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A Dual-Load Flow Calorimeter for RF Power Measurement to 4 GHz

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A new dual-load flow coaxial calorimeter power meter has been constructed at the National Bureau of Standards, Boulder Laboratories. Designed for use as a reference standard, the frequency range of the calorimeter extends up to 4 GHz and beyond. The power range extends from 2 W to 100 W with an error limit of 0.38 percent.

Design details, error analysis, and results of intercomparison with other standards are given.

Key Words: Coaxial, flow calorimeter, radio frequency power.

1. Introduction

The increasing complexity and higher performance characteristics of radio frequency and other electronic equipment in recent years has resulted in the need for more accurate measurement of the rf quantities. In rf power measurements, for example, 1 percent uncertainty for measurements in industrial standards laboratories is often required. Formerly, uncertainties of 5 percent were tolerable. Because uncertainties are accumulated in a chain of calibrations, the uncertainties in reference standards maintained by the National Bureau of Standards must be less than 1 percent.

The dual-load flow calorimeter described here is essentially a refinement of earlier calorimeters of this type [1][1] and was developed to meet the need for greater accuracy, and extend the range of NBS reference power standards up to 100 W. This development made possible the intercomparison between this standard and the NBS dry-load calorimeter [2] (50 mW to 5 W), thereby increasing the confidence in each.

2. Theory of Operation

The calorimetric principle has been considered the most accurate method for the measurement of rf power. This principle is based upon the first Law of Thermodynamics, or the conservation of energy. The measurement of electrical power using this principle depends upon the complete conversion of the electrical energy as delivered by a generator into thermal energy in a resistive load. The heat generated in the load results in a temperature rise in the load and its surroundings. This temperature rise is a monotonic function of the input power level and may be detected, for example, with a thermopile located between the load and a reference body whose temperature is stable with time.

Two types of calorimeters could be constructed to measure power at the levels of interest. They are the absolute flow calorimeter and the substitution flow calorimeter. (The use of dry-load calorimeters at these power levels, 5–100 W, is not practical because of the large physical size of loads required and the long measurement time constant.) An example of a "true" or "absolute" calorimetric system is shown in figure 1. In this system, power is measured in terms of mass, time, and temperature by the equation $P=Fc\Delta T$. In this equation F is the mass flow rate of the calorimeter fluid, c is its specific heat, and ΔT is the equilibrium temperature rise of the fluid. A conservative measure of the uncertainty with which such a measurement can be made is the sum of the uncertainties with which F, c, and ΔT can be determined. The value of c is known very accurately for the common fluids. The value of ΔT, however, is difficult to determine accurately for low input power levels, and F can be measured with an uncertainty no better than 0.5 percent at usual values of flow rate. In addition great care must be taken to prevent heat exchange with surroundings, and a correction must be made for heating due to friction flow of the fluid. Therefore, the uncertainty in power measurement using an absolute flow calorimeter is usually 1 percent or more.

Many of the above difficulties can be overcome by use of the dual-load calorimeter employing d-c substi-

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[1] Figures in brackets indicate the literature references on page 116.

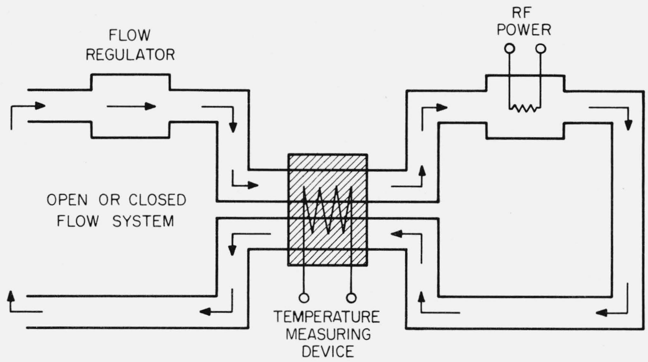

FIGURE 1. *Flow type "absolute" calorimeter.*

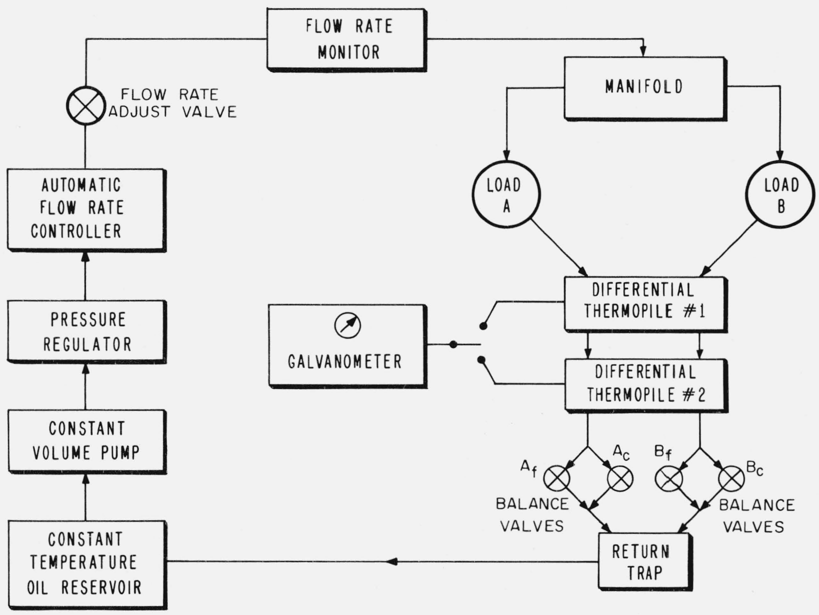

FIGURE 2. *Block diagram of dual-load flow calorimeter power meter 2–100 W, dc to 4 GHz.*

tution. A block diagram showing the system is given in figure 2. As the name implies, the dual-load calorimeter consists of two nearly identical loads connected in series or parallel to the fluid flow supply. Radio frequency power is applied to one load while d-c power is applied to the other. A differential thermopile, or other temperature sensing device, detects the temperature difference between the two streams on the downstream side of the loads when the system has reached thermal equilibrium. The d-c power level is adjusted to make the temperature difference zero, and the rf power is equated to the d-c power. Prior to the above measurement, it is necessary that the system be balanced by applying equal d-c power to each load at or near the rf power level to be measured. If the loads are in parallel to the fluid flow, then the flow rate through either one or the other may be adjusted for a null at the differential thermopile output.

Thus, in the dual-load substitution calorimetric technique, accurate knowledge of flow rate and temperature is not required for accurate measurement results. In addition heat exchange with surroundings due to external sources is not a problem as long as it remains constant during the measurement period. The substitution principle is based upon the assumption that heat generated by d-c or low frequency power absorbed by a load will have the same effect on the device used to sense the temperature rise of the load or a fluid surrounding it as heat generated by an equal amount of rf power. However, in general, equal quantities of rf and d-c power will not produce exactly the same calorimeter sensor response. Thus, an error, commonly known as the rf-dc substitution error, may exist. This error arises primarily because the rf current distribution in the load resistor is not identical to the d-c current distribution. This results in a difference in the distribution of heat sources in the load in the two cases. In flow calorimeters, this error is minimized since the load resistor and mount structure are in intimate contact with a moving fluid, and the heat generated by the load tends to be transferred to the liquid regardless of the distribution of heat sources.

The main problems associated with measuring power by the substitution calorimetric method are the relatively long measurement time constants and the difficulty in maintaining thermal environmental and flow stability over this time period. The dual-load flow calorimeter was designed with emphasis on reducing some of these problems. For example, by reducing the time constant of the system to a minimum, the need for extremely stable rf sources and temperature control devices was reduced.

3. Description of Calorimeter and Operating Procedure

3.1. Loads

The loads (see fig. 3) were designed for rapid transfer of heat and low VSWR (≤ 1.03 referenced to 50 Ω at frequencies up to 4 GHz). The load resistor is a thin metal film deposited by vacuum evaporation onto a truncated conical substrate. The load is mounted inside a cylindrical outer conductor. This type of design was proposed by D. Woods [3]. The sheet resistivity, ρ, of the film is uniform over the area of the cone and the resistance is given by

$$R=\frac{\rho}{2\pi \sin \theta} \ln b/a \quad (1)$$

where θ is the cone semiangle, and b/a is the ratio of outer to inner diameter of the coaxial line. The temperature coefficient of the resistive film is less than 10 ppm/°C thus insuring a nearly constant value of R at all power levels. The characteristic impedance of the section of coaxial line containing the conical resistor is

$$Z_0=\frac{Z_m}{2\pi} \ln b/a \quad (2)$$

where $Z_m=\sqrt{\mu/\epsilon}$ is the wave impedance of the medium. By making $\rho/\sin \theta$ equal to Z_m, $Z_0=R$ at any point along the length of the load. This condition tends to assure the same current distribution along the resistor for both rf and dc. Measurements using a time domain reflectometer indicated that small discontinuities of the order of 0.1 Ω did exist along the length of the load. Thus, it appeared probable that a small substitution error could exist. The upper limit of the error was evaluated and is discussed in the following section.

The resistors are capable of absorbing up to 100 W of power with no significant change in their impedance characteristics. The physical dimensions of the loads were made small to reduce the measurement time. In order to absorb 100 W without damage to the film, the oil had to be circulated rapidly around and through the resistor body. At low levels of input power (2–5 W) the minimum oil flow rate was such that the temperature rise of the oil was approximately 5 deg. This flow rate per watt was about $\frac{15 \text{ cm}^3/\text{min}}{\text{watt}}$. At higher levels of input power, the flow rate per watt was reduced to about $\frac{7.5 \text{ cm}^3/\text{min}}{\text{watt}}$ so that the temperature rise was 10 deg centigrade.

3.2. Temperature Detection System

This system consists of two differential thermopiles (T.P. #1 and T.P. #2), of 10 junctions each, and a sensitive galvanometer. A selector switch allows either thermopile to be connected separately or both in series, to the galvanometer. The junctions of the thermopiles are located in the path of the moving oil as shown in figure 2. The oil is mixed thoroughly in a chamber downstream from the loads and then

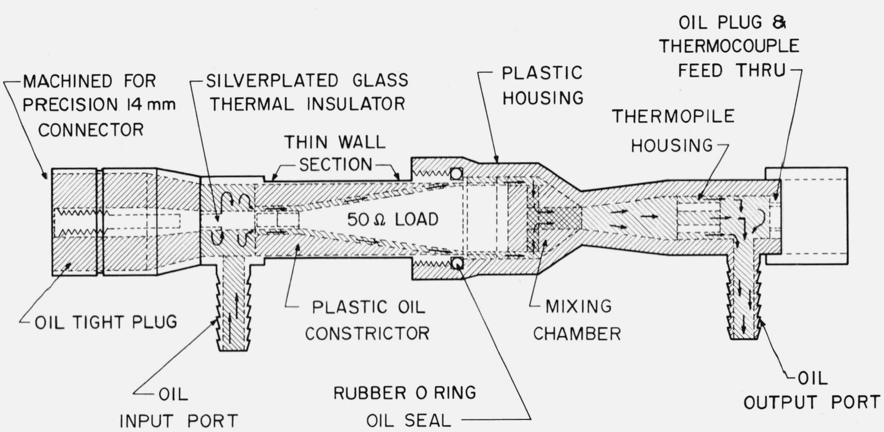

FIGURE 3. *Oil flow calorimeter load.*

passes around and through a plastic block in which the junctions of T.P. #1 are located. The close proximity of the thermojunctions of T.P. #1 to the load resistors results in rapid temperature detection and reduces the possibility of heat leakage before detection. Thermopile #2 was installed as a cross check against thermopile #1. Its junctions are mounted symmetrically inside plastic holders located farther downstream from T.P. #1. Any differences in the temperature of the oil flowing in channel A as compared to channel B will result in an emf generated by both T.P. #1 and T.P. #2. Either one or the sum of these emf's is detected by the galvanometer and within the limits of ± 0.02 percent, it is possible to detect any balance in the calorimeter system.

3.3. Flow System and Reservoir Temperature Control

The flow system of the dual-load flow calorimeter employs precision needle valves, a flow controller and meter, pressure regulator, constant volume pump, and reservoir, all incorporated into a closed circulation system (see fig. 2). Oil pumped from the reservoir passes through the pressure regulator which is set at 15 psi. It is then filtered and flows on to the flow rate meter and controller which is adjusted for the desired flow rate. Following the flow meter, the oil flow is divided into two channels, A and B, by means of the manifold. The flow path through each load is indicated by the arrows in figure 3. Oil leaving the loads passes through the mixing chamber, across thermopile #1, and across thermopile #2, on through the balance valves, to the return trap, and thence to the reservoir. The flow division between the two channels is regulated by means of the balance valves $A_F - A_C$ and $B_F - B_C$. These valves were placed downstream from the loads because this arrangement causes a back-pressure which resulted in better stability and control and insured that the load bodies were completely filled with oil at all times. Each valve has an adjustment range of 350:1 and by properly setting the ratio of flow between the fine and course valves, very small adjustments can be made in the flow division between channels.

The temperature of the oil in the reservoir is controlled at 28 ± 0.02 °C by a conventional automatic control circuit-cooling coil combination. This provides a nearly infinite heat sink for the system and helps to reduce the measurement time constant.

4. Estimation of Uncertainties

Uncertainties in measurement of power with the dual-load flow calorimeter were minimized by careful design and precision flow control and adjustment. The uncertainty of measurement is the difference between the true value and the measured value. This difference is usually expressed as a percentage of the true value. Sources of significant error and a brief explanation of each are given below.

4.1. Flow Division Instability and Thermal Effects

The instability in the flow division through each channel and the thermal drift are both reflected as a null shift or unbalance in the outputs of the thermopiles between loads A and B. As mentioned earlier, the effect of heat exchange with surroundings is much reduced in the dual-load configuration as compared to the single-load "absolute" calorimeter. Efforts were, nevertheless, made to minimize and equalize heat exchange between the two loads and their surroundings. Unequal heat exchange is not critical because the effect can be cancelled by proper adjustment of the flow rate through the individual loads during the d-c balancing operation. It is required, however, that the heat exchange be constant during the time a measurement is being made. After initial null (zero temperature difference between the oil leaving loads A and B) was achieved, the emf output of the thermopiles was recorded over a time period much greater than the measurement time constant which was approximately 5 min. Tests at several power levels indicated that for periods of up to 30 min the maximum drift was no greater than 6 μV. Since an oil temperature rise of 10 deg centrigrade produces a net thermopile output of 4000 μV, a maximum emf unbalance of ± 6 μV, corresponds to 0.15 percent shift in the thermal balance between the loads.

4.2. Detection System

The degree to which the two channels are balanced is a function of the overall resolution of the system. The sensitivity of the complete system is limited by the temperature fluctuations in the oil and not by the detection system which consists of the galvanometer and differential thermopile. These fluctuations limited the resolution to 0.02 percent.

4.3. RF–D-C Substitution Error

As mentioned earlier, the calorimeter loads and temperature detecting system were designed to minimize the rf–d-c substitution error. The loads were designed to provide matched terminations and thus insure, as nearly as possible, identical rf and d-c current distributions. In addition, the oil flowing over the resistor surfaces tends to absorb all the heat generated in the load regardless of the distribution of heat sources in the load. A small portion of heat may be conducted away at the points where electrical connection is made between the load resistor and the mount. Negligible heat conduction to the mount occurs at the input end where the center conductor is immersed in the moving oil stream for a distance of 1½ cm. At the grounded end of the resistor, where it contacts the outer conductor, some heat conduction is possible. In order to check for a temperature difference in this area a 10-junction thermopile was cemented to the outer conductor of one of the loads and referenced to an ice bath. "Equal" levels of d-c or rf power were then applied alternately to the load.

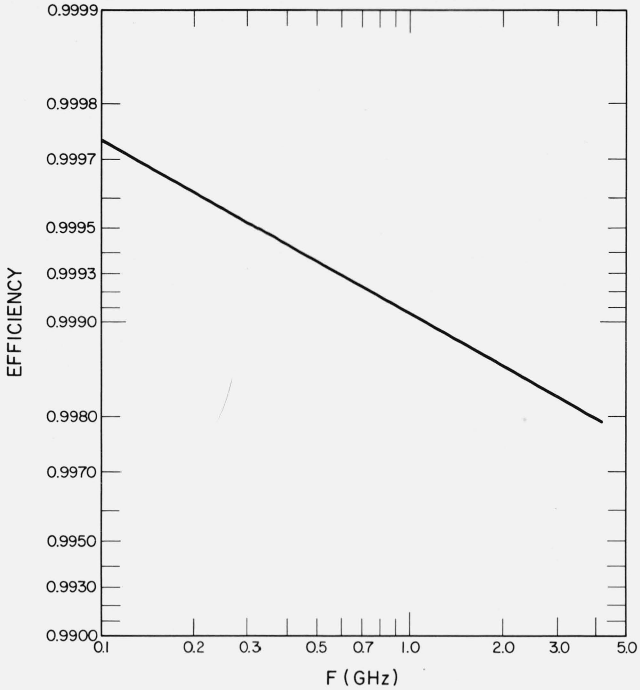

FIGURE 4. *DLFC input line efficiency versus frequency.*

At a frequency of 4 GHz, a difference in temperature of 0.035 °C was observed while at 2 GHz no measurable difference was discernible. Calculations were made (appendix) which show that at 4.0 GHz, with a temperature difference of 0.035 °C, an error less than 0.1 percent exists.

On the basis of the above tests the rf–d-c substitution uncertainty was estimated to be 0.1 percent at frequencies of 1 GHz and above and 0.05 percent at frequencies below 1 GHz. The resolution of the measurement, due to noise and ambient temperature variations, was approximately 0.05 percent.

4.4. Uncertainty in Input Lines and Mismatch Losses

In the load bodies as described in the preceding section, the only portion of input transmission line not immersed in the oil stream is a length of approximately 3.7 cm. The portion immersed in oil can be considered as a part of the load since the I^2R loss will be absorbed by the oil. The loss in the remaining 3.7 cm of input line was calculated using the following equation: [4]

$$\alpha_T = 8.686 l \left[\alpha_0 \sqrt{f} \frac{1/a + 1/b}{\ln b/a} + \frac{\omega}{2} \sqrt{\mu\epsilon} \tan \delta \right] dB \quad (3)$$

where $\alpha_0 = \frac{1}{2}\sqrt{\frac{\pi\epsilon}{\sigma}}$ and $\omega = 2\pi f$,

ϵ = dielectric constant,
μ = permeability,
σ = conductivity of metal used for inner and outer conductors,
a = inner conductor radius,
b = outer conductor inside radius,
f = frequency,
l = input line length, and
$\tan \delta$ = loss tangent of dielectric.

The results of this calculation as a function of frequency are plotted in figure 4. The uncertainty in the calculations of the loss factor is due to the combined uncertainty in measuring a, b, l (length = 3.7 cm), and in the assumed values of ϵ, μ, σ, and $\tan \delta$. The combined uncertainty of these factors could be as great as ±35 percent at 4 GHz. This was primarily due to the uncertainty in the thickness of the silver plating on the inner and outer conductors of the line, hence an uncertainty in the value of σ. For example, at 4 GHz the following data were obtained from calculations for the loss of the input line:

Loss in input connectors	0.0026 ± 0.0005 dB
Loss in straight region	.0030 ± .0009 dB
Loss in taper region	.0028 ± .0019 dB
Total loss	.0084 ± .0033 dB

The loss is then 0.2 ± 0.07 percent or an efficiency of 99.8 ± 0.07 percent. Thus the power at the input connector was higher than that measured by the calorimeter by the factor 1.002 ± 0.0007. The rf efficiency factor versus frequency is shown in figure 4. At lower frequencies the loss in the input line decreases and below 10 MHz the efficiency is assumed equal to unity.

Due to the fact that the calorimeter loads are not perfectly matched to Z_0, part of the incident power will be reflected. Because a measurement of the incident power is usually desired, reflections cause the calorimeter to read low with respect to the incident power. The impedance of both loads was matched to Z_0 (50 Ω) using a time domain reflectometer so that VSWR < 1.03 ± 0.01 at frequencies from 1.0 to 4.0 GHz and < 1.015 ± 0.005 at frequencies below 1.0 GHz. A plot of VSWR versus frequency for each load is shown in figure 5.

At the maximum VSWR of 1.03, 0.02 percent of the incident power will be reflected resulting in a 0.02 percent error in the power measurement if the reflection loss is neglected. For a VSWR of 1.015, the reflected power is only 0.01 percent of the incident source. Combining the maximum expected uncertainty in the correction factor for rf efficiency with the maximum mismatch error gives 0.09 percent above 1 GHz and 0.04 percent below 1 GHz.

4.5. D-C Power Measurement Error

The d-c power substituted in the loads is calculated from measured values of current and voltage. The voltage drop across a 1 Ω standard resistor in series with the termination is measured with a potentiometer

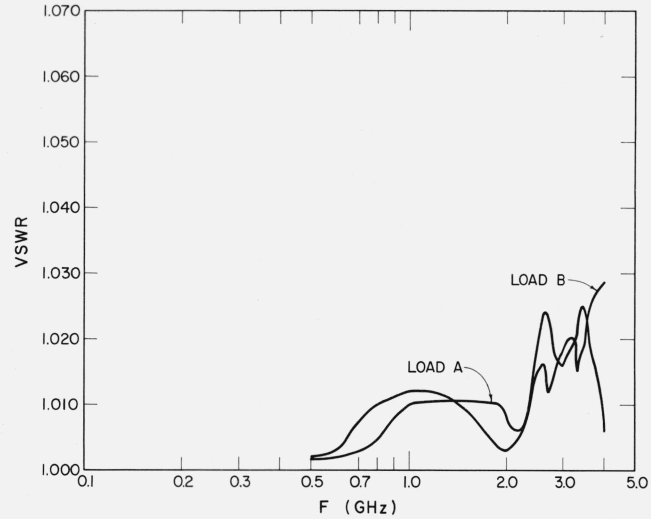

FIGURE 5. *VSWR versus frequency of DLFC loads.*

to obtain the current flowing into the loads, and the voltage drop across the loads is measured directly with a digital voltmeter. The power is then found by the simple equation $P=VI$. Both V and I can be determined accurately to 0.01 percent giving a maximum d-c measurement error of 0.02 percent.

The errors discussed are believed to be the only significant ones in the calorimeter and measuring system described herein. The overall limit of error can be found by adding the maximum values:

	0–1 GHz	1–4 GHz
1. Flow division stability	0.15	0.15
2. Detection system	.02	.02
3. RF–D-C substitution	.05	.10
4. Line loss and rf reflection (mismatch errors)	.04	.09
5. D-C measurement error	.02	.02
Limit of error	0.28%	0.38%

5. Conclusions

The dual-load flow calorimeter was designed and constructed to provide a reference standard for cw power measurements in the range 2 to 100 W at frequencies up to 4.0 GHz. A maximum uncertainty or error limit of 0.38 percent was achieved. This is a significant improvement over prior capabilities at these power levels. Also the frequency range of the NBS reference standards was extended from 1.0 GHz up to 4.0 GHz in the power range of 5 to 100 W.

Intercomparisons at 1, 3, and 4 GHz have been made between this calorimeter and the reference standard dry-load calorimeter which has a total estimated uncertainty of 0.35 percent. The intercomparisons included measurements at power levels of 2 W and 4 W and the disagreement was no greater than 0.2 percent.

6. References

[1] J. P. Vinding, An accurate calorimeter for high microwave power, The Microwave Journal **4,** No. 1, 41–46 (Jan. 1961).

[2] P. A. Hudson, A calorimetric reference standard power meter for the frequency range 0–4000 MHz. Paper in process.

[3] D. Woods, Improvements in precision coaxial resistor design, IRE Trans. on Instr. **I-II,** Nos. 3–4 305–309 (Dec. 1962).

[4] S. Ramo and J. R. Whinney, Fields and waves in modern radio, (John Wiley & Sons, Inc., New York, 2d edition, fifth printing, Nov. 1960). See Table 9.01 between pages 364–365. Equation (3) was derived using equations in this table.

7. Appendix

7.1. Analysis of RF–D-C Substitution Error

In the following analysis of the rf–d-c substitution error, an upper bound is arrived at which, though derived from approximate considerations, is felt to have significance.

The total input power to the calorimeter, P_t, is related to the power absorbed by the oil, P_a, and the power P_c absorbed elsewhere, by

$$P_t = P_a + P_c. \tag{1A}$$

Using additional subscripts, rf and d-c, to indicate when the input power is respectively rf and d-c (1A) becomes

$$P_{t\mathrm{dc}} = P_{a\mathrm{dc}} + P_{c\mathrm{dc}} \tag{2A}$$

and

$$P_{t\mathrm{rf}} = P_{a\mathrm{rf}} + P_{c\mathrm{rf}}. \tag{3A}$$

The measuring technique used with the calorimeter results in

$$P_{a\mathrm{dc}} = P_{a\mathrm{rf}}. \tag{4A}$$

Using (2A), (3A), and (4A), one can obtain the relation

$$\frac{P_{t\mathrm{rf}}}{P_{t\mathrm{dc}}} = 1 + \frac{P_{c\mathrm{dc}}}{P_{t\mathrm{dc}}}\left[\frac{P_{c\mathrm{rf}}}{P_{c\mathrm{dc}}} - 1\right]. \tag{5A}$$

Thus, if $P_{c\mathrm{rf}} = P_{c\mathrm{dc}}$, there would be no substitution error. However, this condition may not hold for all frequencies and a measure of the ratio of $P_{c\mathrm{rf}}$ to $P_{c\mathrm{dc}}$ is obtained from the following considerations.

As noted in the text, there is little chance for heat losses to the external environment except possibly at the junction of the load resistor with the outer conductor. A thermopile connected externally between this area and an ice bath indicated that there was no difference in the temperature for frequencies up to 2 GHz when equal rf and d-c power were alternately applied to the calorimeter. However, at 4.0 GHz a temperature difference of 0.035 °C was measured. Because of the construction and nature of operation of the calorimeter, the principle mode of heat transfer to the external environment is by conduction. Since the rate at which heat flows by conduction is proportional to the temperature difference between the source and sink,

$$\frac{P_{c\mathrm{rf}}}{P_{c\mathrm{dc}}}=\frac{T_{\mathrm{rf}}-T_{\mathrm{amb}}}{T_{\mathrm{dc}}-T_{\mathrm{amb}}}, \tag{6A}$$

where T_{rf} and T_{dc} are the respective temperatures at the junction of the load resistor and outer conductor when rf and d-c power are alternately applied to the calorimeter. The ambient temperature is noted by T_{amb}. From experimental data at 4 GHz,

$$\frac{P_{c\mathrm{rf}}}{P_{c\mathrm{dc}}}=1.023. \tag{7A}$$

An upper bound for the ratio of $P_{c\mathrm{dc}}/P_{t\mathrm{dc}}$, obtained from using the dual-load calorimeter as an absolute flow calorimeter, is

$$\frac{P_{c\mathrm{dc}}}{P_{t\mathrm{dc}}}=0.03. \tag{8A}$$

Substituting (7A) and (8A) into (5A), the upper limit for the substitution error is 0.07 percent which was increased to 0.1 percent because of the approximations used.

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