NASA/TM—1998-208809

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November 1998

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Remote Heat Flux Measurement using a Self Calibration Multiwavelength Pyrometer and a Transparent Material

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Introduction

A self calibrating multiwavelength pyrometer (Ref. 1) was used to conduct remote heat flux measurements using a transparent sapphire disk by determining the sapphire disk's front and back surface temperatures. Front surface temperature (T_{fs}) was obtained from detection of surface emitted radiation at long wavelengths ($\lambda > 6$ µm). Back surface temperature (T_{bs}) was obtained from short wavelength (1 to 5 µm) radiation transmitted through the sapphire disk. The thermal conductivity κ of the sapphire disk and the heat transfer coefficients h_1 and h_2 of its surfaces are determined experimentally. An analysis of the heat flux measurement is presented.

Method and Experiment

Heat flux sensing is achieved using a sapphire disk and a thin layer of graphite paint deposited on one of the disk's surfaces. The sensor is positioned at the opening of a black body furnace maintained at temperature T_b with the graphite coated surface oriented to receive the radiative and convective heat fluxes from the furnace. The furnace temperature T_b is measured separately by a thermocouple. During the experiment, the multiwavelength pyrometer spectrometer recorded the spectra (Figure 1) of radiation coming through the sapphire sensor in response to the temperature changes of the black body furnace.

Because of the small thickness (two coatings using the application brush) of the graphite paint layer, its temperature is assumed to be the same as that of the sapphire disk surface (T_{bs}) on which the graphite paint is deposited. The thermal conductivity of the sapphire disk is κ. The heat transfer coefficients of the sapphire sensor surfaces are h_1 at the (hotter) surface inside the black body furnace and h_2 at its other (colder) surface. The temperature at distances far away from the front surface is T_∞.

Short and long wavelength radiation are detected by the heat flux sensor and recorded by the multiwavelength pyrometer. The self calibrating pyrometer described in Ref. 1 is applied to determine the sapphire's back (T_{bs}) and front (T_{fs}) surface temperatures. The availability of several radiation spectra at several different temperatures is crucial to a successful determination of the sapphire surface temperatures without knowing the emissivity and transmissivity of the elements in the optical path of the system.

The following heat flux equations are applicable during heat transfer taking place at the graphite paint interface:

$$\varepsilon_b \sigma\left(T_b^4 - T_{bs}^4\right) + h_1\left(T_b - T_{bs}\right) = \frac{\kappa}{t}\left(T_{bs} - T_{fs}\right) + \int S\left(\lambda, T_{bs}\right) d\lambda \tag{1}$$

$$\frac{\kappa}{t}\left(T_{bs} - T_{fs}\right) + \int S\left(\lambda, T_{bs}\right) d\lambda = \int S\left(\lambda, T_{bs}\right) d\lambda + h_2\left(T_{fs} - T_\infty\right) \tag{2}$$

From Eqns. (1) and (2) we obtain by addition and elimination

$$\varepsilon_b \sigma\left(T_b^4 - T_{bs}^4\right) + h_1\left(T_b - T_{bs}\right) = \int S\left(\lambda, T_{bs}\right) d\lambda + h_2\left(T_{fs} - T_\infty\right) \tag{3}$$

In these equations, σ is the Stefan-Boltzman radiation constant, ε_b is the graphite paint spectral emissivity, and $t = 6$ mm, is the thickness of the sapphire disk. $S(\lambda, T_{bs})$ is the radiation spectrum coming from the graphite paint and τ_λ is the sapphire transmissivity in Eqn (5). The integral $\int S(\lambda, T_{bs}) d\lambda$ in the equations contains the radiative heat flux transmitted through the sapphire disk from the graphite paint surface, and is evaluated from the experimental spectrum numerically. To a very good approximation, the black body furnace emissivity and graphite emissivity are very close to unity, although in the pyrometric determination of temperature from the radiation spectra transmitted through the sapphire disk, the exact values of graphite paint emissivity and the sapphire transmissivity are not necessary.

A commercial spectrometer/radiometer equipped with an indium antimonide/mercury cadmium telluride detector and filter wheel monochromator for radiation from 1.3 to 14.5 µm was used to acquire the spectra in Fig. (1). The self calibrating feature of the multiwavelength pyrometer eliminated the need to know the graphite emissivity and sapphire transmissivity for temperature determination. For all the spectra in Fig. 1, two wavelengths, λ_1 = 3.878 μm and λ_2 = 5 μm were selected and the data analyzed according to

$$y(t)=\frac{S(\lambda_1,0)}{S(\lambda_1,t)}=\frac{\left[\frac{A'(\lambda_2)}{S(\lambda_2,0)}\frac{c_1}{\lambda_2^5}+1\right]^{\frac{\lambda_2}{\lambda_1}}-1}{\left[\frac{A'(\lambda_2)}{S(\lambda_2,t)}\frac{c_1}{\lambda_2^5}+1\right]^{\frac{\lambda_2}{\lambda_1}}-1}=\frac{\left[A'(\lambda_2)\frac{c_1}{\lambda_2^5}x(\lambda_2,0)+1\right]^{\frac{\lambda_2}{\lambda_1}}-1}{\left[A'(\lambda_2)\frac{c_1}{\lambda_2^5}x(\lambda_2,t)+1\right]^{\frac{\lambda_2}{\lambda_1}}-1} \tag{4}$$

This equation is obtained from Eqn (12) of Ref. 1, after replacing the quantities V(λ,t) and A(λ) by S(λ,t) and A'(λ) in that equation according to

$$S(\lambda,t)=\frac{V(\lambda,t)}{g_\lambda}=\varepsilon_\lambda\tau_\lambda L(\lambda,T(t)) \tag{5}$$

$$A'(\lambda)=\frac{A(\lambda)}{g_\lambda}=\varepsilon_\lambda\tau_\lambda \tag{6}$$

$$x(\lambda_2,t)=\frac{1}{S(\lambda_2,t)} \tag{7}$$

where S(λ,t) is the spectrum intensity at wavelength λ at time t when the temperature is T(t), g_λ is the spectrometer calibration constant. L(λ,T(t)) is Planck's equation defined by:

$$L(\lambda,T(t))=\frac{c_1}{\lambda^5}\frac{1}{\left(\exp(c_2/\lambda T(t))-1\right)} \tag{8}$$

c_1 and c_2 are the usual radiation constants. y(t) and x(t) are now the experimentally measured quantities. The quantity $A'(\lambda_2)=\varepsilon_\lambda\tau_\lambda$ is determined from these measured data at wavelengths λ_1 and λ_2 using statistical least square methods. The resulting curve fitting is shown in Fig. 2.

After $A'(\lambda_2)$ is determined, it is used to determine the back surface temperatures T(t) of all the spectra according to

$$T(t)=\frac{c_2/\lambda_2}{Ln\left(\frac{A'(\lambda_2)}{S(\lambda_2,t)}\frac{c_1}{\lambda^5}+1\right)} \tag{9}$$

Because sapphire is not transmitting to radiation at wavelength longer than about 6 μm, the sapphire front surface temperature is determined by fitting a Planck curve of temperature T_{fs} to the radiation spectrum in this region. A constant sapphire emissivity is used in the curve fitting. The result is shown in Fig. (3).

<u>Heat Flux Results</u>

The temperatures of the black body furnace and the sapphire disk front and back temperatures at which the experiments were conducted are:

Table I. Measured Temperatures (K)

Blackbody	1329.1	1200.8	1079.1	961.9	851.9	746.9
Front Surface	730	645	570	505	455	410
Back Surface	904	776	673	587	516	459

Eqn (1) is transformed into

$$\frac{\varepsilon_b \sigma\left(T_b^4 - T_{bs}^4\right) - \int S\left(\lambda, T_{bs}\right) d\lambda}{\left(T_b - T_{bs}\right)} = \frac{\kappa}{t} \frac{\left(T_{bs} - T_{fs}\right)}{\left(T_b - T_{bs}\right)} - h_1 \tag{10}$$

To a good approximation, the emissivity inside the black body furnace and the emissivity of the graphite paint are safely taken to be unity. The quantity on the left hand side is easily calculated because the integral can be evaluated numerically from the measured spectrum. Some error may be introduced in the numerical integration because a triangular approximation estimated the integral from zero wavelength to the shortest wavelength measured (an over estimate), and a truncation occurred after the longest wavelength measurement (an under estimate). The left hand side quantity is plotted against the quantity $(T_{bs}-T_{fs})/(T_b-T_{bs})$. The result is shown in Fig. (4), fitted by a straight line of slope $\kappa/t = 0.105$ and intercept $-h_1 = -0.012$.

Eqn (2) is equivalent to

$$T_{bs} = \left(1 + \frac{h_2}{\kappa / t}\right) T_{fs} - \left(\frac{h_2}{\kappa / t}\right) T_{\infty} \tag{11}$$

Shown in Fig. (5) is a plot of T_{bs} against T_{fs} giving a straight line, whose slope is $(1+h_2/(\kappa/t)) = 1.38$, the intercept is $-(h_2/(\kappa/t))T_\infty = -114$. From the intercept and slope, we obtain $T_\infty = 300$ K, which is room temperature. Because κ/t has been determined from Eqn (10), we obtain $h_2 = 0.0399$.

Eqn. (3) is rewritten to provide another estimate of h_1 and h_2

$$\frac{\varepsilon \sigma\left(T_b^4 - T_{bs}^4\right) + \int \varepsilon_\lambda \tau_\lambda L\left(\lambda, T_{bs}\right) d\lambda}{\left(T_b - T_{bs}\right)} = h_2 \frac{\left(T_{fs} - T_\infty\right)}{\left(T_b - T_{bs}\right)} - h_1 \tag{12}$$

The quantity on the right is plotted against $(T_{fs}- T_\infty)/(T_b-T_{bs})$ to produce a straight line (Fig. (6)) of slope $h_2 = 0.038$ and intercept $-h_1 = -0.01$. The heat transfer coefficients h_1 and h_2 are in good agreement with the results determined from Eqn (10) and Eqn (11). From the results of Eqn (10) and Eqn (11), $\kappa = 6\ \mathrm{Wm^{-1}K^{-1}}$, this is lower than the reported value of 15 to 30 $\mathrm{Wm^{-1}K^{-1}}$. However the sapphire disk used is slightly yellowish in color.

The measured heat flux ($\dot{q}$) sensed by the sapphire/graphite paint is the sum of conductive and radiative contributions given by

$$\dot{q} = \frac{\kappa}{t}\left(T_{bs} - T_{fs}\right) + \int S\left(\lambda, T_{bs}\right) d\lambda \tag{13}$$

The incident heat flux from the black body furnace: $\sigma(T_b^4-T_{bs}^4)+h_1(T_b-T_{bs})$, the quantity of Eq (13) and radiative heat flux in the experiment are summarized in Table II. The columns represent values at different temperatures. The maximum radiative heat flux contribution is less than 7.5 %.

Table II. Input, Measured and Radiative Heat Flux, ($\mathrm{W/cm^2}$)

Input Heat Flux	18.1	14.0	10.6	7.9	5.9	4.4
Measured Flux	18.8	14.0	10.8	8.5	6.3	5.1
Radiative Flux	1.34	0.78	0.46	0.27	0.17	0.10
Radiative Flux (%)	7.4	5.5	4.3	3.4	2.8	2.3

Conclusion

A remote heat flux sensing is achieved using a transparent sapphire disk coated with a thin graphite layer. The total conductive and radiative heat fluxes were measured. Under the measurement conditions, the dominant component is conductive, with radiation comprising about 7 % of the total heat flux. The ambient temperature, the thermal conductivity of the sapphire disk and the convective heat transfer coefficients of it surfaces were determined.

References

(1) Ng, Daniel, Self Calibration of a 2-wavelength Pyrometer, NASA/TM—1998-208808, 1998.

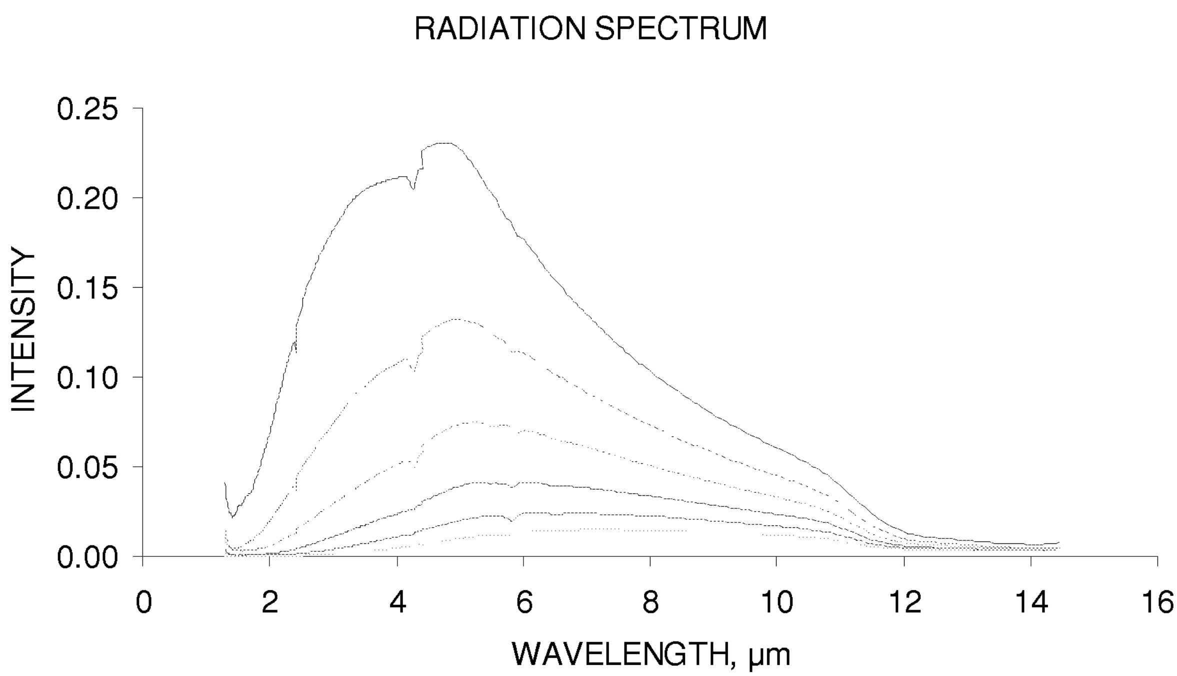
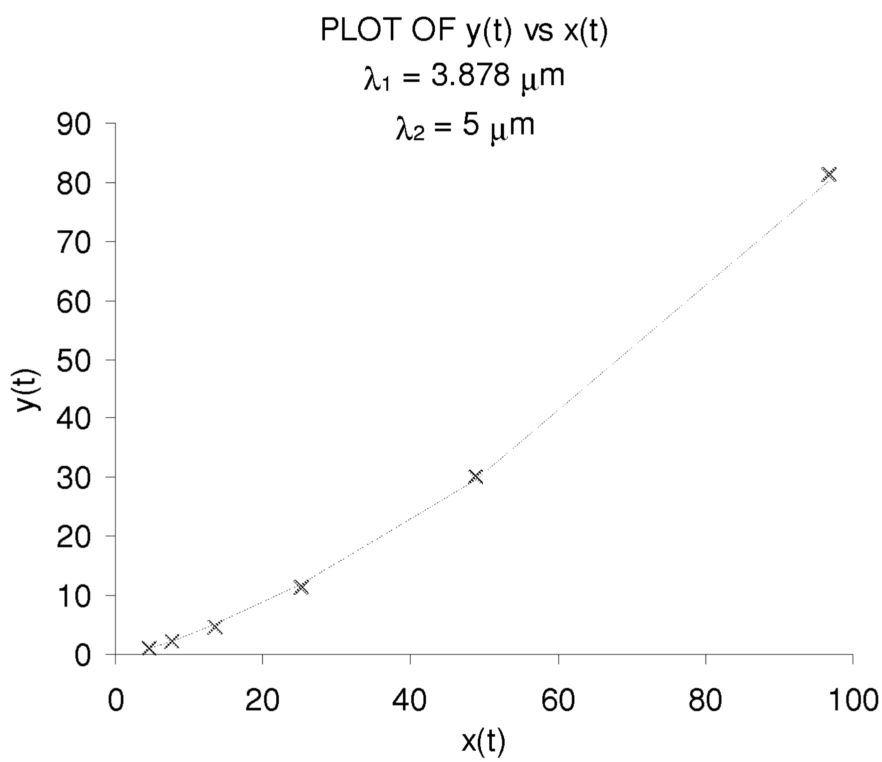


Figure 1



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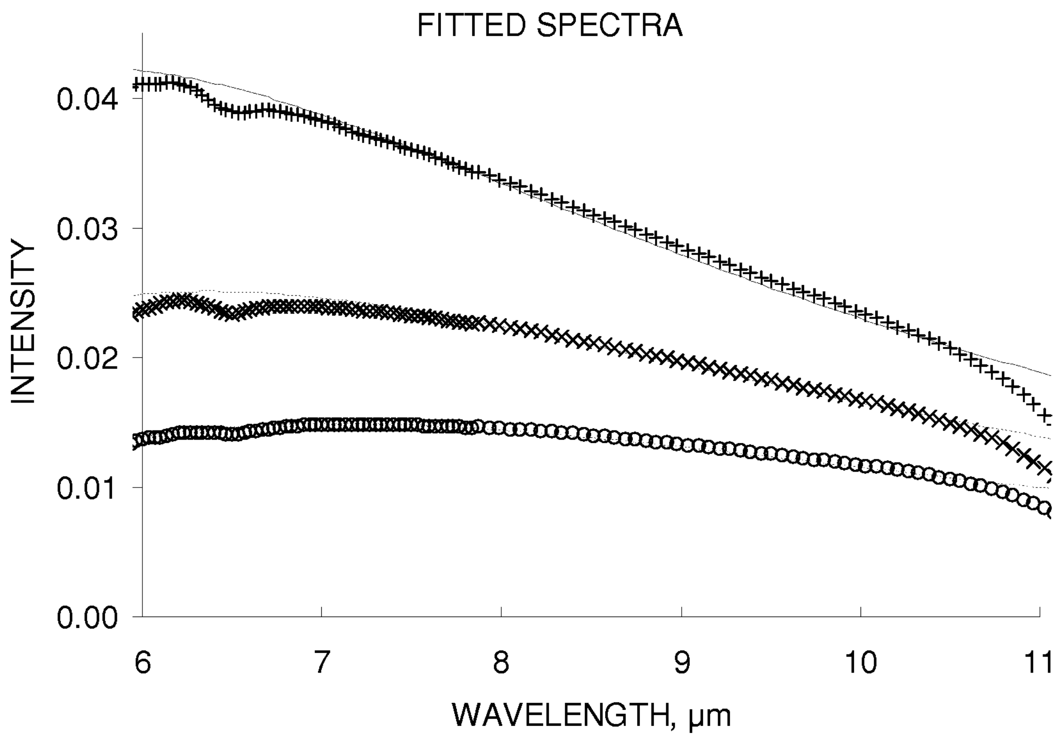

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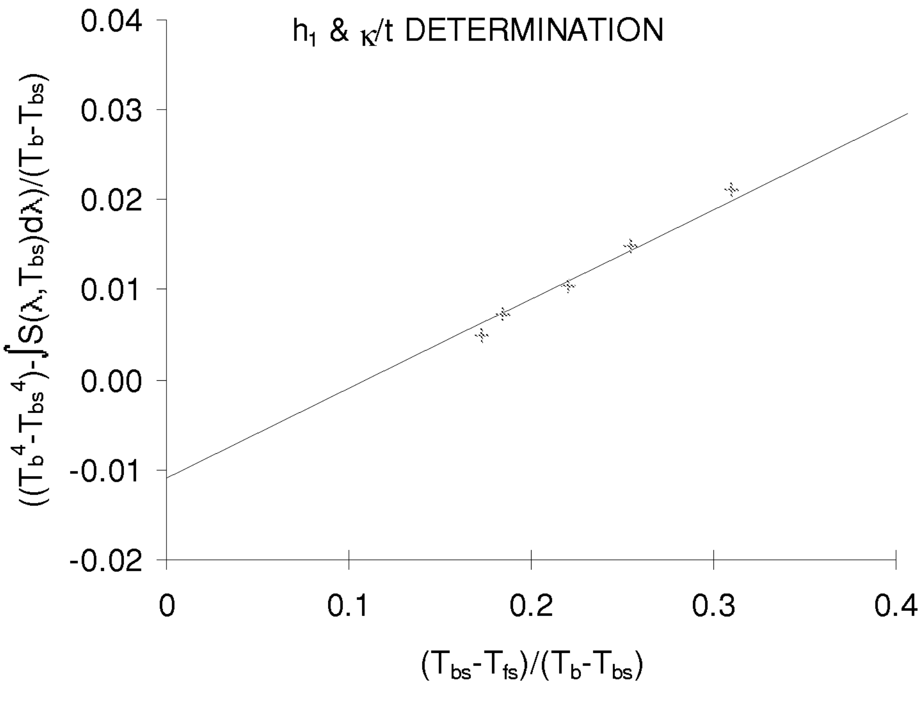

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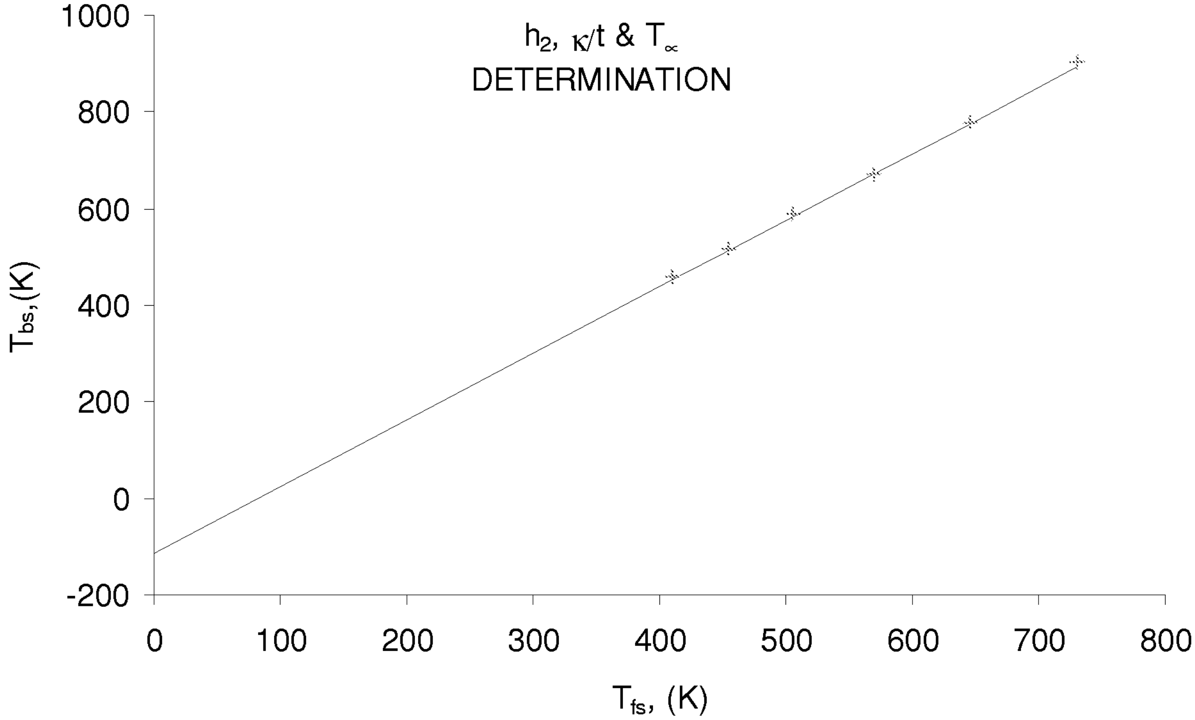

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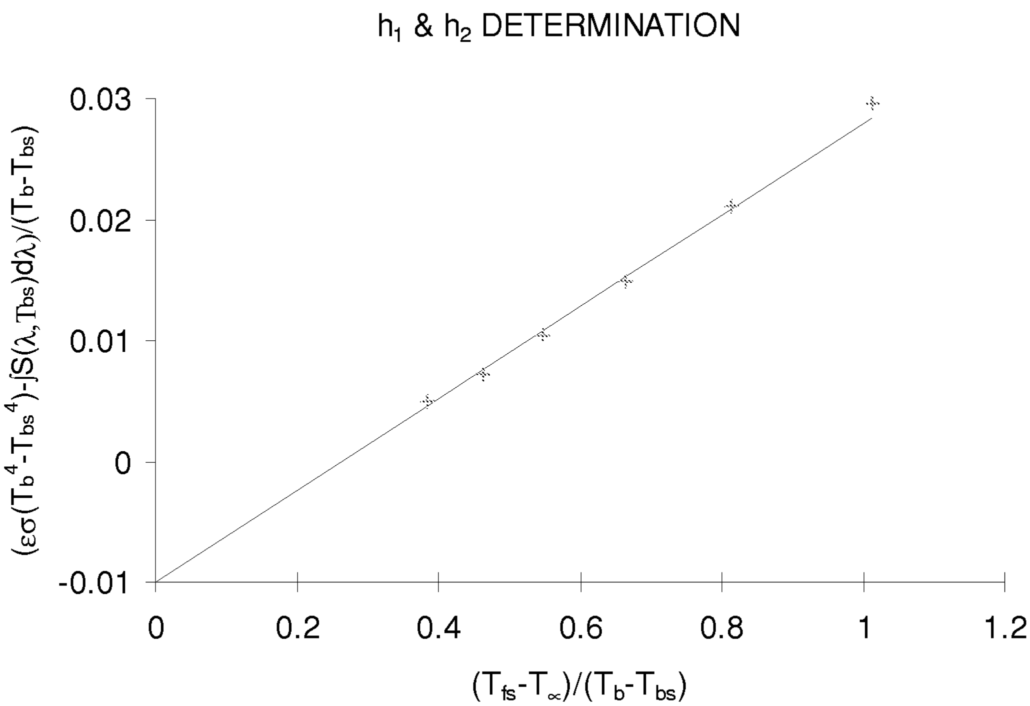

Figure 6

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	November 1998	Technical Memorandum

4. TITLE AND SUBTITLE

Remote Heat Flux Measurement Using a Self Calibration Multiwavelength Pyrometer and a Transparent Material

5. FUNDING NUMBERS

WU–523-21-13-00

6. AUTHOR(S)

Daniel Ng

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–11399

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM—1998-208809

11. SUPPLEMENTARY NOTES

Responsible person, Daniel Ng, organization code 5510, (216) 433-3638.

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Subject Category: 35 Distribution: Nonstandard

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13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS

Heat flux; Pyrometer; Heat flux sensor

15. NUMBER OF PAGES

12

16. PRICE CODE

A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	