Broad-Band Calorimeters for the Measurement of Low and Medium Level Microwave Power. I. Analysis and Design*

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Summary—Design considerations for a group of broad-band calorimetric power meters, capable of accurately measuring low (zero to one milliwatt) and medium (zero to 100 milliwatts) power levels over a frequency range from zero to 75,000 mc, are presented. The power meters are of the nonadiabatic, twin, dry-load type and utilize the substitution of dc power. The conflicting requirements imposed upon the design by the need to realize broad-band performance, adequate sensitivity, reasonably short response time, negligibly small rf-dc equivalence error, freedom from "zero" drift and from other types of error are discussed. An analysis is given of the known sources of error which enables the accuracy of the individual instruments to be reliably estimated.

THERE is a definite need for a more accurate method of measuring microwave power at low and medium levels than is at present afforded by bolometers. The latter, in addition to being subject to pulse power[1] and rf-dc substitution (or equivalence)[2] errors[3,4] are also subject to errors which are caused by mount inefficiency.[5–7] Calorimetry naturally suggests itself as an alternative. In recent years calorimetric techniques have been extended to the direct measurement of microwave power in the same range for which bolometers are generally used.[8–13] Three basically different calorimeter types—flow, adiabatic, and nonadiabatic—have been employed for this purpose, all utilizing the substitution principle. The calorimeters of Carter[8] and Strom[9] are flow devices, the Naval Research Laboratory calorimeter described by Fellers[10] is of the adiabatic type, and those described by Ernst and Schussle,[11] by Macpherson and Kerns,[12] and by Sharpless[13] are nonadiabatic.

The present paper is concerned with the basic design principles which underlie a broad-band nonadiabatic calorimeter of the twin dry-load type. A schematic diagram of the rectangular waveguide version of this device is shown in Fig. 1. Units covering the frequency band 0–75,000 mc per sec have been built with a power measuring range of approximately 100 microwatts–100 milliwatts and the design data and operating characteristics are described in a companion paper.[14]

The basic equation defining the operation of an idealized nonadiabatic calorimeter (*i.e.*, where heat losses

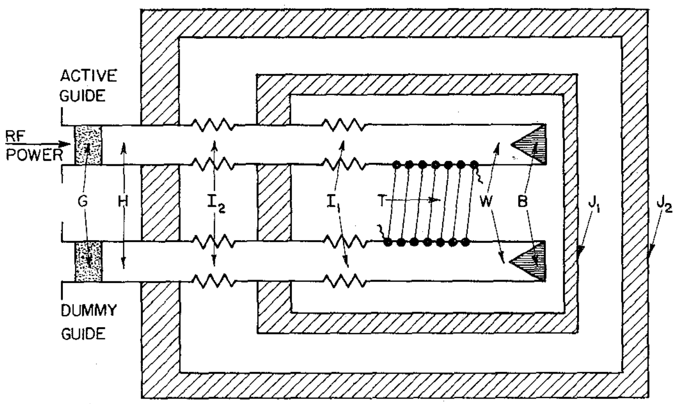

Fig. 1—Schematic diagram of calorimeter in rectangular waveguide. J_2, outer jacket; J_1, inner jacket; W, thin-walled waveguide calorimeter termination; B, broad-band load; T, thermopile, I_1, inner isolating section; I_2, outer isolating section; H, entry waveguide; G, polyfoam plug.

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[1] 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.

[2] The substitution error occurs when the rf and dc power distributions differ over the absorbing load. Because of this, rf and dc powers may produce different heating effects and thereby produce an error in the dc calibration.

[3] H. J. Carlin and M. Sucher, "Accuracy of bolometric power measurements," PROC. IRE, vol. 40, pp. 1042–1048; September, 1952.

[4] E. Weber, "On microwave power measurements," *Elektrotech u. Maschinenbau*, vol. 71, pp. 254–259; September, 1954.

[5] J. A. Lane, "The Measurement of power at a wavelength of 3 cm by thermistors and bolometers," *Proc. IEE*, vol. 102, pt. B, pp. 819–825; November, 1955.

[6] J. Collard, G. R. Nicoll, and A. W. Lines, "Discrepancies in the measurement of microwave power at wavelengths below 3 cm," *Proc. Phys. Soc.*, (*London*), vol. B63, pp. 215–216; March, 1950.

[7] M. Sucher, "A Comparison of Microwave Power Measurement Techniques," *Proc. Symp. on Modern Advances in Microwave Techniques*, New York, N. Y., pp. 309–323; June, 1955.

[8] C. J. Carter, "Calorimeter Type Power Meters," The Ohio State Univ. Res. Foundation, Columbus, Ohio, Engineering Rep., Wright Air Dev. Cntr. Contract W33-038-ac-15162, ASTIA AD No. 26873; August, 1953.

[9] L. D. Strom, "A calorimeter for microwave low level power measurements," *1955 Aeronautical Electronics Digest*, IRE Dayton Chapter, pp. 158–159; May, 1955.

[10] R. G. Fellers, "Measurement Techniques at Millimeter Wavelengths," *Proc. Symp. on Modern Advances in Microwave Techniques*, New York, N. Y., pp. 355–367; June, 1955.

[11] E. W. Ernst and J. H. Schusse, "Conduction Calorimeter Power Meter," University of Illinois, Urbana, Ill., Tech. Rep. No. 3, Elec. Eng. Res. Lab., Contract W33-0380-ac-014538; April, 1951.

[12] A. C. Macpherson and D. N. Kerns, "A microwave microcalorimeter," *Rev. Sci. Instrum.*, vol. 26, pp. 27–33; January, 1955.

[13] W. M. Sharpless, "A calorimeter for power measurements at millimeter wavelengths," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. 2, pp. 45–47; September, 1954.

[14] A. V. James and L. O. Sweet, "Broad-band calorimeters for the measurement of low and medium level microwave power. II—Construction and performance, this *issue*, p. 195.

are not effectively eliminated as in the adiabatic type, but taken care of by appropriate calibration, usually by substitution of known amounts of low-frequency power) is

$$P(t) = C \frac{d\theta}{dt} + \frac{\theta}{R} \qquad (1)$$

where

$P(t)$ = power input in watts,

C = heat capacity of calorimetric body in joules per °C,

θ = temperature vise of body with respect to its surroundings in C°

$\frac{d\theta}{dt}$ = time rate of temperature rise of body with respect to its surroundings in °C per sec.,

R = thermal resistance of the body to its surroundings in °C temperature rise per watt.

This equation assumes Newton's law of cooling, and further, that the body is at uniform temperature throughout, with C and R independent of temperature.

For constant power input P, the solution of (1) is

$$\theta = \theta_0(1 - \epsilon^{-t/\tau}) \qquad (2)$$

where θ_0 is the steady-state temperature rise due to a power P and τ is the thermal time constant of the body. Here

$$\theta_0 = RP \qquad (3)$$

$$\tau = RC \qquad (4)$$

$$R = \frac{1}{G}, \quad G = \text{thermal conductance.} \qquad (5)$$

If the steady-state temperature rise is used as a measure of the applied power, as is generally the case, then the power sensitivity of the calorimeter (defined as temperature rise per unit power input) is equal to R. The relation between measurement time and time constant may be illustrated by the fact that a waiting time equivalent to four, five, and six time constants results in a corresponding temperature rise which is 98.2, 99.3 and 99.8 per cent of the steady-state value, respectively, if the temperature build-up is truly exponential. To achieve a short measurement time, the large value of R, associated with high sensitivity, must be counteracted by a small heat capacity, C, so that the time constant, RC, shall be sufficiently short. The sensitive nonadiabatic calorimeters reported in the literature achieve their small heat capacity by use of thin-walled construction of the metal casing which houses the rf power absorbing load. Generally, the necessary thermal isolation (large R) is obtained by a substantial reduction of the conductive heat loss, which would otherwise be the major portion of the total heat loss. This had been accomplished earlier by using a short air gap[12,13] in the entry waveguide leading to the casing, but a broad-band technique is used in the present design consisting of thermally isolating sections in the entry waveguide made of suitable dielectric coated with a thin metal film.[11] In this isolator the conductive flow of heat is impeded without appreciable attenuation of the rf power flow. Convective and radiative heat losses from the casing are kept reasonably small by limiting the size of the casing to the degree permitted by other design considerations.

Since the minimum detectable power is as much dependent on the background thermal fluctuations and temperature drift as on the calorimeter sensitivity, great attention is paid to thermally shielding the calorimeter against external temperature variations. Thus, the NBS calorimeter reported in the literature[12] was enclosed in a massive brass can which was immersed in a large oil bath. The limit of resolution in this design is imposed by random fluctuations of temperature experienced by the shield can in contact with the agitated oil bath and is equivalent to about 10 microwatts of power.

The calorimeters described in this paper achieve a power resolution of less than 10 microwatts without the necessity of oil bath stabilization. The techniques required are described in the following sections.

Basic Description of MRI Calorimeters

Performance Characteristics

These calorimeters have their thermal isolating systems and rf power absorbing loads so designed that they operate over broad frequency bands. Furthermore, the design has been deliberately developed so as to minimize errors over the operating frequency band caused by such things as rf-dc substitution, rf attenuation and rf leakage of thermal isolating sections, and drift of zero setting due to fluctuation of ambient temperature. The models were constructed for the Air Force[15] and the Department of the Army[16] as standards of microwave power measurement in the milliwatt range. The calorimeters are portable but are intended primarily for laboratory use under ordinary laboratory conditions; temperature regulation of the laboratory, although helpful, is not required. The minimum detectable power, as limited by thermal fluctuation and drift under typical laboratory conditions, ranges from several tenths of a microwatt for the millimeter wavelength models to about 5 microwatts for the larger waveguide sizes. The maximum power range is 100 to 300 milliwatts depending on the model. The vswr does not exceed 1.3 over the

[15] Under Contract No. AF-30(602)-988, six discrete units, one coaxial and five in waveguide, collectively covering the range from 0 to 40,000 mc were delivered by the Microwave Res. Inst. of the Polytechnic Institute of Brooklyn, Brooklyn, N. Y., to the Rome Air Dev. Ctr., Rome, N. Y.

[16] Under Contract No. DA36-039sc-64579, three discrete waveguide units collectively covering the range from 26,500 to 75,000 mc were delivered to the Signal Corps Eng. Labs., Fort Monmouth, N. J., by the Microwave Res. Inst. of the Polytechnic Institute of Brooklyn, Brooklyn, N. Y.

entire operating frequency band of a standard waveguide size. Collectively the instruments cover practically the entire microwave spectrum in use today—a range from zero to 75,000 mc. The broad-band rf loads are rugged, and the calorimeters are not subject to a pulsed power error as is the case for some bolometer elements. Calibration is accomplished with dc power with an equivalence error of less than several tenths per cent. The over-all accuracy (root mean square of maximum errors from independent sources), based on a careful error analysis, ranges from ± 1 per cent for the lowest frequency waveguide calorimeters to $\pm 2\frac{1}{2}$ per cent for the highest frequency waveguide units at the most favorable power levels. The coaxial calorimeter has an over-all accuracy of 2 per cent at the most favorable power levels. The numerical data for individual sources of error of coaxial and waveguide units are presented in the companion paper.[14] The thermopile outputs of the various calorimeters range from 23 microvolts to 51 microvolts per milliwatt. Ordinary potentiometric measurements can provide a power resolvability of from five to two microwatts. The time constants range from little over one minute to four minutes.

Design Considerations

The following were the calorimeter design objectives: 1) good inherent sensitivity, 2) short time-constant, 3) well-matched rf loads (maximum vswr of 1.3 for the entire operating band of a waveguide), 4) minimal rf-dc equivalence error, 5) suppression of temperature drift and temperature fluctuation effects. It will become clear from the following discussion that the realization of the first four aims places conflicting demands on the design of the waveguide termination and the rf load located within it so that design compromises must be made.

Since the calorimeters were intended to serve as standards of microwave power measurement, a primary design requirement was that the rf-dc equivalence error be bracketed within narrow and determinable limits. The conditions for minimizing this error become almost intuitively evident if one considers a distribution of power sources inside a closed, perfectly (thermally)-conducting envelope. Because of its perfect conductivity the envelope must be an isothermal. Because the rate of heat loss from the envelope to the surroundings is proportional to its temperature elevation, the steady-state temperature rise of the envelope must be proportional to the total power dissipated within it. The proportionality constant is actually the thermal resistance of the envelope to its surroundings and is entirely independent of the distribution of power sources.[17] In this ideal case, it is clear, no equivalence error is possible.

[17] The situation is exactly analogous to that of a closed perfectly conducting shell enclosing a distribution of electric charge. Potential, capacitance, and charge in the electrical case correspond to temperature rise, thermal conductance, and power, respectively, in the thermal case.

Now let the envelope take the form of a long thin-walled metallic cylinder of finite thermal conductivity from whose ends there is no leakage of heat and which contains within it an axially located point source of power. If it is assumed that heat is lost radially from the surface at a rate proportional to the temperature rise and area of the surface element from which it is escaping, then it can be shown that the envelope is no longer an isothermal but possesses a temperature distribution which depends on the location of the source. However, the *integrated* temperature rise (and therefore the average surface temperature rise) is still proportional to the strength of the source and independent of its position along the axis. Again there is no equivalence error if the *integrated* temperature rise is used as an index of the power. If heat is now permitted to escape from the ends of the cylinder, not only does the temperature rise per unit power input (averaged over the surface of the cylinder) decrease, but it becomes a function of the source position as well. Qualitative reasoning (as well as analytic treatment) shows that the longer the cylinder, the smaller the end losses, the greater the cross-sectional thermal conductivity of the cylinder, the less sensitive is the integrated temperature rise to source position, and the smaller is the equivalence error produced by dissimilar distributions of power sources of equal total strength. It follows that the terminating calorimeter waveguides should be long relative to the rf loads located within them, should be constructed of metal having the highest thermal conductivity, and should be conductively well isolated from the metal jacket in which they are enclosed. An approximate ratio of four to one in waveguide to load length was found satisfactory for a 0.015-inch wall thickness of silver waveguide well-isolated by suitable spacers from the enclosing metal jacket. Experimental data on the equivalence error is presented further on.

An rf load which closely resembles a point source will produce negligible substitution error when the thermal detectors are remote from the source. Requirements of ruggedness, power handling capacity, and broad-banding rule out bolometer wires and thermistor beads. Tapered resistive strips axially oriented in the waveguide suggest themselves as broad-band loads. These must be sufficiently long to give a broad-band match, but for reasons of calorimeter sensitivity must be kept as short as possible, so that the associated waveguide termination will be correspondingly short. With increasing frequency, as the attenuation per unit length of the resistive material increases, shorter strips may be used, together with shorter waveguides for containing them.

The thermal conductance G of the waveguide to the surrounding metal jacket (whose reciprocal R determines the temperature rise per unit power input) is composed of the sum of four conductances G_I, G_T, G_L, and G_S. The first three of these, respectively, represent the conductive heat loss through the thermally isolating section of guide connecting the termination to the jacket, the conductive heat loss through the thermocouple wires attached to the waveguide, and the conductive heat loss through the wire leads which connect the rf load to the dc calibrating circuit. The last of these represents the combined heat loss from the waveguide surface due to free convection and radiation. If end effects are neglected the latter is given (in watts per °C) by

$$G_S = gpl$$

where pl is the outer surface area of the waveguide as determined by the waveguide cross section perimeter p and length l (in centimeters) and where the factor g (which is approximately 10^{-3}) represents the convective and radiative heat loss per square centimeter per °C of exposed waveguide surface. Once the minimum value of l has been established (by considerations of load length and equivalence error as described above) the value of G_S is fixed for a given waveguide cross section and frequency band. The isolating section is so designed that G_I is small relative to G_S while the thermocouple wires and dc load leads contribute additional conductances which are less than about 10 per cent of the total. The dominating term in G is therefore G_S, which, for a given waveguide cross section, is proportional to the waveguide length l. As the operating frequency band increases, both p and l decrease, causing a corresponding increase in the calorimeter sensitivity.

The time constant τ of the calorimeter is given by C/G, where C is the total heat capacity and G the total conductance. The former is the sum of C_S, the heat capacity of the terminating waveguide, C_L, that of the load and load holder, C_T, that of the thermopile and attached wires, and C_I, the effective heat capacity contributed by the waveguide isolating section because of its partial heating by the absorbed power. Accordingly,

$$\tau = \frac{C_S + C_L + C_T + C_I}{G_S + G_L + G_T + G_I}.$$

The ultimate time constant τ_u may be defined as C_S/G_S, that belonging to a perfectly (conductively) isolated piece of waveguide unencumbered by load or thermopile. Here

$$C_S = \rho c_h p l t$$
$$G_S = gpl,$$

ρ and c_h being the density and specific heat of the waveguide metal, respectively, and t its thickness. Accordingly

$$\tau_u = \frac{\rho c_h t}{g}$$

and is therefore proportional to the thickness t of metal used, being equal to approximately 100 seconds for silver waveguide of 0.015-inch wall thickness.[18]

In an effort to shorten the time constant the thickness cannot be made arbitrarily small because a small rf-dc equivalence error is dependent on good cross-sectional heat conductivity which increases with thickness. Furthermore, in seeking to reduce the time constant one ultimately reaches a point where any further reduction in wall thickness is accompanied by a significant increase in equivalence error with no substantial decrease in time constant. This occurs when the contributory heat capacities C_I, C_L and C_T (as well as those of flanges which are sometimes required at the ends of the waveguide) begin to dominate the total heat capacity. (In this connection it may be pointed out that a resistive strip load is superior to a volume absorbing load because of the smaller associated thermal mass and time constant.)

To sum up, a short waveguide termination is desirable in order to maximize the calorimeter sensitivity and a thin-walled construction to minimize the thermal time constant. However, the waveguide must be long relative to the rf load and sufficiently thick so as to keep the rf-dc equivalence error within desired limits. Good conductive isolation of the waveguide from the enclosing jacket is desirable both to minimize the equivalence error and to improve the calorimeter sensitivity. A reduction in convective and radiative heat loss from the waveguide increases both sensitivity and time constant. However, the gain in sensitivity might well be offset by the larger errors (*e.g.*, those due to temperature drift) which are associated with the necessarily longer measurement time. At higher frequencies increased sensitivity and more compact construction are obtained because of the accompanying reduction in waveguide cross section and in rf load length.

The suppression of temperature drift and random temperature fluctuations in the calorimeter is accomplished through use of thermal symmetry and massive double shielding. The design seeks to achieve, to the maximum degree possible, identical thermal behavior on the part of the twin calorimetric bodies and identity of the thermal forces impressed upon them because of external temperature variations. If these two aims are realized, then, theoretically at least, any arbitrary change in outside temperature would produce equal and in-phase temperature variations in both bodies without any effect on the temperature difference between them. The first objective requires identical construction of the twin terminations, while the second requires that they be surrounded by an isothermal envelope of very long (theoretically infinite) time constant so that both bodies see a uniform and unvarying temperature around them. A thermally massive aluminum jacket approximates

[18] Silver is best because its heat capacity per unit volume is smaller than that of most other suitable metals and therefore gives the shortest time constant. Because of its superior thermal conductivity, silver also gives the smallest equivalence error for a given thickness.

such an envelope by virtue of its high thermal conductivity and large thermal mass. The former property minimizes temperature gradients along the jacket and the latter prevents the jacket from appreciably following the external temperature variations. The purpose of an outer jacket is to surround the inner one with a similar isothermal envelope, thereby enhancing the total shielding effect. The two jackets are conductively insulated from each other by special waveguide sections whose combined thermal conductance G_I is small relative to the shunting convective and radiative conductances G_S existing between the jacket walls. The combined conductance G, in conjunction with the thermal capacities of the two jackets, forms a low-pass filter with a very low-cutoff frequency, the approximate electrical analog for which is the π section filter shown in Fig. 2. This analog is particularly appropriate in representing the behavior of the shielding system in the transient case. The capacitances C_1 and C_2 represent the thermal capacities of the inner and outer jacket, respectively, and the electrical ground corresponds to the temperature of the reference or "dummy" calorimetric body.

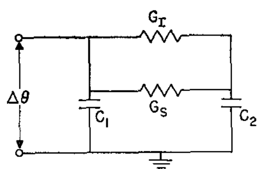

Fig. 2—Simplified equivalent circuit of calorimeter shielding system for transient conditions. C_1, C_2 are the thermal capacities of the inner and outer shielding jackets, respectively; G_I is the combined thermal conductance of the waveguide isolating sections; G_S is the thermal conductance between the walls of the inner and outer jackets; ground represents the temperature of the reference calorimetric body; $\Delta\theta$ is an impressed temperature change on the entry waveguide of the "active" calorimetric body.

With the above type of construction, the effect of external temperature variations is reduced by a factor of from two to ten thousand. As a result, internal drift rates of approximately 5×10^{-4} to 10^{-4} °C per hour are obtained for external ambient temperature variations having a rate of 1°C/hour. (A double shield system of the type described is ten or more times "quieter" thermally than a single jacket immersed in a stirred bath. The latter has a "graininess" of temperature, due to the impact of the stirred liquid on the jacket, which introduces an unnecessarily large amplitude of thermal noise.)

Sources of Error

The main sources of measurement error are those due to 1) lack of exact equivalence between rf and dc heating, 2) attenuation of rf power between input and calorimetric termination, 3) drift of temperature caused by external temperature variation, 4) nonlinear relationship between thermopile emf and input power, and 5) errors in associated dc instrumentation.

Equivalence Error

The rf-dc equivalence error is attributable to differences in the dc and rf power distribution along the tapered load strip. Such differences cannot altogether be avoided if only for the reason that the power distribution generally varies somewhat with rf frequency. Because of the complexity of the problem, experimental evaluation of the error is much easier and probably more accurate than an analytic determination. Therefore, the former approach was used.

The experimental technique was as follows: first the steady-state thermopile output was measured as a function of the axial position of a point-like source[19] inside the thin-walled guide. A typical curve showing the per cent deviation from maximum thermopile reading as a function of source position is shown in Fig. 3 for a length of RG-52/U waveguide of 0.015-inch wall thickness of either silver or brass construction. (It is seen that the maximum occurs near the half-way point in the guide for both metals, the curve for silver being much flatter than that for brass because of the larger thermal conductivity of the former metal.) If the different power distributions in the strip were known, the curve of Fig. 3 could be used to estimate the equivalence error for a given position of the strip at a given frequency. Even without a detailed knowledge of the distribution, however, limits of error can be estimated from the length of the strip. For example, the RG-52/U loads are about $\frac{5}{8}$ inch (1.6 cm) in length. Such a load, when situated in a silver waveguide so that its midpoint coincides with the source position yielding maximum thermopile reading, would be subject to a maximum error of only 0.3 per cent for the most extreme rf and dc power distribution (*e.g.*, all of the rf power concentrated at the center of the strip and all of the dc power at either end, or vice versa).

To delimit the error still further, studies[20] were next made of the temperature distribution along the strip at various rf frequencies and for various dc input power arrangements. (Because the heat loss from the strip is mainly convective and radiative, the temperature rise at any point is essentially proportional to the power density at that point, the proportionality constant being independent of position. The temperature distribution may therefore be taken as a fair approximation to the actual power density distribution.) In one type of experiment the temperature profile was measured by means of an array of six equally spaced iron-constantan thermojunctions embedded in the bakelite backing of the strip along the latter's longitudinal axis. Tests of this ar-

[19] In the experiments a point source of power was variously approximated by a small piece of IRC resistance card mounted in a bakelite block which was free to slide in the guide, an evaporated metallic film of short length on a piece of glass tubing riding on a movable axially positioned bakelite rod, or a short length of deplated Wollaston wire similarly mounted.

[20] S. Satinsky, "Minimizing substitution errors in a microwave calorimeter," M.E.E. thesis, Polytechnic Institute of Brooklyn, Brooklyn, N. Y.; June, 1955.

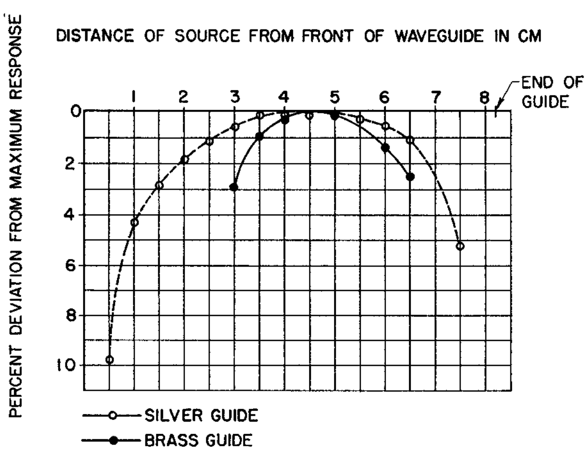

Fig. 3—Curves used in estimating calorimeter equivalence error. The thermopile output of the calorimeter, expressed in per cent deviation from maximum response, is plotted as a function of the axial position of a quasi-point source of power inside the waveguide. Results are for two RG-52/U waveguides of 0.015-inch wall thickness, one brass, the other silver.

rangement showed that the presence of the wires did not appreciably disturb the temperature profile. A typical RG-52/U calorimeter strip load was used which, with wires attached, had a vswr of 1.3 or better over the entire operating band of the waveguide. The thermocouple wires were brought out perpendicular to the plane of the strip through small holes in the side walls of the waveguide in which the strip was mounted. The wires were therefore at right angles both to the E lines and to the axis of propagation and thus presented the least disturbance to the rf field. (Measurement of the effect of the wires alone showed that their attenuation was negligible and their insertion vswr very small.) Provision was made for applying dc power in different distributions by scratching an appropriate contour in the resistive material. Temperature distributions were obtained at 500-mc intervals over a band from 8200 to 12,400 mc. A continuous but not very strong shift in temperature distribution was observed as a function of frequency, the power concentration tending to a maximum at the center of the strip. If a longitudinal dividing scratch, extending part way from the back end toward the tapered end of the strip, was engraved in the resistive material and dc current circulated around this barrier, a temperature distribution could be obtained which resembled in a general way that due to rf power absorption. The dc temperature maximum tended to coincide with the end of the scratch mark where the dc current density was a maximum. By adjustment of the length of the scratch (which incidentally had no observable effect on the rf properties of the strip) the dc temperature maximum could be made to coincide with the average position of the rf maxima at the different frequencies.

The equivalence error was obtained by comparing the expected calorimeter reading per unit power input for the experimentally determined dc load temperature distribution with that for the rf distribution which gave the most widely different result. This was done by computing the weighted mean calorimeter reading for a given temperature distribution (taking the latter as the impressed power distribution for the thin-walled waveguide) using the ordinates of the curve of Fig. 3 as weighting factors. The error evaluation was made for the optimum strip position (center of strip near center of waveguide) and also for a displacement of the strip by one centimeter from the optimum position. The result for these two cases was an indicated error of 0.005 and 0.07 per cent, respectively, for silver waveguide and of 0.013 and 0.26 per cent, respectively, for brass waveguide. Even allowing for imperfect scaling of waveguide models of different frequency range, minor variations in power distributions from load to load, and imperfect positioning of load strips, one obtains an equivalence error, based on the above data, well below 0.3 per cent in the case of the silver waveguide calorimeters which collectively cover the range from 7000 to 26,500 mc.

For the higher frequency calorimeters, separate experiments were performed in which the dc temperature profile was determined by probing the strip with a single movable thermocouple. (The loads were tapered thin mica strips on which a resistive metallic film had been evaporated.) The region of rf power concentration was determined by an auxiliary experiment in which the attenuation of rf power at three typical frequencies (at band limits and midrange) was determined as a function of film length. The peak of the dc power distribution was adjusted so as to coincide approximately with the peak of the rf power distribution. From an experimentally obtained curve of thermopile reading vs point source position, together with the information on rf and dc power distributions, the rf-dc equivalence error is estimated to be less than 0.3 per cent for the higher frequency models.

In the case of the coaxial calorimeter a disk-type concentric resistive film load is used oriented in a plane transverse[21] to the axis of propagation. Theoretically, the rf and dc power distributions should be identical because of the identity of the rf and dc electromagnetic field configurations. Actually, there will be some variation because of the distributed reactances associated with the load and any auxiliary matching structures. However, because of the transverse orientation of the disk these minor dissimilarities in distribution will produce an almost negligible equivalence error.

Attenuation of RF Power

Since any attenuation of rf power between input to the calorimeter and the site of rf power dissipation (the termination; *i.e.*, the terminating waveguide with its resistive load strip) can be applied as a correction, the error from this cause is basically the uncertainty in the

[21] A transverse film would also have been advantageous in waveguide from the point of view of substitution error. However, the longitudinally oriented load is more readily matched over a broad band in rectangular guide.

measured attenuation. The problem is, however, complicated by two factors—the non-negligible reflection factor of the termination and the equally non-negligible insertion vswr of the rf line connecting the calorimeter input to the termination. Even if the attenuation (*i.e.*, insertion loss between matched generator and matched load) of the latter were measured perfectly there would still be an uncertainty in the correction because of the above two factors. Therefore, in estimating the total error, due attention must be paid to this problem. This is treated in more detail in the companion paper.[14]

Drift Error

The error due to drift of calorimeter "zero" tends to increase with the physical size of the calorimeter and the rate of change of the external temperature. Also, the longer the time constant the larger is the error because of the longer measurement time required. The magnitude of this error for the different calorimeters is given in Table III[14] for an assumed ambient temperature drift of 1°C/hour. (This error would, of course, be much less in a temperature-controlled room.) The drift error, in any event, may be substantially reduced by means of a measurement procedure[14] which corrects for the zero drift. This procedure involves the measurement of the input power in terms of the *arithmetic mean* of the *change* in output emf during the heating and cooling of the termination. Any steady drift is thereby cancelled out of the measurement while any reversal in drift direction during the measurement leaves the error uncorrected. In the latter case, however, the correction is unimportant because the drift is generally quite small during a reversal in drift direction.

Nonlinearity Error

The steady-state power sensitivity (thermopile output per unit power input) is found to decrease with increasing power level. This shows that the relation between calorimeter reading and input power must be a nonlinear one. Actually, the relation is approximated by the expression $E=KP^n$, where E is the thermopile emf, P the power input, and K and n constants for a particular calorimeter. The exponent n varies with the physical size of the calorimeter termination but is always less than unity. (In the case of the RG-52/U model, for example, n is approximately 0.93.) The reason for this behavior can be traced to the predominantly convective cooling of the calorimeter which is a nonlinear phenomenon.[4] The nonlinearity may be responsible for a calibration error unless the calibrating power is very closely equal to the unknown rf power. For some calorimeters this error may exceed one per cent at high power levels, where the nonlinearity is greatest, if the calibrating power differs by more than 10 per cent from the unknown power.

Instrumentation Error

The instrumentation error, defined as the error in measuring the calibrating dc power, can be kept to a very small value (better than 0.25 per cent) relative to the other errors, by using precision dc measurement techniques. This is discussed in the companion paper.[14]

Conclusion

This paper has presented the basis for the design of a series of accurate, dry, broad-band calorimeters of high sensitivity. Of particular importance is the fact that all sources of error are clearly delimited so that a definite precision measure can be given when the devices are used in microwave power measurements. These instruments can therefore readily be used as power standards within the accuracy limits stated.