# Broad-Band Calorimeters for the Measurement of Low and Medium Level Microwave Power. II. Construction and Performance*

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*Summary*—**The construction and performance of a series of rugged, broad-band twin-Joule calorimeters, using dry loads, are described. These calorimeters operate over the frequency range of 0 to 75,000 mc. The over-all measurement error, computed as the rms value of the maximum individual errors from known independent sources, is shown to lie between 1 and 2½ per cent for power levels between 1 and 100 mw. Power measuring techniques are discussed and a method using the heating and cooling cycle of the calorimeter is described in detail. Power comparison measurements between the calorimeters and several bolometer mounts illustrate the increasing inefficiency of bolometer mounts with increasing frequency.**

## Introduction

THIS paper describes the operating characteristics and gives design data for a series of broad-band microwave calorimeters of the "twin-Joule" type which cover the frequency band 0 to 75 kmc and directly measure powers from about 50 $\mu$w to 200 mw. In these units a broad-band dry load absorbs microwave power and the temperature rise of a casing surrounding this load is compared with the temperature of an identical reference unit at ambient temperature. The fundamental ideas which form the basis of this design are discussed in a companion article.[1] That paper presents a theoretical analysis of the sources of error such as, substitution effects, ambient temperature drift, etc. The present article shows how the basic analysis is applied to the actual design of the operating instruments and discusses the performance features of the various meters.

## Description

### *Basic Calorimeter Structure*

A sketch of the basic structure of the calorimetric power standard is shown in Fig. 1. Two sections of waveguide ① extend through the outer metal jacket ②. Thermal isolators ③ are interposed between the input waveguides and the inner metal jacket ④. A second set of thermal isolators ⑤ separates the thin-walled waveguides ⑥ ⑩ from the inner metal jacket. Broad-band tapered loads (not shown in the figure) are held in place inside the thin-walled waveguides by load holders ⑦. Either low-frequency or dc power is applied to the loads by means of copper wires ⑧ which pass through the two metal jackets. Iron-constantan thermojunctions ⑨ are bonded in pairs to the active ⑥ and reference ⑩ waveguides. The inner metal jacket is supported by standoff insulators ⑪. The output leads of the thermojunctions, $E_0$, pass through the metal jackets in a common cable with the load wires. A cut-away view of the calorimeter in guide size RG-96/U is shown in Fig. 2 (next page).

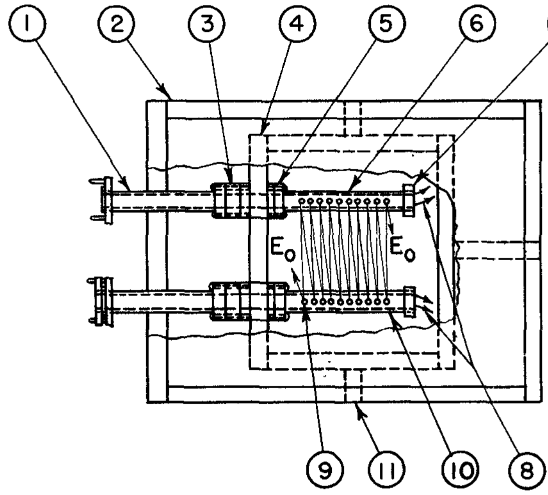


Fig. 1—Basic calorimeter structure.

That portion of the calorimeter from the input waveguides up to, but not including the flanges of the thin-walled waveguide, will be called the "entry-waveguide system"; this includes the input waveguides, thermal isolators, and all thermal conductive paths shunting the input waveguides. The term "termination" will be given to that part of the calorimeter that is connected to the entry-waveguide system; it includes the loads and the thin-walled waveguides to which the thermojunctions are attached.

In the ideal case, the active termination will experience the same average temperature rise when rf power is dissipated in it as when dc power is used. This temperature rise is very nearly proportional to the input

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[1] M. Sucher and H. J. Carlin, "Broad-band calorimeters for the measurement of low and medium level microwave power. I. Analysis and design," this issue, p. 188.

power and causes the thermojunctions to generate an output voltage very nearly proportional to the input power. However, an output voltage can be produced by other means as well. Any temperature difference between the two input waveguides will cause a temperature difference between the two thin-walled waveguides. Temperature differences can be caused by ambient temperature variations or by handling. The ability of a calorimeter to measure small rf powers is limited by these unwanted temperature differences.

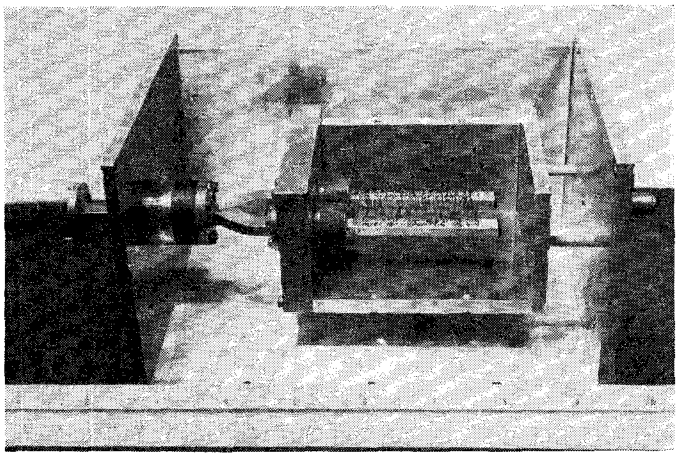

Fig. 2—Cut-away view of 26,500–40,000-mc (RG-96/U Waveguide Size) calorimeter.

An analysis of the thermal circuit of the calorimeter shows that the entry-waveguide system, along with the terminations and associated thermo junctions, forms an electric bridge circuit analog of the thermal system.[2] A simplified schematic of the thermal circuit of the calorimeter is shown in Fig. 3. $R_1$ and $R_2$ represent the thermal resistances associated with the two input waveguides, and $R_3$ is the thermal resistance between these guides. $R_4$ and $R_5$ are the thermal resistances of the thermal isolators and $R_6$ is the shunt thermal path between them. $G_1$ and $G_2$ are the two thin-walled waveguides and associated thermojunctions. $R_7$ and $R_8$ are the thermal resistances from the thin-walled waveguides to the inner metal jacket, while $R_9$ represents the thermal resistance between the inner jacket and the external environment. $P_{dc}$ and $P_{rf}$ represent the dc and rf power sources, respectively. $\Delta T$ represents the temperature difference between the two thin-walled waveguides.

It is clear that whenever the dc power, $P_{dc}$, or the rf power, $P_{rf}$, is applied to the active termination, a temperature difference, $\Delta T$, will exist between the terminations. Also, if the temperature balance between the input waveguides, terminals 1 and 2, is disturbed in any way whatsoever, a $\Delta T$ will be developed. By making the thermal resistance $R_3$ very small in comparison with $R_4$ and $R_5$, $\Delta T$ will be very small. It is obvious that if input terminals 1 and 2 were connected together, $\Delta T$ would be zero for $P_{dc}$ and $P_{rf}$ equal to zero.

The calorimeters were designed to have a low-thermal resistive path between the input waveguides; this was accomplished by using thick copper cover plates for the inner jacket and by placing the input waveguides close together.

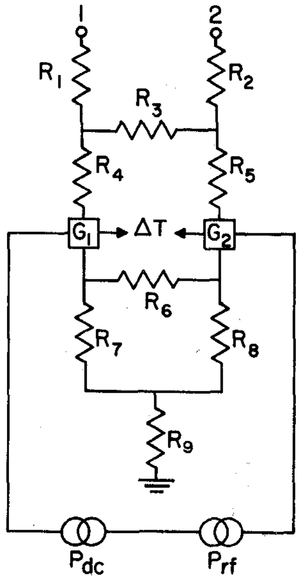


Fig. 3—Simplified equivalent thermal circuit of calorimeter.

The calorimeters in guide sizes RG-52/U, RG-96/U, RG-97/U, and RG-98/U were designed using a symmetrical "Y."[2,3] The "Y" effectively connects terminals 1 and 2 together (thermally, but not rf-wise) and gives additional reduction in temperature drift. Some of the various calorimetric powermeters are shown in Fig. 4.

*Isolating Sections*

Four types of thermal isolators were used. These were silver sprayed bakelite, electroplated bakelite, electroformed pieces, and thin-walled brass tubing. The silver sprayed bakelite spacers were used in the RG-51/U, RG-52/U, and RG-107/U calorimeters, and they were fabricated by spraying two or three coats of an air drying silver paint on the bakelite. Electroplated bakelite was used in the RG-96/U, RG-97/U, and RG-98/U calorimeters. These spacers were made by evaporating a coating of silver onto the bakelite and then electroplating silver onto the coating. The over-all thickness of the silver was about 0.0003 inch. Electroformed spacers

[2] A. V. James, "Broadband, Rugged Calorimeter Powermeters", Polytechnic Institute of Brooklyn, Brooklyn, N. Y., First Quar. Rep. R-414.3-55, PIB-346.3; April, 1955.

[3] A. V. James, "A sensitive millimeter calorimetric powermeter," M.E.E. thesis, Polytechnic Institute of Brooklyn, Brooklyn, N. Y.; April, 1956.

were used in the RG-66/U and coaxial calorimeters. The recommended electroforming procedure is to successively plate 0.0003 inch of copper, 0.001 inch of nickel, and a copper flash on a polished aluminum mandrel. The mandrel is then cast in an araldite resin, and after the resin hardens the mandrel is slowly dissolved with hydrochloric acid. Thin-walled brass sections 0.003 inch thick also were used as isolators in the coaxial calorimeter. These sections were fabricated by careful machining. Different types of isolators are shown in Fig. 5.

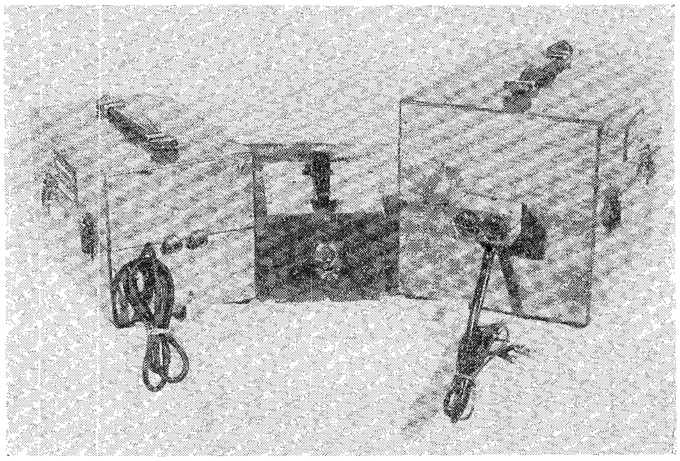

Fig. 4—Calorimeter power heads—coaxial model and waveguide sizes RG-66/U, RG-96/U.

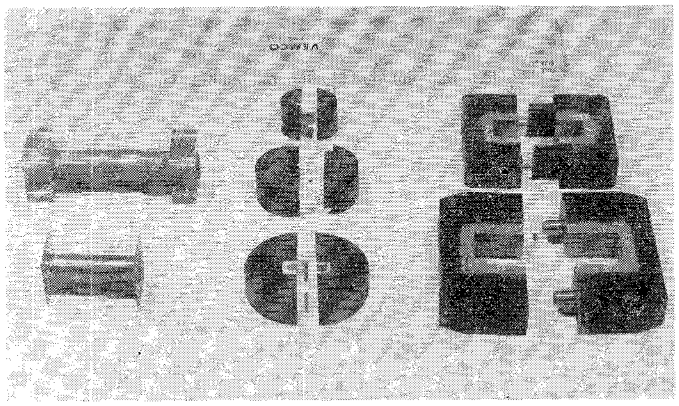

Fig. 5—Construction of various thermal isolating sections.

*Loads*

The waveguide loads were made of resistance[4] cards or a chromium film evaporated on mica, and each load was terminated by a short circuit. A scratch that extends most of the length of the resistive material was made to provide an approximately even distribution of dc power. The coaxial load resistor took the form of a concentric resistive film on mica. The resistive material consisted of a mixture of 1 part liquid bright platinum No. 5 and 3 parts gold essence No. 31. These solutions are manufactured by the Hanovia Chemical Company.

[4] Manufactured by the International Resistance Co., Philadelphia, Pa.

*Thermopiles*

The iron-constantan thermojunctions were made of number 30 and 33 wires depending on the calorimeter, and each junction had a sensitivity of about 52 $\mu$v/°C. The junctions were insulated by gluing strips of insulated copper squares to the waveguide and soldering the thermojunctions to these squares. Care was taken to avoid the use of excessive heat, and for this reason a low melting point solder was used. The squares were fabricated by first bonding 0.0027-inch thick copper to a $12'' \times 12''$ sheet of epoxy-glass 0.006-inch thick and tinning the copper with solder. The squares were then formed by photo-etching the spaces between the squares down to the epoxy-glass surface. The strips were then cut from the $12'' \times 12''$ sheet.

## Power Measurement Techniques

The measurement of rf power depends essentially on a comparison of the thermopile output of the calorimeter when rf power is applied to the termination with that obtained when equal dc power is dissipated in the same termination; *i.e.*, on the use of dc-rf substitution. This may be accomplished in a number of different ways, the most accurate of which is to calibrate the calorimeter with dc power either immediately before or after the calorimeter response to the unknown rf power has been measured.

For greatest accuracy (at levels exceeding one milliwatt) the following procedure was used. The calorimeter termination was first allowed to reach a steady-state temperature with the unknown rf power applied. The resulting thermopile emf was then measured and converted into an approximate power reading with the aid of a previously obtained graph of *input power* vs *thermopile emf*. The purpose of this step was to determine the level of dc power to be used in the ensuing exact calibration. The rf power was then cut off, the termination allowed to cool, and the residual thermopile emf, $e_1$, measured. An accurately known amount of stable dc calibrating power, $P_{dc}$ (equal to the rf power within ten per cent), was then applied and the resultant emf, $e_2$, measured. The dc power was then cut off and the residual emf, $e_3$, measured. Finally, the rf power was again applied and the final emf, $e_4$, measured. The rf power, $P_L$, was then determined from

$$\frac{P_L}{P_{dc}} = \left(\frac{e_4 - e_3}{e_2 - e_1}\right). \tag{1}$$

A standard waiting interval of five time-constants was allowed between the application or removal of power and the reading of the resultant thermopile output.

Such an interval is sufficient for a temperature rise or fall to reach 0.993 of its steady-state value in an exponential buildup or decay process such as occurs in the heating and cooling of the termination. The time sequence of operations is illustrated in Fig. 6.

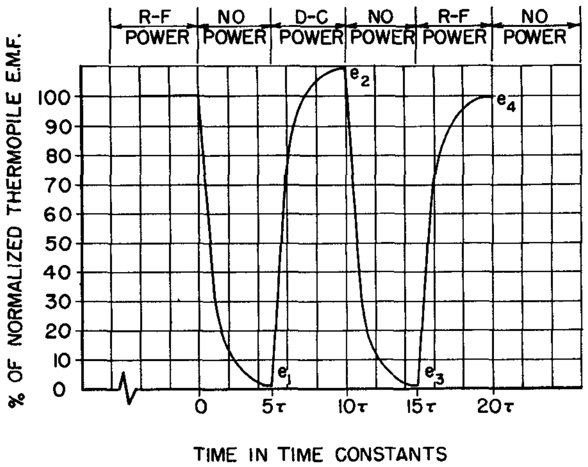


Fig. 6—Time sequence of operations in calibration of calorimeter, $\tau$ is the thermal time constant.

The above method has two advantages. It serves to reduce the error due to "zero" drift in the calorimeter, which is particularly important at low power levels, and to calibrate the calorimeter anew for each measurement, thus making the result independent of any long-time changes in the properties of the calorimeter or of day to day changes in the ambient temperature at which the measurement is performed. Approximate equality of dc calibrating and rf power helps to minimize errors due to the somewhat nonlinear relation between output emf and input power which is particularly noticeable in most calorimeters at power levels above 10 mw.[5] Obviously the success of this procedure depends a good deal on the stability of the rf source.

A type K-2 Leeds and Northrup potentiometer in conjunction with a Minneapolis-Honeywell "ElectroniK" null indicator was found satisfactory for output emf measurements at power levels above one milliwatt. (The "ElectroniK" null indicator is equal in sensitivity to the conventional galvanometer but much faster in its response.) For lower power levels it is almost essential to use a high-gain, stable dc amplifier of low-internal noise, such as the Perkin-Elmer Model 53 or Liston-Becker Model 14 breaker type. Such an amplifier permits the measurement of emf with a resolution of better that 0.01 $\mu$v so that the ultimate limitation on the detectable power is determined purely by the thermal fluctuation and zero drift of the calorimeter.

A convenient method of obtaining an accurately determinable dc calibrating power is to incorporate the active calorimeter load in one arm of a balanced precision Wheatstone bridge as shown in Fig. 7 and to determine the dc power from a precision measurement of the voltage across the bridge and the value of the load resistance. The same potentiometer which is used to measure the thermopile emf also can be used to measure the bridge voltage with the aid of a volt-box or precision potential divider. Alternatively, the power can be determined from a measurement of the bridge current with the aid of a multirange precision milliameter (0.1 per cent full-scale accuracy). The latter method (for reasons of convenience) was used in one of the calibration setups with an accuracy of better than 0.5 per cent. Even better precision can be obtained with the potentiometer method.

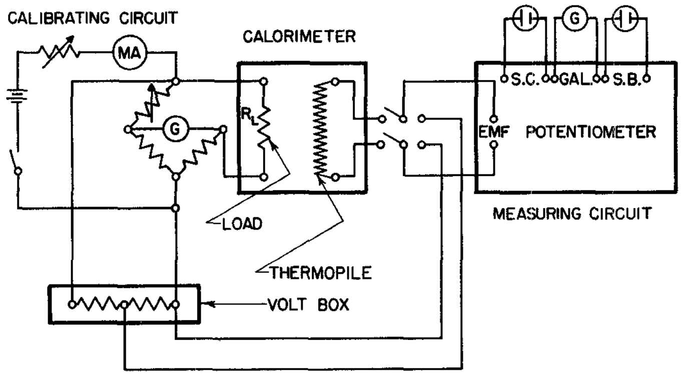


Fig. 7—Schematic diagram of a calorimeter calibrating and measuring circuit.

Additional power measurement methods include reading the thermopile output on a sensitive galvanometer (*e.g.*, the Rubicon 3412 spotlight galvanometer or equivalent) in conjunction with an Ayrton shunt for accurate range switching or on a stable electronic microvoltmeter (such as the L. & N. 9835-A) equipped with a suitable range switch and referring to a previously obtained calibration curve of power versus instrument deflection. Another method is to feed adjustable dc power into the dummy load so as to balance out the effect of the unknown rf power in the active load, a sensitive null indicator being used to detect the thermopile output. The deflection methods are not as accurate as the potentiometric methods, while the balance technique, in addition to demanding some experience from the operator, also requires a determination of the correction factor to be applied to the measurement because of a slight (usually one or two per cent) difference in the response of the dummy and active terminations to equal amounts of dc power.

[5] The nonlinearity is attributable to the fact that the termination is predominantly cooled by "free-convection." The convective heat loss is proportional to the temperature elevation above ambient raised to the 1.2 power, hence the nonlinearity. (See Sucher and Carlin, *op. cit.*)

## Errors and Over-All Accuracy

The types of errors that occur when the heating and cooling cycle method is used to measure rf power can be divided into two categories, those that are independent of rf power level and those that depend upon the amount of rf power being measured. Among the former are attenuation, 4-pole, substitution, and dc power measurement errors, while the latter kind of errors are caused by thermal drift, limit of resolution, and nonlinearity. These errors were analyzed in the companion article[1] and methods of measurement, as well as measured data on the values encountered in practice, will be given here. The calorimeter can only indicate the power dissipated in the termination itself, and any power dissipated in the entry waveguide system is not directly measured. It is, therefore, necessary to measure the attenuation of the connecting section of waveguide (this section can be considered a 4-pole) and apply this as a correction to the power indicated. The attenuation of this connecting 4-pole was measured for the waveguide calorimeters covering the range from 7–40 kmc by terminating the 4-pole in a lossy movable short, varying the position of this short, and accurately determining the radius of the resulting circular locus of the input reflection coefficient.[6] Since the attenuation is a slowly varying function of frequency, it was sufficient to make the measurement at three frequencies to define it over the entire band. By using this technique the attenuation was determined with an error of 1 per cent or less for the entire operating bands of the calorimeters. The attenuation of the RG-97/U and RG-98/U calorimeters was measured by noting the change in output level of a bolometer biased with dc and fed from a square wave modulated rf source. By making many repeated measurements at 2-kmc intervals, the attenuation was determined with an error of about 2 per cent. The attenuation of the 4-pole in the coaxial calorimeter was measured with equipment supplied by the Weinschel Engineering Company, Kensington, Md. In this method, square-wave modulated rf power was split and fed to two bolometers. The outputs of the bolometers were amplified in separate channels and then subtracted to obtain a null. One of the channels contained a precision audio attenuator and the change in this attenuator that was necessary to reproduce a null after the 4-pole had been inserted was the attenuation of the 4-pole. This method has the advantage that the measurement is largely independent of power fluctuations of the rf source. Furthermore, the sensitivity of the equipment was such that a 0.01-db change could be readily distinguished. The attenuation of the coaxial 4-pole over the frequency band was obtained with an error of 1 per cent.

[6] H. M. Altschuler and A. A. Oliner, "A shunt technique for microwave measurements," IRE Trans., vol. MTT-3, pp. 29–30; July, 1955.

The ratio[7] of power absorbed in the termination to the total power absorbed in the calorimeter is given by

$$K = \frac{P_L}{P_T} = \frac{|S_{12}^2 + S_{22}(\Gamma_{in} - S_{11})|^2 - |\Gamma_{in} - S_{11}|^2}{|S_{12}|^2(1 - |\Gamma_{in}|^2)}, \quad (2)$$

where $P_L$ and $P_T$ are the powers absorbed in the termination and entire calorimeter, respectively; $\Gamma_{in}$ is the input reflection coefficient of the calorimeter; and $S_{11}$, $S_{22}$, and $S_{12}$ are the scattering parameters of the connecting 4-pole. In general, the value of $K$ depends upon both the phases and magnitudes of the scattering and reflection coefficients. In practice, only the magnitudes of these quantities would be known at best, and so there will be an uncertainty in the value of $K$. For practical purposes one can take

$$K = |S_{12}|^2 \quad (3)$$

which is more or less midway between the maximum and minimum possible values of $K$. The maximum error in $K$ that is incurred by using (3) is termed the "4-pole error." One obtains $|S_{12}|^2$ from the attenuation of the 4-pole since the attenuation equals $-10 \log |S_{12}|^2$. The measured 4-pole error ranged from 0.7 per cent to about 2 per cent, depending on the calorimeter.

When using dc power to calibrate a calorimeter, one actually assumes that equal amounts of dc and rf powers will produce equal thermopile output voltages. The amount by which this assumption is incorrect is the substitution error. The analysis made by Sucher and Carlin[1] shows that the substitution error is quite small and is of the order of 0.1 per cent. The substitution error for the coaxial calorimeter is essentially zero, since the load is a planar resistive ring perpendicular to the direction of propagation and rf and dc powers distribute similarly.

When calibrating a calorimeter with dc power, the load was connected in a Wheatstone bridge. With such an arrangement and by using a milliameter of 0.1 per cent accuracy to measure the bridge current, it was possible to measure the dc calibrating power to within $\pm 0.5$ per cent.

Because of asymmetry in the thermal structure, there usually was a thermopile output with no power incident on the calorimeter, and ambient temperature variations caused this output to vary or drift. The amount of drift was determined by means of two tests. For the first test the thermocouple output and room temperature were recorded over a period of about 18 hours. The second type of test involved recording the thermopile voltage variation that occurred after the calorimeter was connected to a typical rf setup including all associated

[7] L. O. Sweet and M. Sucher, "The available power of a matched generator from the measured load power in the presence of small dissipation and mismatch of the connecting network," IRE Trans., vol. MTT-5, pp. 167–168; April, 1957.

equipment. Sufficient attenuation was used so that there was essentially zero rf power incident on the calorimeter. Based on these tests and assuming a maximum room temperature change of 1°C per hour, the largest possible drift error ranges from 6 to 12 $\mu$w for the calorimeters covering the range up to 26.5 kmc and is 1 $\mu$w or less for the remaining calorimeters. The drift error was considered to be approximately $1\frac{1}{2}$ times the maximum drift in a five time constants period of time.

The resolution error depends on the microvolt per milliwatt sensitivity (this ranged from 25 to 50 $\mu$v/mw) of the calorimeter which in turn depends on the thermal sensitivity of the calorimeter (temperature rise per unit power input) and the number of thermojunctions used. The error was taken to be a power equivalent to twice the minimum detectable change of thermopile emf of about 0.15 $\mu$v when the L. & N. Type K-2 potentiometer is used. The resolution error for the series of calorimeters was close to 10 $\mu$w.

The nonlinearity error is illustrated in Fig. 8. If $e_{dc}$ is the thermopile emf corresponding to a calibrating power $P_{dc}$ and $e_{rf}$ that corresponding to the unknown rf power, then the rf power would be computed (on the assumption of a linear relationship between thermopile emf and power) as

$$P_L' = P_{dc} + \frac{e_{rf} - e_{dc}}{\tan \phi} \tag{4}$$

where

$$\tan \phi = \frac{e_{dc}}{P_{dc}} \cdot \tag{5}$$

The correct value, $P_L$, which is obtained from the true curvilinear relation, differs from $P_L'$ by an amount $\Delta P$ (shown greatly exaggerated in the figure). In practice, $\Delta P$ is relatively small because the curve is actually very nearly a straight line and $P_{dc}$ is chosen close to $P_L$. If $P_{dc}$ is within 5 per cent of $P_L'$, the nonlinearity error is negligible up to power levels of 20 mw. The error increases with increasing power level, but even at the 100 mw level it is less than one per cent.

The accuracy of a calorimeter is taken as the rms value of the different errors cited. The drift and resolution errors contribute most to the over-all error at low power levels (less than 1 mw), while at high levels (100 mw) the nonlinearity error is a significant factor in the over-all error. The best accuracy (1–$2\frac{1}{2}$ per cent) is achieved at levels of about 10 mw.

Since the heating and cooling cycle method is the most accurate, the errors applicable to this technique were mentioned. However, the discussion of attenuation, 4-pole, substitution, and dc power measurement errors also applies to any of the other possible measurement methods. Table I gives a breakdown of the errors associated with the various power meters.

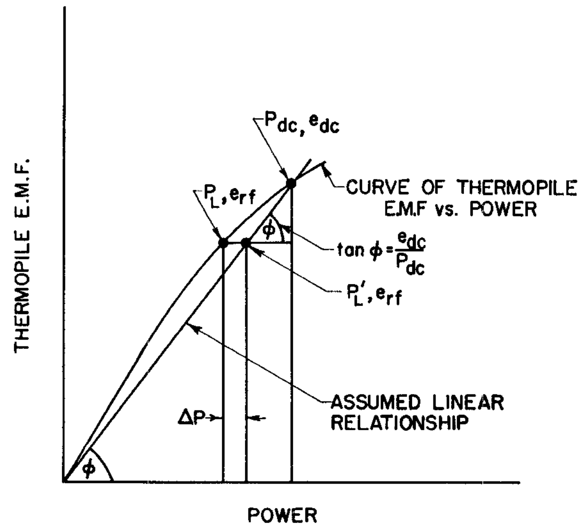


Fig. 8—Illustration of calorimeter nonlinearity error. $P_L$ is the actual rf power corresponding to a measured thermopile emf, $e_{rf}$, and $P_L'$ is the calculated value based on a calibrating power, $P_{dc}$, and an assumed linear relationship between thermopile emf and power. The measurement error is $\Delta P$.

## Experimental Power Comparisons

Power comparisons between the calorimeters and bolometer mounts were made, and the results are summarized in Table II. The results and accuracies are given to the nearest 0.5 per cent. The comparisons take into account any difference in the vswr of the bolometer and calorimeter, and the uncertainties in the measurements caused by a mismatched generator were included on the accuracy figure.[8]

The coaxial and RG-107/U calorimeters were checked against the 627-A and 616-A bolometer mounts respectively, manufactured by the Polytechnic Research and Development Company. RG-51/U and RG-52/U calorimeters were compared against a Hewlett-Packard 485B tunable X-Band mount; a $\frac{1}{2}$-inch brass adapting section was used with this mount for the comparison with the RG-51/U calorimeter. The RG-66/U, RG-96/U, and RG-97/U calorimeters were compared against bolometer mounts made by the Microwave Research Institute of the Polytechnic Institute of Brooklyn.

The results of the different power comparisons seem to show a definite trend toward greater bolometer mount inefficiencies as the frequency increases. Part of the difference between the powers measured with a bolometer mount and a calorimeter at 10.5 kmc might be attributed to the modulation of the barretter with modulated rf power, but this effect is probably not greater than 2 per cent.[9]

[8] R. W. Beatty and A. C. Macpherson, "Mismatch errors in microwave power measurements," Proc. IRE, vol. 41, pp. 1112–1119; September, 1953.
[9] T. Moreno and O. C. Lundstrom, "Microwave power measurement," Proc. IRE, vol. 35, pp. 514–518; May, 1947.

TABLE I
BREAKDOWN OF ERRORS

| Calorimeter | Power Level | $\|S_{12}\|^2$ | 4-Pole | DC Power | Drift | Potentiometer | Substitution | Nonlinearity | Total rms Error |
|---|---|---|---|---|---|---|---|---|---|
| Coaxial | $10^{-3}$ watts<br>$10^{-2}$ watts<br>$10^{-1}$ watts | 1 per cent | 1.7 per cent | 0.5 per cent | 0.6 per cent<br>0.1 per cent<br>0 per cent | 1.0 per cent<br>0 1 per cent<br>0 per cent | 0 per cent | 0 per cent<br>0 per cent<br>1 per cent | 2.4 per cent<br>2.0 per cent<br>2.3 per cent |
| RG-51/U | $10^{-3}$ watts<br>$10^{-2}$ watts<br>$10^{-1}$ watts | 0.7 per cent | 0.7 per cent | 0.5 per cent | 1.2 per cent<br>0.1 per cent<br>0 per cent | 1.0 per cent<br>0 1 per cent<br>0 per cent | 0.3 per cent | 0 per cent<br>0 per cent<br>1 per cent | 1.9 per cent<br>1.1 per cent<br>1.5 per cent |
| RG-52/U | $10^{-3}$ watts<br>$10^{-2}$ watts<br>$10^{-1}$ watts | 0.7 per cent | 0.7 per cent | 0.5 per cent | 0.7 per cent<br>0.1 per cent<br>0 per cent | 1.3 per cent<br>0.1 per cent<br>0 per cent | 0.3 per cent | 0 per cent<br>0 per cent<br>1 per cent | 1.9 per cent<br>1.1 per cent<br>1.5 per cent |
| RG-107/U | $10^{-3}$ watts<br>$10^{-2}$ watts<br>$10^{-1}$ watts | 0.7 per cent | 0.7 per cent | 0.5 per cent | 0.6 per cent<br>0.1 per cent<br>0 per cent | 1.0 per cent<br>0.1 per cent<br>0 per cent | 0.3 per cent | 0 per cent<br>0 per cent<br>1 per cent | 1.6 per cent<br>1 1 per cent<br>1.5 per cent |
| RG-66/U | $10^{-3}$ watts<br>$10^{-2}$ watts<br>$10^{-1}$ watts | 0.7 per cent | 0.7 per cent | 0.5 per cent | 0.8 per cent<br>0.1 per cent<br>0 per cent | 0.9 per cent<br>0.1 per cent<br>0 per cent | 0.3 per cent | 0 per cent<br>0 per cent<br>1 per cent | 1.7 per cent<br>1.2 per cent<br>1.5 per cent |
| RG-96/U* | $10^{-3}$ watts<br>$10^{-2}$ watts<br>$10^{-1}$ watts | 0.7 per cent | 1.1 per cent | 0.5 per cent | 0.1 per cent<br>0 per cent<br>0 per cent | 0.7 per cent<br>0.1 per cent<br>0 per cent | 0.3 per cent | 0 per cent<br>0 per cent<br>1 per cent | 1.6 per cent<br>1.4 per cent<br>1.7 per cent |

* Errors of RG-97/U and RG-98/U calorimeters are essentially the same as those of the RG-96/U size except for $|S_{12}|^2$ which was determined with a precision of ±2 per cent.

TABLE II
POWER COMPARISONS*

| Calorimeter | Frequency (kmc) | Modulation | Power Level in Milliwatts | Comparison Against | Result | Accuracy of Comparison |
|---|---|---|---|---|---|---|
| Coaxial | 9.0 | cw | 1.5 | PRD 627-A Bolometer Mount† | calorimeter was 6 per cent higher | ±3 per cent |
| RG-51/U | 9.0 | 1000 cps square wave | 4.7 | HP-485B Tunable Bolometer Mount‡ | calorimeter and bolometer were the same | ±2.5 per cent |
| RG-52/U | 10.5 | 1000 cps square wave | 8.4 | | calorimeter was 5 per cent higher | ±3.5 per cent |
| RG-107/U | 12.6 | 1000 cps square wave | 1.3 | PRD 616-A Bolometer Mount | calorimeter was 3 per cent higher | ±3 per cent |
| RG-66/U | 23.3 | 1000 cps square wave | 0.7 | | calorimeter was 4.5 per cent higher | ±2 per cent |
| RG-96/U | 29.7 | 1000 cps square wave | 1.0 | MRI Bolometer Mounts§ | calorimeter was 7.5 per cent higher | ±3 per cent |
| RG-97/U | 42.0 | 1000 cps square wave | 0.4 | | calorimeter was 8 per cent higher | ±3 per cent |

* Data for frequencies above 50 kmc were not available at the time this table was prepared.
† Polytechnic Research & Development Co., Brooklyn, N. Y.
‡ Hewlett-Packard Co., Palo Alto, Calif.
§ Microwave Research Institute, Polytechnic Institute of Brooklyn, Brooklyn, N. Y.

## CONCLUSION

A series of broad-band calorimetric powermeters which are suitable for use as laboratory standards and covering the frequency range from dc to 75 kmc have been designed and constructed. These calorimeters enable one to make absolute power measurements with an accuracy of from 1 to $2\frac{1}{2}$ per cent at power levels of from 1 to 100 mw.

They thus can be used to calibrate a bolometer directly without resorting to the use of directional couplers. Furthermore, the calorimeters can be used to measure pulsed power without the attendant error

TABLE III
SUMARY OF CALORIMETER CHARACTERISTICS

| Guide Size | Frequency Range (kmc) | Entry Waveguide | Sensitivity ($\mu$v/mw) | Time Constant (minutes) | Power Handling Capacity (mw) | Minimum Measurable Power With 5 Per Cent Accuracy* (in microwatts) |
|---|---|---|---|---|---|---|
| 3/8″ Coaxial | 0 –10 | twin | 32 | 1.2 | 100 | 140 |
| RG-51/U | 7.5–10 | twin | 30 | 4.0 | 100 | 250 |
| RG-52/U | 8.2–12.4 | Y | 23 | 2.6 | 100 | 140 |
| RG-107/U | 12.4–18 | twin | 29 | 2.7 | 100 | 140 |
| RG-66/U | 18 –26.5 | twin | 41 | 1.7 | 100 | 170 |
| RG-96/U | 26.5–40 | Y | 46 | 1.8 | 300 | 50 |
| RG-97/U | 33 –50 | Y | 41 | 1.1 | 200 | 50 |
| RG-98/U | 50 –75 | Y | 51 | 1.1 | 100 | 50 |

* Based on use of Liston-Becker Model 14 Breaker-Amplifier or equivalent.

present when bolometers are used.[10] If one desires, the calorimeters can be calibrated and used as field instruments since they are rugged devices. Sensitivities are such that powers of as low as 50 to 100 $\mu$w can be measured with reduced accuracies of the order of 5–10 per cent. Table III is a summary of calorimeter characteristics.

[10] M. Sucher and H. J. Carlin, "The operation of bolometers under pulsed power conditions," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. 3, pp. 45–52; July, 1955.

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# Amplitude Stabilization of a Microwave Signal Source *

GLENN F. ENGEN†

*Summary*—**Recent developments in the microwave field have provided new tools for use in regulating the output amplitude of a microwave signal source. An amplitude or power stabilizer has been constructed at the National Bureau of Standards Boulder Laboratories, using the recently developed self-balancing dc bolometer bridge and a commercially available, electrically controlled, ferrite attenuator which achieves power stabilities of a few parts in $10^4$ per hour.**

**Use of a high directivity directional coupler permits stabilization of the forward traveling component of the signal, thus providing the equivalent of a *matched*, stable generator. In practice, a broad-band source match of vswr less than 1.05 is achieved, and this figure may be further improved, at a given frequency, by suitable tuning. In addition, the device has applications as a precision broad-band attenuator, since known changes in power level may be achieved by switching certain of the associated dc components.**

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THE recent and continuing advances in the micro wave measurements art are continually imposing greater demands upon the stability of the microwave signal source. Except for the use of regulated power supplies, and stabilized environmental conditions, the problem of amplitude or power stability has received comparatively little attention—much less than the companion problem of frequency stability, and such efforts as have been made in this field[1,2] have apparently stopped short of recognizing all of the potential advantages of this technique. On the general philosophy of stabilization a recent author has appropriately

[1] I. K. Munsen, "Microwave power stabilizer," *Rev. Sci. Instr.*, vol. 21, p. 622; July, 1950.
[2] J. P. Vinding, "An automatic gain control system for microwaves," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. 4, pp. 244–245; October, 1956.