JPL-81-42

JPL PUBLICATION 81-42

Radiometer for Accurate (±1%) Measurement of Solar Irradiances Equal to 10,000 Solar Constants

J. M. Kendall, Sr.

July 1, 1981

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

23.2083

JPL PUBLICATION 81-42

Radiometer for Accurate (±1%) Measurement of Solar Irradiances Equal to 10,000 Solar Constants

J. M. Kendall, Sr.

July 1, 1981

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

The research described in this publication was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

ABSTRACT

The 10,000-solar-constant radiometer has been developed for the accurate (±1%) measurement of the irradiance produced in the image formed by a parabolic reflector or by a multiple-mirror solar installation. This radiometer is water-cooled, weighs about 1 kg, and is 5 cm (2 in.) in diameter by 10 cm (4 in.) long. A sting is provided for mounting the radiometer in the solar installation.

The 10,000-solar-constant radiometer is capable of measuring irradiances as high as 20,000 solar constants (20,000 W/m^2).

The radiometer is self-calibrating. Its accuracy depends on the accurate determination of the cavity aperture, and absorptivity of the cavity, and accurate electrical measurements.

The spectral response is flat over the entire spectrum from far UV to far IR.

The radiometer responds to a measurement within 99.7% of the final value, within 8 s.

The radiometer is water-cooled, requiring a flow of about 4 l/min through the radiometer. During a measurement of the 10,000-solar-constant irradiance the temperature rise of the water is about 20°C.

The acceptance angle is such that the radiometer has perfect cosine response up to 60° off the radiometer axis.

DEFINITION OF SYMBOLS

A	area in square centimeters
Ag	chemical symbol for silver
AU	astronomical unit (average distance earth to sun)
C_f	correction factor, $C_f = 1/(A \times \alpha)$
cm	centimeters
e	base of natural logarithms
E	calibrating volts
I	calibrating current in amperes
IR	infrared radiation
K_{calib}	calibration constant
K_{Cu}	thermal conductivity of copper
l	liters
m	meters
ml	milliliters
mV_1	millivolts of output for zero irradiance input
mV_2	millivolts of output for irradiance being measured
q	equivalence
s	seconds
T	temperature in degrees Celsius
ΔT	change in temperature
UV	ultraviolet radiation
V	volts
W	watts
α	absorptivity
ε	emissivity
2.54	factor for converting inches to centimeters
4.182	factor for converting calories to watt seconds

CONTENTS

I. DESCRIPTION OF RADIOMETER 1-1

II. PROCEDURE FOR CALIBRATING THE RADIOMETER 2-1

III. CALIBRATION EQUIVALENCE OF ELECTRIC HEATING TO IRRADIANCE HEATING 3-1

IV. HEAT FLUX BETWEEN CAVITY AND RADIOMETER BODY 4-1

V. EXPERIMENTAL TEST OF EQUIVALENCE 5-1

REFERENCE 6-1

APPENDIX

CORRECTION FACTOR A-1

Figures

1-1. Assembled Radiometer 1-6

1-2. Exploded View of the 10,000-Solar-Constant Radiometer 1-6

1-3. Details of Radiometer 1-7

1-4. Minicontrol Unit for 10,000-Solar-Constant Radiometer 1-7

1-5. Schematic Wiring Diagram for 10,000-Solar-Constant Radiometer and Minicontrol Unit 1-8

3-1. Graphic Solution of Laplace's Equation for Calibrating Heat Flux in the Thermal Resistor 3-4

3-2. Graphic Solution of Laplace's Equation for Solar Heating of the Thermal Resistor 3-4

SECTION I

DESCRIPTION OF RADIOMETER

The 10,000-solar-constant* water-cooled radiometer shown in Figures 1, 2, and 3 is self-calibrating. An electric calibrating heater mounted on the receptor cavity provides heating that is accurately equivalent to heating from radiation that comes through the aperture.

In order to obtain the absolute calibration of the radiometer, the following information must be available:

(1) Value of the electric power fed to the calibrating heater.

(2) Area of the aperture.

(3) Value of the absorptivity of the cavity.

(4) Millivolt-output of the thermopile in response to the electric power fed to the calibrating heater.

The detailed procedure for calibrating the radiometer is given in Section II.

The spectral response of the radiometer is flat over the entire solar spectrum from the far UV to the far IR.

The acceptance angle of the radiometer is 60° each side of the axis, or 120° total. Within this acceptance angle the radiometer has accurate cosine response.

The 10,000-solar-constant radiometer is quite capable of making measurements of solar intensity as high as 20,000 solar constants. The highest so far actually measured was 15,000 solar constants at Edwards Test Station from the thermal bed collector (TBC) parabolic solar collectors there.

---

*The solar constant as measured out of the earth's atmosphere is very near 1371 W/m^2 at 1 AU. However, for practical purposes when considering solar energy, the extraterrestrial solar constant is never attained on the surface of the earth where (at the present time) all solar power installations are located. When an irradiance level of 1000 W/m^2 occurs on the surface of the earth, it is about as high as is usually observed.

For the sake of simplicity in this report, the value of the solar constant is taken as 1000 W/m^2, or 0.1 W/cm^2.

The response time is 1.3 s for 1/e response. Thus, if the radiometer is suddenly subjected to a constant irradiance, at the end of 1.3 s the radiometer will have responded to within 0.6321 of its final response. After six time constants (8 s) the response will be within 99.7% of the final value.

If the irradiance is varying at a uniform rate, either in time or with the radiometer's position in the solar image (as during a scan across the solar image), the radiometer response lags by 1.3 s. In other words, the value of response indicated is that which occurred 1.3 s earlier. With reasonable rates of scanning of the solar image, it is easily possible to correct for the effect of this time lag.

The radiometer has been designed for measuring solar irradiance in images that are of much larger diameter than the diameter of the radiometer (5.08 cm (2 in.)). Heat is absorbed over the entire surface of the radiometer, and adequate cooling is provided by the cooling water flowing through the radiometer body and heat shield.

During calibration it is necessary that a normal flow (4 l/min (1 gal./min)) of water be maintained through the radiometer in order to hold the radiometer temperature reasonably constant during calibration.

If, during the measurement of an intense solar image, the incoming water has been inadvertently put into the OUT tube instead of into the IN tube, the radiometer will operate at a much higher temperature during measurement of the high-intensity irradiance; it will be heated by the heat shield's absorbed heat, which heats the water before it flows through the radiometer. The accuracy of the measurements would thereby be degraded. Accordingly, it is absolutely necessary to make certain that the cooling water being fed into the radiometer is fed into the IN tube and not into the OUT tube.

It is very desirable that thermocouples be mounted on the IN and OUT water tubes to monitor the rise in temperature of the water flowing through the radiometer. There are two possible ways that the thermocouples could be mounted on these tubes. An insulated thermocouple could be mounted on each tube and the two temperatures measured independently. Or an insulated differential thermocouple could be mounted on the tubes and the difference of the temperatures measured.

The temperature rise of the water flowing through the radiometer while measuring 10,000 solar constants results from heat absorbed by both the heat shield and the radiometer. The frontal area of the heat shield is

$$A = \pi \left(\frac{5.08\ \text{cm}}{2}\right)^2 = 20.27\ \text{cm}^2$$

The absorptivity α of the silver plating of the heat shield at 0.5 microns is 0.08 (Ref. 1). (Note: The absorptivity of gold at 0.5 microns is much higher, about 0.3). If the intensity of radiation is 1000 W/cm^2 (10,000 solar constants) the front surface of the heat shield absorbs

$$0.08 \times 1000 \times 20.27 \times 1/4.182 = 388\ \text{calories/s}$$

If water flows through the radiometer at the rate of 4 l/min, then $4000 \div 60 = 66.66$ ml/s gives the flow rate through the radiometer and heat shield. This causes a rise in the temperature of water flowing through the radiometer, due to frontal surface heating, that can be calculated as $388 \div 66.66 = 5.8°\text{C}$.

Heat will also be absorbed by the cylindrical portion of the heat shield. The heat shield is 5.08 cm (2 in.) in diameter x 10.16 cm (4 in.) long. The area of the cylindrical portion of the heat shield is

$$\pi \times 5.08\ \text{cm} \times 10.16\ \text{cm} = 162\ \text{cm}^2$$

The absorptivity on the side of the cylinder will be much less than absorptivity on the frontal surface. The reduced absorptivity on the side takes place because of the almost grazing angles at which rays strike the cylindrical surface. It is here assumed that the absorptivity is effectively about 0.25 of the absorptivity for normal incidence, thus giving an effective absorptivity of $0.25 \times 0.08 = 0.02$.

It is important to note that the silver plating of the radiometer must not be touched with the fingers. Fingerprints would increase the absorptivity.

With effective absorptivity = 0.02, and the area of cylinder = 162 cm^2, then 1000/4.182 x 162 x 0.02 = 774.7 calories/s absorbed. Water flows through at the rate of 66.66 ml/s.

Temperature rise due to heat absorbed by the cylindrical portion of the heat shield can be calculated as ΔT = 774.66/66.66 = 11.62°C.

Some heat is also absorbed through the aperture, which has an area of 0.01072 cm^2. With irradiance of 1000 W/cm^2, the calories absorbed are 1000 x 0.01072/4.182 = 2.56 calories/s. Water flows through the radiometer at 66.66 ml/s. The temperature rise then is 2.56/66.66 = 0.0385°C. Total temperature rise is 5.8°C + 11.62°C + 0.0385°C = 17.5°C, the total expected temperature rise of water.

A copper constantan thermocouple has been mounted on the body of the radiometer inside the heat shield in order to monitor the body temperature and verify that cooling water is flowing at all times.

In the event that the cooling water supply fails, the radiometer would be destroyed in less than one minute. ON THIS ACCOUNT IT IS NECESSARY THAT THE TEMPERATURE OF THE RADIOMETER BE MONITORED DURING ALL TIMES THAT THE RADIOMETER IS EXPOSED TO CONCENTRATED SOLAR IRRADIANCE.

Supplied with the 10,000-solar-constant radiometer is the minicontrol unit shown in Figures 4 and 5. Additional equipment needed by the user of the 10,000-solar-constant radiometer is a high-quality voltage supply for calibrating power, capable of putting out 20 V maximum, and 0.5 amp maximum. This supply is connected to the minicontrol unit terminals marked POWER.

Also needed is a high-quality digital voltmeter (DVM) having a resolution of 1 μV. The DVM is connected to the minicontrol-unit terminals marked DVM.

The radiometer is connected into the minicontrol unit through the 10-pin connector. An extension cable can be used if necessary. The extension cable will have a mating 10-pin connector for the connector shown in the photo in Figure 1. The extension cable can be of considerable length, up to 200 m if necessary. Of course, the cable must be free of electromagnetic interference over its entire length. The minicontrol unit, the DVM, and the power supply can then be located at any convenient location.

All connections to the minicontrol unit are made on the back side. On the front side is the three-position switch and the ON and OFF switch for the calibrating current, and thereby the power, to the radiometer.

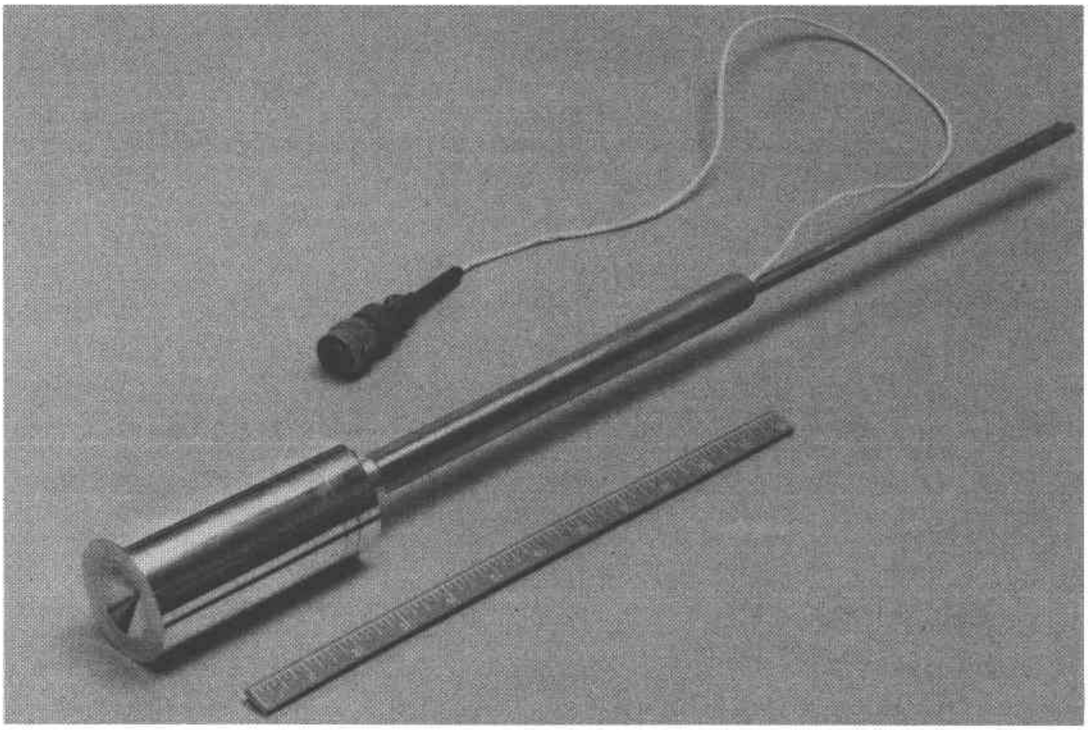


Figure 1-1. Assembled Radiometer

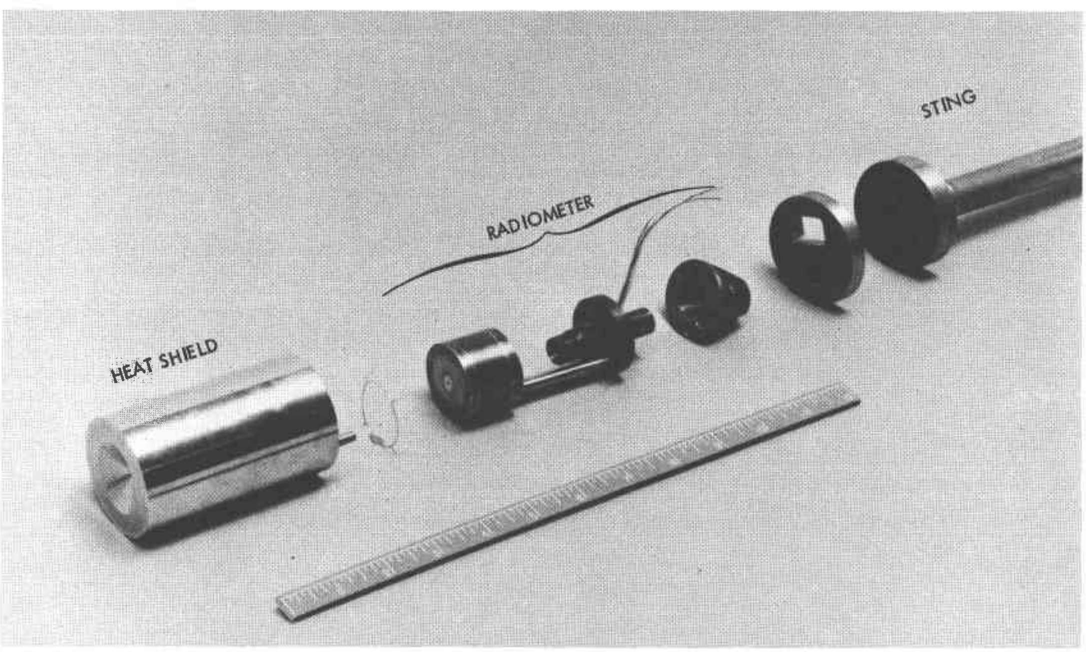


Figure 1-2. Exploded View of the 10,000-Solar-Constant Radiometer

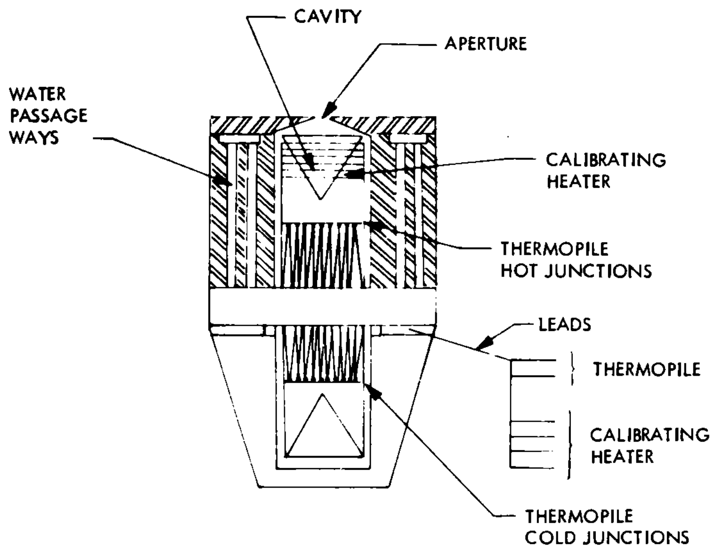


Figure 1-3. Details of Radiometer

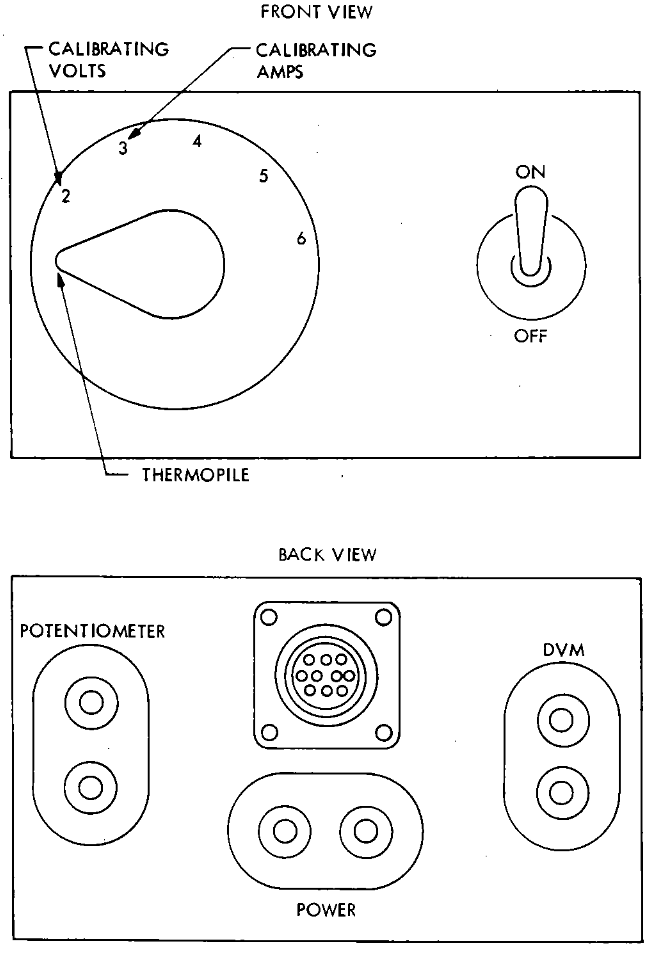


Figure 1-4. Minicontrol Unit for 10,000-Solar-Constant Radiometer

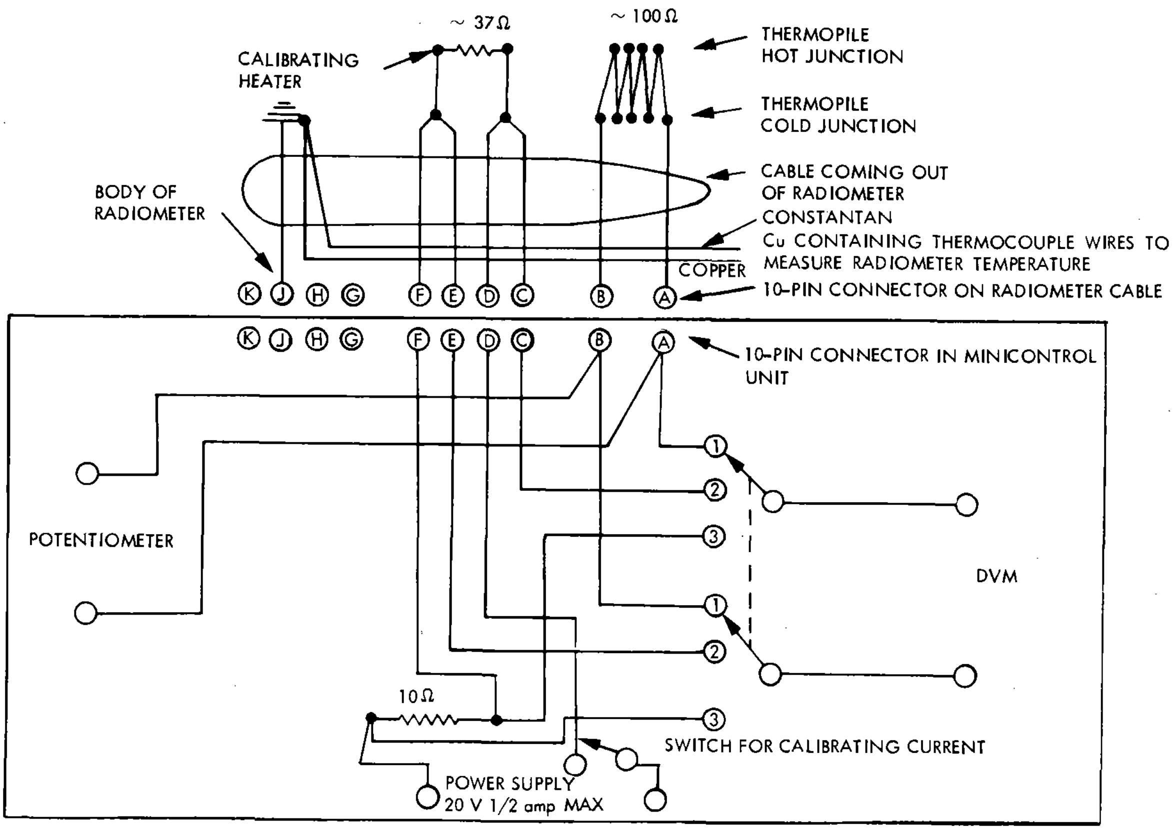


Figure 1-5. Schematic Wiring Diagram for 10,000-Solar-Constant Radiometer Minicontrol Unit

SECTION II

PROCEDURE FOR CALIBRATING THE RADIOMETER

With the radiometer connected to the minicontrol unit, as explained above, and with 4 l/min of water flowing through the radiometer, and with no irradiance applied to the aperture, the radiometer can then be calibrated.

The first operation is to note and record mV_2, that is, any zero or "tare" reading shown on the DVM from the radiometer with no irradiance applied to the aperture. When making this observation of the tare, the minicontrol-unit 3-position switch is on position 1, and the power switch is in the OFF position (down). The mV_2 voltage should not exceed 2 or 3 μV.

After the tare reading has been determined, the power switch is turned to ON and the 3-position switch is turned to position 2. The power-supply voltage output as shown by the DVM is adjusted to the desired value (which should never be over 20 V). The value of the calibrating voltage E is then recorded, and the 3-position switch turned to position 3 to record the calibrating current I. The DVM reading is 10 times the current in amperes since the DVM reads the voltage drop across a 10-ohm precision resistor. The values of E and the current I are recorded.

Then the 3-position switch is turned to position 1, and the mV_1 output on the thermopile is recorded. There should be a time interval of at least 10 s after the calibrating voltage has been set to the desired value, before the mV_1 value is recorded. The purpose of this interval is to permit the cavity to reach its final temperature before mV_1 is recorded. Then the power switch is turned to the OFF position.

The calibration constant K_{calib} can then be calculated as follows:

$$K_{calib} = \frac{E \times I \times C_f}{(mV_1 - mV_2)_{calib}}$$

where

E = calibrating voltage

I = calibrating current in amperes

C_f = correction factor = $\frac{1}{A \times \alpha}$ = 940,200 (see Appendix)

mV_1 = mV thermopile output from applied calibrating power

mV_2 = mV zero reading or tare

α = absorptivity of cavity = 0.990

The calibration constant K_{calib} so obtained should generally be very near to the value of 1,370,000.

It is worth noting that the radiometer is not perfectly linear in response. Measuring higher levels of calibrating power or higher levels of irradiance will result in a slightly <u>decreased</u> K_{calib}. This is caused by the sensitivity of the thermopile elements (chromel-constantan) <u>increasing</u> slightly as the temperature at which the thermojunctions are operating is raised.

Having obtained the calibration constant K_{calib}, one can then proceed to the measurement of the irradiance.

The formula for the measured irradiance is

$$W/m^2 = K_{calib} \; (mV_1 - mV_2)_{meas}$$

The value of $(mV_1 - mV_2)_{meas}$ should generally be around 10 mV for 1,370,000 W/m^2 (which is ~13,700 solar constants where 1 solar constant is taken as 1000 W/m^2.)

SECTION III

CALIBRATION EQUIVALENCE OF ELECTRIC HEATING TO IRRADIANCE HEATING

The knowledge of how equivalent electric heating is compared to radiation heating is very important. The cavity can be heated either by electric power during calibration, or by incoming radiant flux through the aperture during irradiance measurement.

The calibrating heater mounted on the cavity produces a heat-flux pattern very similar to the pattern of radiant heating. This is especially true of the heat-flux streamlines in the thermal resistor in the vicinity of the thermopile hot junctions.

The heat produced either by electric heating or by radiant heating mostly travels to the water-cooled body of the radiometer through the copper thermal resistor. Some of the flux, however, is conducted to the radiometer body through the air between the cavity and the body, thus bypassing the thermopile.

A plot of the heat-flux streamlines in the thermal resistor shows that the temperature drop in the part of the thermal resistor where the thermopile hot junctions are located is essentially identical, whether from a radiant source of heat or from an electric heating source.

Figures 3-1 and 3-2 show the steady-state heat-flux streamlines (or stream tubes) through the thermal resistor. Figure 3-1 shows the pattern resulting from electrical heating of the cavity during calibration, while Figure 3-2 is the pattern resulting from solar heating during irradiance measurement.

These patterns of streamlines are graphic solutions of the Laplace equation $\nabla^2 T = 0$. Associated with the flux lines are the isothermal surfaces, which are normal to the flux lines, and indicate $\partial T/\partial X$.

The temperature is always increasing in the direction toward the conical cavity, away from the heat sink. This is true because heat only flows from the conical cavity end of the thermal resistor to the heat sink.

Also shown in Figures 3-1 and 3-2 is the location on the thermal resistor of the hot junctions of the thermopile.

It is important to note in these figures that the pattern of streamlines and associated isothermal surfaces between the thermopile hot junctions and the heat sink is for all practical purposes identical, whether from electrical heating or from solar heating. The significance of this circumstance is that the electrical heating in the thermal resistor at the location of the hot thermopile junctions is the same whether from electrical or solar heating, and therefore the electrical heating is accurately equivalent to solar heating. This is the basis on which the accuracy of the radiometer depends, along with accuracy of area of aperture, absorptivity of the cavity, and electrical measurements.

Hence no allowance need be made in the Correction Factor, C_f, for the equivalence; i.e., q = 1.

The following calculation shows that about 99.3% of the heat flux is through the copper thermal resistor and about 0.7% through the air between the cavity and the water-cooled body. It makes very little difference whether the heat comes from electric heating, or from radiant heating; i.e., the slight flux through the air is nearly the same for both types of heating, and has a negligible effect on the accuracy of the radiometer since the effect of this heat flux is calibrated out. Hence there is no loss of accuracy due to heat flux through the air.

The copper thermal resistor is 1.27 cm (0.5 in.) in diameter and 2.54 cm long. The thermal conductivity of copper is 0.93 calories/cm^2/cm/s/°C or 3.88926 W/cm^2/cm/°C.

An irradiance level of 1000 W/cm^2 (10,000 solar constants) gives a temperature drop in the thermal resistor of ΔT, (where heat flux = 10.72 W).

The temperature drop ΔT in the thermal resistor is

$$\Delta T = \frac{\text{length x W}}{\text{A x } K_{cu}}$$

where

length is in cm

A_{Cu} = area in cm^2

K_{Cu} = thermal conductivity of copper $W/cm^2/°C$

W = heat flux at 10,000 solar constants

$$\Delta T = \frac{2.54 \text{ cm x } 10.72 \text{ W}}{3.88926 \text{ x } 1.2667 \text{ cm}^2}$$

and

$$\Delta T = 4.35195°C$$

temperature drop across the thermal resistor.

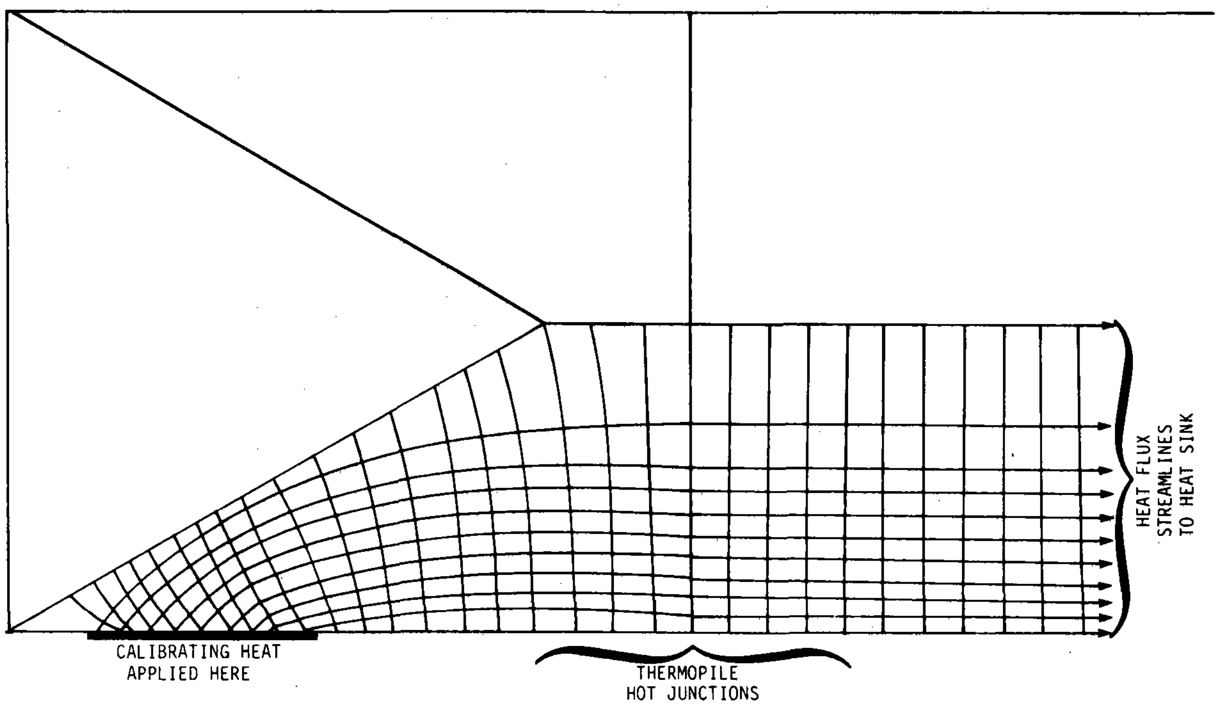


Figure 3-1. Graphic Solution of Laplace's Equation for Calibrating Heat Flux in the Thermal Resistor

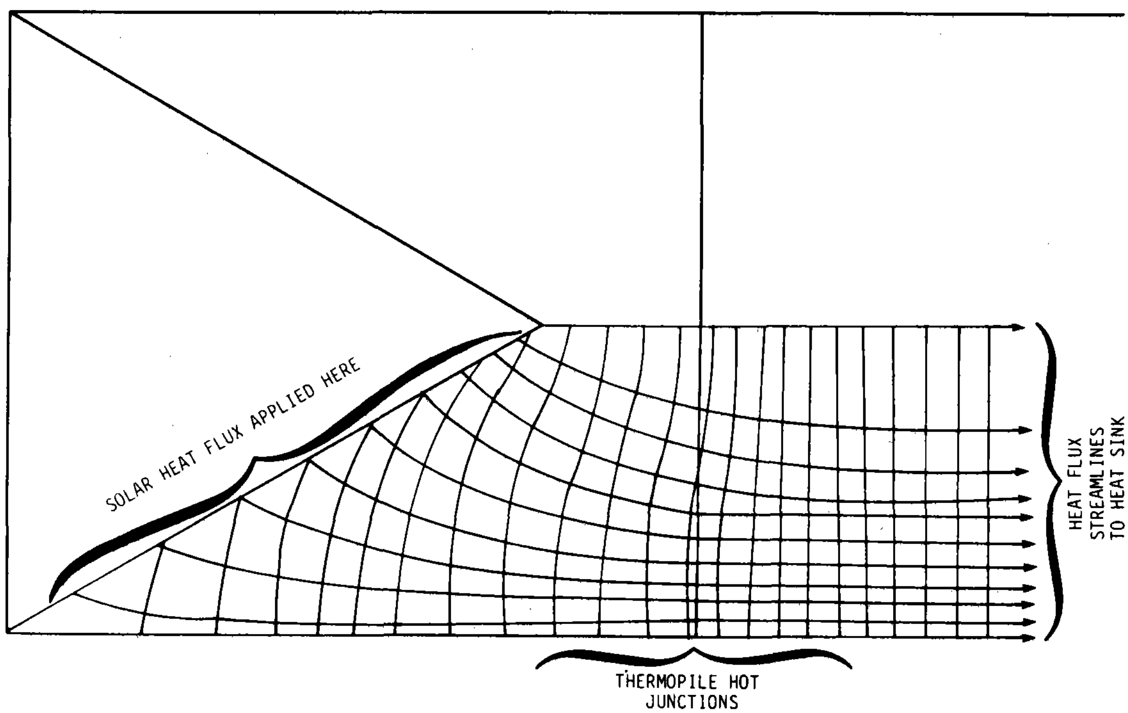


Figure 3-2. Graphic Solution of Laplace's Equation for Solar Heating of the Thermal Resistor

SECTION IV

HEAT FLUX BETWEEN CAVITY AND RADIOMETER BODY

As stated above, the air between the cavity and the radiometer body conducts a certain amount of the heat that enters through the aperture or that is produced by electric heating during calibration. The separation between the cavity and the radiometer body is 0.1143 cm. The air conduction area, A, is 2 x 1.27 cm x π = 7.9796 cm^2.

The heat flux through the air is

$$W = \frac{A \times \Delta T \times Kair}{cm_{separation}}$$

$$W = \frac{7.9796 \times 4.35195 \times 0.000058 \times 4.182}{0.1143} = 0.0737 \text{ W}$$

Heat flux through the aperture = 10.72 W.

The proportion of heat flux through the air is then 0.0737/10.72 = 0.007, or 0.7%.

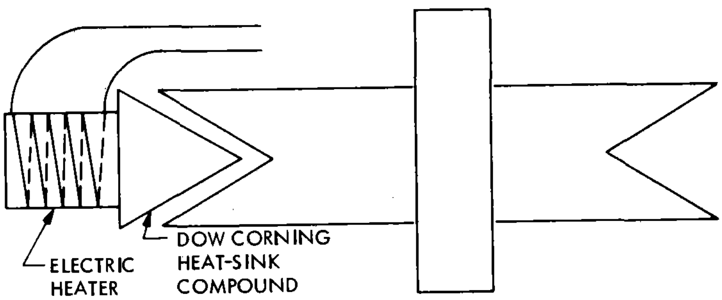
SECTION V

EXPERIMENTAL TEST OF EQUIVALENCE

The following experiment was performed to determine the equivalence of electric heating to irradiance heating.

An electric heater designed to heat the conical cavity in the same manner as radiant heat was constructed and tested.

The electric heater was shaped as shown in the sketch below:



The copper conical point was made to fit snugly into the cavity. In addition, Dow Corning heat-sink compound was put over the surface of the heater cone, so that there would be an almost perfect heat transfer from the electric heater into the conical cavity.

The radiometer was first calibrated using the radiometer built-in calibration heater and then calibrated again using the external electric heater shown in the above sketch.

The same electric power was then applied to the external conical electric heater. The thermopile mV output was found to be within 0.015% of being equal to that of the built-in calibrating heater.

As a result of this experiment, as well as the calculation of the amount of heat going through the air from the cavity to the body of the radiometer, it has been concluded that the equivalence of electric heating with radiant heating is essentially perfect.

REFERENCE

1. Pepperhoff, Werner, Temperature Strahlung, Verlag von Dr. Dietrich Steinkopff, Darmstadt, 1956, p. 53 (in German).

The correction factor C_f is obtained using the area of the aperture, the absorptivity of the cavity, and the equivalence of electric heating and radiant heating.

Whether heat flux into the cavity is from electric heating or from radiation heating, the heat flux through the air is the same with either type of heating. The equivalence is good and has been assumed to be perfect, as already mentioned above, in determining the correction factor

$$C_f = \frac{1}{A \times \alpha \times q} = \frac{1}{A \times \alpha}$$

where

A = area of aperture

α = absorptivity of cavity

q = equivalence = 1

$$C_f = \frac{1}{\pi(1/2 \times 0.046 \times 2.54)^2 \times 0.990 \times 1} = 94.209 \text{ for W/cm}^2$$

0.01072

and therefore the value of C_f for W/m^2 = 942,090.

NASA—JPL—Coml., L.A., Calif.