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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1263

The JPL Standard Total-Radiation Absolute Radiometer

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CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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Abstract

The JPL Standard Total-Radiation Absolute Radiometer, a primary standard, has been developed to provide the capability for accurate calibration of other radiometers. These radiometers are used to measure intensity levels of simulated solar sources in space simulators, measuring either collimated or hemispherical radiation with equal accuracy. Surrounded by a thermal guard in the standard radiometer is an isothermal quasi-spherical cavity giving increased effective blackness of the aperture. These and other features provide an absolute accuracy of ½% or better in measuring absolute total-radiation intensity. This percentage represents an appreciable increase of accuracy over the Jet Propulsion Laboratory (JPL) cone-type absolute radiometer. Other improvements to achieve higher accuracy include improved electronic equipment and determinations of and allowances for miscellaneous disturbances which, if not allowed for, would total no more than 1%.

Temperatures in the radiometer are measured to an accuracy of 0.04°C by platinum resistance thermometers traceable to the National Bureau of Standards (NBS). In order to gain confidence in the accuracy of the radiometer, an absolute determination of the Stefan–Boltzmann constant has been made that agrees with the theoretical value to within ½%. Cavity temperatures at which infrared energy was emitted for determining the Stefan–Boltzmann constant ranged from 26° to 136°C (peak energy from 10 to 7 μm).

The JPL Standard Total-Radiation Absolute Radiometer

I. Introduction

The Standard Total-Radiation Absolute Radiometer, a primary standard developed especially for spacecraft work, provides an absolute standard of high accuracy ($<0.5\%$ error between 0.045 and 0.16 W/cm^2) useable throughout the ultraviolet, visible, and infrared ranges. Against this standard, other radiometers can be compared or calibrated. The high accuracy obtainable is mostly due to its black receiver which is a quasi-spherical cavity, internally coated with Parsons' black matte lacquer. The effect of the cavity is to yield an enhanced effective emissivity and absorptivity at the aperture; both are more or less independent of coating characteristics. This circumstance, in turn, appreciably increases the accuracy of this radiometer over other radiometers (Ref. 1) that use more open types of receptors, such as cones and flat plates.

Use is made of electrical heating equivalence for radiation out through the aperture. The associated electronics have been set up to make the best use of the radiometer capabilities.

Careful attention to a multitude of necessary details which contribute to its accuracy include several analyses providing information for minor corrections in data reduction, the total of which amounts to less than 1%. This radiometer must be used in a good vacuum, i.e., pressure of 1×10^{-5} torr or less. Thermal conduction effects of the ambient gas can then be disregarded.

The cavity radiometer has an accurate hemispherical response, i.e., it is Lambertian. For off-axis collimated radiation, the response is proportional to the cosine of the off-axis angle. Were this response not Lambertian, it would not be possible to make accurate absolute measurements of isotropic, thermal, hemispherical radiation.

The maximum operating temperature (200°C) of the radiometer is limited by the black lacquer coating inside the cavity. This temperature permits the measurements of intensities up to slightly over 0.28 W/cm^2 (250 W/ft^2 or 2 solar intensities at 1 AU).

The following report describes the radiometer, electronic equipment, method of use, error analysis, and setup for calibrating radiometers, and the determination of the Stefan–Boltzmann constant.

II. Description of the Radiometer

The radiometer, shown in Fig. 1, has overall dimensions of a 1¼-in. diameter by a 1½-in. length. It consists essentially of a gold-plated copper thermal guard which, except for the aperture, surrounds an internally blackened, isothermal, cavity receptor.

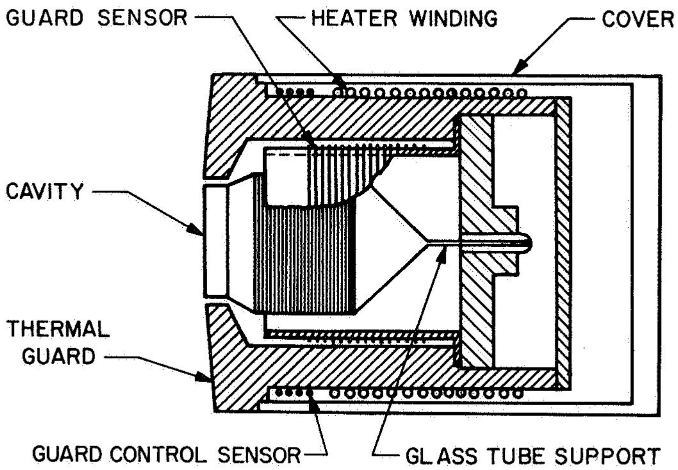

Fig. 1. Standard radiometer

The copper thermal guard, gold-plated inside and out, has thick walls to assure isothermality. Wound on the outside of the thermal guard is a heater winding of Evanohm wire with a resistance of about 100 Ω. This winding provides a means of raising the radiometer to any desired temperature within its operating range. Also, on the outer surface of the thermal guard is a platinum wire winding that serves as a sensor for controlling the thermal guard temperature. The rear end of the thermal guard is closed with two internal coverplates, and the entire radiometer is enclosed in a gold-plated housing.

The cavity is fabricated from 5-mil-thick silver. On its cylindrical portion is a combined heating and sensing winding. The cylinder, with a 9/16-in. diameter, is spun down to a smaller cylinder of short length to form the aperture.

For radiation considerations, it would, perhaps, have been better to avoid the short cylinder by letting the aperture be formed by the cutoff cone. The added short cylinder, however, has the advantage that it is easier to make accurate determinations of the area of the aperture and the annulus between the aperture and the thermal guard.

A cone of 40-deg half-angle is silver-soldered to the rear edge of the 9/16-in. cylinder to complete the cavity. The high-thermal conductivity of the silver in the cavity conducts the heat from the winding, where it is generated, to the various places of the cavity from which it is radiated out the aperture.

The greatest temperature drop anywhere in the cavity is usually less than 0.1°C and is allowed for in the data reduction. The high-thermal diffusivity of the silver provides rapid reestablishment of temperature equilibrium after any thermal change.

The heater-sensor winding provides a highly accurate means of measuring the temperature of the cavity and supplies the necessary heat to maintain accurately its temperature equal to the temperature of the thermal guard. This winding is electrically well-insulated from the silver cavity by a layer of 1-mil-thick H-Film (made of DuPont Kapton or Pyre ML) and is impregnated with a thin coating of Pyre ML varnish to hold the winding in place and to decrease the thermal resistance between the platinum wire and the cavity.

This thermal resistance has been carefully measured so that the small temperature drop between the wire (where heat is produced and temperature is measured) and the silver in the cavity can be accurately allowed for. The internal surface of the cavity is coated with Parsons' black matte lacquer with an average weight of coating of 0.007 g/cm^2, which is just enough to give perfect hiding.

The thermal coupling between the cavity and the thermal guard is made as small as possible, to avoid degraded sensitivity and accuracy. The outside surface of the cylindrical part of the cavity is covered by the heater-sensor winding. This surface would have a high emissivity for radiation, thereby increasing thermal coupling, were it not for a jacket of ½-mil-thick aluminum foil over the winding, decreasing the emissivity to a low value. The remainder of the outside surface of the cavity is bright silver, and naturally has a low emissivity. Thermal coupling is further decreased by polishing and gold-plating the inside surface of the thermal guard.

The cavity is supported in the thermal guard by a small glass tube on the apex end and by eight glass fibers, 1-mil in diameter, at the aperture end. The thermal conductance of these glass supports is small enough to be neglected. Two No. 40 AWG copper wire leads carry heating and sensing current to the winding. The leads are attached at a point on the cavity where the temperature is of nearly average value, hence, nearly equal to the thermal guard temperature, so that there is very little heat conduction by the leads between cavity and thermal guard. Because of their place of attachment, the leads contribute very little to the thermal coupling between cavity and thermal guard.

Located inside the thermal guard, and in good thermal contact with the guard, is the guard sensor. This sensor consists of a cylinder of 20-mil-thick silver on which is wound yet another 1.5-mil platinum wire for measuring the thermal guard temperature with the greatest possible accuracy.

The coating in the radiometer cavity has thermal resistance, i.e., the temperature of the part of the coating from which radiation is emitted is lower than that of the substrate. The order of magnitude of the thermal resistance for Parsons' black lacquer is 2.5°C drop/W/cm² as measured in air by Blevin and Brown (Ref. 2). In a vacuum, the resistance is probably a little higher because of the absence of thermal conduction of air between the coating particles. Thermal resistance of this amount is certainly great enough to require taking into account. However, if one uses a calorimetric measurement (described later) of emissivity made in vacuum, the thermal resistance automatically gets taken into account by showing up as a reduced temperature at the radiating surface of the coating, and this emissivity based on substrate temperature is reduced. Even if one used a value of emissivity based on the true temperature of the radiating surface of the coating, the cavity effect of the radiometer would reduce considerably the resulting error. Since the area of the inside surface of the cavity is much greater than the area of the aperture, the thermal flux per cm² through the coating is reduced accordingly. Since a calorimetrically determined value of emissivity is generally more accurate for our purpose than values determined by other methods, it has been used here with no allowance for thermal resistance of the coating.

The cavity radiometer has a higher absorptivity for visible light than it does for infrared radiation. Furthermore, incoming collimated light is absorbed more completely than incoming hemispherical radiation. Hence for solar radiation, natural or artificial, the effective absorptivity of the radiometer is approximately 0.998.

III. Electronic Circuit

The electronic circuit must maintain three functions for effective operation. These essential functions are

(1) To maintain the thermal guard at a known, preset, constant temperature.

(2) To supply exactly enough electrical heat to the cavity to make up for heat lost by radiation out of the aperture.

(3) To measure accurately the electrical power required to fulfill the requirement of item (2).

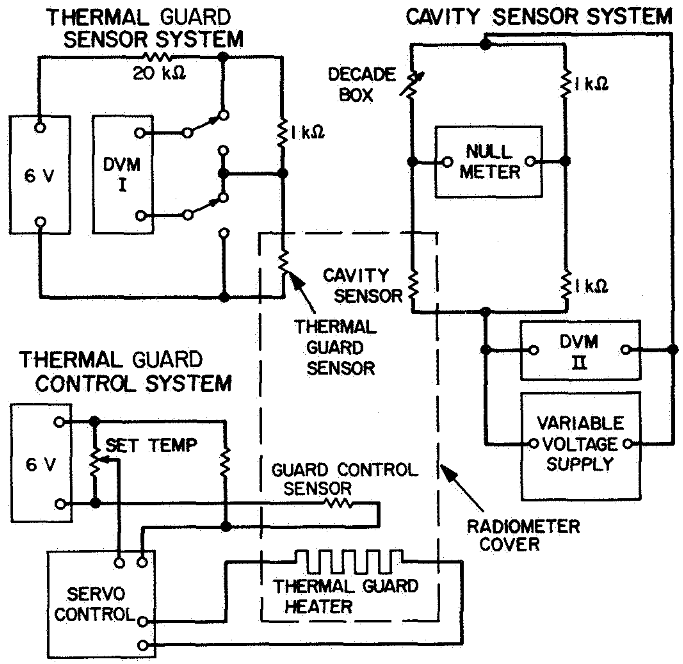

Fig. 2. Electronic circuit

Figure 2 shows the electronic circuit. The three independent systems are (1) thermal guard control system (temperature control sensor and servo control) for maintaining the radiometer at the set temperature; (2) thermal guard sensor system for accurately determining thermal guard temperature; and (3) cavity sensor system and associated bridge circuit for accurately measuring cavity temperature and for supplying an exact amount of heat to maintain the cavity at the exact temperature of the thermal guard.

System (1) automatically maintains by servo control the thermal guard at the set temperature, determined by the position of the potentiometer marked *set temp*. The sensing current through the guard control sensor (made of 1.5-mil platinum wire) is small enough so that heat generated in it is negligible. The temperature must be set high enough so that, when a radiation intensity measurement is being made, the net radiation through the aperture is *out*, i.e., the radiometer is warmer than the surroundings; or, if collimated radiation is coming into the aperture it will not heat the cavity to a temperature higher than the temperature of the thermal guard when no electrical heating is applied to the cavity. Further consideration of the function of the radiometer is given later in this paper.

System (2) accurately measures the thermal guard temperature which system (1) is maintaining. The thermal guard sensor is wound with 1.5-mil platinum wire on a ⅝-in.-diameter cylinder that surrounds the cavity. The 2-pole, 2-position switch manually connects the digital voltmeter (DVM I) either to the precision 1-kΩ resistor carrying the same current as the thermal guard sensor, or to the thermal guard sensor. The thermal guard sensor resistance, measured to an accuracy of five significant figures, serves as a resistance thermometer capable of being calibrated with high accuracy ($\pm$0.025°C).

System (3), the cavity sensor and associated bridge circuit, serves two purposes. It heats the cavity until its temperature equals the thermal guard temperature. The heating current put through the cavity winding of 1.5-mil platinum wire also serves as the sensing current.

The resistance of the cavity winding as a function of temperature is determined (calibrated) simultaneously with the thermal guard sensor calibration. The decade box is set to the resistance value of the cavity sensor R_c required for the temperature of the thermal guard. The variable voltage supply is manually adjusted until the heating (and sensing) current raises the temperature of the cavity to exactly that of the thermal guard. When the cavity resistance is equal to the decade box resistance, the null meter reads zero; the DVM II is then used to read the voltage E across the bridge (Fig. 2), one half of which is across the cavity heater-sensor. The heating into the cavity is simply $(E/2)^2/R_c$.

The time constant of the radiometer, if it had no automatic controls, would be inconveniently long (30 min). Amplification and manual control, however, make it possible to obtain full accuracy in about 1 min from a sudden change in incoming intensity level. To get this accuracy assumes, of course, that the thermal guard has already settled out at its operating temperature.

Johnson noise in the frequency range involved ($<$1 Hz) is negligible. Depending on temperature, the cavity heater-sensor has a resistance varying from 450 Ω at 20°C to about 850 Ω at 190°C.

IV. Calibrating Resistance Thermometers

The cavity radiometer has two platinum resistance windings, (1) the cavity sensor and (2) the thermal guard sensor. These windings must be very accurately calibrated (resistance vs temperature). As shown in Fig. 3, this calibration is done with the aid of a massive copper oven of 4-in. diameter and 4¾-in. length. A hole in the oven center is just big enough to accept an assembled radiometer. The outside surface of the oven is wound with a Nichrome wire heater capable of raising the oven to any desired temperature. A thermocouple located in one side is used with an electronic control apparatus to maintain the temperature at the set value. A Leeds and Northrup platinum resistance thermometer is mounted in a well in the side wall and is used to measure the oven temperature and contents to an accuracy of 0.01°C. The oven is placed in a 3-gal galvanized scrub bucket and packed around with Pyrex glass wool. Because of the massiveness of the oven and the insulation of the glass wool, the temperature of the oven can be held constant, and accurately measured with the platinum thermometer during a radiometer temperature calibration. For each desired temperature at which the oven is held constant, resistances of the cavity and guard sensors are measured using the electronic equipment previously described.

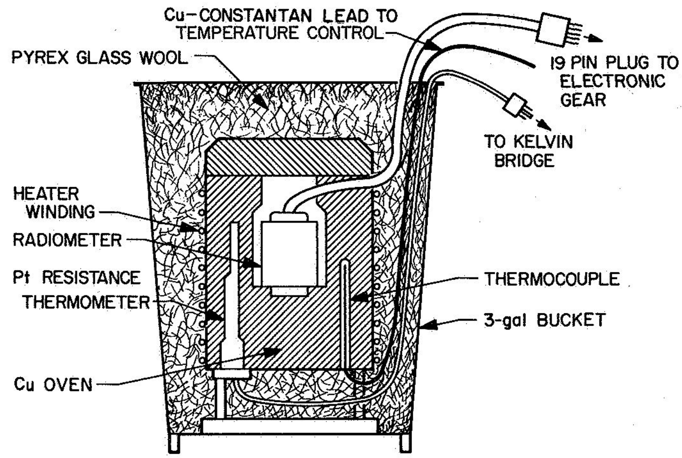

Fig. 3. Thermometer calibrating oven

V. Miscellaneous Small Corrections

For making measurements from which the Stefan–Boltzmann constant (discussed later) was determined, a test configuration (Fig. 4) with a cold cavity in a vacuum chamber was used. The radiometer was positioned in the cold cavity aperture. Radiation from the surrounding vacuum chamber enters the cold cavity through the annulus around the radiometer in the aperture. Radiation also enters the cold cavity off the warm radiometer. By reflection, a small portion of each of these sources of energy enters the radiometer aperture and must be allowed for. Also, the cold cavity, which is maintained at a temperature of 77°K, emits energy characteristic of 77°K into the radiometer.

In addition, there is heat transfer by radiation from the thermal guard to the outside surface of the radiometer cavity, because of the thermal gradient in the radiometer

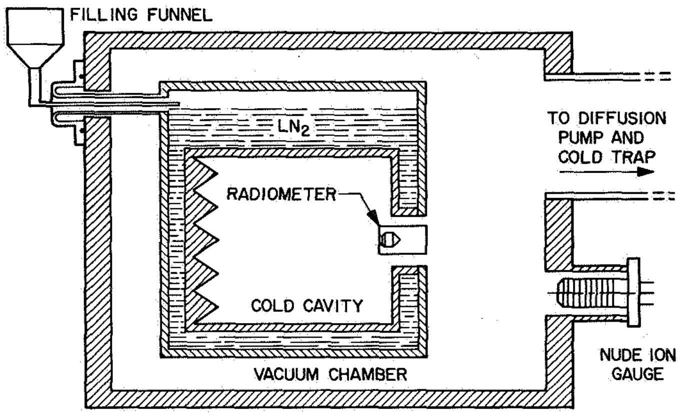

Fig. 4. Radiometer in cold cavity and vacuum chamber

cavity. The combination of all these radiations into the radiometer cavity amount to about one quarter of one percent of the radiation going out the aperture. While these effects are small, they are not negligibly small, and must be taken into account.

The combination of the thermal gradient in the silver of the cavity and the view factors relating radiation from each zone of the cavity out the aperture require another correction to be made. Figure 5 shows the temperature distribution in the cavity as computed by the use of view factors. This curve was used in estimating the radiative and conductive heat transfer from thermal guard to cavity. The radiation out the part of the cavity near the apex of the terminating cone is slightly reduced because of the slightly lower temperature in this region. Also there is a drop of temperature from the platinum winding on the cylindrical part of the cavity where the temperature is accurately equal to the thermal guard temperature to the silver in the cavity. To compensate for these temperature drops, a correction factor has been derived that makes allowance for the slight reduction of radiation out of the aperture.

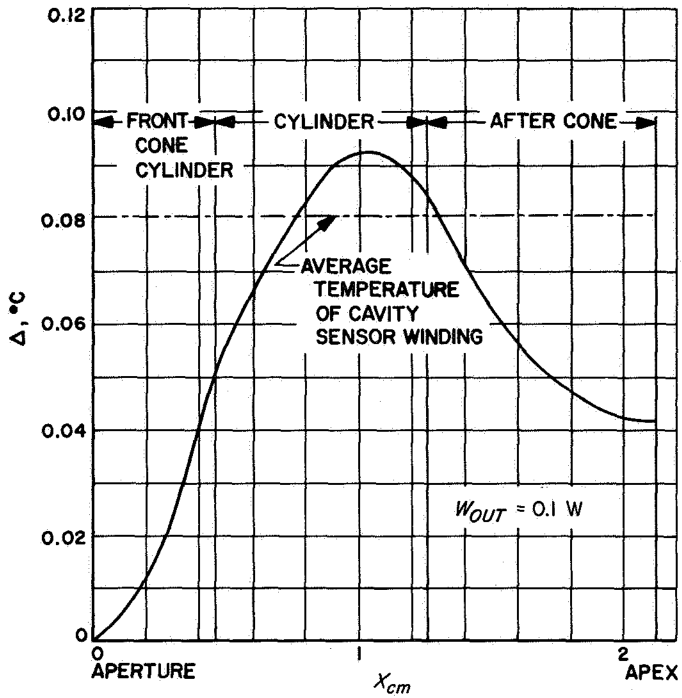

Fig. 5. Cavity temperature distribution

The silver cavity has a coefficient of thermal expansion of 18×10^{-6} per °C. Therefore, the aperture area is a function of the temperature as given by $A = 1.01630 + 0.00003812\,T\,(°C)$. Over the temperature range of about 25°C–200°C, the area changes about ½%.

Since all measurements were made at temperatures between 26° and 135°C, no correction had to be made because of the difference between the international practical temperature scale (IPTS) and the thermodynamic temperature scales. Table 1 gives the approximate quantitative information on the stray radiation effects, the variation of area with temperature, and the correction factor for the temperature distribution in the cavity.

Table 1. Correction quantities for measurement of Stefan–Boltzmann constant

Effect	26°C	83°C	115°C	135°C
Surround-radiation entering through annulus reflected into radiometer	95 μW	95 μW	95 μW	95 μW
Emitted radiation off radiometer reflected back into radiometer	13 μW	35 μW	40 μW	49 μW
Emitted radiation off cold cavity walls at 77°K into radiometer	17 μW	17 μW	17 μW	17μW
Radiative and conductive heat transfer from thermal guard to radiometer cavity	32 μW	65 μW	93 μW	114 μW
Variation of aperture area with temperature	1.0181 cm²	1.02025 cm²	1.02145 cm²	1.0222 cm²
Temperature drop between Pt winding and Ag in cavity (correction factor for radiation out the aperture)	0.9995	0.9991	0.9988	0.9984

Table 2. Error analysis

Parameter	Method of determining	Nominal value	Estimated error	Resulting error in value of σ_{meas} after making corrections, %
Area A, cm^2	Optical comparator	1.0173 at 26°C	0.1%	±0.1
Emissivity of coating	Calorimetric	0.945 in infrared	1%	±0.16
Temperature	Pt thermometer	492–684 Ω	0.04°C	±0.05
Electric power	E^2/R	0.045–0.16 W	0.000015	±0.02
Temperature drop (heater winding to cavity coating)	Measured, calculated	0.14°C drop at 0.16 W	0.01°C	±0.01
Heating of cavity by electrical leads	Calculated	46 μW at 0.16 W	5 μW	±0.003
Heat transfer to cavity by thermal coupling	Measured, calculated	62 μW	10 μW	±0.007
Cold cavity radiation at 77°K	Calculated	0.0002 W	20 μW	±0.01
Reflection back into radiometer	Calculated	0.00014 W	14 μW	±0.01
				Total 0.370%

VI. Error Analysis

Table 2 gives a listing of estimated errors in all the various parameters recognized as significant. These errors remain after all possible corrections have been made. If these errors are added up as a simple sum, they amount to a little over ⅓%. Actually the probable error is almost certain to be less than ⅓%, since surely some of the errors would cancel out some other errors. One might guess that the overall error is about ±¼%.

VII. Emissivity of Cavity

In the general expression for measuring the Stefan–Boltzmann constant,

$$\sigma = W/\epsilon T^4$$

the quantities W (W/cm^2) and T (°K) can each be measured by straightforward means. The ϵ, however, is not so easily measured. Principally, two methods can be used to measure ϵ.

One is the calorimetric method, in which the required amount of electrical heating is applied to a black-coated flat surface suspended in a cold cavity to maintain a given temperature of the emitting surface. This method yields the *product* $\epsilon_{cal}\,\sigma_{cal}$ for this coating at temperature equal to W/T^4. The value of σ_{cal} from this measurement is assumed to be unknown.

The other is the emissivity method, in which the measurement of ϵ is made by measuring the normal specular emissivity. In this method, the energy radiated at each wavelength in the normal direction by the coated surface at temperature T°K is compared with the energy radiated from a good black body (a cavity) at the same temperature and over the same wavelengths. The emissivity ϵ_λ is the ratio of the two measurements. Integration gives ϵ for the entire radiated spectrum. This value we call ϵ_{em}; there is no σ involved in ϵ_{em}.

The calorimetric method, being a more straightforward, simpler method, yields a result more accurate for our purpose than the emissivity method. However, it yields only a product, one term of which is the Stefan–Boltzmann constant, the quantity we wish to measure. To take advantage of the greater accuracy of the calorimetric method, and at the same time to avoid the involvement of σ, the following procedure of combining the two methods has been devised to give the most accurate value of ϵ for use in the measurement of σ_{meas}.

In applying the expression $\sigma = W_c/\epsilon T^4$ to the cavity-type radiometer (where W_c = watts radiated per cm^2 by the cavity radiometer and T = temperature °K), we must use the *effective* emissivity of the aperture. This is considerably closer to 1 than the emissivity of the coating, because of the cavity enhancement of emissivity (or absorptivity) of the coating. The effective emissivity is here designated as $[\epsilon_{coating}]_{eff}$. From the IBM 1620 computer results for the cavity of this radiometer, we obtain the equation

$$[\epsilon_{coating}]_{eff} = A\epsilon_{coating} + B \qquad (1)$$

Equation (1) represents the effective emissivity of the coating with an accuracy of closer than 2 parts in 10,000 over the range of $\epsilon_{coating}$ values involved when the best values of A and B are used. With these values inserted, the equation becomes

$$[\epsilon_{coating}]_{eff} = 0.1813128\,\epsilon_{coating} + 0.8195525 \tag{2}$$

Since $\epsilon_{coating}$ has been measured by two different methods, we distinguish between them as ϵ_{cal} for the calorimetric method and ϵ_{em} for the emissivity method. The calorimetric method can give only the product $\epsilon_{cal}\,\sigma_{cal}$, which is designated as E. Values for the following quantities have been measured: E, ϵ_{em}, A and B, T_c, and W_c, and are available for computing σ.

We can break the products forming E into ϵ_{cal} and σ_{cal}, if we have a suitable value for σ_{cal} that is of even nominal accuracy. Using ϵ_{em}, which is here used to give a provisional value, gives

$$\sigma_{em} = \frac{W_c}{[\epsilon_{em}]_{eff}\,T_c^4} = \frac{W_c}{(A\epsilon_{em} + B)\,T_c^4} \tag{3}$$

W_c and T_c were measured by the cavity radiometer.

We now assume, with hardly any loss of accuracy in the final result, that $\sigma_{cal} = \sigma_{em}$. Then, we get $\epsilon_{cal} = E/\sigma_{em}$. The cavity enhanced value of this is

$$[\epsilon_{cal}]_{eff} = A\,\frac{E\,(A\epsilon_{em} + B)\,T_c^4}{W_c} + B \tag{4}$$

After making all substitutions and simplifying, we get

$$\sigma_{meas} = \frac{W_c}{[\epsilon_{cal}]_{eff}\,T_c^4} = \frac{W_c^2}{E\,(A^2\,\epsilon_{em} + AB)\,T_c^8 + BW_cT_c^4} \tag{5}$$

The calorimetric emittance data on Parsons' black lacquer were determined and reported in March 1967 by TRW Systems on a JPL purchase order. The information on normal emittance of Parsons' black lacquer was supplied by Dr. D. L. Stierwalt of U.S. Naval Weapons Laboratory, Corona, California.

A program was set up for the IBM 1620 computer to calculate the effective emissivity as a function of the diffuse coating emissivity for the cavity of the standard radiometer. Basically, the method used was that of Truenfels (Ref. 3). A check computation using the exact integral equation method of Sparrow and Jonsson (Ref. 4) showed that, for the cavity used here, the simpler method of Truenfels was quite satisfactory.

VIII. Measurement of Stefan–Boltzmann Constant

As a test of the absolute accuracy of the radiometer, measurements of the Stefan–Boltzmann constant σ were made. These measurements were made with the help of the setup with the cold cavity shown in Fig. 4. This cavity was mounted in a vacuum chamber where the pressure never exceeded 5×10^{-6} torr. The cold cavity is a double-walled vessel (inner wall copper) with liquid nitrogen, LN_2, maintained between the walls to ensure that the temperature of the internal surface of the cold cavity was always at the boiling point of LN_2 (77°K). The back internal surface of the cold cavity consisted of large concentric V-grooves to give additional enhancement to the blackness of the Parsons' black lacquer coating the entire inner surface.

The radiometer, mounted in the aperture of the cold cavity, sees only the cold black walls. Almost all radiation emitted through the radiometer aperture is absorbed in the cold cavity. Practically no radiation comes off the walls of the cold cavity back into the radiometer. However, as previously explained, allowance is made for the small amounts of radiation that do get back into the radiometer.

The Stefan–Boltzmann constant relates the amount of energy per unit area radiated from a surface with a given emissivity and temperature to the fourth power. In our case, the emissivity is the effective emissivity of the radiometer aperture, and the temperature is that of the radiometer. Essentially, then, the measured Stefan–Boltzmann constant is

$$\sigma_{meas} = \frac{W_c}{A\epsilon_{eff}\,T_c^4} \tag{6}$$

where

W = watts radiated out through the aperture

A = area of aperture, cm^2

ϵ_{eff} = effective emissivity of aperture

T = temperature, °K

Measurements of σ are shown in Table 3.

Table 3. Measurements of Stefan–Boltzmann constant

Temperature, °C	λ_{max}, μm	ϵ_{cal}	σ, W/cm²/°K × 10^{-12}	Measured/theoretical
136	7.1	0.946	5.6735	1.0007
115	7.45	0.941	5.6850	1.0027
83	8.1	0.935	5.6888	1.0034
26	9.6	0.925	5.6992	1.0052
		Average	5.6866	1.0030
		Theoretical value	5.6697[a]	

[a]Value of $\sigma = 5.6697$ was adopted by NBS from the general physical constants recommended by NAS–NRC (Ref. 5).

The trend of decreasing disagreement as the temperature is increased is probably due to small, as yet unrecognized, systematic effects, or possibly due to under- or over-corrections. The measured quantities from which the Stefan–Boltzmann constant is obtained are smaller at the lower temperatures, hence, are less accurate than the larger quantities resulting from the higher temperature measurements. Nevertheless, all values of the Stefan–Boltzmann constant given here are in considerably closer agreement with the theoretical value than the most recently published measured values. Table 4 gives representative values of sigma obtained by several experimenters in previous years. All of these previously obtained values are higher than the theoretical value. While the value obtained in this report is also higher, it approaches the theoretical value more closely.

The measurements using the cavity radiometer are all made in the infrared range. The wavelength λ_{max} for maximum intensity of thermal radiation lies between 7 and 10 μm, as given by

$$\lambda_{max} = \frac{2981}{T\,(^\circ\mathrm{K})} \tag{7}$$

Table 4. Some previous measurements of the Stefan–Boltzmann constant

Experimenter	Year	Measured value	Measured/theoretical
Coblentz[a]	1915	5.722	1.009
Wachsmuth	1921	5.73	1.011
Hoffman	1923	5.764	1.017
Kussmann	1924	5.795	1.022
Hoare	1928	5.736	1.012
Mendenhall	1929	5.79	1.021
Muller	1933	5.771	1.017
Eppley and Karoli[b]	1957	5.772	1.017
Present work	1968	5.6866	1.003

[a]See Ref. 6.
[b]See Ref. 7.

The well known theoretical value σ_{th} is

$$\sigma_{th} = \frac{2\pi^5 k^4}{15 h^3 c^2} \tag{8}$$

where k = Boltzmann constant, h = Planck constant, c = velocity of light.

Substituting the presently accepted value of k, h, and c gives

$$\sigma_{th} = 5.6697 \times 10^{-12} \mathrm{W/cm^2/(^\circ K)^4} \tag{9}$$

The more closely the measured values of σ agree with σ_{th}, the greater the presumed accuracy of the radiometer and the greater the confidence that can be placed in measurements made with it.

The accuracy of an absolute radiometer of this sort can also be verified by irradiating it with a known intensity of radiation. Figure 6 shows an isothermal hohlraum (inside-black-coated isothermal cavity) with the radiometer in place. Since the blackness of the hohlraum is at least 0.999, the intensity of radiation into the radiometer is accurately σT^4_{hohl}. The pressure in the vacuum chamber is not permitted to exceed 1×10^{-5} torr, to eliminate the effect of gas conduction. No data verifying the accuracy of this radiometer by the hohlraum are given here since the accurate determination of the Stefan–Boltzmann constant using the cold cavity is presumed to justify confidence in its accuracy. However, tests made with this hohlraum always give results with less than 1% disagreement.

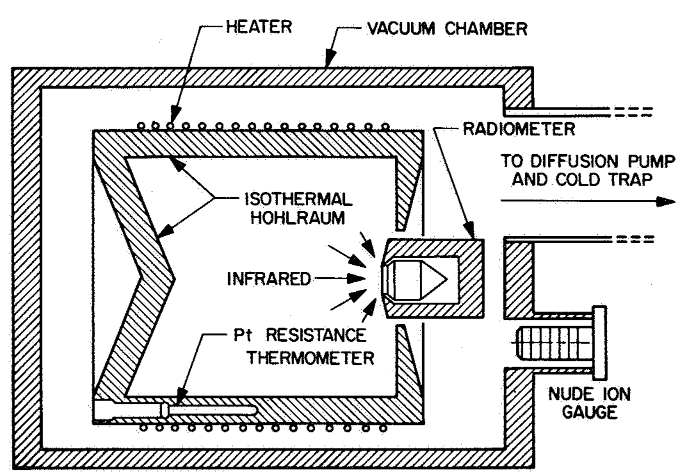

Fig. 6. Setup for verifying accuracy of absolute radiometers

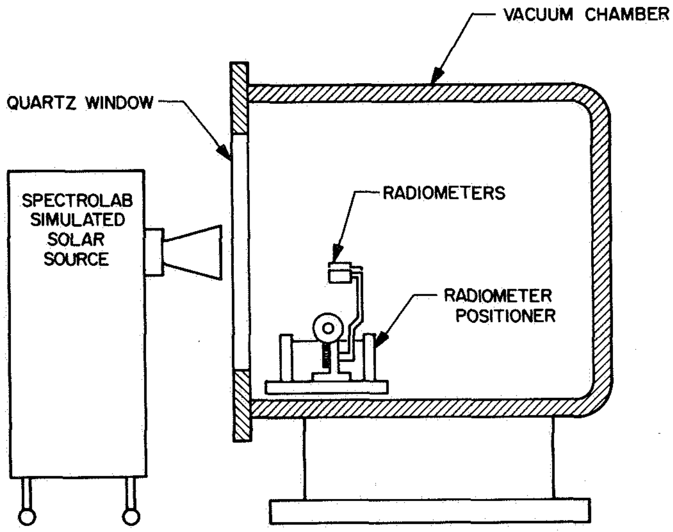

Fig. 7. Setup for radiometer calibrating

IX. Setup for Calibrating Radiometers

Most radiometers, particularly commercial radiometers, use a flat surface receptor. The spectral absorptivity of a flat surface depends entirely on the coating, which may not be uniform over the spectral range. In calibrating such a radiometer, it is almost necessary to use radiation with a spectrum closely matching that of the radiation to be measured. For spacecraft work, the source is usually the sun.

The setup shown in Fig. 7 shows the Spectrolab simulated solar source and the radiometers mounted on the radiometer positioner in the vacuum chamber. The chamber, 26 in. in diameter by 48 in. long, has the provision of cooling the walls down to the LN_2 temperature. The Spectrolab source intensity can be set at any desired level up to several solar (at 1 AU) intensities. The radiometer positioner permits locating radiometers in the beam center where the beam intensity is most uniform. Readings are taken of each radiometer, from which a calibration of the radiometer under test can be made.

Figure 8 shows a more detailed view of the radiometer positioner. A motor driving a worm rotates a worm gear to permit successive positioning of the radiometers in the center of the beam.

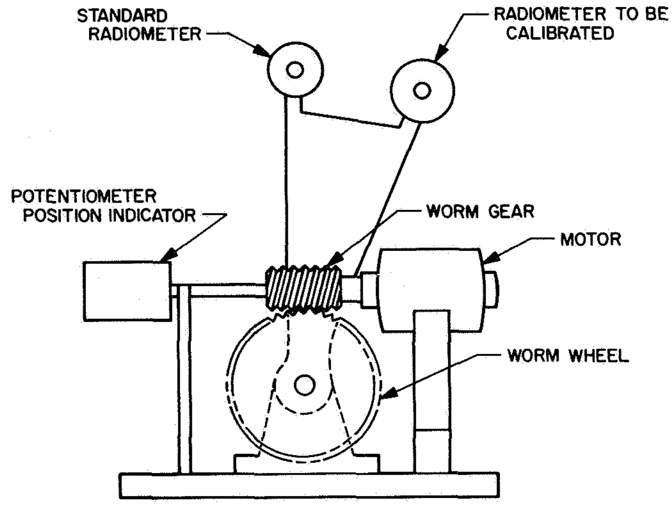

Fig. 8. Radiometer positioner

When the cavity radiometer is used to measure an unknown intensity, the thermal guard temperature is set high enough so that, when the cavity is at the same temperature, the net radiation through the aperture is *out*. The thermal guard sensor coil, being in intimate thermal contact with the thermal guard and having neither radiant heat exchange nor electrical heating, always accurately approaches the thermal guard temperature. The temperature taken up by the cavity, however, depends on the thermal coupling with the thermal guard, the net radiation out of the aperture, and the amount of electrical heating received. The heat transfer between cavity and thermal guard is made zero by maintaining the cavity at the exact temperature of the thermal guard. To achieve temperature equality, electrical heating equal to the difference between the radiation out of the aperture and the unknown radiation into the aperture must be added to the cavity. Hence, in terms of W/cm^2, the unknown radiation into the aperture can be calculated from

$$W_{unk} = T^4_{rad} - W_{elec} \tag{10}$$

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