Comparison of Emissivity Evaluation Methods for Infrared Sources

Stephen D. Scopatz*, Jason A. Mazzetta, John E. Sgheiza, Miguel A. Medina
Electro Optical Industries, 859 Ward Drive, Santa Barbara, CA, USA 93111

ABSTRACT

This paper starts with a back to basics review of the definition of blackbody emissivity, how it is measured and how it is specified. Infrared source vendors provide emissivity specifications for their blackbodies and source plates, but there is fine print associated with their declarations. While there is an industry agreement concerning the definition of emissivity, the data sheets for blackbodies and source plates are not consistent in how they base their claims. Generally, there are two types of emissivity specifications published in data sheets; one based on design properties of the source and thermometric calibration, and another based on an equivalent radiometric calibrated emissivity. The paper details how the source properties including geometry, surface treatment, and coatings are characterized and result in an emissivity value by design. The other approach is that the emissivity can be claimed to be essentially 100% when measured directly with a radiometer. An argument is derived to show that as the optical parameters of the unit under test and the radiometer diverge, the less useful an equivalent radiometric emissivity claim is. Also discussed, is under what test conditions the absolute emissivity does not matter. Further suggestions on how to achieve the clearest comparative emissivity specifications are presented.

Keywords: Emissivity, Blackbody, Radiation, Reflection, Absorption

1. BACKGROUND

Heat transfer is governed by three distinct mechanisms, convection, conduction, and radiation. (Heat transfer by radiation is the primary concern of most infrared-optics applications). Unlike convection or conduction, heat transfer through radiation does not have to occur through matter. To understand this phenomenon one must conceptualize and enter into to the atomic or "quantum" realm. All atoms, at finite temperatures, are continuously in motion. Consequently, it may be understood that the mechanism of radiation is derived from the energetic vibrations and oscillations of these atomic particles; namely electrons. At finite temperatures, conditions exist in which electrons are in a thermally excited state. These conditions are sustained by the internal energy of the matter within which they occur, and thus are directly associated with temperature. In these thermally excited states electrons emit energy in the form of "quanta" or "photons"; thus, one may associate this with the propagation of electro-magnetic waves. Accordingly, the emission of these electromagnetic waves, brought about by the thermally excited states of electrons, make up the thermal radiation portion of the electromagnetic spectrum. Which occurs between .1 µm and 100 µm. Thermal radiation thus encompasses the near UV, and the entire VIS and IR portion of the electromagnetic spectrum. (See fig. 1).

*sscopatz@electro-optical.com; phone 805.964.6701; fax 805.967.8590; www.electro-optical.com

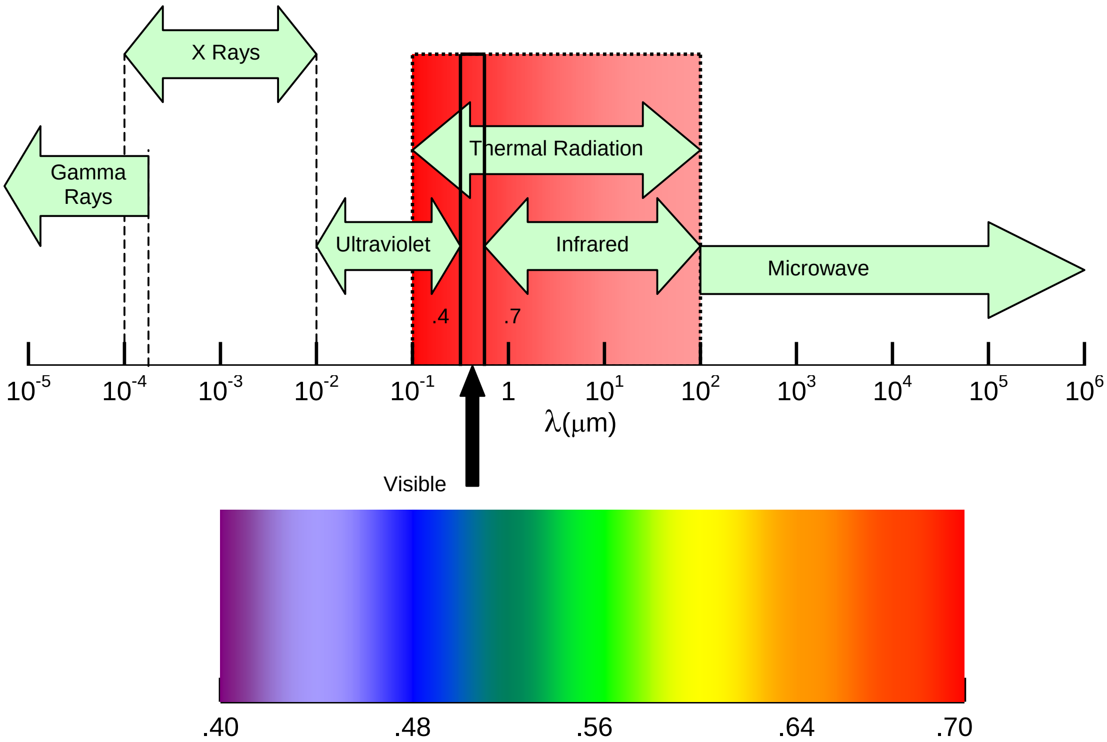

Figure 1. A portion of the electromagnetic spectrum, from gamma rays on the small wavelength end to microwaves on the long wavelength end. Thermal radiation encompasses some of the ultraviolet portion of the spectrum and all of the visible and infrared portions of the spectrum.

Thermal radiation propagates from a radiating surface in all possible directions and is emitted over a range of wavelengths. Thus, the magnitude of emitted radiation must be described such that it is defined both by its wavelength and its direction; its spectral and its directional components, respectively. Consequently, the ability to describe the directional and spectral distribution of radiation is desirable. As a result, radiative terms are used to treat these components. *Spectral intensity* $I_{\lambda,e}$, is defined as the rate of radiation energy, at a specific wavelength λ, per unit area, in a direction normal to that area, per unit solid angle about that direction, per unit wavelength. (See fig. 2) The spectral intensity has units of (W/m^2*sr*μm) and is given by Equation 1.

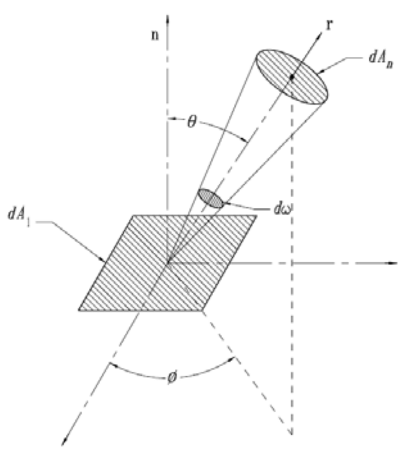

Figure 2. Solid Angle Diagram

$$I_{\lambda,e}(\lambda,\theta,\phi) = \frac{dq}{dA\cos(\theta)d\omega d\lambda} \quad (1)$$

Alternatively, *spectral emissive power* E_λ, is defined as the rate of radiation energy, at a wavelength λ (emitted in all directions), per unit area, per unit wavelength; and is in units of ($W/m^2 * \mu m$) and is given by Equation 2.

$$E_\lambda(\lambda) = \int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,e}(\lambda,\theta,\phi)\cos(\theta)\sin(\theta)\,d\theta\, d\phi \qquad (2)$$

It should be noted that E_λ is the energy flux based on the surface area of the actual radiating surface while $I_{\lambda,e}$ is the energy flux through a projected area. It is also necessary to account for incident radiation on a surface due to emission and reflection of radiation from other surfaces. The incident radiation from all surfaces is defined as the *irradiation* (Γ_λ); Γ_λ is the rate of radiation energy at a wavelength λ that is incident on a surface, per unit area, per unit wavelength. It has units of ($W/m^2 * \mu m$) and is given by Equation 3.

$$\Gamma_\lambda(\lambda) = \int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,i}(\lambda,\theta,\phi)\cos(\theta)\sin(\theta)\,d\theta\, d\phi \qquad (3)$$

Finally, the *radiosity* can be introduced (P). The radiosity is similar in definition to the emissive power but also accounts for irradiation. As a result P is associated with the radiant energy from both direct emission and reflection and P_λ is thus defined as the radiant energy, at a wavelength λ, (in all directions), per unit area, per unit wavelength. It has units of ($W/m^2 * \mu m$) and is given by equation 4. (Note, the subscript "e+r" refers to the total intensity due to both emission and reflection, respectively).

$$P_\lambda(\lambda) = \int_0^{2\pi}\int_0^{\pi/2} I_{\lambda,e+r}(\lambda,\theta,\phi)\cos(\theta)\sin(\theta)\,d\theta\, d\phi \qquad (4)$$

In order to connect these terms and their associations with real surfaces, they must relate to something of theoretical measure. This relation of course is the concept of a *Blackbody*. A Blackbody is a theoretical object that is both the perfect emitter and absorber of radiation; it is an ideal surface. The characteristics of a blackbody are as follows:

- A blackbody absorbs all incident radiation independent of wavelength and direction.
- For a given wavelength and finite, non-zero temperature, no object can emit more energy than a blackbody at the same temperature.
- A blackbody is a *diffuse* emitter.

The Planck Distribution estimates a blackbody; where the spectral intensity of a blackbody at a given temperature is of the form of Equation 5.

$$I_{\lambda,b}(\lambda,T) = \frac{2hc^2}{\lambda^5[\exp(hc/\lambda kT)-1]} \qquad (5)$$

and the spectral emissive power is of the form of Equation 6.

$$E_{\lambda,b} = \pi I_{\lambda,b}(\lambda,T) = \frac{2\pi hc^2}{\lambda^5[\exp(hc/\lambda kT)-1]} \qquad (6)$$

Wien's displacement law prescribes a peak wavelength to a given temperature, and is given by Equation 7.

$$\lambda_{max} = \frac{C_3}{T} \qquad \text{Where } C_3 = 2897.8\ \mu m{*}K \qquad (7)$$

For example, the sun, which can be approximated as a blackbody at 5800 K, has a max spectral distribution at about .5 µm using Wien's displacement law. (See Fig.2) This peak spectral distribution is in the visible spectrum. Alternatively, a blackbody at 1450 K, would have a max spectral distribution at about 2.0 µm; corresponding to short wavelength IR portion of the electro-magnetic spectrum and is thus, invisible to the naked eye. Accordingly, the peak spectral distributions of blackbodies with temperatures significantly lower than 5800 K, are not visible to the naked eye.

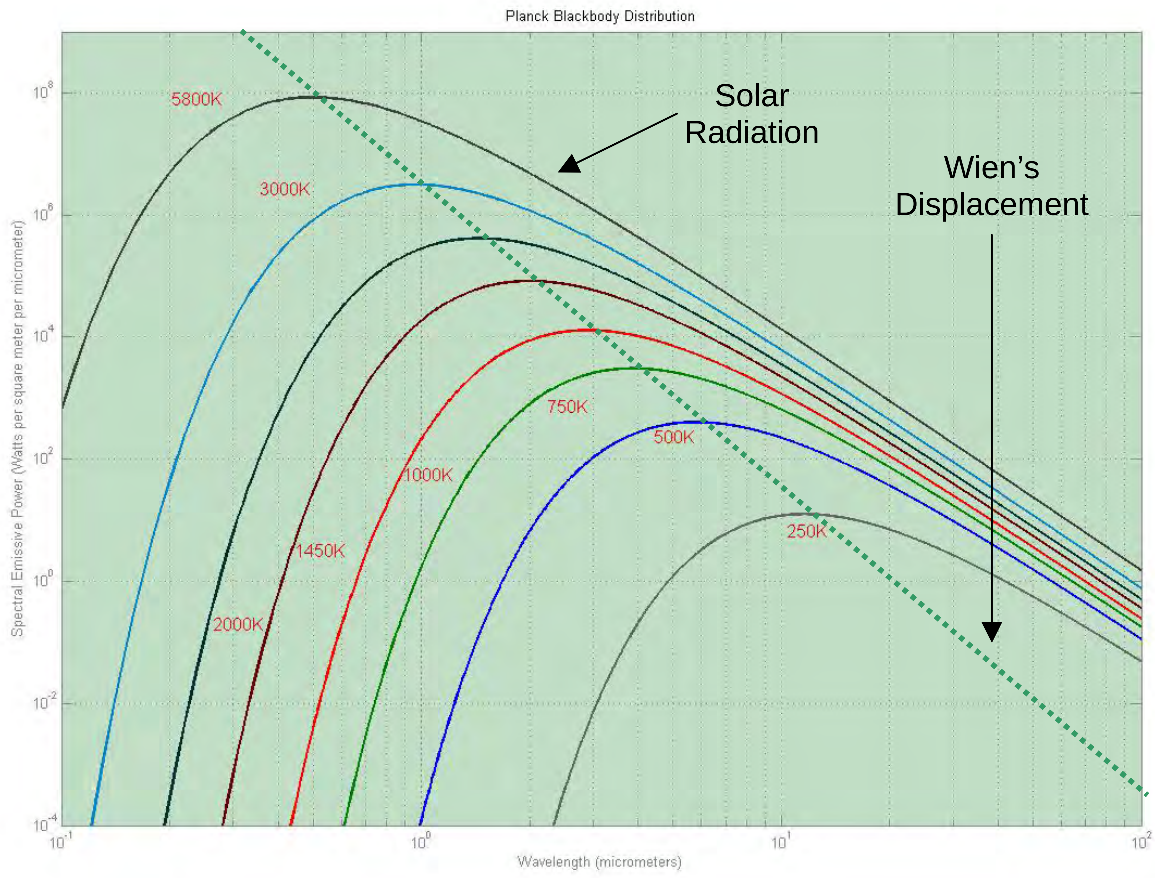

Figure 2: LogLog plot of the spectral distribution of blackbodies at various temperatures. (Spectral emissive power vs. wavelength). Wien's Displacement Law prescribes a max wavelength corresponding to a max spectral emissive power.

The total emissive power of a blackbody may be found using the *Stefan-Boltzmann law*. The Stefan-Boltzmann law expresses the total emissive power of a blackbody by Equation 8.

$$E_b = \int_0^\infty \frac{C_1}{\lambda^5[\exp(C_2/\lambda T)-1]} d\lambda = \sigma T^4 \quad (8)$$

Where $C_1 = 3.742\text{x}10^8$ W*µm^4/m^2 and $C_2 = 1.439\text{x}10^4$ µm*K

With all the previous concepts understood, blackbody phenomenon may now be introduced.

2. INTRODUCTION

The ideal surface, known as a blackbody, is both the perfect absorber and emitter of radiation. Any real body can never emit or absorb more energy than a blackbody at the same temperature. However, it is convenient to analyze real surfaces in reference to blackbodies. Thus, any real radiating surface can be considered by the dimensionless parameter, ε, known as the *emissivity*; which may be defined as the ratio of the radiation emitted by a real surface to that radiated by a blackbody at the same temperature. The *total emissivity*, that is the emissivity averaged over all wavelengths and in a hemispherical direction, is given by the total emissive power of the real surface at a given temperature over the total emissive power of a blackbody at the same temperature, see Equation 9.

$$\varepsilon(T) = \frac{\mathrm{E}(T)}{\mathrm{E}_b(T)} = \frac{\mathrm{E}(T)}{\sigma T^4} \tag{9}$$

It is however important to realize that spectral radiation by a real surface differs from the Planck Distribution and additionally, is not necessarily diffuse. For instance, a real surface may have a preferential distribution of radiation in certain directions or wavelengths. Therefore, analogous wavelength dependent and directional dependent emissivities are considered. The spectral directional emissivity is thus the ratio of the intensity of the energy radiated by a surface at a wavelength λ in the direction θ, ϕ, over the intensity of the energy radiated by a blackbody at the same temperature and wavelength. The spectral directional emissivity is given by Equation 10.

$$\varepsilon_{\lambda,\theta}(\lambda,\theta,\phi,T) = \frac{\mathrm{I}_{\lambda,e}(\lambda,\theta,\phi,T)}{\mathrm{I}_{\lambda,b}(\lambda,T)} \tag{10}$$

Hence, the *total directional emissivity* is defined as the ratio of the spectral average of the intensity of the radiation emitted by a surface in the direction θ, ϕ, over the intensity of the radiation emitted by a blackbody at the same temperature and is given by Equation 11.

$$\varepsilon_{\theta}(\theta,\phi,T) = \frac{\mathrm{I}_e(\theta,\phi,T)}{\mathrm{I}_b(T)} \tag{11}$$

Conversely, the *spectral hemispherical emissivity* is defined as the ratio of the radiation emitted by a surface at a particular wavelength λ in a hemispherical direction, over the radiation of a blackbody at the same temperature and wavelength; (the ratio of the spectral emissive power of a surface at wavelength λ over the spectral emissive power of a blackbody at wavelength λ). The spectral hemispherical emissivity is given by Equation 12.

$$\varepsilon_{\lambda}(\lambda,T) = \frac{\mathrm{E}_{\lambda}(\lambda,T)}{\mathrm{E}_{\lambda,b}(\lambda,T)} \tag{12}$$

As a result, absorptivity, transmissivity, and reflectivity are defined by the ratio of irradiation absorbed by a surface to the total irradiation, the ratio of irradiation transmitted through the surface to the total irradiation, and the ratio of the irradiation reflected by the surface to the total irradiation, respectively. Absorptivity, transmissivity, and reflectivity are denoted by α, τ, ρ, respectively and are related by equation 13.

$$\alpha + \tau + \rho = 1 \tag{13}$$

For opaque surfaces, the transmissivity term goes away.

In an isothermal enclosure, that is, an enclosure at a uniform and constant temperature, (i.e. at equilibrium), there is zero net exchange of radiation. That is for any surface inside the enclosure the radiation in equals the radiation out; there is no accumulation of energy. (See Fig 3) This may be shown by a simple energy balance given by Equation 14.

$$\alpha_1 \Gamma A_1 - \mathrm{E}_1(T_s) A_1 = 0 \tag{14}$$

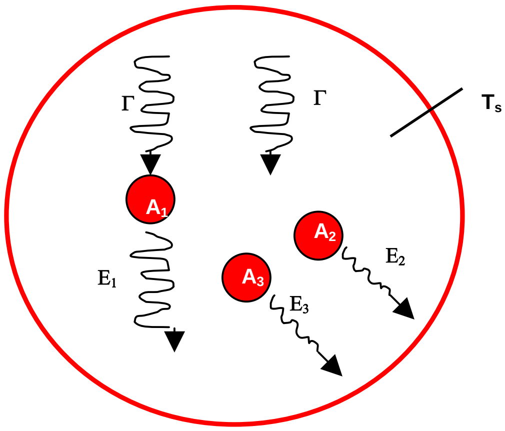

Figure 3: Exchange of radiation in 3 small surfaces within an isothermal enclosure.

Equation 14 states that the amount of radiation absorbed is equal to the radiation that is emitted out. Under these same conditions any body that lies within the enclosure must be diffuse, and thus the irradiance is equal to the emissive power of a blackbody at the same temperature of the isothermal cavity. Therefore by combining the previous statement with Equation 14 the following is derived.

$$\Gamma = \mathrm{E}_b(T_s) \quad \Rightarrow \quad \alpha_1 \mathrm{E}_b(T_s) A_1 - \mathrm{E}_1(T_s) A_1 = 0 \quad \Rightarrow \quad \frac{\mathrm{E}_1(T_s)}{\alpha_1} = \mathrm{E}_b(T_s)$$

Which yields Equation 15 for any body inside the isothermal enclosure, which is otherwise known as Kirchhoff's Law and also proves that no body can emit or absorb more radiation than a blackbody.

$$\frac{\mathrm{E}_1(T_s)}{\alpha_1} = \frac{\mathrm{E}_2(T_s)}{\alpha_2} = \frac{\mathrm{E}_3(T_s)}{\alpha_3} = \ldots = \mathrm{E}_b(T_s) \tag{15}$$

This enclosure is therefore consistent with the concept of a blackbody cavity. Thus, Kirchhoff's Law alternatively states that the absorptivity equals emissivity inside of a blackbody cavity, equation 16.

$$\frac{\varepsilon_1}{\alpha_1} = \frac{\varepsilon_2}{\alpha_2} = \frac{\varepsilon_3}{\alpha_3} = 1 \tag{16}$$

This is also true for directional and wavelength dependent forms of the emissivity and absorptivity, (i.e. the spectral, hemispherical emissivity equals the spectral, hemispherical absorptivity).

3. SPECIFYING EMISSIVITY OF COMMERCIAL BLACKBODIES

In the commercial market there are blackbodies available in a number of configurations. Technically, all of the commercial blackbodies are “graybodies” since their emissivity is less than one, in industry this distinction is rarely applied and these products are referred to generically as blackbodies; just as Klennex™ is used for tissues. So for the remainder of this paper the term blackbody will be used instead of the strictly correct term of graybody.

The geometry of the blackbody can produce higher emissivity but at a cost. In the preliminary discussion, the equations apply to a surface at a specific temperature. In the world of commercial blackbodies, the most common geometries are cavities and plates.

Radiation emitted from a source plate follows the equations to the first order. The reflectance and absorbance of the source plate is determined by its surface treatment. The coating applied to the surface greatly enhances the emissivity. Unfortunately for the predictability of the radiance from the surface the coating behavior is not always ideal.

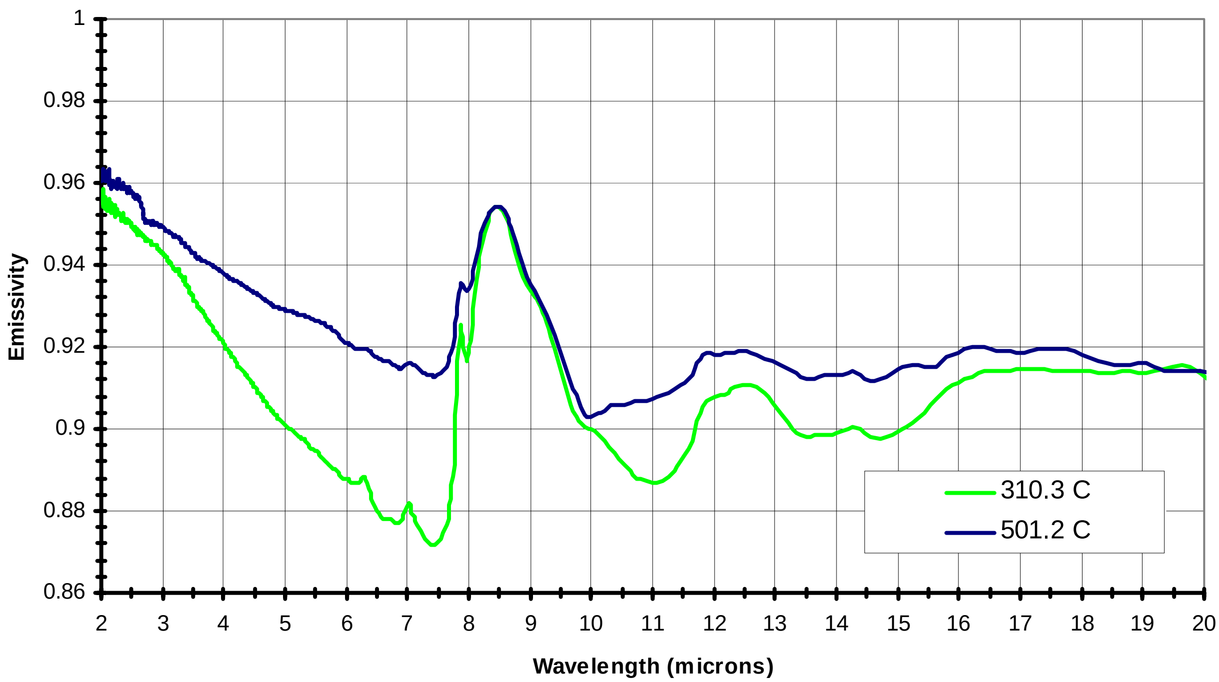

Figure 4: Spectral emissivity of standard sample

Figure 4 is the spectral emissivity of a sample coupon coated with a high temperature material. This data is taken with a hemispherical reflectometer. The real world performance shows that the emissivity of the coating on a specific surface is not uniform with respect to wavelength and temperature. In this particular example the emissivity performance in the MWIR is several percentage points higher than in the LWIR. There is considerably lower emissivity near room temperature than when the sample is heated.

Knowledge of the coating performance properties can allow the customer to calculate the expected output from a source plate for a given wavelength range. Using a single emissivity value will lead to small errors in expected radiance.

There are surface treatments that improve the emissivity of the source plate even using the same coating. See Figure 5 for an emissivity scan of an enhanced surface treatment.

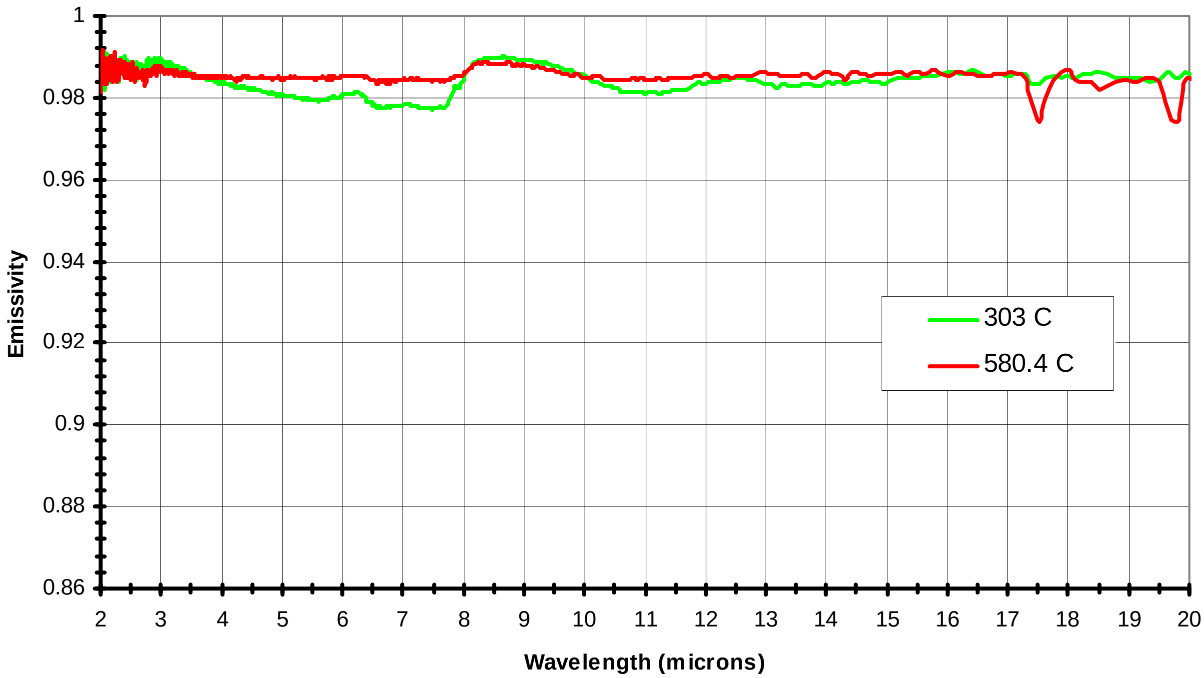

Figure 5: Spectral emissivity of enhanced sample

Using this information convolved with the radiance equations will give a good prediction of radiance output of the plate verses temperature. In this case the temperature of the plate is precisely calibrated using commercially available, NIST traceable temperature measurement equipment.

A radiometric calibration of the source place can be done by comparing the output of the plate to a "known" primary standard. There are several additional sources of error that come with the radiometric calibration. The wavelength range of sensitivity of the calibration device must match the spectral sensitivity of the UUT that will be used with this blackbody. Otherwise, one could see that if the radiometric calibration was done with a detector that is active 8-12 µm range but the UUT is sensitive in the 3-5 µm range; there will be skewed result.

The other major geometry of blackbodies is cavities. Cavities essentially force the majority of the photons emitted from the surface to bounce off other surfaces within the cavity before the photon finds its way out of the cavity. This randomization improves the uniformity but at the same time creates a directed beam of photons instead of full Lambertian output. Common cavity shapes are cylindrical, conical and spherical. The emissivity of a cavity blackbody is a combination of its geometry and surface treatment.

The relative emissivity that comes from the geometry is ranked from cylindrical, conical, spherical and is highest with a reverse conical design. The calculations to support this assertion are covered in "Chandos and Chandos" and "The Infrared Handbook". As Table 1 shows, even with a nominal coating emissivity of 0.8, a conical cavity will achieve emissivity greater than 0.97.

Table 1: Geometric emissivity enhancement summary

Cavity Type	Effective Emissivity-ε (eff) with		
	0.7 coating	0.8 coating	0.9 coating
Cylindrical (L/R=8)	0.9946	0.9966	0.9984
Conical (14°)	0.9534	0.9716	0.9869
Spherical ($A_c/4\pi R_s^2$=0.9)	0.958	0.970	0.985
Reverse Conical (14°)	0.9996	0.9998	0.9999

An example of a conical cavity is in Figure 6. The radiant output of a 1 inch (25.4 mm) diameter cavity diverges in a cone of 11°; 0.2 steradian, instead of the 2π steradian solid angle from the source plate. Typically, the cavity is used to uniformly illuminate a target close to exit of the cavity. This target is usually positioned at the focal point of an optical collimator to project an image of the target at a specific temperature. The other way the target is used is to focus the UUT on the target.

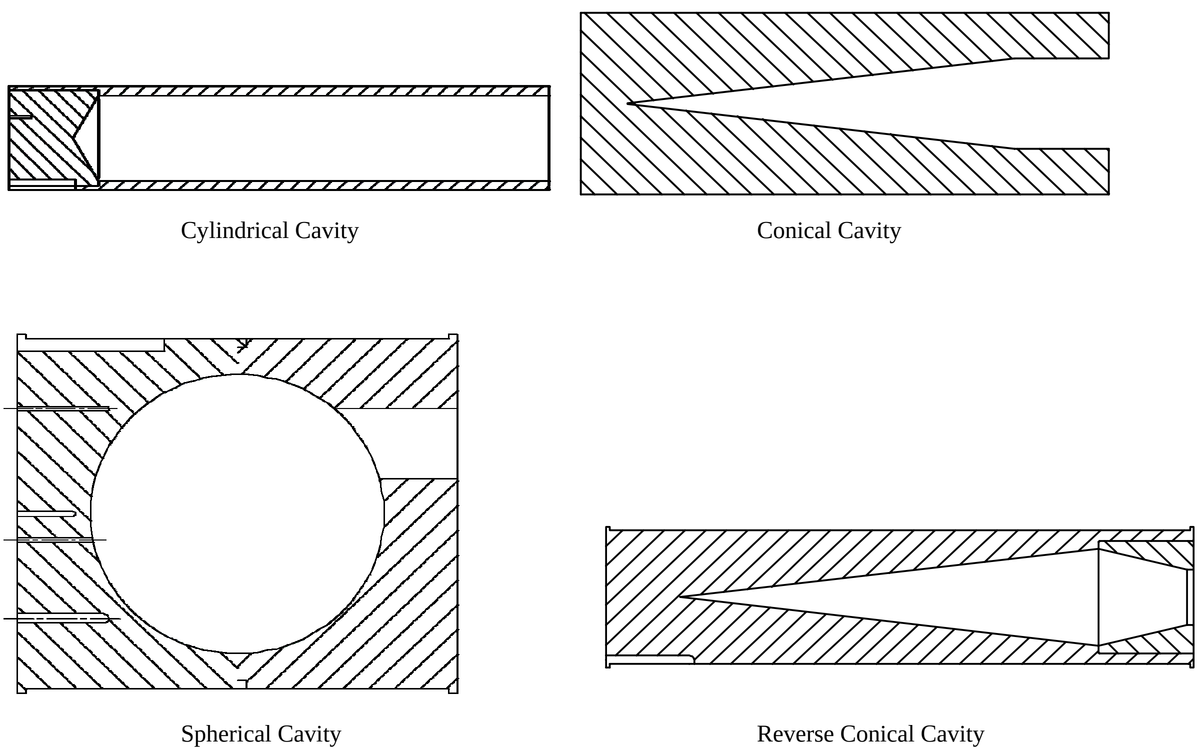

Figure 6: Typical cavity type blackbody geometries

As in the case of the source plates, the emissivity of the surface or surface coating changes with spectrum and temperature. In this case, as long as the emissivity of the surface is nominally the same, it is a small effect compared to the geometry. So the effects due to the properties of the spectral variation of surface emissivity do not have to be calculated beyond the first order to determine the emissivity of a cavity.

There are two ways to calibrate cavity blackbodies. One can measure the temperature of the surface with a contact thermocouple. Using this method the output of the cavity can be calculated using Plank's equation. Using a radiometric method introduces other potential sources of error. Because a cavity blackbody emits in a limited cone angle, there is a possibility of the detector's FOV not matching the UUT's FOV. In the uniformity example below (Fig. 7), you can see that the uniform cone of this cavity is limited to ± 2 degrees, many radiometers have a wider field of view than this; allowing the radiometer to include some cooler temperature signals from the edges and the background. If the detector used for radiometric calibration of the blackbody does not have the same optical properties as the UUT; FOV, spectral sensitivity and other properties of the detector could produce a calibration that is inferior to the thermometric calibration.

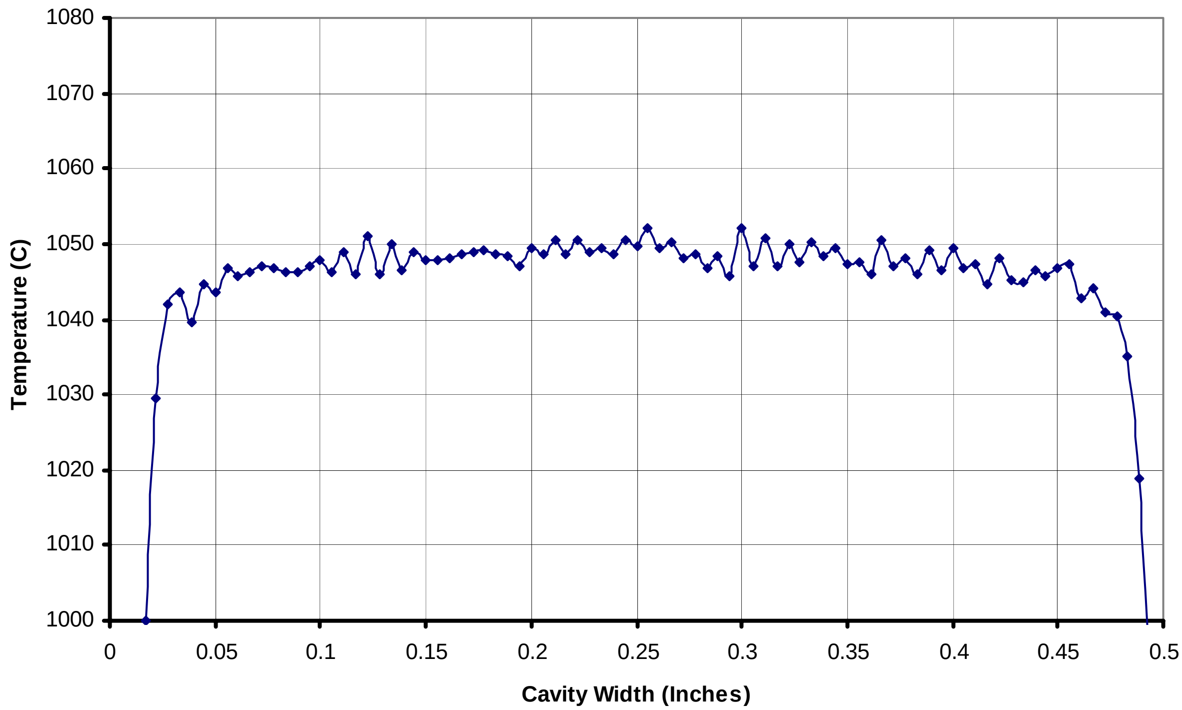

Figure 7: Half inch cavity blackbody temperature uniformity

There are uses for blackbodies when the absolute emissivity is not a parameter to take into consideration. If one is looking for uniform response across a focal plane array for example; the uniformity of the source plate is more important than whether the emissivity of the source is 0.92 or 0.99. In other cases the repeatability of the output is the key parameter to compare the response of detectors produced over time.

With the knowledge of the emissivity value one may calculate its radiometric equivalent based on the thermometric calibration or one may perform a radiometric calibration. The thermometric calibration can be NIST traceable to 0.01°C for 0-100°C and 0.28°C for values up to 1400°C. Radiometric calibrations tend to have lower accuracy in the lower temperature range. Radiometric calibrations are effected the detector response by wavelength and the coating emissivity by wavelength, leading to potential misrepresentation of the expected photons for the UUT if the wavelength response of the UUT does not match the calibration instrument. A similar argument applies to mismatching the FOV of the UUT and the calibration instrument. Making a transfer measurement against a standard to claim effective 0.99 emissivity for a blackbody with true emissivity of significantly less, is error prone due to spectral and FOV differences.

4. CONCLUSION

The basic equations used to predict the output of photons from a surface are restated here to provide the background for the discussion of emissivity specifications.

In summary, choosing a blackbody that is designed for high emissivity will provide superior results. The closer the emissivity of the blackbody is to 1.0 is by design, the less spectral differences will effect the UUT's readings. The closer the designed in emissivity is to 1.0 the more reliable the prediction of the output is by thermometric calibration. Even with lower emissivity values (i.e. $\varepsilon = 0.9$), a thermometric calibration is able to predict output with precision as a function of wavelength.

REFERENCES

[1] Middleman, Stanley, [An Introduction to Mass and Heat Transfer], John Wiley & Sons, Inc., New York, (1998).
[2] DeWitt, David P, Incropera, Frank P, [Introduction to Heat Transfer (3rd ed)], John Wiley & Sons, New York, (1996).
[3] Young, Hugh D., Freedman, Roger A., [University Physics (11th ed)], Addison Wesley, San Francisco, (2004).
[4] R. J. Chandos and R. E. Chandos, [Appl. Opt., 13, 2142], (1974).
[5] W. L. Wolfe and G. J. Zissis, [The Infrared Handbook, revised edition], Environmental Research Institute of Michigan, Ann Arbor, (1989).