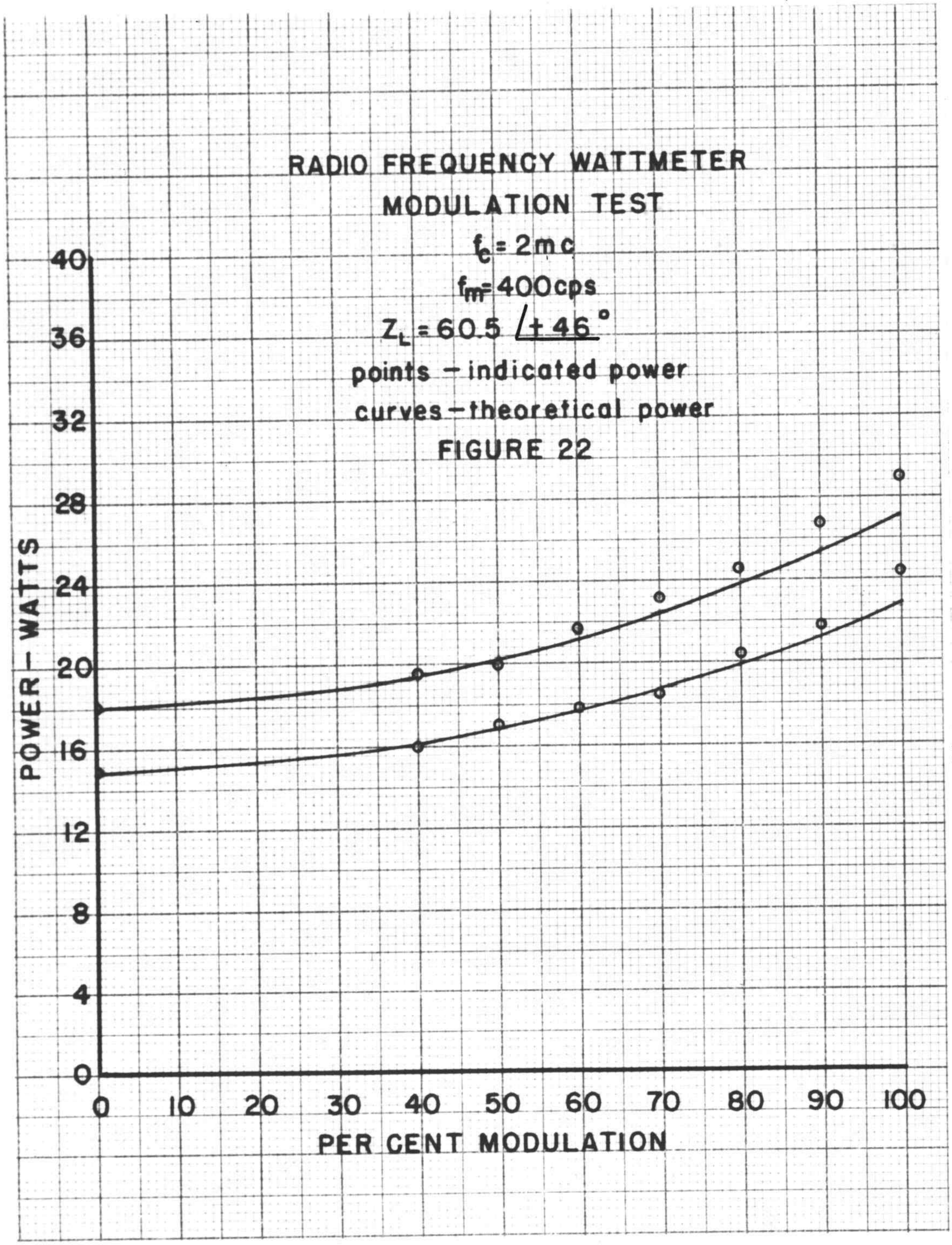
The results of this investigation indicated that power may be measured with reasonable accuracy with the wattmeter when the carrier is modulated with an audio frequency signal. The error introduced is approximately five per cent of full scale with one hundred per cent modulation. The error decreases as the modulation factor decreases and is quite negligible below fifty per cent modulation.

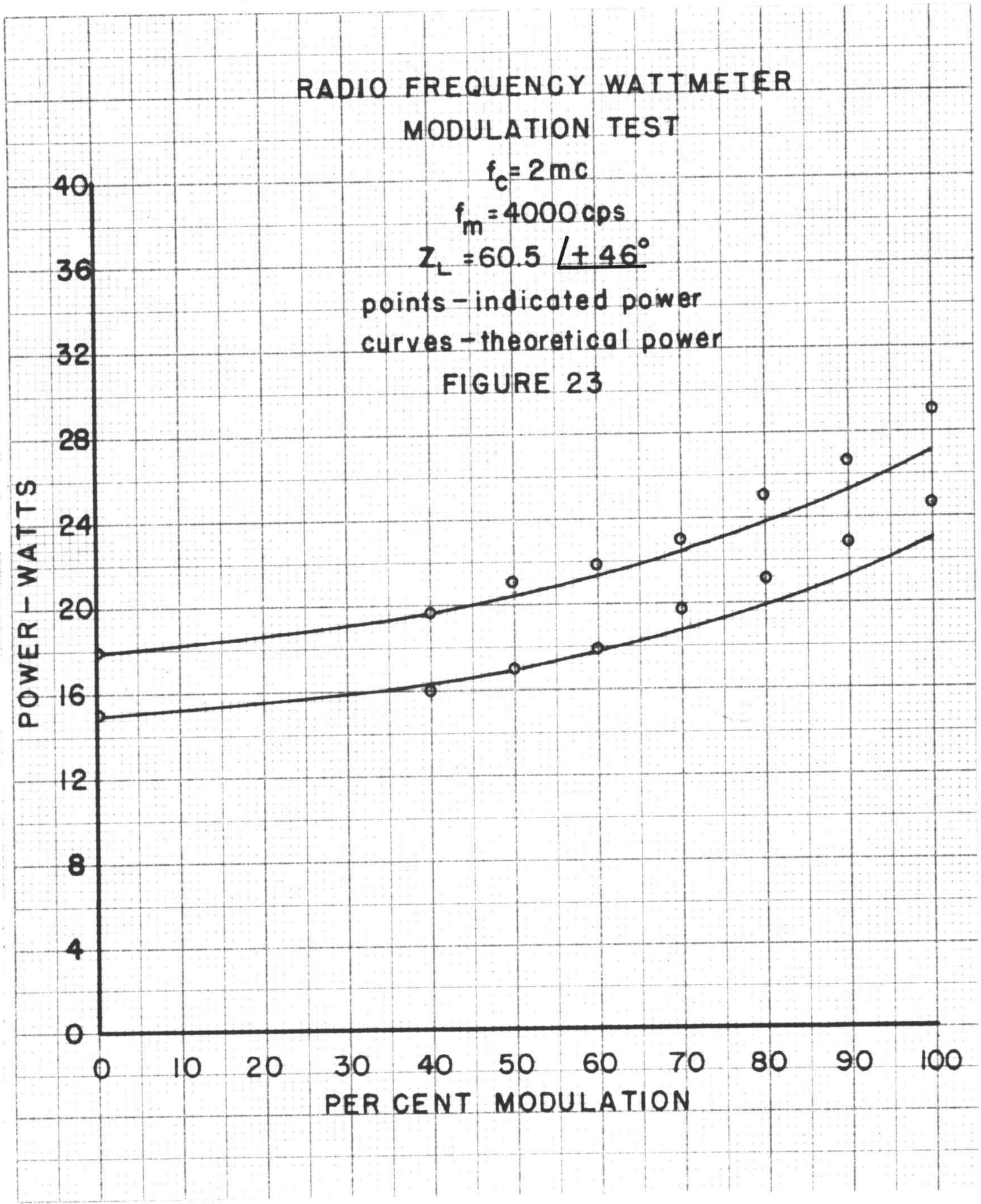
Limitations--From theoretical considerations, the wattmeter described in the preceding sections should correctly indicate power regardless of load impedance or frequency. However, in the actual instrument, there are certain factors that limit the useful operating range.

One definite source of error is introduced because of the fact that the vacuum thermocouples are not exact square law devices. The actual relationship between the couple current and the heater current is given by the equation

$$I_c = KI_H^n \tag{46}$$

where n is a constant that can be determined from experimental data. For the thermocouples used in the experimental wattmeter, the value of n is 1.87 for one and 1.89 for the other. The nature of the error


RADIO FREQUENCY WATTMETER
MODULATION TEST
$f_c = 2$ mc
$f_m = 400$ cps
$Z_L = 60.5 \angle +46°$
points – indicated power
curves – theoretical power
FIGURE 22
POWER – WATTS
0
4
8
12
16
20
24
28
32
36
40
0
10
20
30
40
50
60
70
80
90
100
PER CENT MODULATION


RADIO FREQUENCY WATTMETER
MODULATION TEST
$f_c = 2$ mc
$f_m = 4000$ cps
$Z_L = 60.5 \angle +46°$
points - indicated power
curves - theoretical power
FIGURE 23
POWER - WATTS
0
4
8
12
16
20
24
28
32
36
40
0
10
20
30
40
50
60
70
80
90
100
PER CENT MODULATION

produced by this deviation from a true square law is revealed by Figure 24. In this figure, the quantity $V_i^{n_1} - V_r^{n_2}$ is plotted as a function of $V_i^2 - V_r^2$, where n_1 and n_2 are the exponents for the actual thermocouples used. The standing wave ratio is the family parameter for this set of curves. It can be seen that the curves show a definite tendency to be concave downward, and this tendency becomes more pronounced as the standing wave ratio is increased. Referring to the calibration curves of Figures 12 through 21, it is evident that the actual wattmeter deflection follows this trend very definitely.

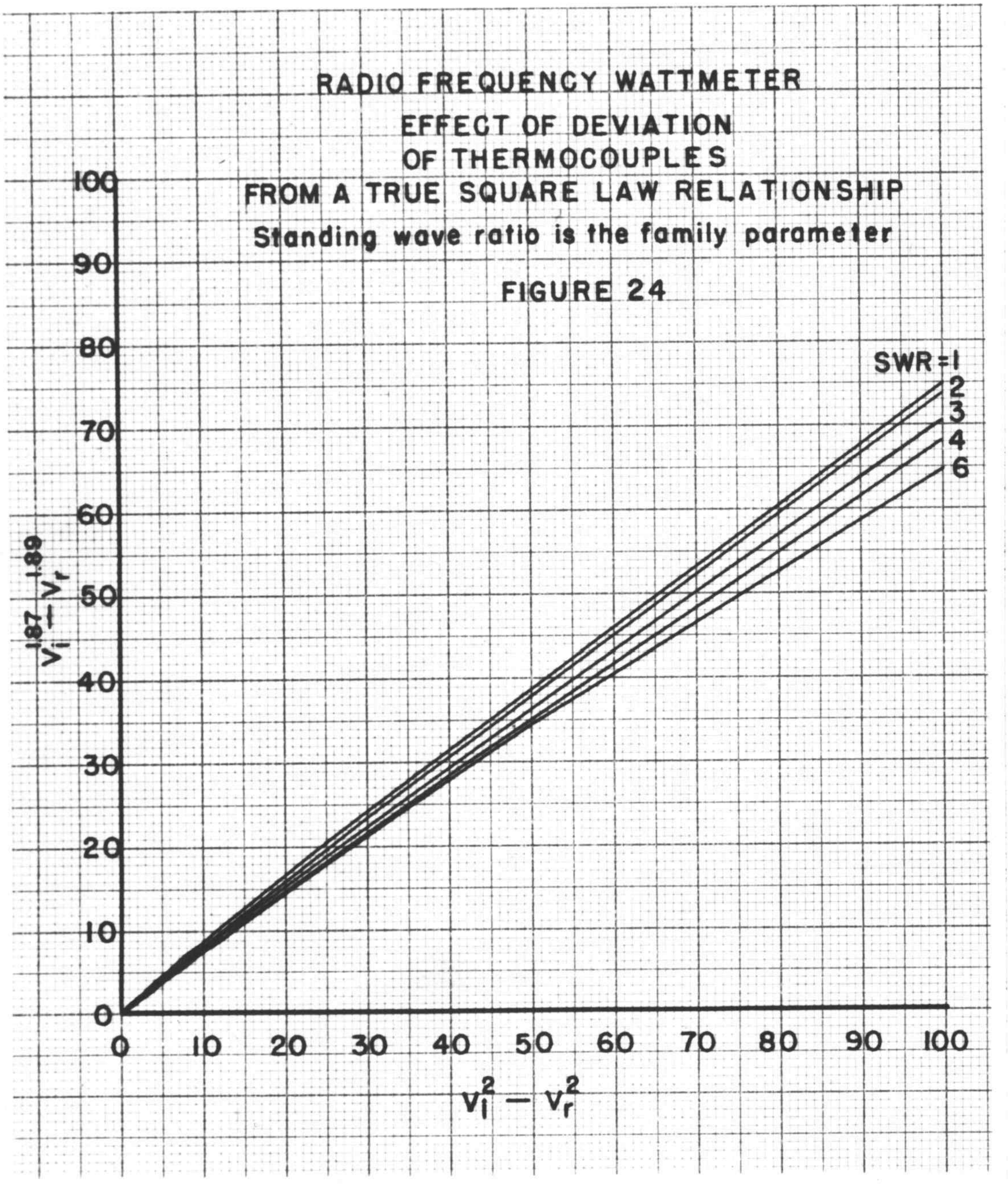
The standing wave ratio may be approximately determined by means of the wattmeter by taking separate readings of $(KV_i)^2$ and $(KV_r)^2$ and substituting these quantities in equation (43). If the magnitude and phase angle of the load impedance are known, the standing wave ratio may be determined by first determining the reflection coefficient from the following equation.

$$K = \frac{\frac{Z_L}{Z_o} - 1}{\frac{Z_L}{Z_o} + 1} \tag{47}$$

In this equation, K is the reflection coefficient and in general will be a complex quantity. The standing wave ratio will then be

$$SWR = \frac{1 + |K|}{1 - |K|} \tag{48}$$

The quantity $|K|$ in this expression is the magnitude of the reflection


RADIO FREQUENCY WATTMETER
EFFECT OF DEVIATION
OF THERMOCOUPLES
FROM A TRUE SQUARE LAW RELATIONSHIP
Standing wave ratio is the family parameter
FIGURE 24
SWR = 1
2
3
4
6
$V_i^{1.87} - V_r^{1.89}$
$V_i^2 - V_r^2$
0
10
20
30
40
50
60
70
80
90
100

coefficient.

The calibration curves indicate that power may be measured with accuracy if the standing wave ratio has a magnitude of about six or less.

A limit must be placed on the maximum power that can be measured because of the current rating of the thermocouples. The maximum allowable power will be different for different values of load impedance because the relationship between V_i and V_r will be different for each case. The limit will be reached when the current in the heater circuit of the thermocouple measuring V_i reaches the rated value. For the thermocouples used in the experimental model wattmeter, the open circuit couple voltage is ten millivolts when rated heater current is flowing. By means of the circuit shown in Figure 25 the maximum allowable deflection of the microammeter can be determined as a function of the standing wave ratio.

This circuit represents the microammeter circuit of the wattmeter including the two thermocouples in series with the microammeter. From this circuit, the deflection of the microammeter will be

$$\text{deflection} = \frac{E_1 - E_2}{R_T} 10^6 \text{ ua} = \frac{E_1 - E_2}{30.5} 10^6 \text{ua} \qquad (49)$$

where: $(KV_i)^2 = E_1, \qquad KV_i = E_1^{1/2}$

$(KV_r)^2 = E_2, \qquad KV_r = E_2^{1/2}$

The maximum allowed deflection will occur when E_1 equals 10^{-2} volts.

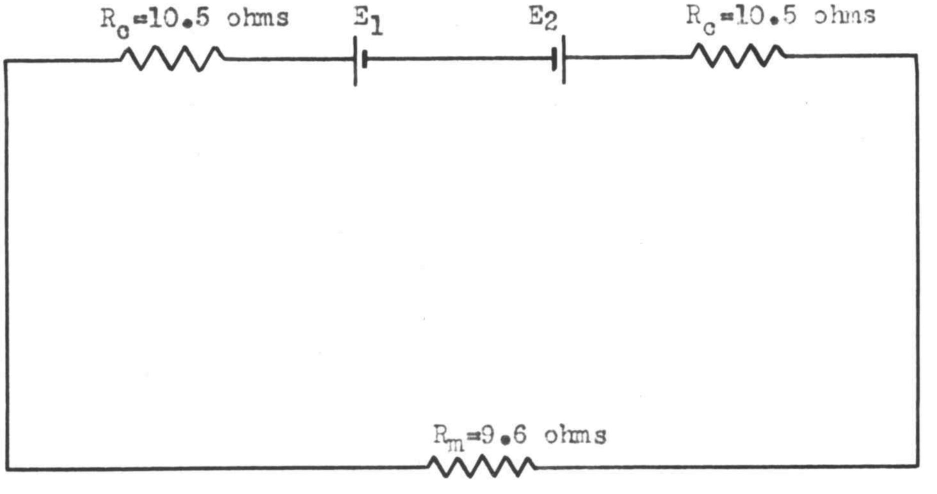


FIGURE 25

Circuit for determining maximum allowable deflection of the microammeter.

SYMBOLS: E_1= open circuit couple voltage for incident reading thermocouple.
E_2= open circuit couple voltage for reflection reading thermocouple.
R_c= couple resistance.
R_m= meter resistance.
$R_t = 2R_c + R_m = 30.5$ ohms

Therefore:

$$\text{maximum deflection} = \left(\frac{10^{-2} - E_2}{30.5}\right) 10^6 \text{ uamps} \tag{50}$$

The standing wave ratio can be expressed as

$$SWR = \frac{KV_i + KV_r}{KV_i - KV_r} \tag{51}$$

For the case of maximum deflection this becomes

$$SWR = \frac{10^{-1} + KV_r}{10^{-1} - KV_r} \tag{52}$$

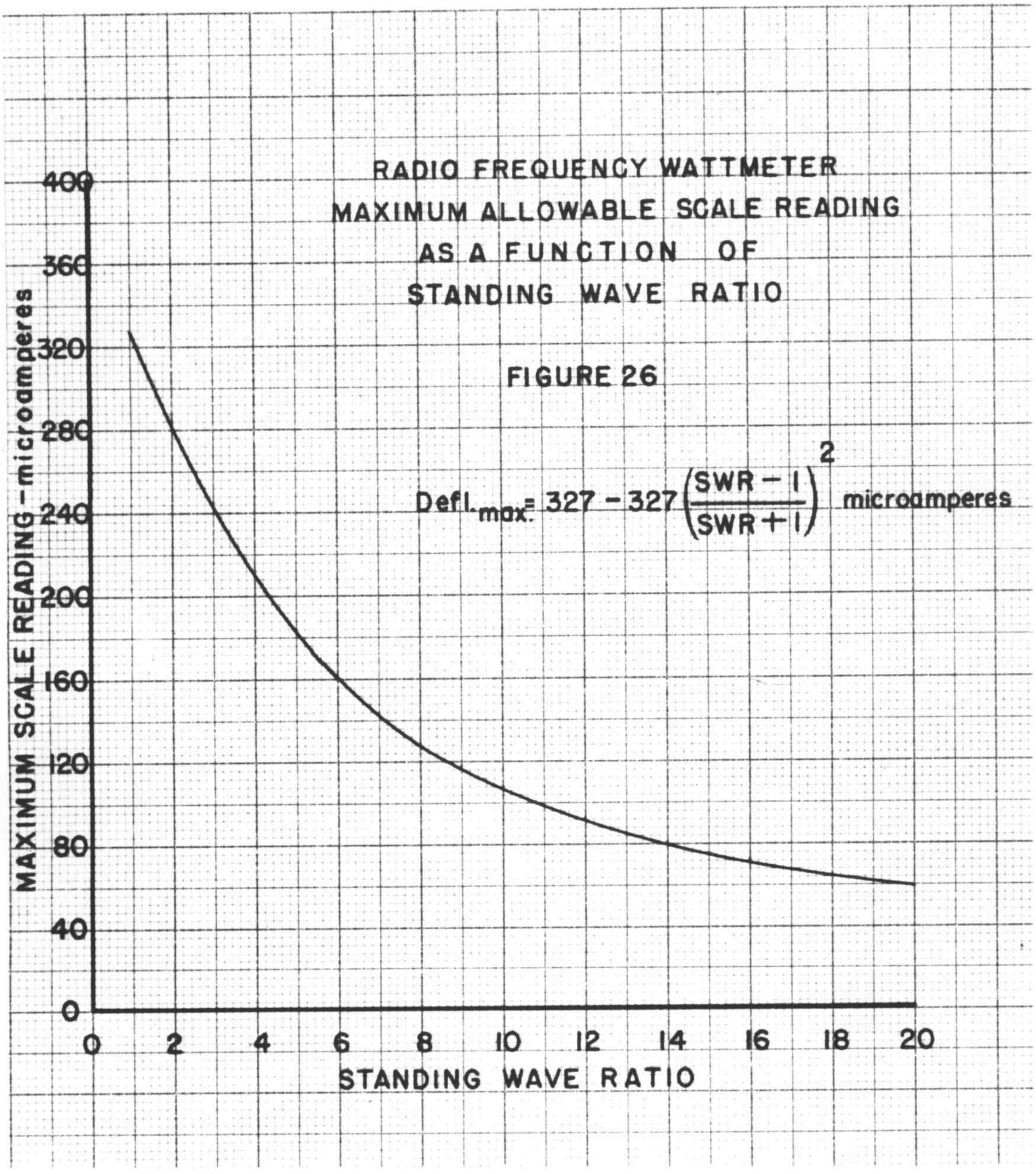
Solving this expression for KV_r:

$$KV_r = 10^{-1} \left(\frac{SWR - 1}{SWR + 1}\right) \tag{53}$$

The value of (KV_r) from equation (53) can be substituted in equation (50) for the maximum allowable deflection, giving an expression for the maximum allowable deflection as a function of the standing wave ratio.

$$\underset{\text{(microamps)}}{\text{Maximum deflection}} = 327 - 327 \left(\frac{SWR - 1}{SWR + 1}\right)^2 \tag{54}$$

Figure 26 shows the maximum allowable deflection as a function of the standing wave ratio in graphical form. The maximum scale reading for the microammeter used is two hundred microamperes. It can be seen from this figure that for a standing wave ratio of eleven, half of the scale, or a deflection of one hundred microamperes, may


RADIO FREQUENCY WATTMETER
MAXIMUM ALLOWABLE SCALE READING
AS A FUNCTION OF
STANDING WAVE RATIO
FIGURE 26
Defl.$_{max}$ = $327 - 327\left(\frac{SWR-1}{SWR+1}\right)^2$ microamperes
MAXIMUM SCALE READING - microamperes
400
360
320
280
240
200
160
120
80
40
0
0
2
4
6
8
10
12
14
16
18
20
STANDING WAVE RATIO

may be used.

Frequency Response--It was mentioned previously that the useful frequency range of the wattmeter would be limited by the reactance of the series resistor in the center conductor of the coaxial cable. This reactance should be one tenth or less the magnitude of the resistance for proper operation.

The actual detector circuit, consisting of the IN34 crystals and associated filter, should present a high impedance compared to the circuit across which it is placed. For any fixed value of capacitor, C_1, this fact will tend to place a low frequency limit on the useful range of the wattmeter.

POSSIBILITIES FOR FUTURE DEVELOPMENT

The radio frequency wattmeter that has been described apparently is a more versatile instrument for measuring radio frequency power than most of those now available. It will indicate power directly and accurately even though the load impedance may vary over wide limits. Also, it will indicate power correctly when the carrier is modulated with an audio signal.

The experimental wattmeter herein described was constructed for the sole purpose of demonstrating the possibility of measuring power by the method set forth under the theoretical discussion. No attempt was made to construct an instrument that would be immediately practical for a commercial application. However, it should be possible, with some revision, to construct a wattmeter operating on this principle for almost any application at broadcast frequencies.

The range of the instrument could be extended to measure a wider range of power by proper selection of circuit constants and by means of potentiometers in the thermocouple circuit.

The overall accuracy of the instrument could undoubtedly be improved by obtaining thermocouples that more nearly follow a square law and by carefully matching the two thermocouples used. More refined methods for constructing the series resistor would probably make it possible to reduce the reactance of this resistor below the value obtained in the experimental model.

Although the experimental wattmeter was constructed for use with a coaxial cable, the principle could be applied to an open wire line as well.

This principle for measuring power might well be applied to studies involving dielectric or induction heating applications where it is desired to measure the power delivered to the load when the load impedance may change appreciably during the heating cycle.

CONCLUSIONS

A method for the construction of a direct reading radio frequency wattmeter has been described that operates on the principle that the power delivered to a load over a transmission line is the difference between the power contained in the incident traveling wave and the reflected traveling wave.

This instrument will correctly indicate power regardless of the magnitude of the load impedance over a wide range of load impedances. Also, power may be measured even though modulation is present. Experimental evidence is presented indicating the accuracy to be expected from the instrument with the conditions specified.

Some of the factors that limit the accuracy and range of the experimental wattmeter are discussed so that these factors may be given particular attention in the design of a wattmeter of this type for any specific application.

The possibilities for future development of this wattmeter are discussed, and it is pointed out that the instrument would be particularly convenient for applications in which the load impedance varies during the period when measurements are being made.

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2. Jones, Mack C. and Sontheimer, Carl. The micromatch. QST 31: 15-20. April 1947.

3. Terman, Fredrick Emmons. Radio engineers handbook. New York, McGraw-Hill, 1943. 1019 p.

APPENDIX

RADIO FREQUENCY WATTMETER

DATA FOR CALIBRATION CURVES

FREQUENCY - 2MC

Figure 12 - $Z_L = 49 \angle -11.8^\circ$

Applied Voltage (volts)	Calculated Power (watts)	Scale Reading (microamperes)
40.5	32.8	185
35.5	25.2	144
30.0	18.0	99
23.0	10.6	58
14.8	4.4	20
12.5	3.1	12

Figure 13 - $Z_L = 53.3 \angle -23.8^\circ$

44.0	34.8	184
38.0	24.8	140
32.0	17.7	100
25.0	10.8	59
15.0	3.9	18
12.6	2.7	10

Figure 14 - $Z_L = 60.5 \angle +46^\circ$

54.5	34.2	180
48.0	26.6	142
40.0	18.4	102
31.5	11.4	60
19.5	4.4	20
14.5	2.4	10

Figure 15 - $Z_L = 164 \angle +2^\circ$

75.0	34.4	178
66.0	26.6	142
54.5	18.2	100
43.0	11.3	62
25.3	3.9	18
17.4	1.8	7

RADIO FREQUENCY WATTMETER

DATA FOR CALIBRATION CURVES

FREQUENCY - 2MC

Figure 16 - $Z_L = 172 \angle -18.8^{\circ}$

Applied Voltage (volts)	Calculated Power (watts)	Scale Reading (microamperes)
78.5	34.2	178
68.0	25.5	140
57.5	18.3	102
44.0	10.7	58
27.2	4.1	20
19.0	2.0	8

Figure 17 - $Z_L = 19.8 \angle -35.4^{\circ}$

Applied Voltage (volts)	Calculated Power (watts)	Scale Reading (microamperes)
30.5	38.5	180
27.8	32.0	162
25.5	26.8	142
23.4	22.7	120
21.0	18.3	100
16.8	11.6	60
10.5	4.4	20
7.0	2.0	6

Figure 18 - $Z_L = 175 \angle +20.1^{\circ}$

Applied Voltage (volts)	Calculated Power (watts)	Scale Reading (microamperes)
78.0	32.6	173
69.0	25.4	141
57.0	17.5	99
46.0	11.3	62
27.4	4.0	20
17.6	1.7	7

Figure 19 - $Z_L = 81.7 \angle -59.7^{\circ}$

Applied Voltage (volts)	Calculated Power (watts)	Scale Reading (microamperes)
73.0	33.0	180
63.0	24.6	140
53.0	17.4	100
41.0	10.4	62
25.0	3.9	20
16.7	1.7	7

RADIO FREQUENCY WATTMETER

DATA FOR CALIBRATION CURVES

FREQUENCY - 2MC

Figure 20 - $Z_L = 24.8 \angle +53.5^{\circ}$

Applied Voltage (volts)	Calculated Power (watts)	Scale Reading (microamperes)
34.0	27.8	140
28.0	18.8	101
21.4	11.0	60
17.5	7.4	40
11.8	3.3	16
9.0	1.9	8

Figure 21 - $Z_L = 15.5 \angle +56.8$

Applied Voltage (volts)	Calculated Power (watts)	Scale Reading (microamperes)
24.5	21.0	99
18.5	12.0	61
11.4	4.6	22
7.6	2.0	8

RADIO FREQUENCY WATTMETER

DATA FOR MODULATION TEST

Figure 22
$Z_L = 60.5 \underline{/+46^\circ}$
Carrier Frequency - 2 megacycles
Modulating Frequency - 400 cycles

Initial scale deflection - 80 microamperes

Per cent Modulation	Carrier Voltage	Scale Reading	Indicated Power	Theoretical Power
0	36	80	15.0	15.0
40	36	86	16.0	16.2
50	36	92	17.0	16.9
60	36	97	17.8	17.7
70	36	101	18.5	18.7
80	36	110	20.4	19.8
90	36	118	21.8	21.1
100	36	132	24.4	22.6

Initial scale deflection - 100 microamperes

Per cent Modulation	Carrier Voltage	Scale Reading	Indicated Power	Theoretical Power
0	39	100	18.0	18.0
40	39	107	19.6	19.5
50	39	110	20.0	20.3
60	39	118	21.8	21.3
70	39	126	23.2	22.4
80	39	133	24.5	23.8
90	39	144	26.8	25.3
100	39	155	29.0	27.0

RADIO FREQUENCY WATTMETER

DATA FOR MODULATION TEST

Figure 23
$Z_L = 60.5 \angle +46^\circ$
Carrier Frequency - 2 megacycles
Modulating Frequency - 4000 cycles

Initial scale deflection - 80 microamperes

Per cent Modulation	Carrier Voltage	Scale Reading	Indicated Power	Theoretical Power
0	36	80	15.0	15.0
40	36	87	16.0	16.2
50	36	91	17.0	16.9
60	36	98	17.9	17.7
70	36	106	19.8	18.7
80	36	113	21.0	19.8
90	36	122	22.8	21.1
100	36	133	24.5	22.6

Initial scale deflection - 100 microamperes

Per cent Modulation	Carrier Voltage	Scale Reading	Indicated Power	Theoretical Power
0	39	100	18.0	18.0
40	39	108	19.6	19.5
50	39	114	21.0	20.5
60	39	119	21.8	21.3
70	39	125	23.0	22.4
80	39	135	25.0	23.8
90	39	144	26.8	25.3
100	39	155	29.0	27.0

CALCULATED DATA

EFFECT OF DEVIATION OF THERMOCOUPLE EXPONENT FROM A TRUE SQUARE LAW ON THE READING OF THE RADIO FREQUENCY WATTMETER

Figure 24

Standing wave ratio = 1

V	V^2	$V^{1.87}$
1	1	1
2	4	3.66
4	16	13.4
6	36	28.7
8	64	49
10	100	75

Standing wave ratio = 2

V_i	V_r	$V_i^2 - V_r^2$	$V_i^{1.87} - V_r^{1.89}$
4	1.3	14.32	11.76
6	2	32	25
8	2.67	56.8	42.6
10	3.33	88.9	65.7

Standing wave ratio = 3

4	2	12	9.7
6	3	25	20.7
8	4	48	34.2
10	5	75	54
12	6	108	75.5

Standing wave ratio = 4

4	2.4	10.25	8.16
8	4.8	41	29.5
12	7.2	92.7	63.5
14	8.4	126	93

CALCULATED DATA

EFFECT OF DEVIATION OF THERMOCOUPLE EXPONENT

FROM A TRUE SQUARE LAW

ON THE READING OF THE RADIO FREQUENCY WATTMETER

Figure 24

Standing wave ratio = 6

V_i	V_r	$V_i^2 - V_r^2$	$V_i^{1.87} - V_r^{1.89}$
4	2.9	7.6	5.9
6	4.3	17.5	12.9
10	7.1	49.5	34
15	10.7	111	70

RADIO FREQUENCY WATTMETER

CALCULATED DATA

MAXIMUM ALLOWABLE DEFLECTION

AS A FUNCTION OF

STANDING WAVE RATIO

Figure 26

$$\text{Maximum deflection} = 327 - 327\left(\frac{SWR - 1}{SWR + 1}\right) \quad \text{microamperes}$$

SWR	Deflection(uamps)
1	327
1.5	314
2	291.4
2.5	267
3	246.2
3.5	226
4	209
4.5	194
5	182
5.5	170
6	160
7	143
8	129
9	118
10	108
12	93
14	81
16	73
18	65
20	59
25	48
30	41