NASA Technical Memorandum 107286

Temperature Measurement Involving Nanostructured Thermal Barrier Coating Using a Multiwavelength Pyrometer

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July 1996

National Aeronautics and
Space Administration

TEMPERATURE MEASUREMENT INVOLVING NANOSTRUCTURED THERMAL BARRIER COATING USING A MULTIWAVELENGTH PYROMETER

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Introduction

It has been reported that erroneous results were obtained when a conventional pyrometer was used to measure the surface temperature of turbine engine components. Temperatures discrepancies were observed in components which were identical, except that one had its measured surface covered by a nanostructured thermal barrier coating (TBC) whereas the other component's surface was not so coated. These components were placed in an identical environment, receiving identical heat fluxes. A pyrometer measured the TBC covered surface hundreds degrees lower. These coatings were about 25 μm thick, consisting of hundreds of layers of finer structures. The TBCs had very low thermal conductivity, heat flux calculations indicated that the temperatures of the coated surface should exhibit much higher temperature than the uncoated surface. Because these coatings were transparent to radiation from the visible to the infrared region, the temperatures measured by the pyrometer should be the temperature of the covered surface. Turbo components' performance and service life depend critically on the temperatures that it would experience, it is therefore important to know accurately and confidently the real surface temperature. Out of these concerns, an investigation into the measurement of nanostructured material surface temperature was carried out.

Method

Because it is difficult to know accurately the temperature of a surface beneath these coatings, in order to verify the accuracy of a pyrometry measurement, we designed a functionally equivalent experiment to investigate the issue of temperature measurement through nanostructured TBC. The multiwavelength pyrometer was calibrated using a black body furnace whose controlled stable temperature is measured accurately by a thermocouple. Nanostructured TBC coatings (thickness about 25 μm) are deposited on sapphire disks 25 mm in diameter and 3 mm thick. The nanostructure coated sapphire disk is positioned in the opening of a black body furnace. The multiwavelength pyrometer views the furnace opening at 90° incidence. Because the sapphire is transparent and non-emitting in the less than 5 μm spectral region, temperature measurement obtained using radiation in this region would give the temperature of the black body furnace. Measurement of the furnace temperature through the sapphire nanostructure combination is therefore equivalent to temperature measurement of turbo components beneath nanostructure TBCs.

Results

Radiation of the black body furnace is received by the multiwavelength pyrometer (1) directly, (2) through a plain sapphire disk, and (3) through a nanostructure TBC coated sapphire disk. These radiation spectra are shown in Figure 1. The black body furnace is at a temperature of 1334 K measured by a thermocouple. The apparent transmission coefficients of the plain sapphire disk and the nanostructure coated sapphire disks were obtained by dividing the respective spectrum by the direct spectrum of the black body furnace (Figure 2). These transmission coefficients show large fluctuations at the shorter wavelength region due to the poor signal to noise of the multiwavelength pyrometer detector in this spectral region at that temperature. We will show how the temperature of the furnace can be obtained from the spectra shown in Figure 1.

(1) Transmission of Radiation by Nanostructure

The nanostructure coating is a proprietary material. Its exact structure, chemical composition and manufacture process are not revealed by the manufacturer. It is known only that its total thickness is about 25 μm, consisting of hundreds of alternating layers of at least two materials. Based on these two pieces of information, we attempt to analyze the transmission mechanism.

The transmission formula for a general k-layered structure, with k+1 interfaces is given as a ratio of two finite quantities given by[1]

$$\tau=\frac{t_1 t_2 t_3 \ldots\ldots t_{k+1}\exp(-i[\phi_1+\phi_2+\ldots\ldots+\phi_k])}{1+\sum r_{l_1}.r_{l_2}\ldots\exp(-2i[\Phi_{l_1}-\Phi_{l_2}+\ldots\ldots])} \tag{1}$$

$$\Phi_\nu=\phi_1+\phi_2+\ldots\ldots\phi_{\nu-1},\ \nu=2,3,\ldots k+1;\ \Phi_1=0 \tag{2}$$

where t_1, t_2 .... are the transmission at the boundary interfaces, and r_1, r_2 .... are the reflection at these interfaces, the summation in the denominator is over all the possible even products of r_1 r_2 ... The statement "all the possible" means one must take all monotonic subsets of

$$l_1<l_2\ldots\ldots<l_S \tag{3}$$

where S=2,4,6 ...., but never exceeding k+1, and

$$\phi_i=2\pi\frac{2d_i}{n_i}\frac{1}{\lambda} \tag{4}$$

is the phase difference experienced by radiation of wavelength λ passing through a layer, n_i is the nanostructure layer's refractive index, and d_i the thickness of the nanostructure layer. For k=1, the case of a single layer, we have the familiar transmission formula[2]

$$\tau=\frac{t_1 t_2\exp(-i\phi)}{1+r_1 r_2\exp(-2i\phi)} \tag{5}$$

for a single layer interference filter.

Eqn. 1 can be interpreted in the following way: the numerator describes the magnitude of transmitted radiation through the nanostructured layers, and the denominator expresses the constructive and destructive interference of radiation as it passes back and forth through the many layers of the material that makes up the TBC. The wiggles in the transmission curve is manifestation of the interference process. Under most application situations, the denominator is too complicated to write down explicitly in closed form.

Assume that the nanostructure has just 2 different compositional layers, one of them acting as a thin separation boundary and the pattern repeated. There are thus k pairs. For the i-th one, t_i is the result of scattering through this pair. In the nanostructure, the thickness of this layer pair is d/k, where d is now the total thickness of the nanostructure layers, and k the number of pairs in them. The nanostructure is considered to be a collection of scatterers with a density of N per unit volume. Each scatterer has a scattering cross section σ, the radiation that is scattered away by them is $N\sigma d/k$. For a unit intensity input, the unscattered fraction will be transmitted, therefore $t_i=1-N\sigma d/k$, the final fraction that is transmitted after passing through k of them is $(1-N\sigma d/k)^k$. When k is large, this becomes $\exp(-N\sigma d)$.

In the propagation of ultrasonic waves in solids, the acoustic energy is attenuated according to the square of the frequency (frequency is inversely proportional to λ) due to defects. If we consider the nanostructure as a collection of defects as far as radiation propagation is concerned, it is expected that the same process would produce similar optical transmission dependence.

The transmissions of plain sapphire and nanostructure coated sapphire are shown in Figure 2. The transmission of sapphire is uniform throughout the measurement spectral region. The nanostructure transmission indeed exhibited strong spectral variation. A plot of $\mathrm{Ln}(\tau)\lambda^2$ vs λ is shown in Figure 3 in which a constant straight line is obtained for wavelength above 1 μm, thus indicating the presence of a term inversely proportional to the square of the wavelength. The indication of possible $1/\lambda^4$ wavelength dependence at wavelength shorter than 1 μm is also possible because it would indicate Rayleigh scattering, but it might be just due to poor signal to noise in that region there. The peaks and valleys beyond 3 μm are due to the interference effects present in the nanostructure. For our analysis, we assume that the wavelength dependence of nanostructure scattering is inverse square in nature and is expressed as

$$\tau_{nano}(\lambda) = \tau_{sap}(\lambda) \exp\left(-Nd\frac{\alpha}{\lambda^2}\right) \tag{6}$$

where $\tau_{sap}(\lambda)$ is the transmission of the sapphire on which the nanostructure is deposited, α is a constant.

(2) Temperature Determination from a Sapphire Transmitted Black Body Radiation Spectrum

The sapphire transmitted radiation spectrum is described by Planck's law of black body radiation[3]

$$L_\lambda = \tau_\lambda \frac{c_1}{\lambda^5} \frac{1}{\exp(c_2/\lambda T) - 1} = \tau_\lambda \frac{c_1}{\lambda^5} \exp(-c_2/\lambda T) \frac{1}{1 - \exp(-c_2/\lambda T)} \tag{7}$$

where c_1, c_2 are the radiation constants, L_λ and τ_λ the radiation intensity and transmissivity of the optical medium at wavelength λ between the pyrometer and the radiation source, e.g. the plain sapphire disk.

For data analysis, this equation is rewritten as

$$\left(\frac{Ln\left(\frac{c_1}{\lambda^5}\frac{1}{L_\lambda}\right)}{c_2/\lambda}\right) - \frac{Ln\left(1 - \exp(-\frac{c_2}{\lambda T})\right)}{c_2/\lambda} = \frac{1}{T} - \frac{\lambda}{c_2} Ln(\tau_\lambda) \tag{8}$$

This is the working equation of the traditional 1-color pyrometer analysis method which would require knowing the emissivity, which in this case is the transmissivity, but in multiwavelength pyrometry, we do not need to know this value to determine temperature. Because the quantity $(1-\exp(-c_2/\lambda T))$ is practically unity at short wavelengths, the logarithm of which would be zero, Eqn. 8 says that the plot of the data $y = Ln(c_1/(\lambda^5 L_\lambda))/(c_2/\lambda)$ as a function of λ (in the Wien approximation of Planck's law) would be a straight line if $Ln(\tau_\lambda)$ is wavelength independent, and the slope is $Ln(\tau)/c_2$. The intercept of the straight line at $\lambda=0$ is $1/T$, the reciprocal of the unknown temperature. If the transmissivity is not independent of λ but known at each wavelength, Eqn. 1 can be used to calculate the many values of T at the different wavelengths, and the results averaged. Figure 4 clearly indicates that the plotted data at the shortest wavelength is a straight line. The intercept derived temperature is 1332 K. The data deviates from the straight line for wavelengths longer than 2 μm. If the data is modified to include the quantity $(1-\exp(-c_2/\lambda T))$, the straight line then describes the data well beyond 3 μm with a corresponding determined temperature of 1334 K, exactly as measured by a thermocouple for the furnace temperature.

(3) Temperature Determination from the Nanostructure Transmitted Radiation Spectrum

Because the transmission of nanostructure is given by Eqn. 6, Eqn. 8 when used to describe nanostructure becomes

$$\left(\frac{Ln\left(\frac{c_1}{\lambda^5}\frac{1}{L_\lambda}\right)}{c_2/\lambda}\right) = \frac{1}{T} + \frac{1}{\lambda}\frac{ND\alpha}{c_2} - \frac{\lambda}{c_2} Ln[\tau_{saf}(\lambda)] \tag{9}$$

We have neglected the correction $(1-\exp(-c_2/\lambda T))$ term in this formula. The logarithm of the sapphire transmission term can also be ignored because it is almost unity the logarithm of which is therefore almost zero. Eqn. 9 therefore says, the quantity on the left is inversely proportional to wavelength. When the data is plotted as a function of inverse wavelength, a straight line is obtained (Figure 5). The slope is the quantity $Nd\alpha/c_2$. In this way, the scattering coefficient $Nd\alpha$ is determined. The intercept of this straight at zero inverse wavelength ($\lambda=\infty$) is the inverse temperature. From this intercept, we obtained a temperature 1304 K, which differs from the correct furnace temperature by 30 K.

Because the exponential coefficient ($Nd\alpha$) in Eqn. 6 is determinable from the slope, we use its determined value in this formula, and adjusting the sapphire transmission as an adjustable constant to least squares fit the data to Eqn. 7 to obtain the furnace temperature. The temperature obtained is 1335 K, almost exactly the TC temperature of the furnace. The resulting curve fit is shown in Figure 6.

Conclusion

Temperature measurement of nanostructure coated turbo machinery surfaces were reported to be in error when done using traditional pyrometers. The measurement error was found to be due to an inverse square wavelength depending transmission of radiation by the nanostructure. We showed that the multiwavelength pyrometer measured the temperature of an object behind or beneath a nanostructure coating from the spectrum of radiation transmitted through it. The multiwavelength pyrometer made use of it ability to analyze the transmitted radiation, determine its spectral dependence, determine the magnitude of its transmission coefficient, to derive a transmission formula for the nanostructure and to use it to determine the temperature accurately. The multiwavelength pyrometer measured the surface temperature by two approaches: (1) by an intercept method and (2) by a more accurate curve fitting method. At 1334 K, the error was 30 K compared to hundreds of K by traditional pyrometers using the intercept method and 1 K using the curve fitting method.

Reference

1. Zdenek, Knittl, Optics of Thin Films, John Wiley & Sons.
2. Rossi, Bruno, 1957.
3. DeWitt, D.P., Nutter, G.D., Theory and Practice of Radiation Thermometry, John Wiley & Sons, New York, 1988.

Figure Caption

Figure 1	BB Spectra viewed 1) directly, 2) through sapphire,3) through Nanostructured TBC.
Figure 2	Transmission of sapphire and nanostructure.
Figure 3	Wavelength dependence of nanostructure transmission.
Figure 4	Plot of sapphire transmitted spectrum vs wavelength.
Figure 5	Plot of nanostructure transmitted spectrum vs inverse wavelength.
Figure 6	Fitted spectrum of nanostructure transmitted data.

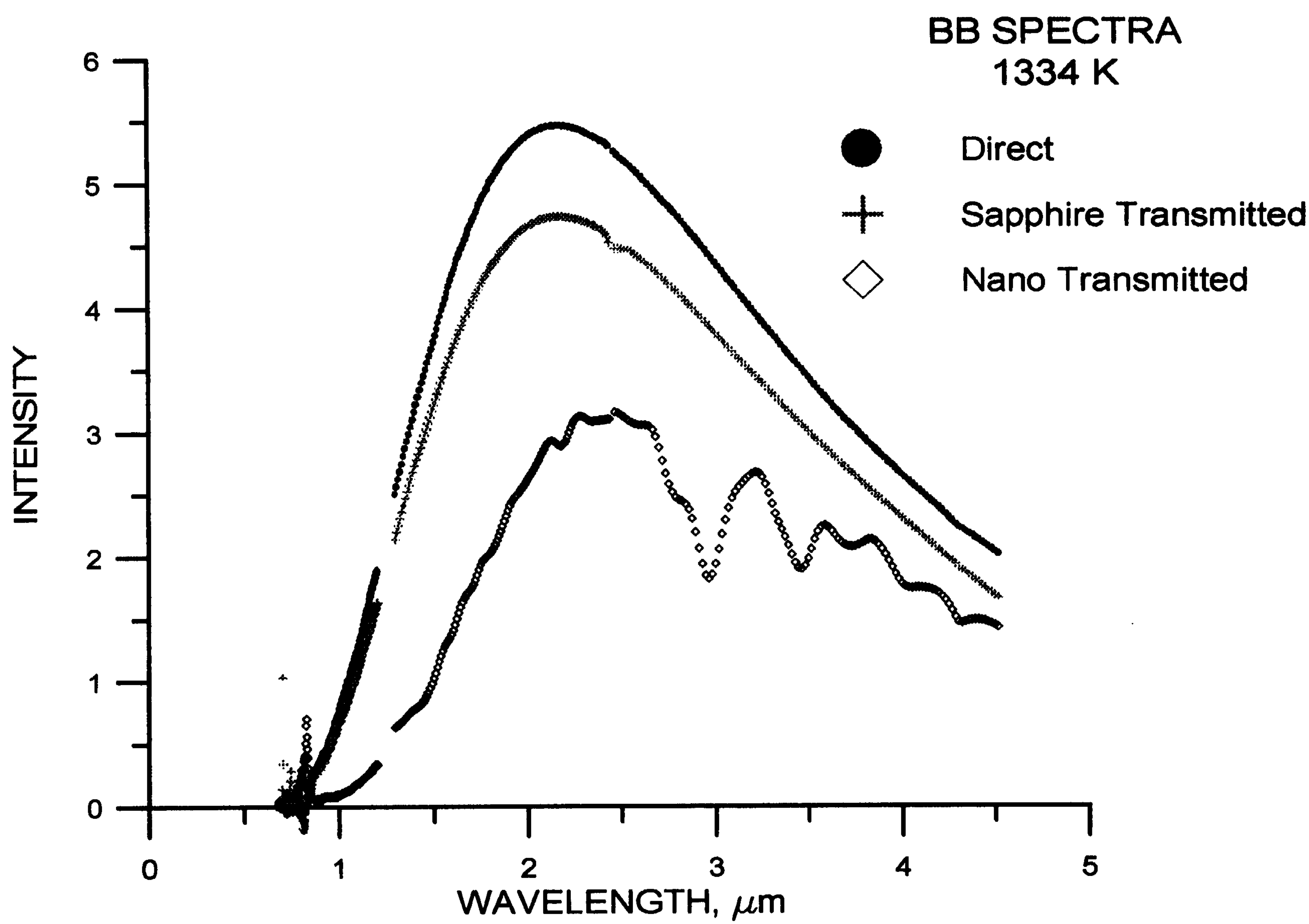

Figure 1 BB spectrum viewed (1) directly, (2) through sapphire, (3) through nanostructured TBC.

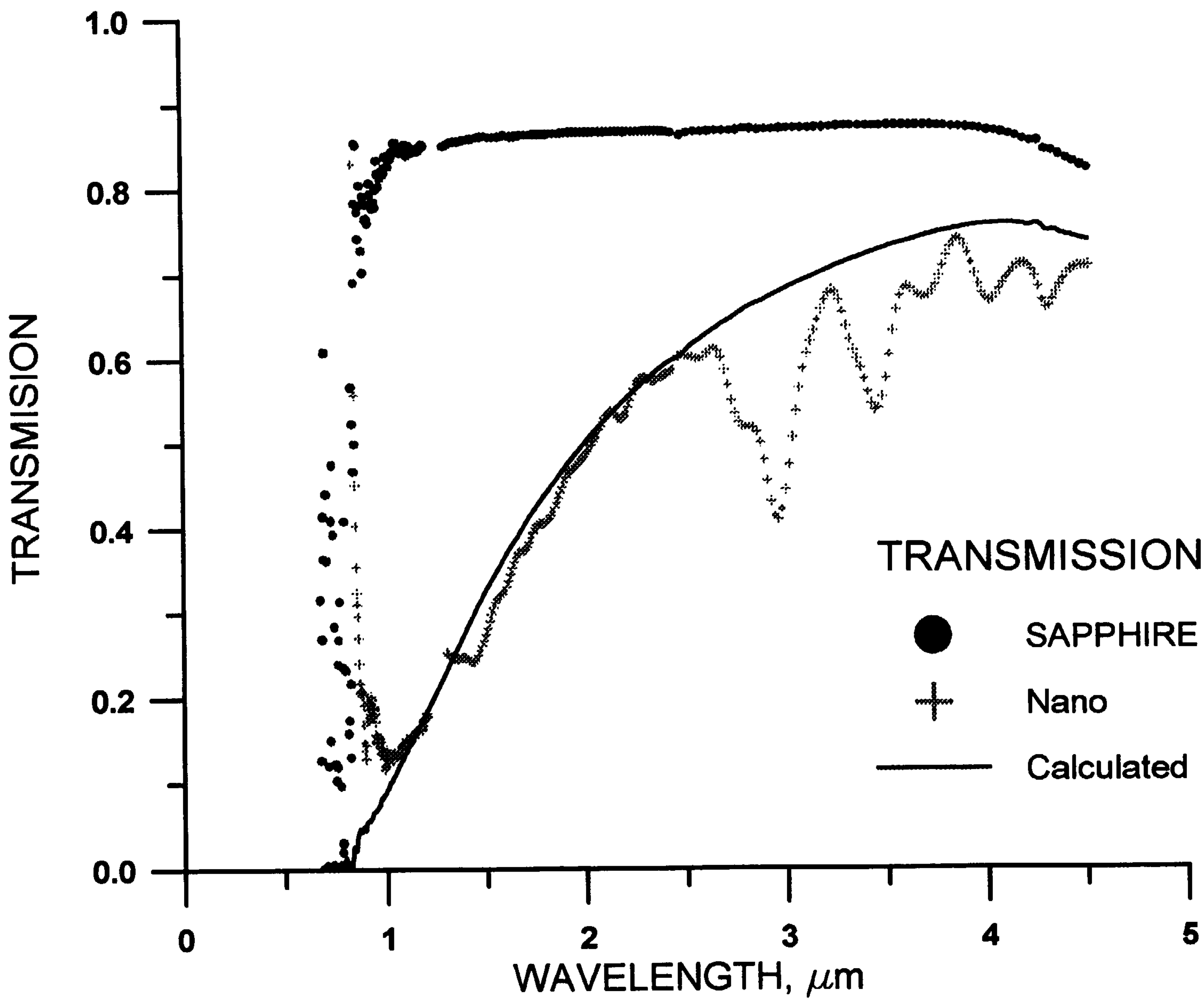

Figure 2 Transmission of sapphire and nanostructure.

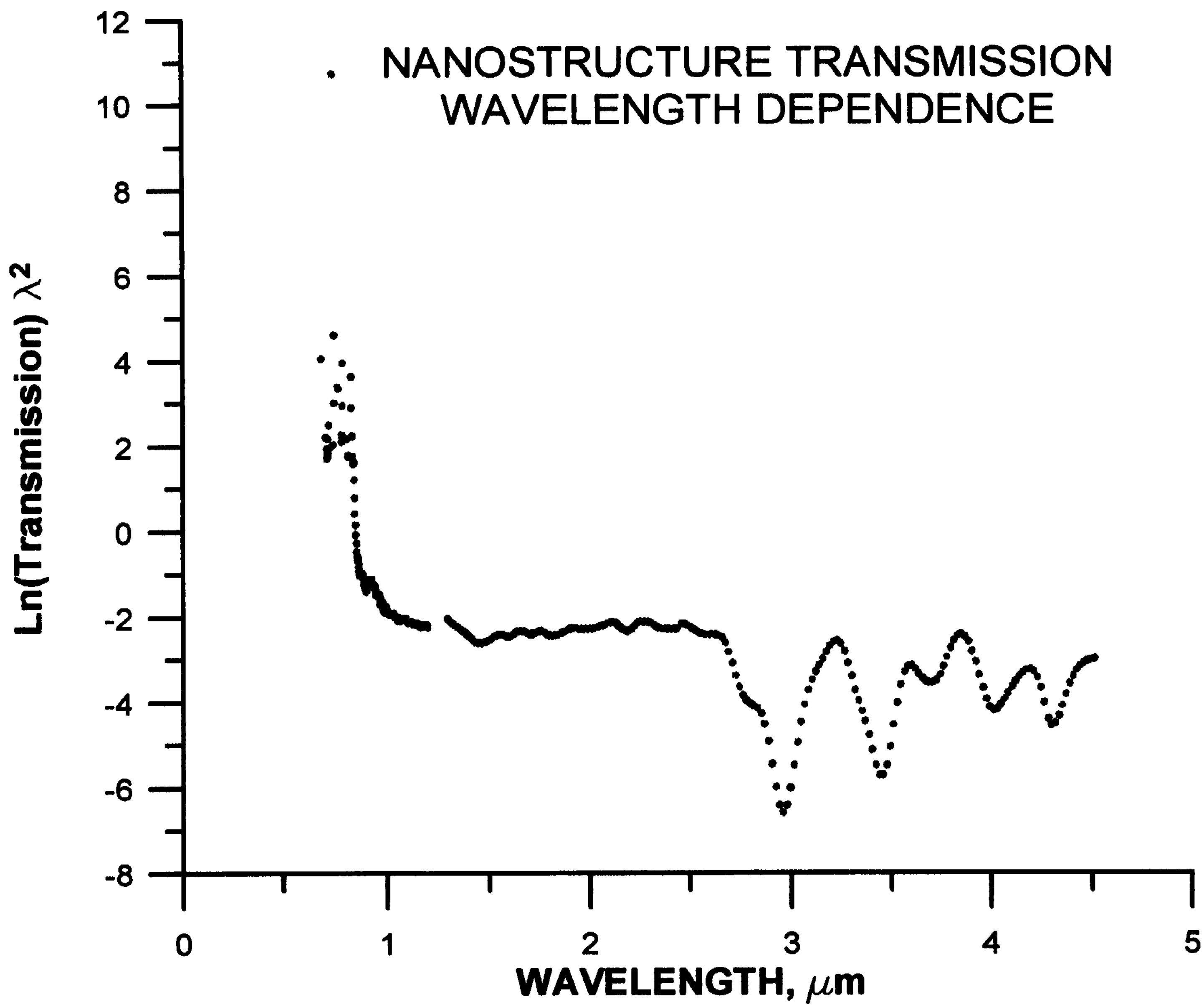

Figure 3 Wavelength dependence of nanostructure transmission.

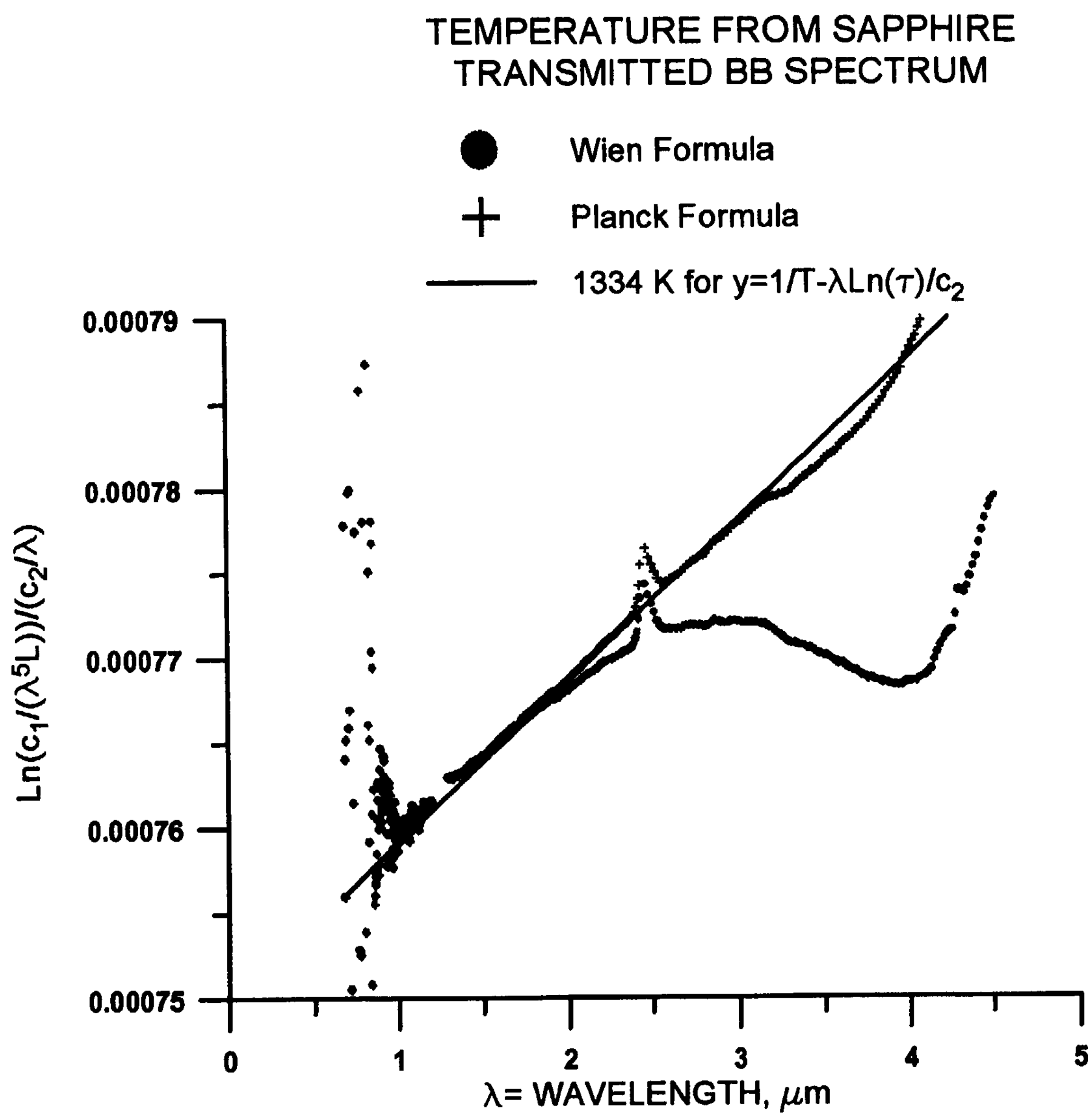

Figure 4 Plot of sapphire transmitted spectrum vs wavelength.

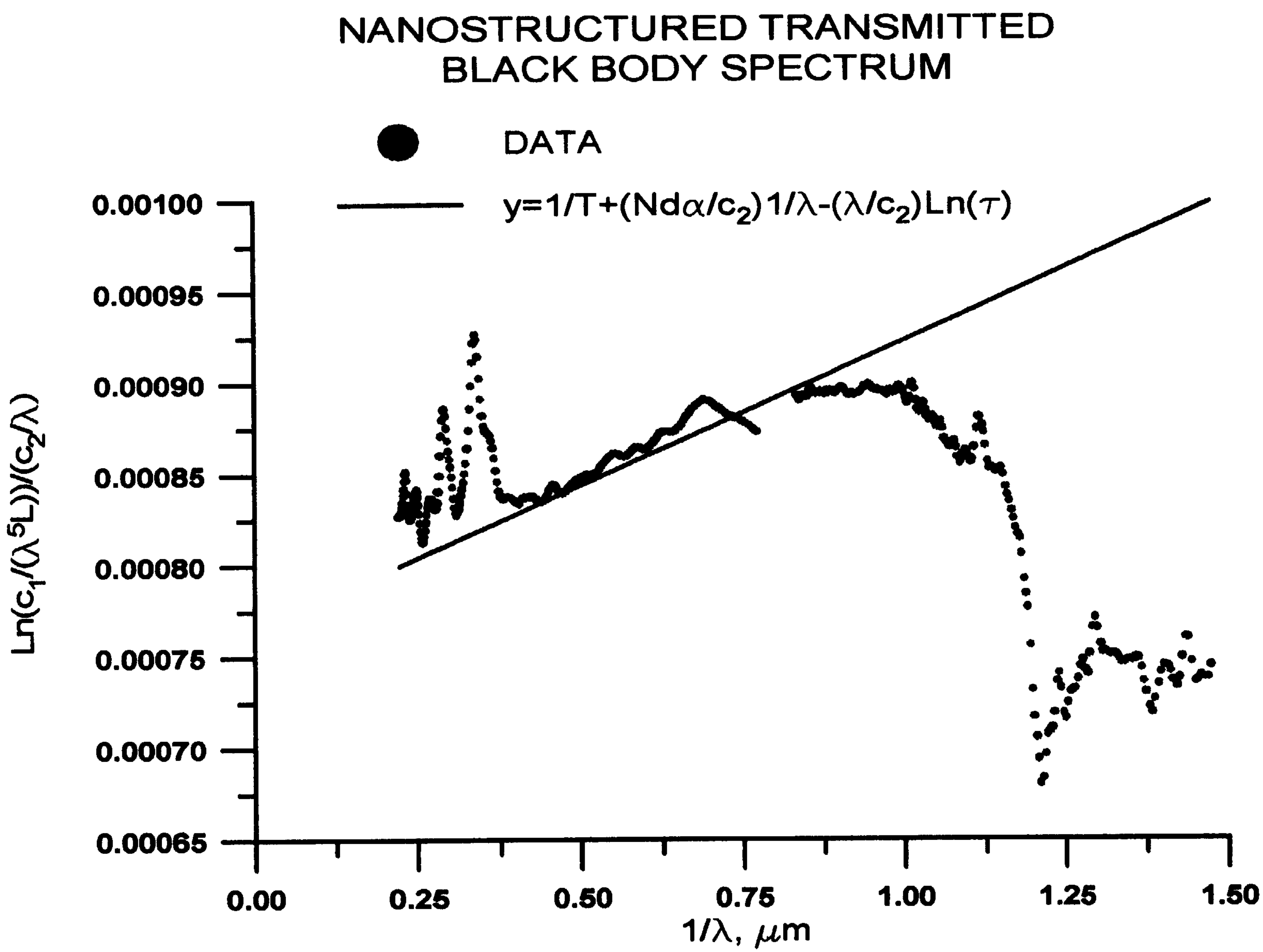

Figure 5 Plot of nanostructure transmitted spectrum vs inverse wavelength.

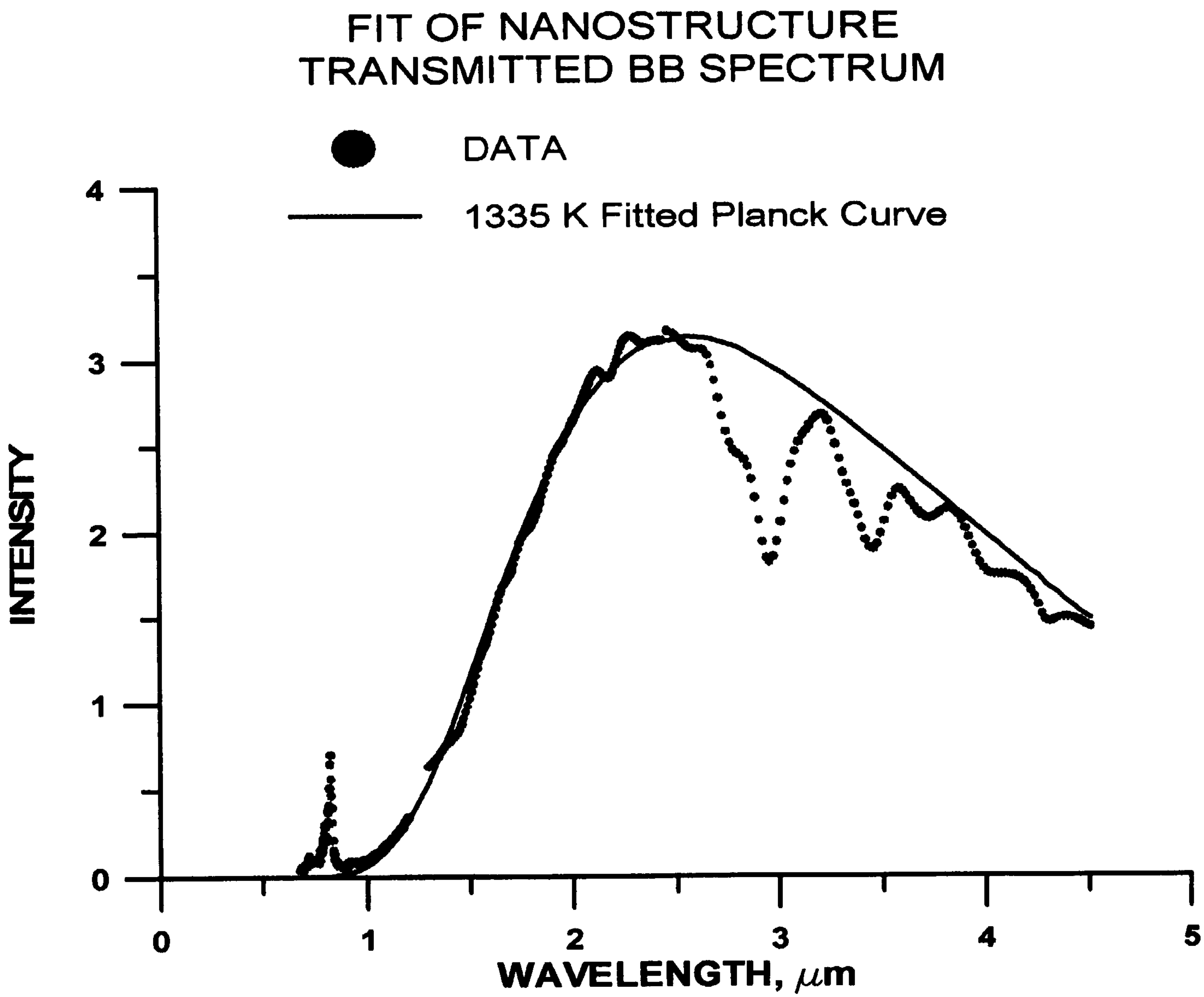

Figure 6 Fitted spectrum of nanostructure transmitted data.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	July 1996	Technical Memorandum

4. TITLE AND SUBTITLE

Temperature Measurement Involving Nanostructured Thermal Barrier Coating Using a Multiwavelength Pyrometer

5. FUNDING NUMBERS

WU–505–63–12

6. AUTHOR(S)

Daniel Ng

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

National Aeronautics and Space Administration
Lewis Research Center
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8. PERFORMING ORGANIZATION REPORT NUMBER

E–10361

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

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–107286

11. SUPPLEMENTARY NOTES

Responsible person, Daniel Ng, organization code 2510, (216) 433–3622.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 35

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

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

It has been reported that erroneous results were obtained when a conventional pyrometer was used to measure the surface temperature of turbine engine components. Temperatures discrepancies were observed in components which were identical, except that one had its measured surface covered by a nanostructured thermal barrier coating (TBC) whereas the other component's surface was not so coated. These components were placed in an identical environment, receiving identical heat fluxes. A pyrometer measured the TBC covered surface hundreds degrees lower. These coatings were about 25 μm thick, consisting of hundreds of layers of finer structures. The TBCs had very low thermal conductivity, heat flux calculations indicated that the temperatures of the coated surface should exhibit much higher temperature than the uncoated surface. Because these coatings were transparent to radiation from the visible to the infrared region, the temperatures measured by the pyrometer should be the temperature of the covered surface. Turbo components' performance and service life depend critically on the temperatures that it would experience, it is therefore important to know accurately and confidently the real surface temperature. Out of these concerns, an investigation into the measurement of nanostructured material surface temperature was carried out.

14. SUBJECT TERMS

Temperature; Pyrometer; Nanostructure; Optical transmission

15. NUMBER OF PAGES

13

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	