Radio-Frequency POWER MEASUREMENTS

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A comprehensive survey of methods and instruments used in making r-f measurements, and data regarding their advantages and limitations

IN RADIO ENGINEERING one of the most difficult quantities to measure is that of r-f power. Several methods are available depending upon the magnitude and frequency of the power to be measured. These will be discussed with particular reference to their limitations as well as their accuracy for high frequency measurements.

The measurement of r-f power is based upon one of two effects, namely: (1) heat and (2) the voltage drop across, or current through, a known impedance. A compilation of the most commonly used methods of power measurements is given in *Table 1*.

In an a-c circuit the power in watts is defined by the expression

$$P = I^2 Z \cos \phi \qquad (1)$$

where I is in amperes, Z in ohms and $\cos \phi$ the power factor. Fortunately, most power measurements can be made with a resistive load, so the power factor is essentially unity, then equation (1) simplifies into

$$P = I^2 R \qquad (2)$$

This is particularly true where the power to be measured is available at the end of a transmission line of known impedance. In this case it is only necessary to match the end of the line with a non-inductive resistor (several of which are available commercially within a range of from 13 to 600 ohms) and either measure the current through the load or the voltage across its terminals. The attenuation of the transmission line must be known at the operating frequency, otherwise a very short line should be used to avoid introducing appreciable loss.

Requirements

Before discussing a particular method of measurement let us consider the requirements of an r-f power measuring device.

a. The instrument or method used should have no deleterious effect on the operation of the apparatus being measured.

b. The method should have adequate sensitivity in order that precision measurements may be made.

c. The calibration should be independent of frequency; if lacking this feature, a known correction factor should be available.

Having decided on the desirable requirements for a measuring device, we will now consider each of the methods as given in *Table 1*.

Wattmeters

Wattmeters of the electrodynamometer type having separate voltage and current coils are unsuited for r-f measurements. In general, their power range is inadequate and the losses, except at very low r-f frequencies, are prohibitive.

An electron tube wattmeter for measuring power of a few microwatts or more has been described in the literature.[1]. Its operation depends upon obtaining a voltage proportional to the load current from a low resistance in series with the power source, and also a voltage from a high resistance across the power source which is proportional to the load voltage. The sum of the instantaneous values of the two voltages is impressed on the grid of one tube and their difference on the grid of another tube as shown in *Fig. 1*. The loss in the series element must be made quite small, and obviously the shunt resistance element should be sufficiently large to make the total power dissipated by the instrument negligible as compared with the load.

The power capacity of the electron tube wattmeter is limited by the maximum allowable grid input voltage. Its use at high frequencies is limited only by the interelectrode tube capacities.

R-F Ammeter

One method of determining high fre-

TABLE I

R-F MEASUREMENT METHODS

Instrument	Measurement based on	Order of Accuracy	Usual Power Capacity	Usual High-Frequency Limit
Electrodynamic Ammeter	*Phyiscal parameters*	*0.3%*	*Medium*	*100 mc*
Electron Tube Wattmeter	*Voltage difference*	*2-5%*	*Low*	*30 mc*
Thermocouple Ammeter	*Heat*	*2-5% to 10 mc*	*Medium*	*100 mc*
Diode Voltmeter	*Voltage*	*2-10%*	*Medium*	*100 cm*
Calorimeter	*Heat*	*3%*	*High*	*10 cm*
P. M. Lamp	*Heat*	*5-10%*	*Medium*	*200 mc*
Bolometer	*Heat*	*3%*	*Low**	*10 cm*

** For high power capacity an attenuating cable is used*

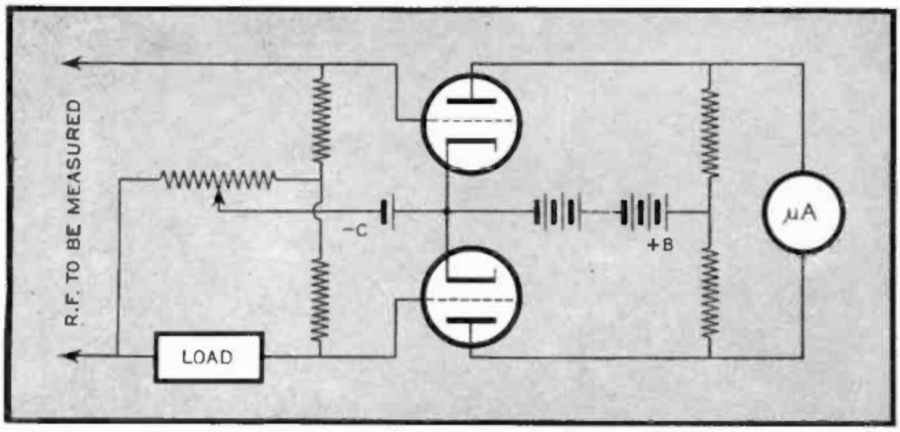


Fig. 1. Schematic diagram of electron tube wattmeter

quency power, depending upon the heating effect of the current, is by the use of a thermocouple ammeter in conjunction with a known resistance. Knowing the magnitude of the current through the resistance, the power can be readily calculated. This method has had widespread application notwithstanding that in certain applications its value as a power measuring device is mediocre. Under proper conditions, however, the thermocouple ammeter may be relied upon for extremely precise measurements.

Basically, the thermocouple ammeter consists of a d-c voltmeter which measures the potential developed across an internal thermal junction (thermocouple). The voltage produced is the result of current passing through the heater, which raises the temperature of the thermal junction. Since the heater has a definite resistance, the power, and likewise the temperature is proportional to the square of the current flowing through it. The voltage developed by virtue of the heater temperature is then proportional to the square of the current. For this reason, unless the indicator portion of the meter has specially shaped pole pieces the pointer deflection will be approximately proportional to the current squared.

Whenever possible the ammeter should be connected into the circuit at a low potential point, although this is not always feasible, in which case a shielded meter should be employed. This consists of a regular meter with a metal shield around its body, the shield and internal parts being bonded together and connected to the "low potential" meter terminal. This terminal should be connected to the r-f source, while the "high potential" terminal is connected to the load. The use of a shield[2] and the bonding together of internal parts, where possible, greatly increases the accuracy of the meter when operated above ground potential. These refinements in design eliminate to a large degree capacitive charging currents which would result in additional heat being transmitted to the heater and thereby cause an erroneous indication. Since the current is through a dielectric path the error increases with frequency.

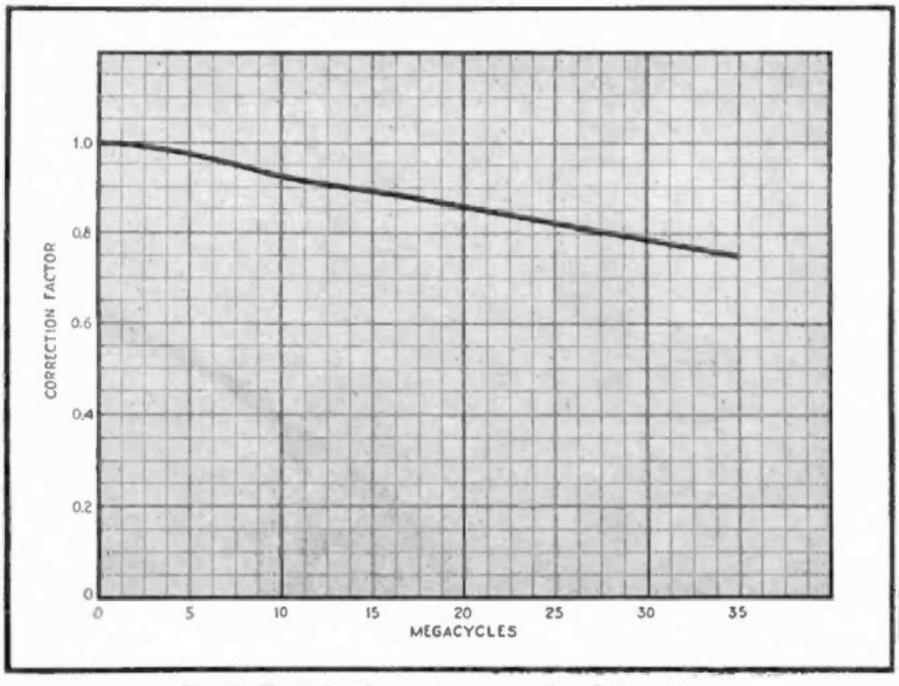


Fig. 2. Typical r-f ammeter correction factor curve

Thermocouples

Some thermocouples are simply mounted on studs set into an insulating material. This type is not particularly sensitive and furthermore is subject to air convection currents and changes in ambient temperature. The better grade units are enclosed in a glass envelope and evacuated to approximately 0.01 mm of mercury. Since the elements are mounted in an evacuated bulb the cooling of its surface is thru radiation therefore a given current will result in a higher heater temperature and greater sensitivity will be obtained. Polished metal elements are usually employed since these are poor radiators of heat.

The resistance of the thermocouple heater increases with frequency, due to skin effect. Increased resistance increases the total heat produced and, since the voltmeter is responsive only to the changes in temperature of the thermal junction, the current indicated at high frequencies is greater than that at low frequencies. Knowing the increase in resistance due to skin effect at a given frequency the approximate correction factor can be determined. *Fig. 2* shows a typical correction factor curve of a commercially available instrument.

Another cause of frequency error in r-f ammeters occurs when the impedance due to capacity of the heater terminals becomes comparable with the impedance of the heater element. At frequencies where this is true, some of the current which would normally go through the heater is bypassed, due to the capacitive path, to the instrument terminals. Eddy currents induced in the thermocouple by current passing through the heater is sometimes troublesome, but in most cases this effect is negligible. By far, the most serious error in high frequency measurements is due to skin effect in the heater elements.

Calibration

Usually r-f ammeters are calibrated at 60 cycles and the frequency correction factor is calculated for the desired range. Photoelectric methods have also been used to some extent. These methods, while fairly satisfactory, are limited in accuracy.

A new method has been developed[3] and improved[4] wherein the characteristics of an ammeter can be calculated from measurements of length, mass and time. The improved instru-

TABLE II

SYLVANIA P. M. LAMP CHARACTERISTICS

Type	PM-3	PM-6	PM-8
Maximum frequency for $Z = R$	*15*	*25*	*55 mc*
Maximum frequency for $R_{ac}=R_{dc}$	*100*	*200*	*900 mc*
Resistance at normal power	*40*	*110*	*110 ohms*
Resistance at Maximum power	*70*	*175*	*195 ohms*
Power Dissipation (Maximum)	*25*	*3.5*	*1 watt*
Inductive Reactance 55 mc	*125*	*140*	**ohms*
Inductive Reactance 110 mc	*300*	*250*	*90 ohms*

**Reactance is negligible compared to the resistance*

ment known as an electrodynamic ammeter employs jewel bearings in place of the quartz suspension originally used. This permits a more sturdy construction and makes the instrument a practical standard for the measurement of current up to at least 100 megacycles.

Briefly, the ammeter resembles an air-cooled transformer with a single-turn primary and a smaller closed turn secondary, which is free to turn on its bearing-pivoted axis with respect to the primary. The primary carries the current to be measured. When the secondary is displaced angularly from the position of zero coupling, it is acted upon by forces which produce mechanical oscillation about its axis. The mechanical oscillation frequently is directly proportional to the amplitude of the current being measured, and is independent of frequency. The induced voltage in the secondary lags the primary current by 90°, and since the secondary current lags its voltage by 90°, the two currents are 180° out of time phase. When current is applied through the primary the secondary will tend to orient itself perpendicular to the primary (zero coupling.) However, because of kinetic energy, the moving secondary will be carried through this point into a region of opposing torque until the secondary finally comes to rest and reverses in direction, thus producing mechanical oscillation which is proportional (cycles vs time) to the current being measured.

Design Requirements

The following design features are desired in an r-f ammeter for high-frequency operation:

a. Heater leads should be short and preferably straight.

b. Heater mounts should utilize a minimum amount of material and be as nearly self-supporting as practical.

c. Meter should be shielded electrostatically and its internal parts bonded together.

VOLTAGE METHOD

The determination of r-f power by the measurement of voltage across a known load resistor is commonly used in radio engineering practice. The accuracy of this metnod at low radio frequencies is entirely satisfactory with the usual vacuum tube voltmeter, but as the frequency increases the accuracy decreases unless special precautions are taken to insure maintenance of calibration and proper connections to the power source. A well designed voltmeter will have negligible influence on the circuit being measured. It will also have adequate sensitivity and its calibration will not change appreciably with frequency.

As previously mentioned, dummy load resistors are available which can be employed as the dissipative element for the power source. The choice of a suitable load is of prime importance and should be carefully considered before attempting to make measurements. Once the load has been chosen and matched to the power source it is then a matter of correctly measuring the voltage across its terminals and using the formula

$$P = \frac{E^2}{R} \qquad (3)$$

where E is in volts, P in watts and R in ohms to determine the power.

Limitations

The matter of correctly measuring the voltage, however, requires some serious consideration, particularly if the frequency is above a few megacycles. The ordinary vacuum tube voltmeter begins to contribute an appreciable loss to the circuit around 30 megacycles, due to its decreased input impedance and the transit time effect. Even the acorn type tubes have their limitations, although with these tubes measurements can be satisfactorily made at frequencies of the order of 200 centimeters if the load resistance is low. This is usually the case, since most measurements are made at the end of low-impedance transmission lines.

Where the load resistance is high a method described by Nergaard[5] has been found very satisfactory. Briefly, this consists of using a small diode as a rectifier to charge a condenser as shown in *Fig. 3.* The potential developed across the condenser is then measured by means of a microammeter in series with a fairly high resistance. This arrangement produces only a very small loading effect on the power source being measured. Precautions should be taken to insure that no resonance occurs due to interelectrode tube capacity and lead inductance. With an acorn type 955 connected as a diode, the resonant frequency of interelectrode capacity and leads occurs at approximately 50 centimeters.

When making measurements at very high frequencies it is imperative that all connecting leads be as short as possible because at these frequencies leads constitute self-inductances which have impedances that can no longer be neglected.

Transit-time effects are still a factor when the electrons traveling between the tube elements require time comparable with the period of the power being measured. In such cases the condenser is not able to charge to the peak amplitude of the measured voltage and the voltmeter will indicate a lower voltage than actually present.

Voltmeter Calibration

A method of diode voltmeter calibration applicable to wavelengths down to 20 centimeters has been described by Strutt and Knol.[6] An r-f voltage source is fed to a parallel open wire transmission line through a resistor equal to the surge impedance of the line. The line is then terminated by a thermocouple having a known resistance at the calibrating frequency as shown in *Fig. 4.* Small capacitors are connected in series with the thermocouple heater to balance out the self-inductance of its leads. The diode voltmeter to be calibrated is now connected across the line at a distance of one-half wavelength from the heater

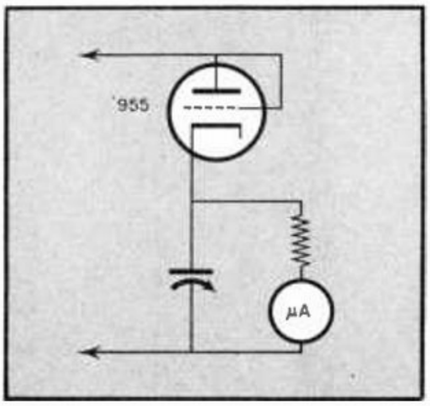


Fig. 3. Schematic of diode v-t voltmeter

termination. After balancing the compensating condensers for a minimum indication at the diode, the voltage is calculated by multiplying the heater resistance in ohms by the current in amperes, as measured with the thermocouple. Because the diode is one-half wavelength from the heater termination, the voltage across its terminals will be the same as the voltage at the terminals of the thermocouple heater.

PHOTOMETRIC METHOD

For rough checks of power output, many engineers simply couple an incandescent lamp to the source of power to be measured, and judging from the brilliancy of the filament estimate the power output. Such remarks as "It lights a 100-watt bulb" have frequently been heard in this connection. While this method does give an indication of the power output, obviously it lacks accuracy and cannot be relied upon to probably closer than plus or minus 30%, as it is nearly impossible to judge the brilliancy of a light source. It is therefore necessary to employ another incandescent lamp operated from d.c. or low frequency a.c. as a comparison. In this way it is possible to match the brilliancy of the unknown lamp to one which is operated from a known source of power. A light-intensity or exposure meter is sometimes used to assist in the matching process.

Several power-measuring lamps are available on the market which have been specially designed for measuring power output. Characteristics of some are shown in *Table 2*. These lamps consist of two filaments of similar characteristics mounted in one bulb. Their small size permits easy connection to the circuit to be measured with a minimum of lead inductance. One filament is connected in the high-frequency circuit while the other is connected to a variable source of low frequency a-c or d-c power. The power in the second filament can be determined to an accuracy of 5% with an ordinary voltmeter and a characteristic curve, as shown in *Fig. 5*, when the brilliancy of the two filaments is adjusted to be the same.

Skin Effect

Skin effect decreases the accuracy very little because the depth of penetration of the power being measured is equal to, or greater than, the radius of the filament of the lamp. Furthermore, the small filament with its high thermal conductivity makes for uniformity of temperature regardless of whether the heat is liberated from the entire cross-section or just from the outside layer. Of course, if the frequency is high enough the ratio of d-c to r-f resistance becomes appreciable, but the r-f current will then be less than the d-c current so the power will still be equal.

In view of the above design features it is practicable to make power measurements at any frequency so long as it is possible to couple the power into the lamp.

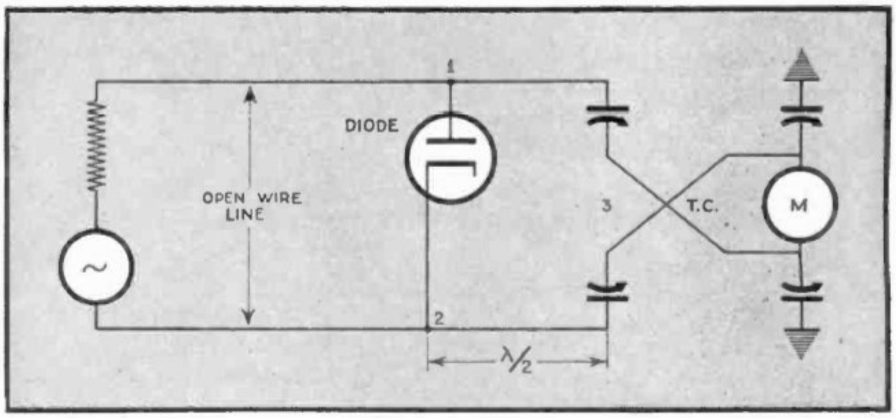


Fig. 4. Diode voltmeter calibrating circuit (after Strutt and Knol)

CALORIMETER METHOD

The calorimeter methods of measuring r-f power is based on the rise in temperature of a fluid surrounding, or circulating around, the load element. When the power to be measured is of the order of a few hundred watts it is general practice to insert two carbon elements into a double-walled container holding a known quantity of water. An ordinary chemical beaker or mason jar will suffice for the container, if it is cooled approximately ten degrees below room temperature before making measurements. The tests should then be continued until the temperature of the calorimeter is an equivalent amount above room temperature. In this way errors due to the cooling effect of the ambient temperature are balanced out.

The load impedance may be adjusted by adding salt or distilled water until the desired load resistance is obtained. Should the load be reactive (determined by detuning effect on the final amplifier) it will be necessary to connect a parallel tuned circuit across it and any losses in this circuit must be added to the power measured in order to obtain the true power output. *Fig. 6* shows a typical measurement setup.

Calibration

We know that one watt is equal to 10^7 ergs per second, and, since one gram calorie of heat equals 4.187×10^7 ergs, it is obvious that

$$\text{Heat in gram calories per second} = \frac{\text{watts}}{4.187} \qquad (4)$$

From the above it can be seen that if the heat in gram calories per second is known, we can calculate the power. This can be readily obtained by measuring the total weight of the components making up the calorimeter, and multiplying each by its respective specific heat. Next, measure the temperature rise of the liquid in degrees centigrade per minute, with the power being dissipated in the calorimeter load, and multiply the two results to-

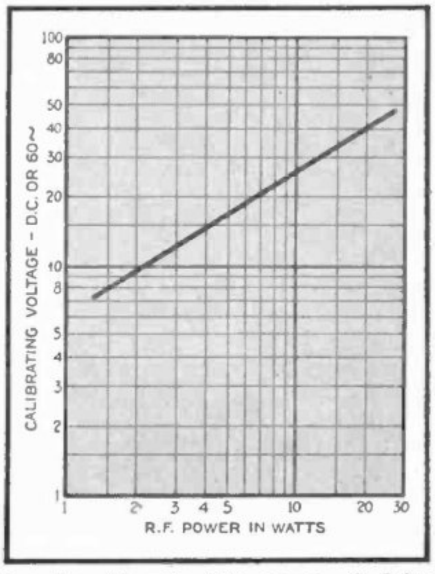


Fig. 5. Characteristic curve of Sylvania Type PM-3 power measurement lamp

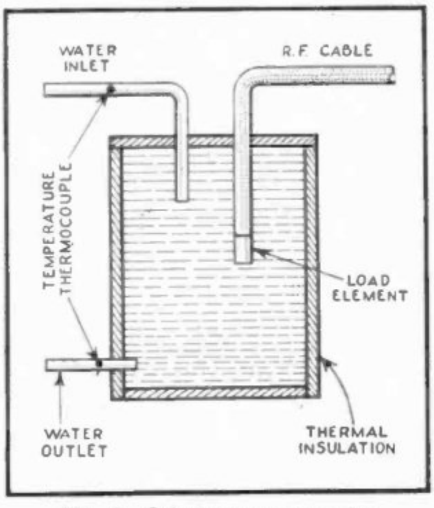
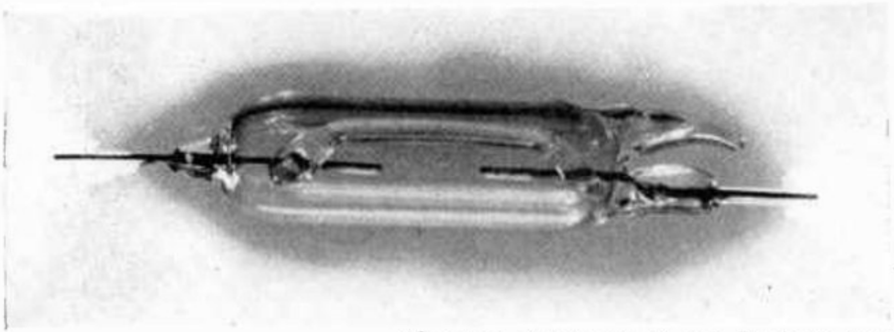


Fig 6. Calorimeter setup for high power measurements



(Courtesy of Sylvania Electric Products, Inc.)

Fig. 7. Type B bolometer

gether. The result is divided by 60 to convert the time into seconds which gives us the heat in gram calories per second. Substituting in equation 5 we have the power in watts.

$$W = 4.187 \times C_s \qquad (5)$$

where C_s is the heat in gram calories per second.

An alternate calorimeter method particularly suited to the measurement of high power output makes use of a small carbon element which is designed to properly match the transmitter. The load element is inserted in a thermal-insulated container which has provisions for circulating distilled water through it. The power can be determined by measuring the rate of flow of the water and the input and output temperatures. These quantities are then substituted in the expression,

$$W = 4.18 \frac{V}{60} (t_1 - t_o) \qquad (6)$$

where V is the volume in litres per minute of the circulating water, t_o and t_i are the incoming and outgoing water temperatures respectively in degrees centigrade, and W is in kilowatts.

TUBE DISSIPATION METHOD

In transmitters having water-cooled final amplifier tubes, the power output may be determined by measuring the d-c or a-c power delivered to the filament, grid and plate circuits with ordinary meters. The power dissipated by the cooling fluid is then determined by its temperature rise and rate of flow. The difference between these two power measurements is approximately equal to the power output. By subtracting the loss in the output circuit, if appreciable, the power being delivered to the load will be determined.

BOLOMETER METHOD

The bolometer, like the calorimeter depends upon the heating effect of the current being measured. In this case the heat changes the value of a specially designed resistor which is used as one arm of a Wheatstone bridge. Various circuit arrangements may be employed.[7] This resistor usually consists of a fine platinum wire which has the property of changing its resistance as its temperature is varied. The element is often enclosed in a small evacuated bulb as shown in *Fig. 7*. The characteristics of one commercially available unit is given in *Table 3*.

Another unit known as a *Thermistor* has also been widely used. These units are physically small and may readily be matched in an r-f transmission line. In this way all of the r-f power travel ing down the line is utilized in heating the element. Caution should, of course, be taken to insure a minimum of stand nig waves on the line, otherwise the element might be located at a current node and a false measurement would be obtained.

Measurements of high power are usually made with an attenuating cable between the power source and the bolometer, since the device ordinarily has a low power capacity. The "lossy" cable also helps minimize mismatching effects which might subject the instrument to excessive power.

One type of bolometer employed where production measurements are required and time is particularly valuable, uses d-c power to heat the bolometer element to a predetermined point. This point is so chosen that the galvanometer across the Wheatstone bridge indicates a balanced condition. This initial d-c power is read and noted. Next, the r-f power is applied and the bolometer element increases in resistance due to the heating effect of the additional current which causes the bridge to become unbalanced. To rebalance the bridge galvanometer, the d-c power is reduced sufficiently to cool the bolometer element to where its decreased resistance restores the balance. The difference in d-c power readings is equivalent to the r-f power being measured.

TABLE III

CHARACTERISTICS OF TUNG-SOL TYPE B-100 BOLOMETER ELEMENT

Characteristic	Rating
Resistance at 0.5 ma	*200 ohms (nominal)*
Maximum current, rms	*1.25 ma*
Optimum Bias Current, rms	*0.50 ma*
Sensitivity (1% change in resistance)	*4.5 microwatts*
Skin Effect to 10,000 mc	*5/16" dia. x 1½"*
Capacitance and Inductance	*Negligible (to 10,000 mc)*
Physical Dimensions (maximum(	*Negligible (below 1000 mc)*

When an attenuating cable is placed between the power source and the bolometer it is convenient to measure the power in terms of db above a zero level of six milliwatts. In other words, suppose the power indicated by the bolometer is 1.2 milliwatts. This is —7 db. Now, if the cable attenuation is 10 db, the actual power output is —7 + 10 or 3 db.

Measurement of Pulsed Transmitters

It is often necessary to know the power output of a pulsed oscillator or transmitter, as for instance a transmitter employed to send out pulses for ionosphere soundings in determining layer heights. Transmitters for this purpose usually emit pulses of the order of several kilowatts, but since the percentage operating time is small the average power is relatively low. To determine the peak power, if both the width of the pulse and the repetition rate at which it occurs are known, it is only necessary to measure the average power and divide it by the pulse width multiplied by the repetition rate.

$$\text{Peak power} = \frac{\text{average power}}{\text{repetition rate} \times \text{pulse width in seconds}}$$

The pulse width should be carefully measured, otherwise a considerable error will result in calculating peak power output.

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