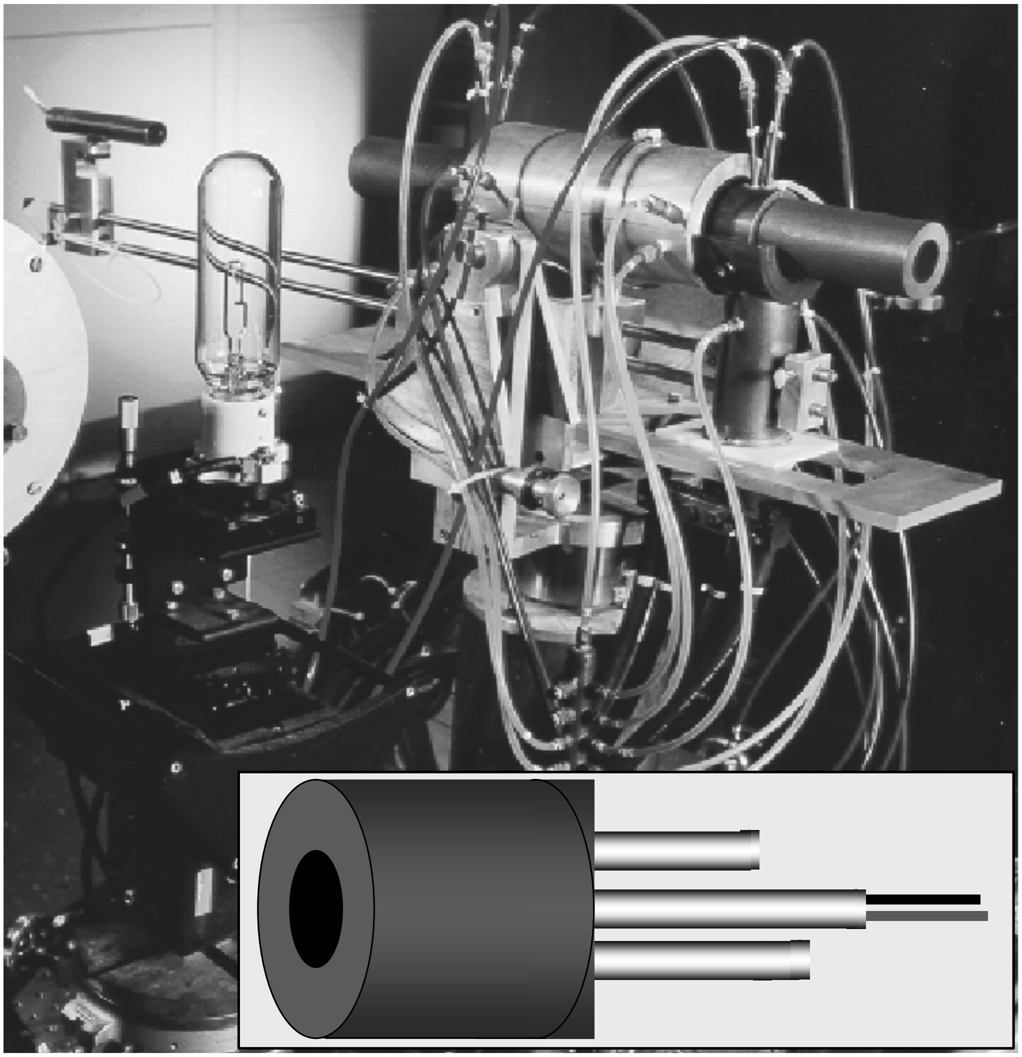
Heat-Flux Sensor Calibration



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David P. Dewitt, and Robert D. Saunders

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NIST MEASUREMENT SERVICES:
Heat-Flux Sensor Calibration

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PREFACE

The calibration and related measurement services of the National Institute of Standards and Technology are intended to assist the makers and users of precision measuring instruments in achieving the highest possible levels of accuracy, quality, and productivity. NIST offers over 300 different calibrations, special tests, and measurement assurance services. These services allow customers to directly link their measurement systems to measurement systems and standards maintained by NIST. These services are offered to the public and private organizations alike. They are described in NIST Special Publication (SP) 250, NIST Calibration Services Users Guide.

The Users Guide is supplemented by a number of Special Publications (designated as the "SP250 Series") that provide detailed descriptions of the important features of specific NIST calibration services. These documents provide a description of the: (1) specifications for the services; (2) design philosophy and theory; (3) NIST measurement system; (4) NIST operational procedures; (5) assessment of the measurement uncertainty including random and systematic errors and an error budget; and (6) internal quality control procedures used by NIST. These documents will present more detail than can be given in NIST calibration reports, or than is generally allowed in articles in scientific journals. In the past, NIST has published such information in a variety of ways. This series will make this type of information more readily available to the user.

This document, SP250-65 (2004), NIST Measurement Services: Heat-Flux Sensor Calibrations is a new publication. It covers the calibration of heat-flux sensors (test number 35101C in SP250, NIST Calibration Services Users Guide). Inquiries concerning the technical content of this document or the specifications for these services should be directed to the author or to one of the technical contacts cited in SP250.

NIST welcomes suggestions on how publications such as this might be made more useful. Suggestions are also welcome concerning the need for new calibrations services, special tests, and measurement assurance programs.

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ABSTRACT

The Optical Technology Division at NIST is developing techniques to calibrate heat-flux sensors to meet the current calibration needs of U.S. science and industry. An outcome of this effort is a calibration service offered now through NIST Calibration Services to calibrate heat-flux sensors up to 50 kW/m^2. The calibration, performed using the 25 mm Variable-Temperature Blackbody as a broadband radiant source, transfers calibration from a primary electrical substitution radiometer standard to the heat-flux sensor. In contrast to other calibration methods using temperature traceability, the objective of this calibration is to provide heat-flux traceability to NIST primary standards. This report gives the calibration principle, the associated laboratory procedure, safety, and typical calibration results of a Schmidt-Boelter type heat-flux sensor.

KEY WORDS: Blackbody, heat flux, sensor

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1. Introduction

The National Institute of Standards and Technology initiated a competence program in the year 1995 to develop techniques for calibration of high heat-flux sensors. An outcome of the competence program is the capability to calibrate heat-flux sensors with traceability to the High Accuracy Cryogenic Radiometer. The current range of calibration, performed with a 25 mm Variable-Temperature Blackbody (VTBB), is up to 50 kW/m^2. The calibration technique [1] uses an electrical substitution radiometer (ESR) as the transfer standard.

The calibration is now available to the user community through the NIST Calibration Services. Several sensors calibrated so far show good repeatability of the technique with an expanded uncertainty of 2 %, corresponding to a coverage factor of $k = 2$ or 95 % confidence level. This report gives a description of the equipment used in the calibration, laboratory procedure currently in practice, and an evaluation of the uncertainties in the measurement process.

2. Measurement principle

Radiant heat flux is essentially a radiometric quantity representing the broadband irradiance or flux received per unit area by a surface. For a radiometer placed in front of a radiant source, the governing measurement equation for the radiometer signal output (V) is

$$V = G \cdot \iint dxdy \iint \cos\theta d\theta d\phi \int d\lambda\, L(x,y,\theta,\phi,\lambda) \cdot R(x,y,\theta,\phi,\lambda) \ , \tag{1}$$

where x and y specify the location on the radiometer on which radiant flux is incident, θ and ϕ specify the direction from which radiant flux is incident on the radiometer, λ is the wavelength, L is the radiance of the incident radiant flux, R is the responsivity of the radiometer, and G is the amplifier gain. The integrals are performed over the entire area of the radiometer upon which radiant flux is incident, over all directions from which radiant flux is emitted by the source and received by the radiometer, and over all wavelengths to which the radiometer is sensitive. Any temporal dependence is excluded in Eq. (1) since heat flux measurements are typically performed under steady-state conditions.

For a given range of directions for the source and radiometer, integration of Eq. (1) over the angles yields

$$V = G \cdot \iint dxdy \int d\lambda\, E(x,y,\lambda) \cdot R(x,y,\lambda) \ , \tag{2}$$

where E is the irradiance. Note that the integral over angles to obtain Eq. (2) depends on both the size of the source and the field-of-view of the radiometer. Also, the incident radiant flux at the reference plane of the radiometer is measured, not the absorbed flux. Effects from a window or the absorptance of the detector are included in the responsivity.

Integrating Eq. (2) over the area of the radiometer, assuming the responsivity is uniform over the area, yields

$$V = G \cdot A \cdot \int d\lambda\, \overline{E}(\lambda) \cdot R(\lambda) \ , \tag{3}$$

where A is the area of the radiometer over which radiant flux is incident and $\overline{E}$ is the average irradiance. The average irradiance is used in Eq. (3) because in nearly all measurement situations the irradiance has a spatial distribution that is a maximum at the center of the radiometer. Therefore, the average irradiance will depend upon the size of the radiometer.

Finally, a typical radiometer used as a heat-flux sensor has a responsivity that is independent of wavelength, so Eq. (4) reduces to

$$V = G \cdot A \cdot \overline{R}\int d\lambda \; \overline{E}(\lambda) \;, \tag{4}$$

where $\overline{R}$ is the average responsivity over wavelength. The product of the amplifier gain, area, and the average responsivity is the quantity calibrated for heat-flux sensors.

3. Traceability

Heat-flux sensor calibrations are traceable to the primary detector standard for radiometric measurements. However, because of the range of radiant powers between the primary standard and the heat-flux sensor (microwatts to watts), the traceability chain involves multiple steps, shown in Fig. 1.

The primary detector standard is the High Accuracy Cryogenic Radiometer (HACR) [2], which uses low-power lasers to calibrate the responsivity of primary trap detectors. These primary trap detectors are used in turn in the Spectral Comparator Facility (SCF) [3], a lamp-illuminated monochromator system, to calibrate the responsivity of quantum efficient detectors (QED). The maximum radiant power for a QED is about 2 mW, which precludes its use to calibrate heat-flux sensors, for which the radiant power is several orders of magnitude greater.

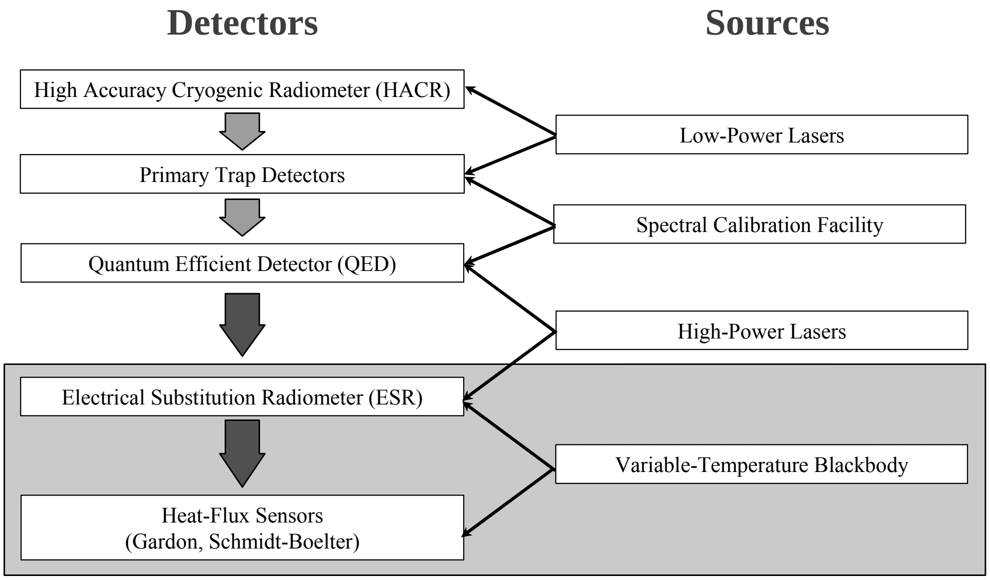

Figure 1. Traceability of heat-flux sensor calibrations

A cavity-type ESR operating at room temperature is the transfer standard for heat-flux sensor calibrations. The QED is used to calibrate the radiant power of a high-power krypton laser, which is then used to calibrate the responsivity of the ESR. The final step in the traceability chain, described in detail in the following, transfers the calibration from the ESR to the heat-flux sensor using the VTBB.

4 Heat-flux sensor calibration

4.1 Variable-Temperature Blackbody

The VTBB is a thermally insulated graphite tube cavity heated electrically. Figure 2 shows a schematic layout of the blackbody and the test arrangement for calibrating a typical heat-flux sensor. Direct resistance heating of the tube using large AC currents at low voltages provides for quick heating and cooling. The heated tube cavity diameter is 25 mm, and the heated section is 28.2 cm long with a center partition, 0.3 cm thick.

The water-cooled end caps of the heated tube connect directly to the heating electrodes. The design provides a sharp temperature gradient between the end cap and the graphite heater element, and a uniform temperature distribution along the cavity-length of the graphite tube. An optical pyrometer measures the blackbody temperature by sensing radiation from one end of the furnace. A Proportional-Integral-Derivative (PID) controller regulates the power supply to maintain the furnace temperature to within ± 0.1 K of the set value. The maximum recommended operating temperature for the blackbody is 2973 K.

With the standard extension installed and the sensor located 1.25 cm from the exit, the distance between the sensor and the end of the heated section will be 17.4 cm. However, the maximum flux-level at this location is limited. With a shorter-extension installed, the sensor location can be closer to the blackbody radiating-cavity resulting in higher flux-levels. At a distance of 1.25 cm from the exit, the maximum flux-level is approximately 50 kW/m^2. Away from the aperture, the irradiance decreases rapidly, and is about 10 kW/m^2 at a distance of 62.5 mm.

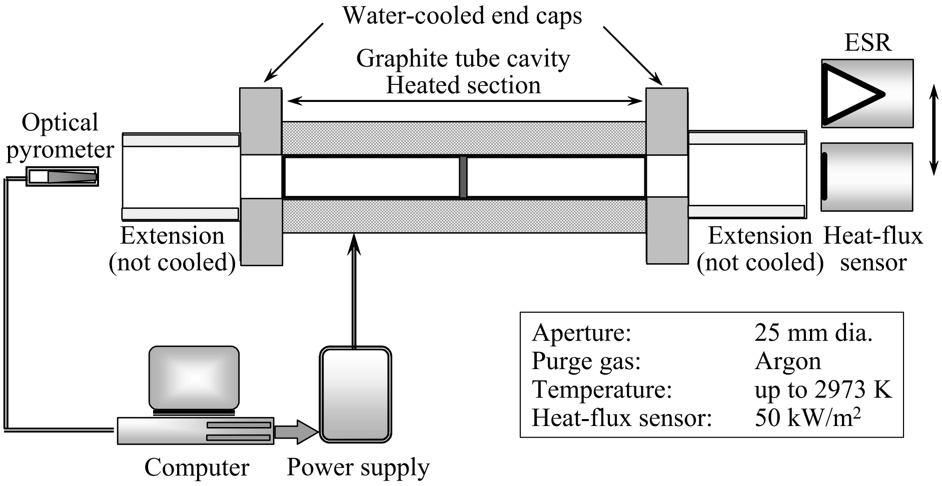

Figure 2. Schematic layout of the VTBB

4.2 Transfer Standard Radiometer

The ESR transfer standard is a water-cooled Kendall radiometer [4],[1] shown in Fig. 3. The ESR absorbs the incident radiant flux almost completely because of the blackened cavity walls and multiple reflections within the cavity. The equivalent electrical power, measured by the current through a precision resistor, required to produce the same cavity temperature rise as the radiant flux, is the power of the radiant flux. The maximum incident radiant power for the ESR is 4.2 W and the aperture area is 1 cm^2. The time constant ($1/e$) for a step change in irradiance is 6 s. For large changes in irradiance, it is necessary to allow about 60 s for stabilization before taking measurements [5]. The manufacturer stated uncertainty of this radiometer is 0.5 %, as determined by an experimental measurement of the Stefan-Boltzmann constant. Tables 1a and 1b give the radiometer and the control unit specification, respectively.

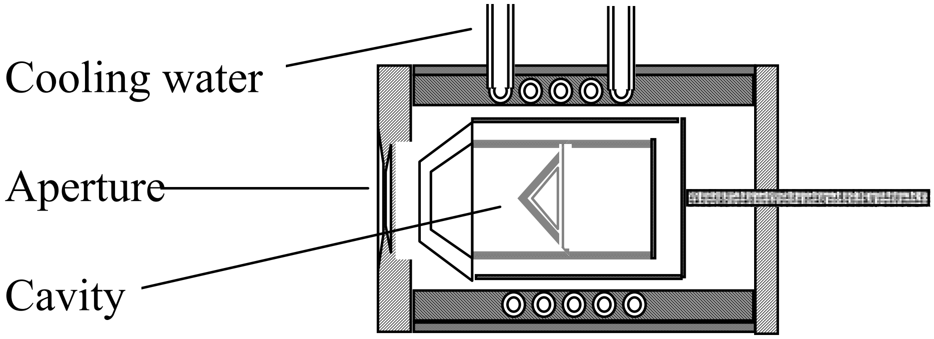

Figure 3. Transfer standard Kendall radiometer layout.

Table 1a. ESR transfer standard specifications

Type	Kendall MK-IV, S/N 47601
Range	0.04 kW/m^2 to 42 kW/m^2
Accuracy	± 0.5 % of reading ± 0.2 mW/cm^2
Time constant	6 s ($1/e$)
Sensitivity	> 10 mV/(W/cm^2)
View angle	No view limiting aperture
Calibration heater	230 W, 150 mA maximum
Outer surface coating	0.005 mm pure gold plate
Mounting	5 mm metric machine screw
Cabling	4 m long, Bendix PT06A-14-19P
Size	51 mm diameter, 76 mm long
Weight	0.9 kg

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[1] manufactured by Technical Measurements Inc., La Cañada, CA. Certain commercial equipment, instruments, or materials are identified in this paper to foster understanding. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment are necessarily the best available for the purpose.

Table 1b. ESR transfer standard control unit specification

Kendall MK-I Radiometer Control Unit (Serial No. 17601)	
Accuracy	Absolute measurement uncertainty < ± 0.5 % full scale
Zero drift	< ± 0.1 % per month of full scale
Time constant	< 2 s (1/*e*)
Display	± 39 999 counts normal range
Output: Analog	± 10V, ± 5 mA
Output: Digital	Buffered, stored, parallel BCD
Size	43 cm wide, 14 cm high, 46 cm deep
Weight	10 kg

4.3 ESR Calibration

The self-calibration feature of the ESR facilitates absolute measurements of the incident irradiance within the stated experimental uncertainties. However, other uncertainties related to cavity heating and long-term drift make it desirable to characterize the radiometer independently by comparison to a QED with a high-power krypton laser [1]. The calibrations from three different sets of measurements of the ESR showed a high degree of linearity with a regression factor of 0.999. The calibration constant agreed to within 1 % between two tests conducted a year apart. From these tests, the relation between the corrected (E_c) and the indicated (E_i) ESR readings is obtained as [Appendix A]

$$E_c = 0.9855 E_i \ , \tag{5}$$

All of the calibrations performed with the VTBB use this relation to provide consistency and establish the long-term repeatability of the calibration technique. The uncertainty associated with the ESR calibration is of Type-B [7] in determining the total measurement uncertainty.

4.4 Reference Sensor Calibration

The heat-flux sensor calibration procedure is repeatable as demonstrated from periodic calibrations of a reference sensor. This reference sensor calibration, performed before calibrating a customer-supplied sensor, ensures that the long-term stability of the calibration procedure is monitored. The Schmidt-Boelter type reference sensor, shown in Fig. 4, works on the principle of axial one-dimensional heat flow. It measures the temperature difference across a thin, thermally insulating layer to determine the incident heat flux. Due to the axial flow of heat, the temperature distribution across the sensing surface is uniform. The maximum body temperature is limited to about 200 ^{o}C when the sensor is not water-cooled. For applications involving continuous use, the sensor body is water-cooled. Reference [6] gives a detailed description of Schmidt-Boelter sensor operation.

Table 2 lists the specifications of the Schmidt-Boelter reference sensor. The body diameter and length are 5 mm and 9 mm, respectively. The design heat-flux value of 110 kW/m^2 is representative of the calibration range of interest. A number of calibrations of this sensor performed over a period of time cover different locations from the blackbody aperture, and different blackbody temperature ranges. Figure 5 shows the results of the calibration for incident heat flux of up to 50 kW/m^2.

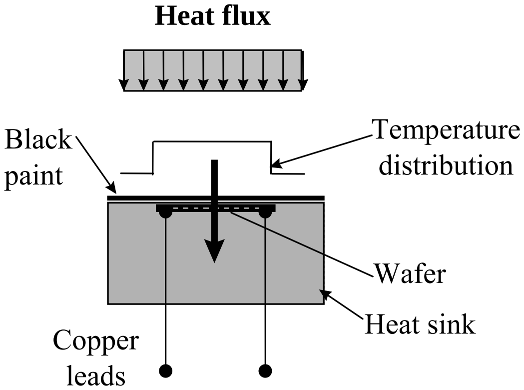

Figure 4. Schematic representation of a Schmidt-Boelter sensor

Table 2. Reference Schmidt-Boelter sensor specification

Type	Schmidt-Boelter
Manufacturer	Medtherm Corp.
Model	12-10-0.35-75-20841J
Serial Number	#94761
Design flux	110 kW/m^2
Body diameter	5 mm
Body length	9 mm
Thermocouple	Shielded copper wires
Body	not water-cooled

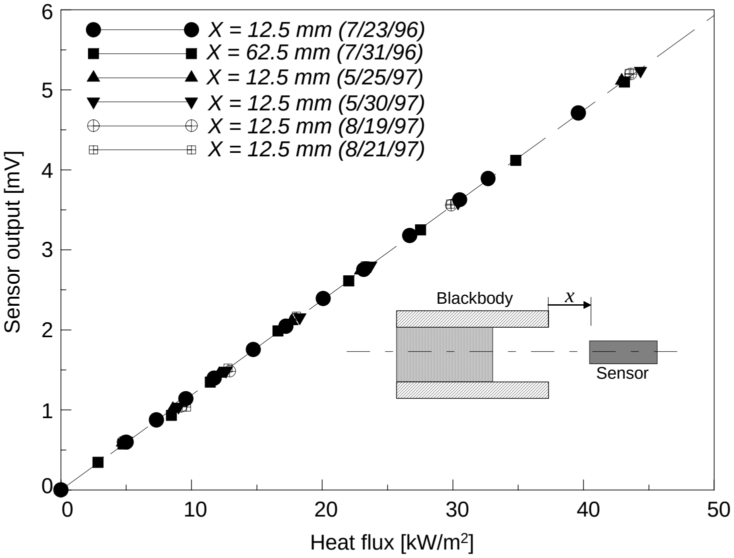

Figure 5. Typical calibration results on the reference sensor.

All of the calibrations show a linear response of the sensor, with regression factors close to unity. Table 3 summarizes the results of the sensor responsivity calculations from linear regression analysis of the measured data. The responsivity values from several calibrations agree to within ± 0.7 % of the mean value. The good repeatability of the data supports the long-term stability of the transfer standard ESR, the reference sensor, and validates the VTBB transfer calibration technique. The standard deviation of responsivity determined from these measurements is an additional source of uncertainty when determining the total uncertainty of other calibrated heat-flux sensors.

Table 3. Summary of linear regression results on the reference sensor

Schmidt-Boelter Sensor (NIST): #94761, 12-10-0.35-75-20841J					
Test		**Distance**	**Intercept**	**Responsivity**	
No.	**Date**	***x* mm**	**kW/m^2**	**mV/(kW/m^2)**	**Deviation %**
1	23-Jul-96	12.5	0.0018	0.1189	-0.18
2	31-Jul-96	62.5	-0.0687	0.1184	-0.59
3	25-Apr-97	12.5	0.0608	0.1190	-0.04
4	30-Apr-97	12.5	0.0186	0.1181	-0.83
5	19-Aug-97	12.5	0.0077	0.1191	0.06
6	21-Aug-97	12.5	0.0202	0.1197	0.50
7	9-Nov-97	12.5	0.1003	0.1200	0.76
8	11-Nov-97	140	-0.0186	0.1180	-0.92
9	2-Jun-98	12.5	0.1348	0.1189	-0.16
10	16-Jul-98	12.5	0.0318	0.1199	0.71
11	17-Jul-98	62.5	0.0053	0.1187	-0.31
12	27-May-98	12.5	0.1149	0.1188	-0.27
13	29-May-98	12.5	0.2526	0.1183	-0.62
14	9-Jul-00	12.5	-0.0644	0.1201	0.86
18	22-Jul-01	12.5	0.0300	0.1186	-0.38
19	16-Aug-01	12.5	0.0364	0.1183	-0.62
20	5-Nov-01	12.5	0.0374	0.1211	1.70
21	6-Nov-01	12.5	0.0472	0.1198	0.60
22	18-Aug-02	12.5	-0.0006	0.1187	-0.27
Arithmetic mean			**0.0393**	**0.1191**	**0.00**
Standard Deviation			**0.0732**	**0.0082**	**0.69**
Standard Error			**0.0168**	**0.0019**	**0.16**

5. Calibration Procedures

The following specifies the stepwise procedure for calibrating heat-flux sensors with reference to the transfer standard radiometer using the VTBB.

5.1 Pre-Calibration inspection

The continuity of the sensor signal leads is checked and the value of the resistance, using a multi-meter, is recorded. The condition of the high absorptance coating on the sensor surface is inspected. If the conditions indicate the need for repainting, the customer is informed. The surface is not repainted at NIST.

5.2 Additional test equipment

Heat-flux sensors have a wide range of configurations. Standard mounting blocks and sensor holders are readily available for mounting the 25 mm diameter Gardon and 5 mm diameter Schmidt-Boelter sensors. However, some sensors may require special mounting arrangement. If so, a suitable accessory is designed for fabrication in advance of the calibration. The cooling requirements for the sensor, and the need for any special instruments like amplifiers, thermometers etc., are checked.

5.3 Calibration

Appendices A and B detail the heat-flux sensor calibration procedure. The reference standard radiometer (ESR) requires self-calibration prior to testing. Appendix A describes the self-calibration procedure. The self-calibration, at a radiant power of approximately 920 mW, is necessary to be consistent with the radiometer settings during calibration and use. Self-calibration at other radiant powers within the range of the radiometer is acceptable as long as the instrument settings during calibration and use are identical. Appendix B describes the heat-flux sensor calibration procedure at about 8 to 10 heat flux levels covering the calibration range. Table 4 shows the required temperature settings of the VTBB and corresponding heat-flux level at the sensor, for different locations of the sensor from the blackbody aperture.

Table 4. Heat-flux values at sensor location for different blackbody temperatures

***X* = 12.5 mm**		***X* = 62.5 mm**		***X* = 140 mm**	
Temperature [K]	Heat-flux [kW/m^2]	Temperature [K]	Heat-flux [kW/m^2]	Temperature [K]	Heat-flux [kW/m^2]
1573	8.84	1823	5.09	1073	0.32
1773	13.07	1963	7.43	1573	1.30
1973	18.91	2108	9.72	1973	2.99
2123	24.19	2233	11.91	2273	5.11
2273	30.88	2373	14.94	2473	7.04
2273	30.91	2573	20.38	2573	8.21
2373	36.19	2773	27.08	2673	9.52
2453	41.17				
2553	47.31				
2653	54.81				

X: Distance from blackbody aperture to sensor location

The heat-flux values listed are approximate and are useful in deciding the optimum sensor location from the blackbody aperture to cover a desired calibration range. The actual heat flux values may vary over the long term because of aging of the graphite heating element and other factors. However, this variation will have no effect on the actual calibration. The transfer standard radiometer measurements give the actual heat flux values. Prior to calibrating the test sensor, it is desirable to perform a calibration on the reference Schmidt-Boelter sensor described in Sec. 4.4.

5.4 Post-Calibration inspection

The heat-flux sensor is removed from the test installation after disconnecting the signal lead, thermocouple lead, and cooling water. The signal lead continuity and the resistance are checked, as well as the condition of the high absorptance coating to ensure that it did not changed during the calibration process.

5.5 Data reduction

Appendix C gives the data reduction procedure. An EXCEL spreadsheet or other standard statistical software may be used. The measured heat flux is calculated from the measurement equation,

$$E_{\mathrm{c}} = \frac{V_{\mathrm{s}} - V_{\mathrm{d}}}{S} \ , \tag{6}$$

where V_{s} is the measured sensor signal in V or mV, V_{d} is the measured dark signal of the sensor in V or mV, and S is the measured responsivity of the heat-flux sensor expressed in mV/(W/cm^2) or mV/(kW/m^2). The regression curve fit for the data is generally linear with regression factors close to unity. In some cases, a small degree of non-linearity may appear at low heat flux levels, when calibrating with the sensor located close to the blackbody aperture. This non-linear effect is due to argon purge-gas flow effects, and reduces with increasing heat flux. The calculated responsivity depends largely on the readings at high heat flux levels.

5.6 Calibration report

A calibration report is prepared as per the standard format, shown in Appendix D, including any special comments specific to the calibration and measurement uncertainties.

6. Measurement uncertainty

The measurement uncertainty evaluation follows the procedure described in reference [7]. The individual uncertainty at each stage of the calibration is either of Type-A, evaluated using statistical methods, or Type-B, evaluated by other means[2]. The combined uncertainty is the root-sum-square of the individual uncertainty values. In the transfer technique calibration of heat-flux sensors, the measurement uncertainties accrue at two different stages. First, the uncertainty associated with the calibration of the transfer standard radiometer; and secondly, the uncertainty arising while calibrating the heat-flux sensor with the VTBB.

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[2] Previous measurement data, experience, manufacturer's specification, other sources of data

6.1 Transfer standard radiometer

The uncertainty associated with the transfer standard radiometer calibration, discussed in Secs. 3 and 4.3, is a Type-B uncertainty and estimated to be 0.6 %.

6.2 VTBB temperature

The absolute temperature of the VTBB has no influence on the transfer technique calibration because the heat flux is determined independently from the radiometer measurements. It is only necessary that the blackbody temperature be stable over the time interval of the radiometer and test sensor measurements. The VTBB has a long-term stability within ± 0.1 K of the set temperature. The corresponding uncertainty in the radiant heat flux is 0.01 % at 1000 K and 0.004 % at 2773 K. This is negligible compared to the other uncertainties and can be ignored.

6.3 VTBB emissivity

The estimated emissivity of the VTBB is 0.99. However, the blackbody emissivity has no influence on the transfer calibration. Higher emissivity values result in realizing higher heat flux levels at the sensor surface for a given operating temperature.

6.4 VTBB radiation - aperture uniformity

The uniformity of radiation from the VTBB aperture has no major influence on the calibration because of identical effects on both the transfer standard and the test sensor. However, even with a uniformly radiating aperture, the irradiance distribution at the sensor location may not be uniform. This non-uniform distribution may require a correction to the measured responsivity of the sensor, as detailed in Sec. 6.7.

6.5 Alignment error (distance)

The location of the effective aperture of the VTBB is close to the heated end, about 8.5 cm inside the blackbody aperture with the short extension piece installed. The test sensor and the transfer standard radiometer are at a fixed distance from the blackbody aperture. Assuming a maximum error of about 0.2 mm in the location of the transfer standard radiometer and the sensor with respect to the reference plane, the corresponding uncertainty values will be 0.2 %, 0.14 % and 0.09 % at sensor locations corresponding to 12.7 mm, 62.5 mm, and 140 mm from the blackbody aperture, respectively. The uncertainty in the longitudinal location of the sensor translates into a corresponding change in the configuration factor (C_{fa}) between the radiating aperture and the sensor. Figure 6 shows the relative change in the configuration factor with respect to location of the sensor from the aperture [8]. At large distances, the irradiance varies inversely as the square of the distance from the aperture. Hence, the uncertainty in irradiance at the sensor will be approximately two times that due to positioning uncertainty. The corresponding uncertainty values for the irradiance are 0.4 %, 0.3 % and 0.2 % at sensor locations of 12.7 mm, 62.5 mm, and 140 mm, respectively.

6.6 Alignment error (angular)

The errors due to angular misalignment vary as the cosine of the angle. Assuming a maximum misalignment of about 2°, the corresponding uncertainty will be 0.06 %.

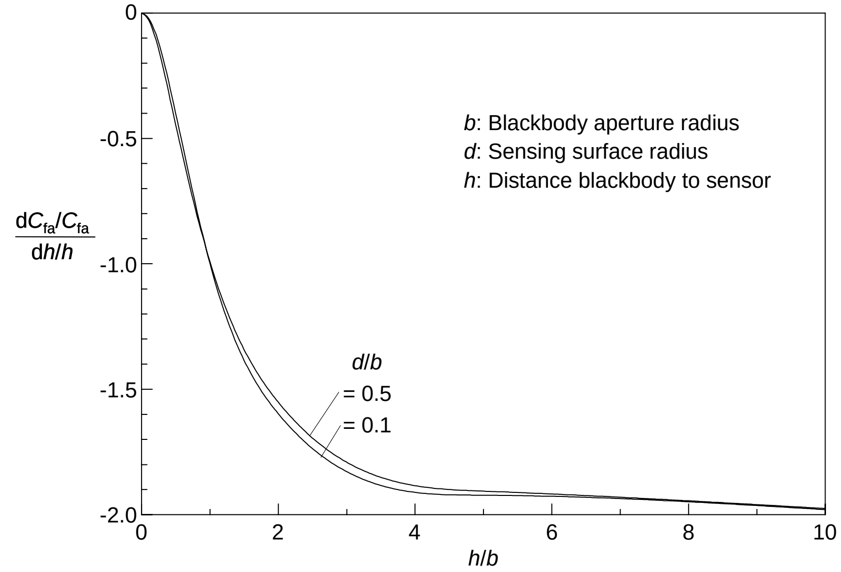

Figure 6. Incremental change in configuration factor with distance [8]

6.7 Radiometer aperture size

The areas on which radiant flux is incident on the transfer standard radiometer and the test sensor are different, and the heat-flux distribution in the test plane is not uniform. The distribution is a maximum at the center, and decreases away from the center. The sensitive area of the heat-flux sensor is generally small, and responds to the peak of the distribution. However, the aperture size of the transfer standard radiometer is much larger. Hence, the response of the transfer standard radiometer will be proportional to the average irradiance over the distribution.

Due to the averaging of the distribution over the aperture area, a correction to the radiometer measurement is necessary to determine the peak value of the distribution from the average reading. This peak value corresponds to the radiation incident on the sensor surface. The correction is a function of the sensor location from the blackbody aperture [8]. Figure 7 shows the calculated correction for different sensor dimensions as a function of sensor location from the blackbody aperture.

The correction factor is unity when the sensor is located at the aperture plane because of the uniform distribution. The correction peaks at a distance approximately equal to the radius of the aperture, and decreases asymptotically to unity at large distances. The correction is a strong function of the ratio of the sensor to the aperture radii. For the VTBB transfer calibration setup, a conservative value of the radiometer-aperture to sensor diameter ratio is about 0.44. The corresponding correction is less than 0.3 % of the measured radiometer reading. The correction increases rapidly when moving closer to the blackbody aperture. The uncertainty involved in evaluating this correction arises mainly from the difficulty of defining the exact position of the effective blackbody aperture. However, even with an uncertainty of about 5 % in the effective location, the corresponding uncertainty in the correction will be less than 0.05 %.

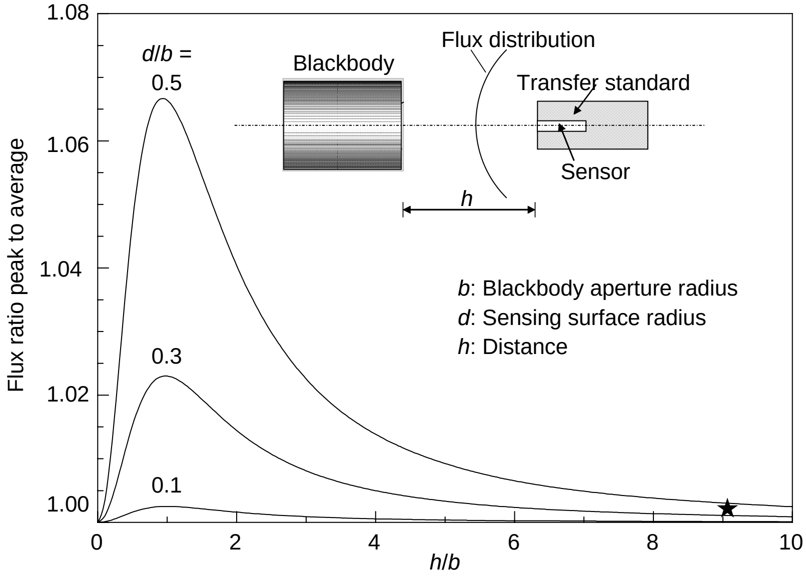

Figure 7. Ratio of peak to average irradiance at sensor location [8]

6.8 Radiometer/Sensor reading

The averaging times for the sensor and the radiometer measurements varies from 10 s to 60 s depending on the heat-flux level. If the sensors are water-cooled, longer averaging times are feasible. Figure 8 shows a typical variation of standard deviation of the mean (standard error) of the sensor output at two locations from the blackbody. The uncertainty will be a maximum of about 0.2 %, and will be much less at heat-flux levels greater than 10 kW/m^2.

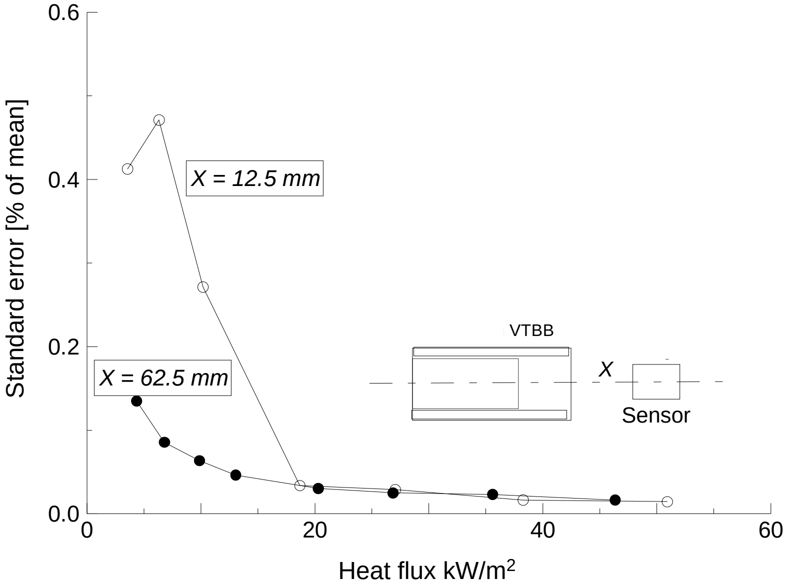

Figure 8. Standard deviation of the mean output for two sensor locations [1]

6.9 Other sources

The VTBB uses low-velocity argon gas flow to purge the cavity continuously during operation. The average exit-flow velocity is about 0.08 m/s. When the sensor is close to the cavity-exit, the low velocity jet impinging the sensor surface causes changes in the local heat transfer. This influence becomes smaller away from the exit because of jet spreading effects. The good agreement in calibrations obtained for different sensor distances from the blackbody suggests that the purge gas effect is not significant, and is within other experimental uncertainties. The agreement also suggests that the sensor's high-absorptance is gray because of different blackbody temperature ranges used to obtain the same heat flux level at the sensor.

The calibration of a heat-flux sensor over a period of time will show statistical variations because of experimental conditions that are difficult to control. Therefore, an uncertainty that indirectly accounts for purge-gas as well as other effects, based on long-term repeatability, is necessary. Several repeat measurements on the same reference sensor give a standard uncertainty value of 0.7 % for repeatability.

6.10 Combined uncertainty

Table 6 lists the individual uncertainties for different sources. The root-sum-square of individual uncertainties gives the combined uncertainty value u_c. The relative expanded uncertainty U, corresponding to a coverage factor of k =2, is about 2.1 %.

Table 5. Estimate of uncertainties in heat-flux sensor calibration [%]
(Heat-flux range 10 kW/m^2 to 50 kW/m^2)

Uncertainty Source	Type	Uncertainty
1. Transfer standard ESR (previous calibration)	B	0.60
2. Blackbody temperature	B	0.01
3. Blackbody emissivity	B	< 0.001
4. Blackbody aperture - radiation uniformity	B	< 0.001
5. Alignment (distance)	B	0.40
6. Alignment (angular)	B	0.06
7. Radiometer aperture size	B	0.05
8. Signal output: Radiometer	A	0.20
Sensor	A	0.20
9. Other sources: purge-gas, repeat tests	A	0.70
10. Relative expanded uncertainty ($U = ku_c$)	**$k = 2$**	**2.1**

References

1. A. V. Murthy and B. K. Tsai, "Transfer calibration of heat flux sensors at NIST," HTD-Vol. 345, *ASME proceedings of the National Heat Transfer Conference*, Edited by D. Kaminski, A. M. Smith and T. F. Smith, **7**, 81-88 (1997).
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3. T. C. Larason, S. S. Bruce, and A. C. Parr, "NIST Measurement Services: Spectroradiometric Detector Measurements: Part I – Ultraviolet Detectors and Part II – Visible and Near-Infrared Detectors," *NIST Special Publication* **250-41** (1998).
4. J. M. Kendall, Sr., and C. M. Berdahl, "Two blackbody radiometers of high accuracy," *Appl. Optics* **9**, 1082-1091 (1970).
5. Instruction Manual for Kendall Radiometer System - Radiometer Model No. MK-IV, Serial No. 47601; Control Unit Model No. MK-I, Serial No. 17601; by Technical Measurements Inc., La Cañada, CA 91011.
6. Kidd, C. T., and Nelson, C. G., "How the Schmidt-Boelter gage really works," *Proceedings of the 41st International Instrumentation Symposium*, pp. 347-368 (1995).
7. B. N. Taylor, and C. E. Kuyatt, "Guidelines for evaluating and expressing uncertainty on NIST measurement results," *NIST Technical Note*, **1297** (1994).
8. A. V. Murthy, B. K. Tsai, and R. D. Saunders, "Aperture proximity effects in high heat flux sensors calibration," *J. Res. Natl. Inst. Stand. Technol*, **103** (6), 621-624 (1998).

Appendix A

Heat-flux sensor: Laboratory procedure manual

HFMLP1:	**Kendall Radiometer Operating Procedure**
HFMLP2:	**Heat-Flux Sensor Calibration Procedure**
HFMLP3:	**Data reduction procedure**

Optical Technology Division (844)
Heat-flux Measurements Laboratory Procedure
Kendall Radiometer Operating Procedure
Page 1 of 2
Written by: Murthy Annageri   Procedure: HFMLP1
Approved by: ……………….   Date: ……………….
Revised by: ……………….   Date: ……………….

Kendall Radiometer Operating Procedure

Figure A1. ESR control unit front panel

1. **Radiometer/Controller set-up**
   a. Radiometer controller power-switch in off-position
   b. Connect radiometer Bendix cable to controller, & controller power cable to mains
   c. Cover the radiometer front end with the cap
   d. Connect the cooling water-pump outlet to the radiometer inlet
   e. Connect cooling water-pump inlet & the radiometer outlet to the coolant reservoir
   f. Adjust the dial on the pump flow-controller to a flow-rate of 0.5 L/m or higher
   g. Switch-on radiometer controller power
   h. Allow about 20 min for stabilization

2. **Digital voltmeter check-out (as and when needed)**
   a. Set switch “S1” to “OPERATE”
   b. Connect a Standard voltage source to the BNC input connector
   c. Set switch “S2” to “ZERO” position
   d. Turn DVM’s “ZERO” adjust potentiometer to set the read-out to zero
   e. Set switch “S2” to “SCALE” position
   f. Adjust DVM’s “SCALE” potentiometer to read the standard voltage source value.

continued

Optical Technology Division (844)
Heat-flux Measurements Laboratory Procedure
Kendall Radiometer Operating Procedure
Page 2 of 2
Written by: Murthy Annageri Procedure: HFMLP1
Approved by: ………………. Date: ……………….
Revised by: ………………. Date: ……………….

3. **Dark signal**
   a. Set both the switches “S1” and “S2” to “OPERATE”
   b. Allow the unit to stabilize for about 20 min
   c. The steady read-out gives the dark-signal value
   d. Turn the “TARE(R17)” adjustment potentiometer to set the read-out to 0.000

4. **Radiometer self-calibration & Operation (See note)**
   a. Set switch “S1” to “SCALE” position, and set switch “S2” to “VOLTS” position
   b. Turn potentiometer “HEATER-R16” to adjust to the desired voltage
   c. Set switch “S2” to “VOLTS” position: Note the voltage “V” on the meter
   d. Set switch “S2” to “CURRENT” position: Note the heater current (I) in mA
   e. Calculate electrical power (P_c) = V (Volts) x I (mA) x C_f (=0.9925)
      [C_f is the radiometer aperture area (cm^2). For the radiometer in use C_f = 0.9925]
   f. Set switch “S2” to “OPERATE” position
   g. Allow the read-out to stabilize: Note the indicated power P_i on the meter
   h. If $P_i \neq P_c$, adjust potentiometer “SCALE(R18)” to set read-out P_i, to P_c
   i. Set both the switches “S1” and “S2” to “OPERATE” position.

Note: The radiometer self-calibration is at a power level ≈ 920 mW corresponding to the calibration power level used in the laser facility. The radiometer calibration gives the actual heat flux value.

Optical Technology Division (844)
Heat-flux Measurements Laboratory Procedure
Heat-flux Sensor Calibration Procedure
Page 1 of 2

Written by:	Murthy Annageri	Procedure:	HFMLP2
Approved by:	……………….	Date:	……………….
Revised by:	……………….	Date:	……………….

Heat-flux Sensor Calibration Procedure

CAUTION
COLLISION

1. Calibration set-up

a. Remove the standard graphite tube extension on the viewing end of the VTBB and replace it with the short extension.
b. Locate/align the reference ESR and the test-sensor at a fixed distance from the VTBB exit using standard gage blocks[3]
c. Note down position values for the Aerotech-stage corresponding to the ESR (**Station-1**) and the test sensor (**Station-2**) location when aligned with VTBB axis
d. Identify another position (**Station-3**) away from the ESR and the sensor, to station VTBB while being heated or cooled
e. Connect cooling water pump to the ESR and set the flow-rate to 0.5 L/m or higher
f. If the test-sensor is water-cooled, make appropriate cooling arrangements as per manufacturer's specification
g. If the test-sensor has body-temperature thermocouple, connect the leads to Fluke thermometer to monitor body temperature during testing
h. Connect analog output of the control unit to **Channel-1** of the HP multi-meter 3457A
i. Connect the sensor signal leads (or the amplifier output) to **Channel-2** of the HP multi-meter 3457A
j. Check connections, signal-polarity and instrument-cooling for proper functioning
k. Record dark signals for the ESR and test sensor for about 60 s.

continued

---

[3] Recommended location of the sensor from the blackbody exit is 12.5 mm, 62.5 mm and 140 mm for calibration up to about 50 kW/m^2, 25 kW/m^2 and 10.0 kW/m^2, respectively.

Optical Technology Division (844)
Heat-flux Measurements Laboratory Procedure
Heat-flux Sensor Calibration Procedure
Page 2 of 2

Written by:	Murthy Annageri	Procedure:	HFMLP2
Approved by:	……………….	Date:	……………….
Revised by:	……………….	Date:	……………….

2. Calibration Measurements

CAUTION
BRIGHT SOURCE
BURN
ELECTROCUTION

IMPORTANT
Prior to calibration of test-sensor, perform a check out calibration on the reference sensor

a. Record laboratory temperature and humidity
b. Locate the VTBB at **Station-3**

c. Turn on the VTBB as per procedure in manual **RTMLP11.1**
d. Set the desired temperature(**Table 4**) and allow the VTBB to stabilize
e. Move the VTBB in front of the ESR located at **Station-1**
f. Allow about 60 seconds for the ESR readings to stabilize
g. Record ESR output for about 20 s to 60 s depending on the heat-flux level[4,5]
h. Move the VTBB to **Station-2** in front of the test sensor
i. If the sensors are not water-cooled, **go to Step (l)**
j. Water-cooled sensors: Record output signal for about the same duration as ESR
k. **Go to Step (m)**
l. Data taking duration: Limited by the sensor body-temperature increase with time. Monitor body-temperature-rise when exposing to radiant heat flux. Limit exposure time to about 10 s or less at high heat flux levels.

m. Move the VTBB to **Station-3**
n. Set VTBB temperature to the next value of heat flux and wait till stabilization
o. Follow **Steps (e) to (m)** till completion of calibration range

p. At the end of calibration, move the VTBB to **Station-3**
q. Shut down blackbody following standard procedure in the Laboratory
r. Remove the radiometer and the test sensor from the setup. Inspect to ensure the instruments are in good condition

---

[4] > 60 s at heat-flux of 10 kW/m^2, 20 s or lower at 50 kW/m^2 when the distance between the blackbody and the sensor is 12.5 mm. About 10 s to 20 s when the distance is 62.5 mm or higher
[5] Note: Use a suitable file name to store the radiometer and sensor output data for later analysis

Optical Technology Division (844)
Heat-flux Measurements Laboratory Procedure
Heat-flux Sensor Calibration Data Reduction Procedure
Page 1 of 1

Written by:	Murthy Annageri	Procedure:	HFMLP3
Approved by:	……………….	Date:	……………….
Revised by:	……………….	Date:	……………….

Data reduction procedure

1. Calculate the mean value of the radiometer output **(E_i)** in W/cm^2, and the test-sensor output (V) from the data for each temperature setting of the blackbody.
2. Subtract the dark signals from the mean values calculated in **Step-1**. For calibration at high heat flux levels, the dark signals are small compared to the signal levels.
3. Calculate statistical quantities of interest such as standard deviation of the mean, from the radiometer and sensor output readings to calculate measurement uncertainty.
4. Convert the indicated radiometer mean value **(E_i)** to corrected radiometer power **(E_c)** by using the relation by $E_c = 0.9855 \times E_i$ [See Fig. A2]
5. Express sensor output in **mV**
6. Perform a linear regression analysis for the heat-flux **(E_c)** and the sensor output **(mV)** The slope of the linear regression gives the responsivity of the sensor in **mV/(W/cm^2)**
7. Plot the calibration data as shown in **Fig. 5** for the reference Schmidt-Boelter sensor.
8. Calculate measurement uncertainty in the calibration as listed in **Table-5**

Note: For calculation of mean value, standard deviation, and standard error, use a spreadsheet or other statistical software.

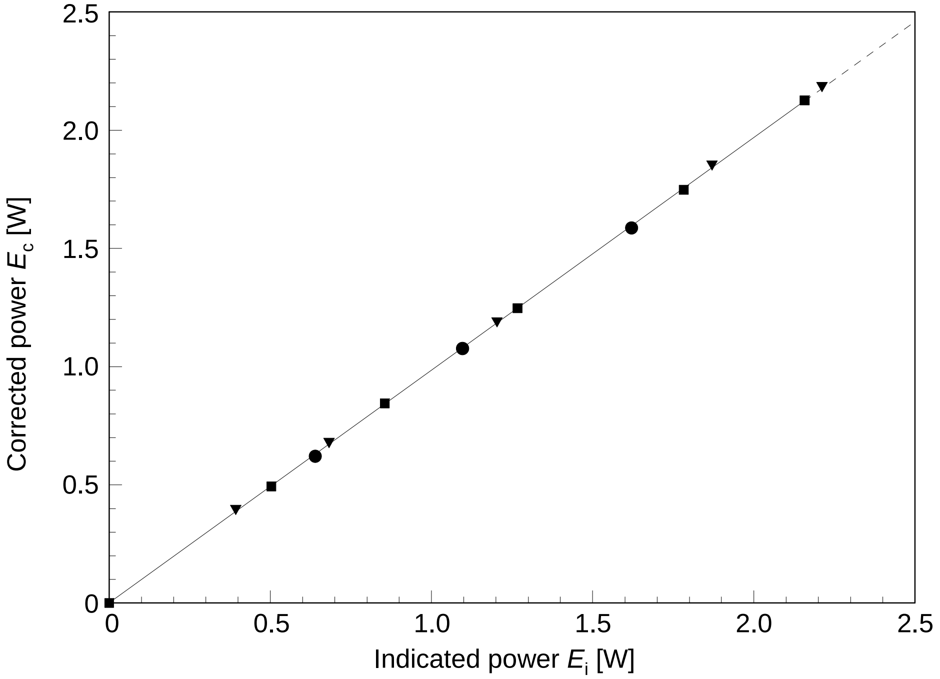

Figure A2. ESR calibration [1]

Appendix B

Heat-flux sensor - Sample Calibration Report

REPORT OF CALIBRATION

35070S Special Test of Heat Flux Sensor

for

HF Sensors, Model # HFT-X-00000J
Serial # 00000, 11111, 22222, 33333, 44444, and 55555

Submitted by:

Radiometric Systems, Inc.
Attn.: John Doe
123 Calibration Blvd. West
Measurement City, MD 00000-0000

(See your purchase order 0446N, dated June 10, 1999)

1. Description of Calibration Item(s)

Six Schmidt-Boelter type heat flux sensors were calibrated by the National Institute of Standards and Technology (NIST) from 0 W/cm^2 to 5 W/cm^2. The Schmidt-Boelter sensor measures the temperature difference between two parallel surfaces normal to the incident heat flux. The thermopile concept is used to make accurate measurement of the temperature gradient across a thin thermally insulating material to determine the heat flux rate to the sensor surface. The test sensors were of miniature type (4 mm body diameter), and the design total (radiant and convective) heat flux range is 5 W/cm^2). Appendix A lists major specifications of the sensors.

Sensor # 11111 showed an open circuit for the body temperature thermocouple leads. This sensor was calibrated without monitoring the sensor body temperature.

2. Description of Calibration

The heat flux sensors were calibrated using the 25-mm Variable Temperature Blackbody (VTBB) as a transfer source. A room-temperature water-cooled electrical substitution radiometer (ESR) was used as a transfer standard. The ESR is a Kendall radiometer model Mark IV self-calibrated at a power level of 920 mW. The cooling water flow rate and temperature were 0.9 L/m and 24 °C, respectively.

Laboratory Environment
Temperature: 23 °C ± 2 °C
Relative Humidity: 50 % ± 3 %

SAMPLE

Calibration Date: August 19, 1999
NIST Test No.: 844/000000-99

Appendix A: Details of Test Schmidt-Boelter Sensors

Manufacturer	HF_Sensors Corporation
Number of Gages	6
Gage specification	HFT-X-00000J
Gage identification	Serial # 00000, 11111, 22222, 33333, 44444 and 55555
Design Heat Flux	5 W/cm^2
Body diameter	4
Body length	8
Sensor area	1 mm x 1 mm
Thermopile lead wires	32 AWG, Stranded copper with Teflon insulation twisted pair. (White positive, Black negative)
Body-temperature thermocouple	Type J (Iron-Constantan), 30 AWG
Maximum body-temperature	204 °C (400 °F)

Appendix B: Schmidt-Boelter Sensors Calibration in VTBB

VTBB	Thermogage Furnace 25 mm diameter cavity (with short extension piece)
Temperature range	1300 °C to 2330 °C
Transfer standard	Electrical Substitution Radiometer, Mark IV Serial No.: 47601, Control Unit Serial No.: 17601 Manufacturer: TMI, La Canada, CA Self-calibration Power Level: 920 mW
Sensor location	On the VTBB cavity axis (1.27 cm from the exit) Located using a gage block. Distance from aperture: 10.7 cm
Calibration type	For incident flux Up to about 5.0 W/cm^2 at the sensor surface, Measured ESR reading used for transferring heat flux
Body temperature	Monitored using a Fluke thermometer
Other accessories	Cooling water flow rate for ESR: 0.9 L/min Cooling water temperature: 24 °C ESR and Sensor thermopile outputs acquired using a HP3857A Digital Voltmeter triggered by Pentium computer.

SAMPLE

The sensors were mounted on a holder/heat-sink for purposes of testing. The ESR and the sensors were located at a fixed distance from the VTBB exit using a standard gage block (1.27 cm thick); corresponding to a distance of 10.7 cm from the end of the blackbody heated region. The variation in the heat flux level at the ESR/sensor location was obtained by operating the VTBB at different temperatures in the range 1573 K to 2603 K.

The output of the ESR (W/cm^2) and the sensors (mV) were recorded by positioning the VTBB, after stabilization of the set temperature, in front of the instruments. Appendix B gives details of the various parameters relevant to this calibration. The ESR readings were recorded after about 60 s exposure to the radiant heat flux to account for the long time-constant. The Schmidt-Boelter sensors outputs were recorded for about 20 s to 40 s depending on the heat flux level. The sensor body-temperature was monitored using a Fluke thermometer during exposure to the radiant flux. The maximum rise in the gage body temperature was less than 20 K at the highest heat flux level.

Before calibrating the test sensors, a reference Schmidt-Boelter type sensor was calibrated. This reference sensor is frequently calibrated to monitor the long-term repeatability of the calibration procedure. The measured responsivity from the check calibration agreed with the mean of previous calibrations within 1.0 %.

3. Results of Calibration

Tables 1a and 1b give the measured output of the sensors for different heat flux levels at the sensor surface. Over the heat flux range tested, the outputs of all the six sensors increased linearly with increasing heat flux. Linear curve fit to the test data showed the calculated regression factor was 1.000 for all the sensors. Figures 1a and 1b show the results of calibration along with the linear regression analysis to the measured data. The responsivity and scale factor values of the sensors calculated from the linear regression are given below. The responsivity is determined from the slope of the curve. The scale factor represents the inverse of the responsivity value.

Serial #	**Responsivity** [mV/(W/cm^2)]	**Scale factor** [(W/cm^2)/mV]
00000	3.084	0.324
11111	2.985	0.335
22222	2.924	0.342
33333	3.540	0.282
44444	3.612	0.277
55555	3.206	0.312

SAMPLE

4. Estimation of Uncertainty

Table 2 summarizes the calculated uncertainty at various stages of testing. First, the uncertainty accrued during the transfer of calibration to the transfer standard (ESR) from the primary radiometric standard is based on previous measurements and is expected to be 0.6 %. Second, uncertainties occur while transferring the ESR calibration to the heat flux sensor using the VTBB for broadband testing. The temperature of the VTBB during the test was stable to within 0.1 K of the set value. The output of ESR and the sensor were recorded for about 20 s to 30 s depending on the heat flux level. The standard deviation of the mean of the readings was found to be within about 0.2 % of the mean value at heat flux levels greater than 1 W/cm^2. The errors due to alignment are expected to be less than 0.4 %, since a fixed length gage block was used to locate the ESR and the gage in front of the VTBB.

Item 10 in Table 2 gives the results of uncertainty from several tests on the reference Schmidt-Boelter sensor in the same facility and using similar instrumentation and experimental setup. The uncertainty based on the long-term repeatability of the calibration of the reference sensor has been conservatively added in the calculation of the total relative expanded uncertainty for a coverage factor $k = 2$ [2].

5. General Information

The results of this calibration apply only to the sensors referenced in this report. This report shall not be reproduced, except in full, without the written approval of this laboratory.

Prepared by:	Approved by:
Charles E. Gibson	Gerald T. Fraser
Optical Technology Division	For the Director,
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(301) 975-2329	(301) 975-3797

References:

[1] A. V. Murthy, B. K. Tsai, and C. E. Gibson, “Calibration of High Heat Flux Sensors at NIST,” *J. Res. Natl. Inst. Stand. Technol.* **102**, 479-488 (1997).

[2] B. N. Taylor and C. E. Kuyatt, “Guidelines for Evaluating and Expressing the Uncertainty of the NIST Measurement Results,” *NIST Technical Note* **1297** (2nd ed., 1994).

SAMPLE

Table 1a
Heat Flux Calibration Results for sensors 00000, 11111 and 22222

	S/N 00000		**S/N 11111**		**S/N 22222**	
Blackbody Temperature [K]	**Incident Flux [W/cm^2]**	**Sensor Output [mV]**	**Incident Flux [W/cm^2]**	**Sensor Output [mV]**	**Incident Flux [W/cm^2]**	**Sensor Output [mV]**
298	0.000	0.000	0.000	0.000	0.000	0.000
1573	0.838	2.577	0.836	2.483	0.840	2.456
1773	1.290	3.978	1.283	3.817	1.290	3.769
1973	1.897	5.835	1.881	5.598	1.884	5.514
2123	2.453	7.556	2.457	7.319	2.454	7.176
2273	3.142	9.665	3.143	9.362	3.159	9.250
2353	3.568	10.974	3.576	10.668	3.574	10.443
2453	4.151	12.795	4.173	12.416	4.177	12.192
2553	4.812	14.862	4.833	14.439	4.831	14.134
2593			5.122	15.278	5.115	14.966
2603	5.180	15.959				

	Linear regression results for calibration data		
	S/N 00000	**S/N 11111**	**S/N 22222**
Error MS	2.35E-04	2.10E-04	1.01E-04
Count	10	10	10
Intercept	-0.008	-0.012	0.000
Slope	3.084	2.985	2.924
R-square	1.000	1.000	1.000

SAMPLE

Table 1b
Heat Flux Calibration Results for sensors 33333, 44444 and 55555

	S/N 33333		**S/N 44444**		**S/N 55555**	
Blackbody Temperature [K]	**Incident Flux [W/cm^2]**	**Sensor Output [mV]**	**Incident Flux [W/cm^2]**	**Sensor Output [mV]**	**Incident Flux [W/cm^2]**	**Sensor Output [mV]**
298	0.000	0.000	0.000	0.000	0.000	0.000
1573	0.834	2.947	0.838	2.992	0.855	2.713
1773	1.283	4.536	1.286	4.612	1.308	4.177
1973	1.874	6.646	1.894	6.795	1.908	6.100
2123	2.454	8.702	2.461	8.842	2.489	7.953
2273	3.154	11.162	3.163	11.378	3.188	10.212
2353	3.587	12.648	3.592	12.947	3.626	11.577
2453	4.166	14.753	4.201	15.121	4.216	13.502
2553	4.841	17.112	4.875	17.582	4.891	15.657
2593	5.116	18.145	5.161	18.643	5.162	16.557

Linear regression results for calibration data

	S/N 33333	**S/N 44444**	**S/N 55555**
Error MS	5.75E-04	4.22E-04	2.84E-04
Count	10	10	10
Intercept	-0.002	-0.031	-0.018
Slope	3.540	3.612	3.206
R-square	1.000	1.000	1.000

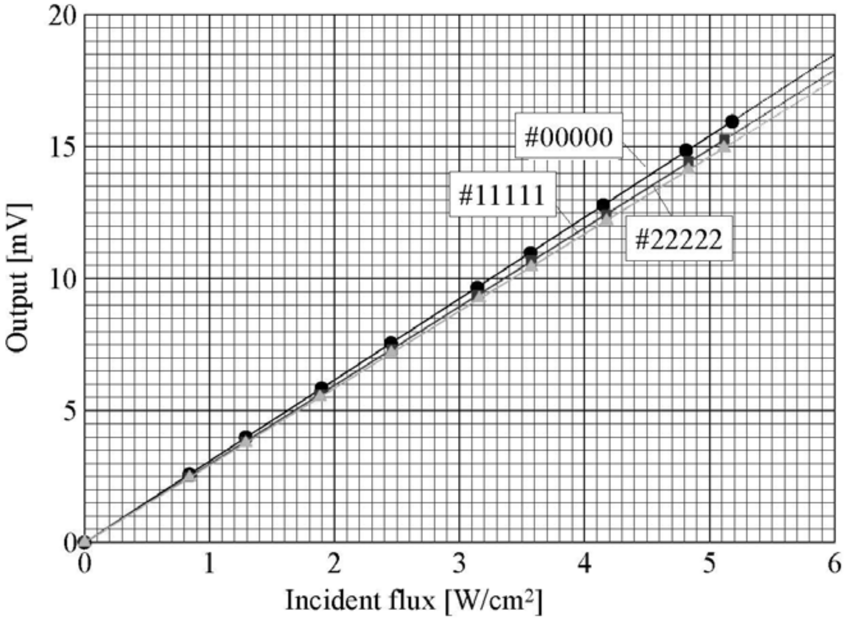

Figure 1a: Heat flux sensor calibration results for sensors 00000, 11111 and 22222

SAMPLE

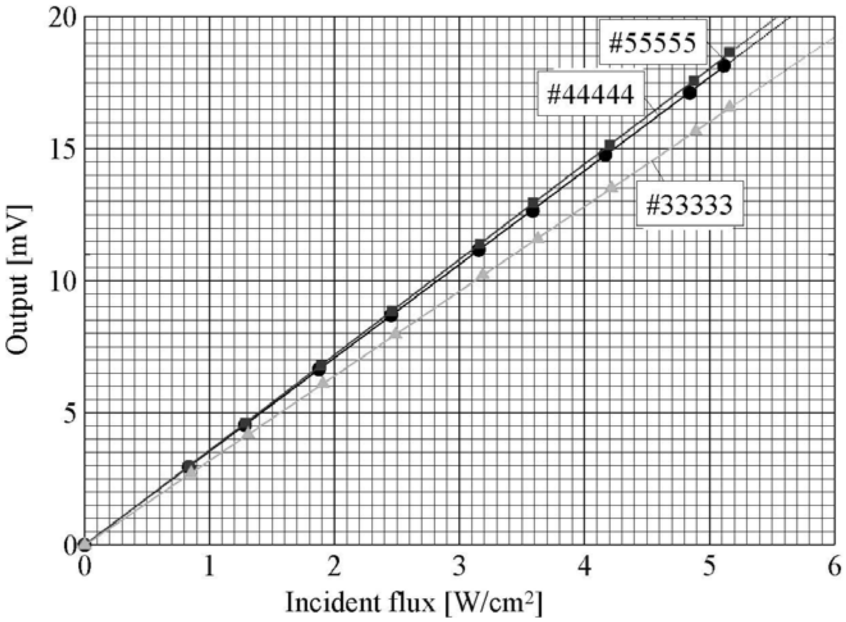

Figure 1b: Heat flux sensor calibration results for sensors 33333, 44444, and 55555

SAMPLE

Table 2
Heat Flux Calibration Uncertainties
(Heat Flux Range 1 W/cm^2 to 5 W/cm^2)

Source of Uncertainty	**Type**	**Uncertainty [%]**
1. Transfer standard ESR (Previous calibration)	B	0.6
2. Blackbody temperature	B	0.1
3. Blackbody emissivity	B	0.0
4. Blackbody aperture uniformity	B	0.0
5. ESR and sensor alignment in VTBB - linear	B	0.4
6. ESR and sensor alignment in VTBB - angular	B	0.1
7. Radiometer averaging effect	B	0.1
8. ESR reading	A	0.2
9. Sensor reading	A	0.2
10. Repeat tests on a similar sensor	B	0.7
Relative expanded uncertainty ($U = k u_c$)	**$k = 1$**	**1.1**
Relative expanded uncertainty ($U = k u_c$)	**$k = 2$**	**2.1**

SAMPLE

Appendix C

VTBB operation: Laboratory procedure manual

RTMLP Safety.1	**Safety Issues**
RTMLP1	**Running General Data Taking Program**
RTMLP11:	**VTBB Operation**

Optical Technology Division (844)
Radiance Temperature Measurements Laboratory Procedure
Safety Issues

Written by: Charles Gibson Procedure: RTMLP1
Approved by: ………………. Date: ……………….
Revised by: ………………. Date: ……………….

Safety Issues

Safety glasses are required in the laboratory at all times.

The following hazards have been identified in this laboratory. Safety measures are in place to reduce the risk of injury from the hazards below.

BRIGHT SOURCE
Avoid staring at the source
Can cause eye damage
Use the correct neutral density filter when viewing is required

BURN
Keep body and clothes away

COLLISION
Keep the boxcar path clear
Do not hang cables from boxcar

ELECTROCUTION
High voltage connections present
Do not touch electrical parts

LASER
Avoid staring into a laser
Can cause eye damage
Block laser or turn off when not in use

Displays, similar to the one below, are used throughout this document to alert the operator to potential hazards.

CAUTION

LASER

Optical Technology Division (844)
Radiance Temperature Measurements Laboratory Procedure
Running General Data Taking Program

Written by:	Charles Gibson	Procedure:	RTMLP1
Approved by:	……………….	Date:	……………….
Revised by:	……………….	Date:	……………….

Running the General Data Taking Program

1. Turn on the computer
2. Enter the **password** to work online, or click on the **Cancel** button to work offline
3. Load the Visual Basic program: *c:\programs\datatakn\pyro.mak* (do one of the following)
    a. Click on the **Pyro.mak** shortcut icon
    b. Double click on the folder *c:\programs\datatakn\pyro.mak* using Windows Explorer
4. Run the program (do one of the following)
    a. Press F5
    b. Click on the _ tool bar icon
    c. Click on the menu item “**Run**” then on “**Start**”
5. The ***Hardware.frm*** is used to set up the equipment with settings used by other programs
6. The ***Software.frm*** is used to input data used by other programs
7. All other programs can be run from these forms

Optical Technology Division (844)
Radiance Temperature Measurements Laboratory Procedure
Variable-Temperature Blackbody Operation

Written by: Charles Gibson — Procedure: RTMLP11
Approved by: ………………. — Date: ……………….
Revised by: ………………. — Date: ……………….

VTBB Operation

CAUTION
BRIGHT SOURCE
BURN
ELECTROCUTION

1. Turn On Procedure

a. Open tap water valve 1/8 turn
b. Check that the blue box flow rate is about 2 GPM
c. Open chilled water valves
    i. open supply valve 1/4 turn
    ii. fully open return valve
d. Press the reset button on the blue water switch box to select chilled water
e. Check that the blue box flow rate is about 5 GPM
f. Fully open the argon cylinder valve
g. Turn on the argon alarm and check that it trips at 10 CFH
h. Purge the BB using a argon flow rate of 70 CFH
    i. Cover both BB openings for 5 s with your hands
    ii. Uncover one end and wait 5 s
    iii. Cover both BB openings for 5 s with your hands
    iv. Uncover the other end and wait 5 s
i. Repeat step h 5 times
j. Reduce the argon flow rate to 10 CFH
k. Check that the BB housing is cool and that the argon is flowing
l. Insert correct detector filter for the initial set point
    i. Filter 0, 700 to 1300 °C, Low with insulation (LIN)
    ii. Filter 1, 1300 to 1800 °C, Medium (MED)
    iii. Filter 2, 1800 to 2500 °C, High (HI)
    iv. Filter 3, 2500 to 3100 °C, Extra High(XH)
m. Switch control mode to [MANUAL]
n. Turn the potentiometer to 0
o. Press the [START], [WATER ON], and [RUN] buttons
    i. Note: The BB does not control the chilled water flow the automatic BB shut off switch has been disabled
p. Turn the potentiometer slowly until the voltmeter reads between 150 VAC and 200 VAC (sets BB below 1300 °C)

2. Operating Procedure

a. Run the BB control program
  i. Program is BBPROG.PRG in BetterBasic
  ii. Enter BB at the DOS prompt
  iii. Enter measurement direction
    (1) ‘0' to run high to low
    (2) ‘1' to run low to high
  iv. Enter set point unit
    (1) ‘C’ for ° C
    (2) ‘F’ for ° F
  v. Enter temperature range
    (1) LOW
    (2) LIN
    (3) MED
    (4) HI
    (5) XH
  vi. Insert the correct filter and press [Enter]
b. Press [Shift S] to enter the initial set point
c. Adjust the potentiometer until the temperature is 20 °C above the set point
d. Switch the control mode to [PC] to maintain the set point

WARNING!
DO NOT INCREASE THE SET POINT BY STEPS LARGER THAN 20 °C TO REDUCE DAMAGE TO THE BB

e. Select a new set point (the set point is in °C or °F depending on set point unit selected)
  i. Press [Shift S] to enter the set point
  ii. Use the numeric keypad to increment the set point
    (1) Press the increment key
      (a) 100 °C ('7' key)
      (b) 10 ('4' key)
      (c) 1 ('1' key)
      (d) 0.1 ('0' key)
    (2) Press the Arrow key to set the new set point
      (a) ↑, to increase the set point ('8' key)
      (b) ↓, to decrease the set point ('2' key)

f. If the new set point is not in the current range then the program will pause (suspending BB control)

    i. Depending on the measurement direction the default set points are
        (1) High to low default set points
            (a) XH 2500 °C
            (b) HI 2300 °C
            (c) MED 1800 °C
            (d) LOW 1300 °C
        (2) Low to high default set points
            (a) LOW 800 °C
            (b) MED 1300 °C
            (c) HI 1800 °C
            (d) XH 2500 °C

    ii. If the new set point is not the default value, then switch the control mode to [MANUAL]
    iii. The program will loop to step 2.a.v. (see ☞)

3. EMERGENCY TURN OFF Procedure

a. Press the [EMERGENCY STOP] button on the power supply (the chilled water and argon will continue flowing)
b. Continue with steps 4.b. to 4.j.

4. Turn Off Procedure

a. Switch the control mode to [MANUAL]
b. Turn to potentiometer to 0
c. Press the [EMERGENCY STOP] button on the power supply (the chilled water and argon will continue flowing)
d. Switch off the main breaker on the wall
e. Wait until the furnace has stopped glowing
f. Close the chilled water supply valve
g. Close the chilled water return valve
h. Close the cold water supply valve
i. Close the argon cylinder valve
j. Close the argon flow meter valve

Appendix D: How to Request Heat-Flux Sensor Calibrations

1. Prepare a purchase order with the following:
   a. Company name and address
   b. Contact person's name and phone number
   c. Billing address
   d. Service ID number requested (include range and points)
   e. Test fee
   f. Address to ship test item
   g. Return shipping instructions (prepay and add, COD, charge to account with shipper)
      i. the test fee does not include shipping costs
      ii. customers are responsible for all shipping costs
      iii. If no instructions are given, NIST will return the test item by common carrier, collect, and uninsured.

2. Send the purchase order to:
   Calibration Services
   National Institute of Standards and Technology
   100 Bureau Drive, Stop 2330
   Gaithersburg, MD 20899-2330

   Tel.: (301) 975-2002
   FAX: (301) 869-3548
   E-mail:
   calibrations@nist.gov

3. Send the test item(s) to:
   Charles Gibson
   National Institute of Standards and Technology
   100 Bureau Drive, Stop 8441
   Gaithersburg, MD 20899-8441

   Tel.: (301) 975-2329
   FAX: (301) 869-5700
   E-mail: cgibson@nist.gov
   WWW: http://physics.nist.gov/Divisions/Div844/staff/Gp3/gibson.html

Heat-flux sensor calibrations are performed in February, May, August, and November. Requests for calibration services are scheduled after the receipt of a purchase order.

NIST policy requires prepayment of all calibration services performed for non-U.S. organizations. Please contact the Calibration Program office to arrange payment.