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## Summary of Splinter Workshop on

# MATERIALS THERMAL & THERMORADIATIVE PROPERTIES/CHARACTERIZATION TECHNOLOGY

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## ABSTRACT

Reliable properties data on well characterized materials are necessary for design of experiments and interpretation of experimental results. The activities of CINDAS to provide data bases and predict properties are discussed. An understanding of emissivity behavior is important in order to select appropriate methods for non-contact temperature determination. Related technical issues are identified and recommendations are offered.

## INTRODUCTION

The intent of this splinter workshop session was to define technical issues and offer recommendations on the thermophysical and thermoradiative properties that are important for materials science characterization in microgravity of thermally important events and behavior. Two presentations were given by the authors and are summarized below. While many of the topics were given discussion by other participants, the remarks are personal rather than consensus opinions.

## THERMOPHYSICAL PROPERTIES

The need for reliable thermophysical properties in the design of microgravity experiments, applications related work and the interpretation of experimental results was clearly made in the proceedings of the last workshop [1, see for example, pp. 72, 76, 81 and 214]. While the goal of the program is to develop new materials, much of the present activity focuses on materials for which there exists literature information which may be quite fragmented, but could be useful for prediction and estimation analyses. We refer to this activity as *data physics*, the methodology for synthesizing existing information and knowledge to property values.

The *Center for Information and Numerical Data Analysis and Synthesis* (CINDAS) founded in 1957 has been recognized as the largest single source of reliable materials property data. Its major functions are:

- literature searches
- data compilation
- data evaluation and analysis
- data synthesis and prediction
- numerical data base development
- on-line operation of data bases
- property research and measurements
- material property publications
- inquiry service

While CINDAS provides these services to a variety of industrial and governmental organizations, its major commitment is to the Department of Defense (DoD) as the *High Temperature Materials - Mechanical, Electronic and Thermophysical Properties Information Analysis Center* (HTMIAC). Further details on HTMIAC and CINDAS services and how they can be accessed are provided in Appendix A.

The *technical issue* is the availability of thermophysical and thermoradiative properties. The resources of HTMIAC-CINDAS, developed over a period of more than 30 years through extensive governmental and industrial support, can be utilized in a cost-effective manner to meet many of the present and future needs of the Microgravity Program. Toward developing a relationship between program investigators and CINDAS, the following *recommendations* are offered:

- the investigators should use the inquiry service to determine the extent *and* value of literature holdings and compiled data on the properties/materials of interest to them,
- program management should develop a priority list of materials and properties of interest so that the coverage and quality of data can be assessed, and
- some special cases where data is not available but is urgently needed should be identified and a demonstration synthesis (data physics) effort initiated to make predictions/estimations.

To effectively support the Microgravity Program, a relationship between NASA and CINDAS should be established which will permit CINDAS to serve as the central source for all properties-related requirements.

## EMISSIVITY AND ITS EFFECT ON TEMPERATURE DETERMINATION

A reoccurring theme voiced during the paper presentations and their discussions was the need to understand material emissivity behavior in order to make reliable non-contact (radiometric) measurements. Specific situations within the Microgravity Program where emissivity data or behavior knowledge is lacking have been identified in the proceedings of the last workshop [1, see for example, pp.58, 59, 72, 75, 76, 149, 180 and 183]. These needs are not specific to only microgravity studies; similar challenges to the radiation thermometrist have been addressed for several decades [2,3]. While the literature on spectral emissivity and radiation thermometry is extensive, it is widely spread and not easily accessed. Recent re-newed interests by the metals processing [4] and petrochemical [5] industries, seeking improved temperature measurement accuracy to achieve increased productivity, have stimulated efforts to address the *central problem* of noncontact temperature determination: how to account for emissivity effects [3].

There are two major *issues* related to understanding material emissivity behavior. First, it is essential to obtain reliable measurements of the spectral emissivity as a function of wavelength and temperature on well-characterized materials under controlled environmental conditions. This information can be generated in apparatus designed specifically for that purpose as has been the case for the large majority of the data reported in the literature. Alternately, this information will come as a consequence of special efforts made during experiments devoted to wider purposes such as are being conducted in the Microgravity Program now.

The second major issue is that of understanding the effect of emissivity on different non-contact or radiometric methods for inferring surface temperatures. In subsequent subsections, five methods are briefly discussed with a view to establishing the role of emissivity behavior or uncertainty in inferring temperature with confidence.

## Narrow-Band or Spectral Methods

From the temperature equation for the spectral method using the Wein's approximation to the Planck spectral distribution law [2] (see also Eq. 2 in Appendix B), the relative uncertainty in inferred temperature due to the uncertainty in the emissivity is

$$\frac{\Delta T}{T} = -\frac{\lambda T}{c_2} \cdot \frac{\Delta \epsilon}{\epsilon} . \qquad (1)$$

Since most practical radiometric systems are operated at $\lambda T \ll 2898$ $\mu$m·K (that is, to the short wavelength side of the spectral radiance maximum of the blackbody curve) and with $c_2 = 14,389$ $\mu$m·K, it follows that the $\lambda T/c_2$ term can range from 1/5 to typically as low as 1/15. Hence, for relative uncertainties in the spectral emissivities as high as ± 10%, there are situations where the resulting error in the inferred temperature may be acceptable. For high emissivity materials, such as many ceramics and oxidized metals, it is reasonable to estimate emissivity values within ± 10%. For well polished metallics, particularly in the emissivity range of 0.1 to 0.2, it may not be possible to make estimates with suitable accuracy to infer temperature with decent confidence.

There are two special features of the spectral method that should be noted. First, the method offers the greatest sensitivity between spectral radiance and temperature changes, implying that instrumentation noise will have the least effect on the temperature determination. Second, experimentally observed spectral radiance temperatures that are not corrected for emissivity are still of value since, when such knowledge is available, the data can be manipulated easily to infer true temperatures.

There are other pitfalls in applying the spectral method, the most difficult of which is avoiding or making corrections for irradiance from the surroundings reflected off the target into the radiometer. This situation occurs frequently when viewing targets being heated in furnaces. If the surroundings are large and isothermal, the correction procedure is straight forward [2]. Such is not the case in many practical situations and the correction procedure is tedious if not very approximate.

## The Ratio Method

The ratio method has two special features: (1) the target need not fill the radiometer field-of-view and (2) effects of absorption on observed spectral radiances along the line-of-sight due to windows or atmospheric gases may be minimal, especially if the two spectral bandpasses are close together. Further, if the emissivity spectra in the region of the bandpasses is gray (spectrally flat), then the ratio temperature determined from the spectral radiance ratio is equal to the true temperature. There are limited situations, such as high emissivity, heavily oxidized surfaces, where the target emissivity behavior is sufficiently gray that true temperature can be inferred with high accuracy by ratio thermometers.

Ratio thermometry was first introduced in steel making applications. As requirements for greater accuracy developed, other methods have been sought, the most successful of which at present are hybrid methods requiring the use of ancillary furnaces, mirrors and multiple detectors [2].

Ratio thermometry has been proposed or is being used in several experiments within the Microgravity Program. Some of these applications take advantage of the aforemention special features. But non-grayness of sample targets, particularly metallics, will likely cause disappointing temperature determination results. Further, observed ratio temperatures cannot be corrected easily for nongrayness and irradiance effects if, at a later time, knowledge of the spectral emissivity becomes available. Ratio thermometers with adjustable off-sets are commercially available and find good utility in many industrial processes. Such instrumentation and practice for use on materials science experimentation is to be discouraged.

*Recommendations.* (1) The applicability and limits of error for ratio thermometer methods to determine true temperature should be thoughtfully examined before reporting temperature determination results. (2) Dual wavelength methodology should be investigated for applications seeking higher accuracy which do not require the two special features of ratio thermometry. A brief overview of recent developments is provided in Appendix B.

## The Multispectral Method

Considerable attention was given to the multispectral (typically 6 to 100 spectral bands) method during the workshop. In separate contributions of this proceedings, Kahn and Spjut conclude that *a priori* emissivity information, such as the form of the emissivity function, is not required and that the method can yield a statistical estimate of the uncertainty in the inferred true temperature. Using six spectral bands in the visible, Oshe and co-workers at the European Transuranium Institute have successfully used the indirect multispectral method with a linear emissivity function on alloys and ceramics [6,7]. The particular application is to determine the rapid change of material temperature during pulse heating experiments to observe thermodynamic and transport properties. A version of the six-wavelength pyrometer based upon this technology has been offered commercially [8].

*Recommendations:* (1) Continued inquiry should be directed toward understanding the features and limitations of multispectral methods. Particularly useful would be in-depth archival literature on recent developments that could be carefully studied by a wide community of workers in the field. (2) While most of the experiences to date with multispectral methodology have been based upon silicon photodetector technology ($\lambda < 1.1\ \mu m$), its implementation to the moderate temperature range below 1000 K needs to be considered. Candidate detector arrays for the mid-IR region multispectral radiometers need to be evaluated.

### Laser Pyrometry

Laser pyrometry [9,10] provides the means to infer the target temperature from observations of the spectral radiance temperature and the directional (near-normal) reflectance. For a specular or diffuse surface, the bidirectional reflectance is directly related to the normal emissivity required of the spectral temperature equation.

If the target material is neither specular nor diffuse, or its degree of diffuseness changes during the course of time as is the case in many materials processes, the bidirectional reflectance is no longer directly related to the normal emissivity. For example, the bidirectional reflectance of a slightly non-specular (due to microstructure changes, for example) surface can be remarkably different than that of the specular surface, yet their normal emissivities may be only slightly different.

Nutter [11] proposed a technique to overcome this difficulty which measures the bidirectional reflectance ratio between two *or* three wavelengths depending upon whether the surface is either diffuse or specular *or* has an unknown degree of diffuseness, respectively. Appendix C provides a brief overview of the critical feature of the method, namely, whether $R_{ij}$, the ratio of the normal-hemispherical reflectance $\rho_{ih}$ to the bidirectional reflectance $\rho_{ij}$, is a linear function with wavelength. Because there is a dearth of bidirectional reflectance distribution function (BRDF) data in the literature, this issue cannot be addressed without conducting specially planned experiments.

*Recommendations:* There is growing national interest and capability in making BRDF measurements on materials with different surface characteristics. Through the design of critical experiments utilizing BRDF data on selected materials, the feasibility of the two- or three-wavelength pyrometry as proposed by Stein and Nutter should be evaluated.

## OTHER TECHNICAL ISSUES

Methods for measuring the spectral emissivity and optical properties of small samples, especially if they are spherically shaped, are limited to ideal smooth surfaces. Krishnan, et al., in a separate contribution to these proceedings, have effectively demonstrated a rotating analyzer-ellipsometry method on ripple free liquid metals. This study has created a significant knowledge base for understanding the changes in emissivity as a function of wavelength and temperature for metals in the liquid state.

Other reliable methods for metallics or ceramics in the solid state have yet to be demonstrated. *Recommendation:* Attention should be given to developing and thoroughly evaluating methods for obtaining thermoradiative and/or optical properties of materials in their processing environment.

Contributions to the archival literature should not be overlooked. It is important that results of experimental studies, especially high quality properties data and temperature measurement methodology, should be disseminated and undergo the peer review process. *Recommendation:* Investigators should be encouraged to publish the results of studies. Special attention should be given to characterization of the materials for which properties data are reported. Further, the investigators should participate in the traditional and specialty conferences organized by technical societies.

During the course of the workshop, the need for radiation thermometer calibration and standardized procedures was discussed. The possibility of requiring improved calibration accuracies at elevated temperatures nearly twice that of present NIST capability was suggested. At present, calibration requirements for ratio thermometers and standard test methods are undefined. *Recommendation:* Because of the long lead time to established improved metrological practices, NIST should remain involved in this program. Their contributions will be welcomed also in the traditional industrial areas.

## SUMMARY AND CONCLUSIONS

The purpose of the splinter workshop session was to identify technical issues and offer recommendations. The first major technical issue discussed was the status of thermophysical and thermoradiative properties. Using CINDAS as a resource, we are recommending that

- investigators utilize CINDAS data bases to determine extent and value of current literature, compiled data, etc., to this problem,
- program management develop a property list of property/materials and an assessment of coverage to be performed, and
- to meet urgent needs, a demonstration synthesis effort be initiated.

Through these steps, the role of CINDAS to serve as a central source for all property related requirements can be demonstrated.

The central problem of radiation thermometry or non-contact temperature determination, how to account for emissivity effects, requires an understanding of the target material emissivity behavior. Two technical issues can be identified: (1) the need for reliable spectral emissivity data on well characterized materials under controlled environmental conditions and (2) understanding the effect of emissivity on different radiometric methods for inferring surface temperature. The first of these issues can be best addressed by individual materials investigators as an integral part of experiments designed for a broader purpose. In regards to methodologies, five recommendations were offered:

- applicability and limits of error for ratio thermometry need to be assessed for each application,
- dual wavelength methodology should be investigated for applications seeking higher accuracies,
- continued inquiry should be directed toward understanding the features and limitations of multispectral ($\geq 3$ wavelengths) methods especially as related to not requiring any *a priori* information and providing estimates for accuracy of inferred temperature,
- evaluation of candidate detector arrays for mid-IR region multispectral radiometers, and
- performing critical experiments to establish the feasibility of two- and three-wavelength laser pyrometry to account for non-gray, non-diffuse material behavior.

The importance of contributions by the program investigators to the archival literature should be stressed. Publication of well-characterized, high quality data will be a stimulus to a wide technical community. Finally, it is recommended that the NIST should remain closely involved in the program in order that improved standards and metrological practices will be available as required.

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## Appendix A

# A CENTRAL SOURCE FOR THEMOPHYSICAL PROPERTIES OF MATERIALS:

## HTMIAC-CINDAS

The Center for Information and Numerical Data Analysis and Synthesis (CINDAS) was founded at Purdue University on 1 January 1957, originally as the Thermophysical Properties Research Center (TPRC). For over 30 years, CINDAS has devoted its efforts solely to the properties of materials. Since 1960 CINDAS has been operating for the Department of Defense (DoD) an information analysis center on materials properties, which evolved to become the Thermophysical and Electronic Properties Information Analysis Center (TEPIAC) in 1973 and to become the High Temperature Materials - Mechanical, Electronic, and Thermophysical Properties Analysis Center (HTMIAC) in 1986. CINDAS has developed for various sponsors the following numerical data bases on materials properties:

- High Temperature Materials Properties Data Base.
- Data Base on Dielectric Materials.
- PC-Version Data Base on Microelectronic Packaging Materials.
- Engineering Materials Properties Data Base.
- Thermophysical Properties of Fluids Data Base.
- Thermophysical and Mechanical Properties of Rocks and Minerals Data Base.

Furthermore, CINDAS' bibliographic data bases on materials properties contain bibliographic information on over 270,000 pertinent worldwide scientific and technical documents.

The properties coverages for different types of materials in different data bases are more or less different. As a typical example, the properties covered in the High Temperature Materials Properties Data Base, which is developed through the operation of HTMIAC for the DoD, are given below:

(A) Thermophysical, Thermoradiative, Optical, and Electronic Properties:

- Ablation energy
- Ablation temperature
- Absorptance
- Absorption coefficient
- Boiling point
- Density
- Electrical resistivity
- Emittance
- Heat capacity
- Heat of fusion
- Heat of vaporization
- Melting point
- Reflectance
- Refractive index
- Thermal conductivity
- Thermal diffusivity
- Thermal expansion
- Transmittance

(B) Mechanical Properties:

- **Compressive modulus**
- **Compressive strain at fracture**
- **Compressive strength, ultimate**
- **Compressive strength, yield**
- **Elastic constants**
- **Elongation**
- **Energy release rate**
- **Flexural modulus**
- **Flexural strength**
- **Fracture toughness**
- **Hardness**
- **Impact energy**
- **Poisson's ratio**
- **Reduction in area**
- **Shear modulus**
- **Shear modulus, in-plane**
- **Shear strain at fracture**
- **Shear strength, in-plane**
- **Shear strength, interlaminar**
- **Shear strength, ultimate**
- **Shear strength, yield**
- **Stress-strain curves, compression**
- **Stress-strain curves, shear**
- **Stress-strain curves, tension**
- **Tensile modulus**
- **Tensile strain at fracture**
- **Tensile strength, ultimate**
- **Tensile strength, yield**

HTMIAC/CINDAS has been disseminating data and information on materials properties through publications, inquiry services, and through on-line operation of the data bases. Over the years CINDAS has published the resulting data and information on materials properties so far in 36 volumes of data books and 26 volumes of properties research literature retrieval guides with a total of over 50,000 pages, and in more than 150 technical reports and numerous research articles. CINDAS has responded to more than 12,000 inquires for data and information on materials properties and for technical consulting, advisory, analysis, and other user support services.

In the on-line operation, the data base is interactive, menu-driven, and user-friendly. Since it is menu-driven, no special query language or commands need to be learned and any user can easily search and retrieve the needed data from the Data Base.

The procedures to use HTMIAC/CINDAS services are as follows:

(1) Write HTMIAC/CINDAS or call (317) 494-9393 for its inquiry services or technical products.

(2) Subscribe to HTMIAC/CINDAS on-line numerical database service.

(3) Contact HTMIAC/CINDAS for major technical work through a purchase order, military interdepartmental purchase request (MIPR), contract, etc.

## Appendix B

# OVERVIEW ON DUAL-WAVELENGTH RADIATION THERMOMETRY METHODS

### Introduction

Dual-wavelength methods are extensions of the ratio method wherein two spectral radiance temperatures, $T_{\lambda 1}$ and $T_{\lambda 2}$, are directly measured, usually with a single detector, rather than the ratio of the spectral radiances for two closely spaced spectral bands [12]. Different algorithms, frequently referred to as emissivity compensation algorithms, have been evaluated by various investigators to infer true temperature from the observed spectral radiance temperatures. An overview of six methods follows.

### Principles of the Methods

The *spectral* temperature equation for the spectral method using the Wein's approximation to the Planck spectral distribution law is

$$\frac{1}{T} = \frac{1}{T_\lambda} + \frac{\lambda}{c_2} \ln \epsilon_\lambda . \tag{2}$$

For the ratio method, using the same relation but written for two spectral conditions, the *ratio* temperature equation is

$$\frac{1}{T} = \frac{1}{T_r} + \frac{\Lambda_r}{c_2} \ln \left( \frac{\epsilon_1}{\epsilon_2} \right) \tag{3}$$

where the ratio temperature, $T_r$, and the equivalent wavelength, $\Lambda_r$, are defined such that

$$\frac{1}{T_r} = \Lambda_r \left[ \frac{1}{\lambda_1 T_{\lambda 1}} - \frac{1}{\lambda_2 T_{\lambda 2}} \right] \qquad \Lambda_r = \frac{\lambda_1 \lambda_2}{\lambda_2 - \lambda_1} . \tag{4,5}$$

To achieve emissivity compensation, the second term on the right-hand side of Eq.(3) needs to be zero or a known constant independent of temperature and surface conditions; that is, the ratio method requires that $\epsilon_1 / \epsilon_2 =$ constant.

The temperature equation and compensation algorithms for the dual-wavelength methods are provided in Table B-1. The Foley method, Eqs. (6-8), is a variation of the ratio method where $K_f$ is the parameter which is adjusted to account for non-gray behavior [13]. Note that when $K_f = 0$, $T_{mr}$, the modified-ratio temperature, becomes the ratio temperature. The Watari method, Eqs. (9,10), is yet another variation of the ratio method and is based upon an exponential spectral emissivity function, Eq. (10) [14,15]. The next three methods shown in the Table B-1 have temperature equations which are empirical in nature. The *ratio-with-offset* (RWO) relationship is commonly used in commercial ratio instruments where emissivity compensation is achieved by adjusting the parameter B. Anderson [16,17] recognized that for metallic surfaces the spectral radiance and ratio temperatures are systematically low and high, respectively, compared to the true temperature. Referred to as the *linear spectral-ratio* (LSR) method, the temperature equation, Eq. (12), is a linear combination of the ratio and spectral radiance temperatures. A variation of this approach, that is slightly improved in some situations, is the *inverse spectral-ratio* (ISR) method, Eq. (14) [12,18]. The forms of the emissivity compensation algorithms for these two methods, Eqs. (13) and (15), are quite complicated but similarly require that the ratio $\ln\epsilon_2/\ln\epsilon_1$ remain constant. The advantage of the ISR method is apparent from the algorithms by noting that $y_o$ is independent of temperature while $x_o$ for the LSR method is not. The Tanaka-DeWitt method [19,20], requires *a priori* information in the form of an emissivity function, Eq. (17), which must be determined by separate experiments over a range of surface conditions the target material might have.

## Discussion and Summary

The Watari, LSR, and Tanaka-DeWitt methods have been reduced to practice. The Watari method has been demonstrated with steels that undergo heat treatment with subsequent oxidation. A commercial instrument based upon the LSR method is being used in the aluminum industry. The Tanaka-DeWitt method has been successfully demonstrated on the galvanneal (zinc dip on steel) process and hot strip mill in the steel industry.

While dual-wavelength methods have been successfully applied to specific applications, as yet there is no general approach to be recommended for new situations. Determining the appropriate form for the emissivity compensation algorithm is the challenge, which of course, depends upon understanding the behavior of the spectral emissivity of the target material in its process environment. There are strong incentives to continue investigations on dual-wavelength methodologies: accuracies of ±3K (in the 800-1000K) have been demonstrated and environment-hardened instrumentation can be built for reasonable costs. Clearly, the obstacle to an improved technology is an improved understanding of the behavior of material.

## TABLE B-1 Dual-Wavelength Temperature Equations and Algorithms

| Method/Author | Temperature Equation | | Compensation Algorithm | | Adjustable Parameter(s) |
|---|---|---|---|---|---|
| Foley [13] | $\frac{1}{T}=\frac{1}{T_{mr}}+\frac{\Lambda_r}{c_2}\left[(1-K_f\lambda_1)\ln \epsilon_1-(1-K_f\lambda_2)\ln \epsilon_2\right]$<br>$\frac{1}{T_{mr}}=\Lambda_r\left(\frac{1-K_f\lambda_1}{\lambda_1 T_{\lambda 1}}-\frac{1-K_f\lambda_2}{\lambda_2 T_{\lambda 2}}\right)$ | (6)<br>(7) | $\frac{\ln \epsilon_1}{\ln \epsilon_2}=\frac{1-K_f\lambda_2}{1-K_f\lambda_1}$ | (8) | $K_f$ |
| Watari [14,15] | $\frac{1}{T}=\frac{1}{T_r}+\frac{\Lambda_r}{c_2}\alpha(\lambda_1^2-\lambda_2^2)$ | (9) | $\epsilon_\lambda=\exp(\alpha\lambda^2)$ | (10) | $\alpha$ |
| Ratio with Offset (RWO) [18] | $T = T_r + B$ | (11) | --- | | B |
| Linear Spectral-Ratio (LSR) [16,17] | $T=(1-x_o)T_r+x_o T_{\lambda 2}$ | (12) | $x_o=\frac{\frac{\lambda_1 T}{c_2}\ln \epsilon_1-1}{\frac{\lambda_1}{\Lambda_r\left[1-\frac{\ln \epsilon_2}{\ln \epsilon_1}\right]}-1}$ | (13) | $x_o$ |
| Inverse Spectral-Ratio (ISR) [12,18] | $\frac{1}{T}=\frac{(1-y_o)}{T_r}+\frac{y_o}{T_{\lambda 2}}$ | (14) | $y_o=\frac{-1}{\frac{\lambda_1}{\Lambda_r\left[1-\frac{\ln \epsilon_2}{\ln \epsilon_1}\right]}-1}$ | (15) | $y_o$ |
| Tanaka-DeWitt [19,20] | $T = f(L_{\lambda 1},L_{\lambda 2},\epsilon_1,\epsilon_2)$ | (16) | $\epsilon_2 = f(\epsilon_1)$ | (17) | --- |

# Appendix C

# OVERVIEW ON LASER PYROMETRY

Laser pyrometry technology has been demonstrated to provide marked improvement in the accuracy of temperature determination as compared to passive techniques [1, p.304]. However, the technique as presently practiced is limited to diffuse (lambertian) targets [10]. Effects due to reflected irradiation, from a hotter furnace wall, for example, can be accounted for in the same manner as treated for passive spectral methods. There are many situations where the target material is diffuse and laser pyrometry can be applied with high confidence. Further, if the degree of diffuseness of the target material is unchanging during the observation periods, the technique can then account for changes in the emissivity of the material due to process variables, temperature or other parameters.

Stein [10] and Nutter [11] have addressed extending the single-wavelength or spectral laser pyrometry method to two and three wavelengths, respectively, in order to account for non-diffuse effects. The technical issue underlying their efforts centers about relationships between three thermal radiative properties: the directional spectral emissivity, $\epsilon_{\lambda,i}$; the directional-hemispherical reflectance, $\rho_{\lambda,ih}$; and the bidirectional reflectance distribution function (BRDF), $\rho_{ij}$. For the temperature equation, such as Eq. (2) for a spectral condition, knowledge of $\epsilon_{\lambda,i}$, where the direction is nearly normal, is required. From a radiation balance,

$$\epsilon_{\lambda,i} = 1 - \rho_{\lambda,ih} \tag{18}$$

where $\rho_{\lambda,ih}$ is the reflectance corresponding to directional irradiation (i) and hemispherical (h) collection. In the laser pyrometry technique, the property that is measured using laser irradiation is the bidirectional reflectance $\rho_{\lambda,ij}$ where the directions (i,j) are slightly off the normal. For a perfect, diffuse reflector, $\rho_{ij} = 1/\pi \text{ sr}^{-1}$; for a perfect, specular reflector, $\rho_{ij}$ can be zero, unity or any intermediate value depending upon the magnitudes of the solid angles of viewing/collection and the choice of directions (i,j). Of special interest is the behavior of

$$R_{ij} = \frac{\rho_{ih}}{\rho_{ij}} \tag{19}$$

the ratio of the directional-hemispherical to the bidirectional reflectance. According to Stein [10], if this ratio is independent of wavelength, then a *two-wavelength* laser technique will provide emissivity compensation. If this ratio is a linear function of wavelength, Nutter [11] postulates that a *three-wavelength* laser technique will be required to provide compensation. To date there have been no demonstrations of either technique.