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MONITORED BACKGROUND RADIOMETER*

by

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INTRODUCTION

The infrared (IR) testing of the Olympus thermal model at the David Florida Laboratory in Ottawa has provided Spar Aerospace Ltd a capability to perform cost-effective thermal balance testing of satellites and satellite components.

One of the requirements of the IR test technique is to accurately measure the radiant flux absorbed by the spacecraft surfaces. Most of the commercially available radiometers did not meet the high accuracy and quick time response required, or were too complex to implement in the test set up because of the presence of fluid loops or power supplies. To overcome this obstacle, a high-accuracy, monitored background radiometer (MBR) was developed at Spar Aerospace Ltd for the measurement of absorbed radiation heat flux encountered during IR thermal vacuum testing of spacecraft (S/C). This paper describes the design, development, calibration of this radiometer.

BACKGROUND AND DESCRIPTION

Various radiometer designs have been used for IR testing. Flat plate calorimeters, which represent one class of radiometer, consist of a control surface with a thermocouple and insulation on its backside (1,2). Many attempts have been made to optimize its design but the major drawbacks of this type of sensor remain the inadequate time response, and the accuracy in conditions different from the calibration conditions due to heat leaks from the sensor plate to the background environment.

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Thermopile type devices have also been used but they require fluid loops or an external power source and therefore increase the complexity of the test set up (3).

A third type of radiometer currently available is the controlled background radiometer. It consist of a sensor surface mounted to a body which is kept at a constant temperature via a heater and control circuit. This type of radiometer also requires an external power source.

As an extension to the above concepts, the MBR was developed to account for heat transfer from the back surface of the sensor plate. This is accomplished by monitoring the temperatures of both the sensor plate and body.

The MBR consists of an aluminum sensor plate (SP) and body. Aluminum was chosen because its high thermal diffusivity ensures uniform temperatures and quick time responses. The SP is attached to the body with insulating teflon stand-offs to limit heat flow, and its outside surface is covered with the same material as the surface whose absorbed flux is to be measured.

To accommodate the various coatings with which the sensor is to be covered, two basic versions of the MBR are currently in use as shown in Figure 1. Rectangular control materials like second surface mirrors, kevlar or graphite fiber epoxy (GFEC) samples can be bonded to rectangular MBR's, and paint or kapton films can be applied to the cylindrical MBR's. Except for their shape, the construction of the two types of MBR is identical.

A flexible foil heater is bonded to the inner surface of the SP to supply the heat input required for calibration, and an aluminized mylar sheet covers the exposed surface of the heater to limit radiation heat loss from the back of the SP to the body.

A very important aspect of the MBR design was to insulate the back of the SP as well as possible from the body and the environment to ensure that the ratio of the radiation heat transfer from the top SP surface to the heat transfer from the back of the SP was large. At the same time, to accurately account for heat transfer from the back of the SP, it was necessary design the MBR in a way that the heat transfer from the back of the SP was mainly to the body with little or no heat loss to the environment. This was done by bonding all the sensor plate leads to the body before they were fed through the body wall. The length of the leads bonded to the body was determined by analysis to prevent any conductive heat loss from the sensor plate to the environment.

Black paint is applied on the inside surface of the body to limit the reflection of incident radiation passing through the gap between the SP and body as shown in Figure 2.

Two high accuracy thermocouples, respectively soldered to the SP and the body, are used to monitor temperatures.

PRINCIPLE OF OPERATION

In a conventional flat plate calorimeter the flux absorbed by the sensing surface equals the flux radiated and conducted to the surrounding environment. The sensing surface reaches an equilibrium temperature, from which the absorbed flux can be computed through a calibration curve. For the computation to be valid the radiometer must be used in conditions equivalent to the calibration conditions. Otherwise, the heat leaks to the environment implicitly included in the calibration curve cause an error to be introduced in the computation. Another peculiarity of a conventional flat plate calorimeter is that the flux measurements can be made only when the temperature of the sensing plate has reached steady state.

The MBR can be classified as a flat plate radiometer but differs from the conventional type in that a second thermocouple is used to measure the background temperature. With this information, both the heat leaks to the background environment and the energy stored in the SP can be evaluated. These values are then used in the heat balance equation of the sensor plate to determine the heat flux absorbed. Because of this the sensor can be accurately used in a wide ranging temperature environment and the absorbed heat flux can be calculated even when the sensor plate temperature has not reached steady state.

A heat balance performed on the sensor plate yields:

$$Qcap + Qcond + Qrad/in + Qrad/out + Qabs = 0 \qquad (1)$$

where Qcap represents the energy stored in the sensor plate, Qcond the SP-to-body conductive heat transfer through the leads and stand-offs, Qrad/in the radiative heat exchange between the sensor and body, Qrad/out the radiative heat loss from the SP to the environment, and Qabs the radiant energy absorbed by the sensor plate.

To characterize the thermal behavior of the radiometer the MBR was mathematically modelled with two nodes. One of the node represents the sensor plate and the second one the body. A two-node model representation was chosen based on the simplifying assumption that temperatures are uniform along the SP and body. The assumption that material properties (specific heat, conductivity and surface emissivity) are constant with temperature was also made. Thus, equation 1 can be rearranged:

$$F1\ dT/dt + F2(Ts-Tb) + \sigma F3(Ts^{4}+Tb^{4}) + \sigma As\ \varepsilon_{s}(Ts^{4}) - Qabs = 0 \qquad (2)$$

where Ts and Tb are the sensor and body temperatures respectively. F1, F2, and F3 are calibration factors which are experimentally determined by measuring Qabs and the resulting Ts and Tb for different Qabs values.

CALIBRATION

The purpose of the calibration activity was to evaluate factors F1, F2 and F3 of equation 2.

The calibration tests were performed in a thermal vacuum (TVAC) chamber with LN2 cooled shrouds. For each MBR, five different power levels were supplied to the SP calibration heater to simulate the heat absorbed by the sensor plate, and the SP and the body temperatures were recorded as a function of time.

For the calibration process the heat absorbed by the sensor plate Qabs can be expressed to account for heat radiation from the chamber wall:

$$Qabs = Qm + \sigma As\,\varepsilon_{s}\ Tw^{4} \qquad (3)$$

where Qm is the measured heater power and Tw the chamber wall temperature, and Qabs here is the simulated absorbed flux.

Equation 2 can then be rewritten:

$$Qcalc - Qabs = 0 \qquad (4)$$

where:

$$Qcalc = F1\ dT/dt + F2\ (Ts-Tb) + \sigma F3\ (Ts^{4}-Tb^{4}) + \sigma As\ \varepsilon_{s}\,Ts^{4} \qquad (5)$$

and Qcalc is the heat flux value calculated from the SP and body temperatures.

For each MBR the difference between the measured absorbed flux (equation 3) and the calculated flux (equation 5) at time i is defined:

$$\phi_i = Qabsi - Qcalci \qquad (6)$$

Function Φ is the summation of the square of the ϕ_i's .

$$\Phi = \sum_{i=1}^{n} (\phi_i)^2 \qquad (7)$$

where n is the number of selected data points for each MBR.

F1, F2, and F3 were computed by minimizing Φ with the constraint that upper and lower bounds were defined for F1, F2, and F3. These bounds were centered about nominal values which were physically representative of the SP capacitance, conductive conductance and radiative conductance from the SP to the body. These bounds were necessary, because a least square minimization without constraints on the independent variables can result in calibration factor values with no physical significance.

The minimization of function Φ was performed using a simplex optimization code (4).

ERROR ANALYSIS

The total uncertainty of the MBR arises from the calibration uncertainty and the uncertainty for usage outside the calibration conditions.

CALIBRATION UNCERTAINTIES

The total calibration uncertainty of the MBR can be expressed as the sum of the RMS deviation of the calculated flux from the measured absorbed flux, and the uncertainties in the absorbed flux measurement.

DEVIATION OF THE CALCULATED FLUX

The goal of the calibration was to obtain an expression which could be used to calculate the flux absorbed by the sensor plate by measuring the SP and body temperatures.

The deviation of the calculated flux was defined as the RMS value of the difference between the calculated and the measured absorbed flux. This deviation can be attributed to the thermocouple uncertainty, the optimization process tolerance, and the simplifying assumptions of the MBR mathematical model.

The typical RMS deviation of an MBR was found to be less than 1% when calibrated with quasi-steady state data ($dT/dt \leq 0.5$ C).

UNCERTAINTY IN THE ABSORBED FLUX MEASUREMENT

The uncertainty in the measured absorbed flux is due to inaccuracies in measuring the heater power and the sensor plate surface area.

The measured absorbed flux consists of the heater power and the test chamber wall radiation (equation 3). The absorbed heat flux density is calculated from:

$$qabs = Qabs/As \tag{8}$$

where As is the sensor plate surface area.

The inaccuracy in the absorbed flux density can be calculated from:

$$\Delta qabs/qabs = \Delta Qabs/Qabs + \Delta As/As \tag{9}$$

where (from equation 3)

$$\Delta Qabs/Qabs = (\Delta Qm + 4\,\sigma\, As\, \epsilon_s Tw^3\, \Delta Tw)/Qabs \tag{10}$$

The contribution of the Tw inaccuracy to the measured absorbed flux inaccuracy can be neglected, and equation 10 is rewritten:

$$\Delta Qabs/Qabs \simeq \Delta Qm/Qm \tag{11}$$

The power dissipated by the heater is measured from the voltage drop across the heater V1 and across a shunt resistance V2 such that:

$$Qm = V1*V2/R \tag{12}$$

where R is the shunt resistance value. The error in R is $\leq$ 1%, in V1 << 0.1%, and in V2 $\leq$ 1%. Thus the total error in Qm is

$$\begin{aligned} \Delta Qm/Qm &= \Delta V1/V1 + \Delta V2/V2 + \Delta R/R \\ &\simeq 2\% \end{aligned} \tag{13}$$

The error on the sensor area was estimated to be $\Delta As/As = 0.5\%$ such that the uncertainty on the absorbed flux density due to the heater power and sensor area measurement uncertainties is 2.5%.

The total calibration uncertainty is the sum of the measured flux inaccuracy (2.5%) and the deviation of the calculated flux from the measured (< 1%). This results in a total calibration uncertainty of less than 3.5% for the MBR.

UNCERTAINTIES FOR USAGE OUTSIDE CALIBRATION CONDITIONS

An additional source of error during the usage of the MBR is the heat transfer between the sensor plate and the environment via the gap between the SP and body. This error was shown to be < 0.1% by analysis.

During the usage of the MBR the temperature difference Ts-Tb varies between 0°C and 30°C, which is less than the temperature difference in calibration, where Ts-Tb varied from 100°C in rapidly changing conditions to 40°C at steady state. Larger Ts-Tb values in calibration result in higher accuracies of the calibration factors F2 and F3. However, as can be seen from equation 1, for the limiting case when the Ts-Tb values approach 0 the contribution of factors F2 and F3 is decreased, in which case the absorbed heat flux value can be calculated from:

$$qabs = \sigma \varepsilon_s Ts^4 \qquad (14)$$

The total error is then given by:

$$\Delta qabs/qabs = \Delta \varepsilon_s / \varepsilon_s + 4 \Delta Ts/Ts, \qquad (15)$$

Therefore an uncertainty of ± 1% in ε_s, and of ± 0.2°C in Ts results in a total error of ± 1.2% for Ts = 130°C and ± 1.5 % for Ts = -100°C. Usually during testing, Ts-Tb varied from 0 to 30°C at steady state resulting in a total error between ± 3.5% and ± 1.5%.

RESULTS

Results of a typical MBR calibration are presented in Table 1. It shows that the RMS error between the calculated and measured flux is 0.85 % for a range of flux values varying from 8 % to 100 % of a solar constant (absorbed).

Results from an actual test where the MBR was used to measure the absorbed flux radiated from IR lamps are presented in Figure 3. It shows the time response of the MBR to a step change of 320 W/m**2 in the incident flux intensity. For curve 1 the capacitance term F1 was included in the flux calculation process, and for curve 2 it was omitted. At the first data point available, after 5 minutes, the flux prediction was 2.8% off for curve 1 from the final stabilized value of 700 W/m**2, and it was 17% off for curve 2 where the flux prediction was made without the capacitance term.

CONCLUSION

This paper has presented the design, development and calibration of a simple , light and accurate radiometer. This radiometer can be used in infrared or solar illumination testing of spacecraft, and requires no fluid loops or power supplies. Results highlighting the quick time response of the device to step heat inputs and the accuracy over a wide range of incident flux were presented.

The monitored background raiometer design was shown to be adequate and reliable during the infrared testing of the Olympus (5) satellite thermal model where 80 MBR's were used to measure the flux absorbed by spacecraft surfaces.

SYMBOLS

As	sensor plate surface area (m**2)
F1	capacitance calibration factor
F2	conduction calibration factor
F3	radiation calibration factor
q	power density (watts/m**2)
Q	power (watts)
T	temperature (Kelvin)

Greek Symbols;

ε	surface emissivity
σ	Stefan-Boltzman constant

Subscripts:

abs	absorbed
b	body
calc	calculated
cap	capacitance
cond	conductive
m	measured
rad	radiative
s	sensor plate
w	test chamber wall

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Qm/As (W/m)	93	166	538	897	1220	COMBINED FOR ALL DATA
N	7	11	13	26	11	68
RMSe	2.1	0.59	0.75	0.67	0.4	0.85

NOTES:

1) Qm/As is the measured flux in the calibration heater divided by the sensor surface area

2) N is the number of data points at each power level

3) RMSe is the RMS error in per cent between Qm and Qcalc

Table 1 - Typical Calibration Results Versus Power Level

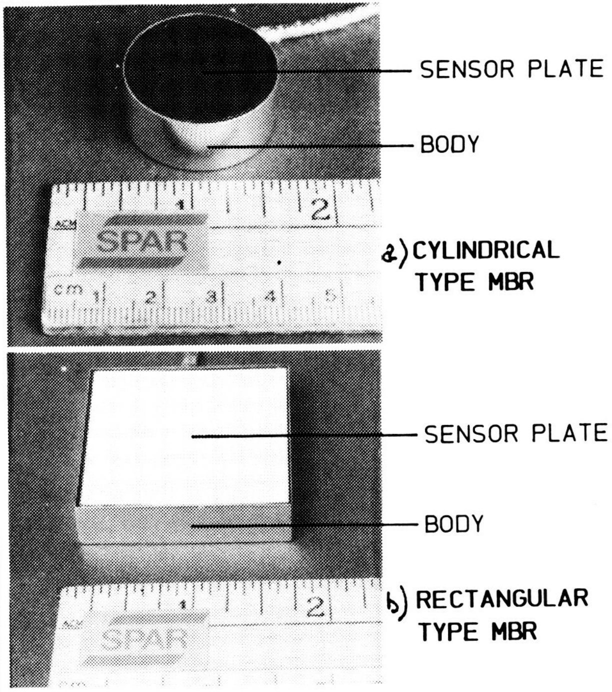

Figure 1 - MBR Types

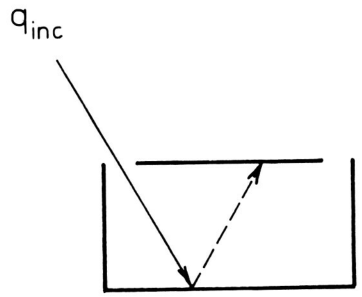

Figure 2 - Reflected Incident Radiation

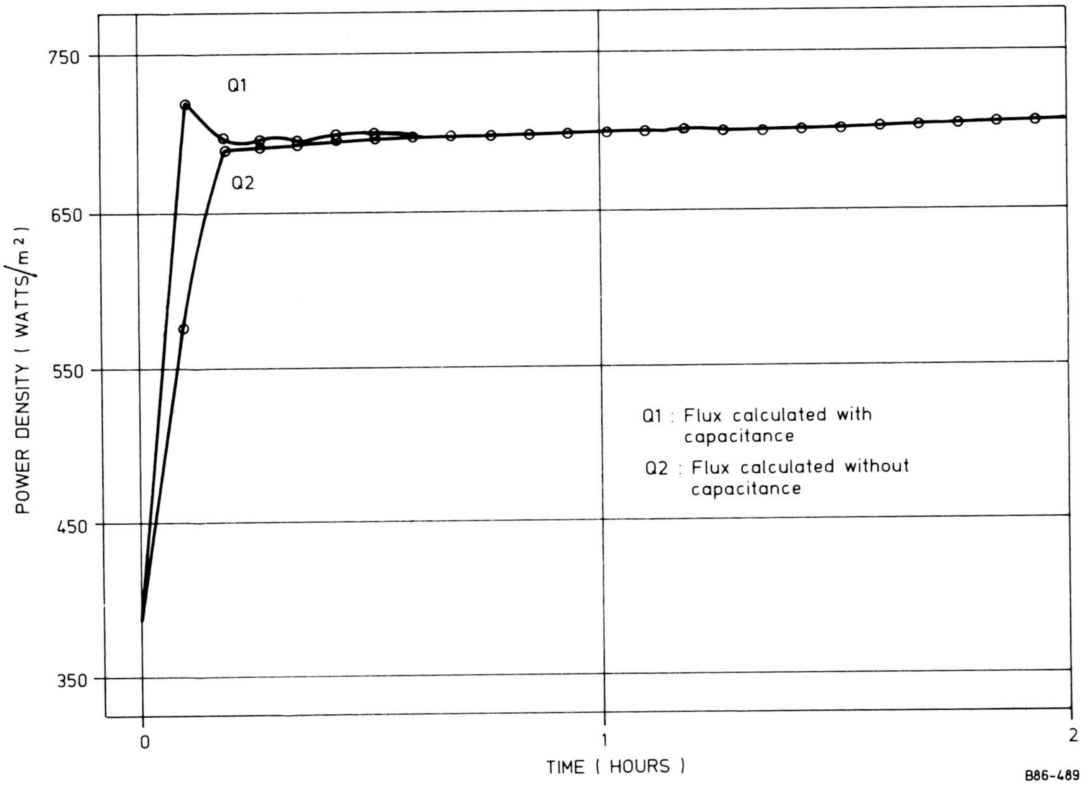

Figure 3 - Response to Infrared Lamp Step Heat Input