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A Certified-Emissivity Blackbody
for Calibrating Infrared Thermometers

As a practical matter, most commercial infrared thermometers are calibrated with "homemade" blackbodies of unknown and uncertified emissivities. This design for a water-immersible certified-emissivity blackbody is intended to provide a simple and inexpensive, but accurate reference for emissivity, referenced to recognized standards and proven mathematical constructions.
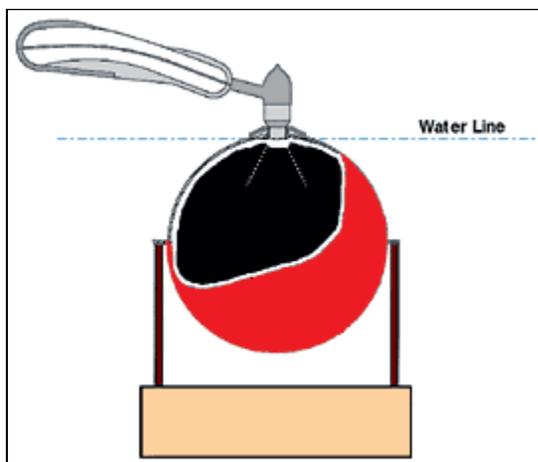
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All infrared (IR) thermometry is based on the concept of *emissivity*, which eventually leads mathematically to the concept of a *blackbody*. It is the blackbody that provides the only theoretically rigorous link between temperature and the radiated energy of precise quantifiable characteristics. Emissivity is a

An inexpensive certified-emissivity blackbody offers accuracy and traceability to recognized standards and mathematics.

coefficient from 0 to 1 that compares the emitted energy of an object to that of a theoretical blackbody at the same temperature. Although not always stipulated, the mathematical concepts of emissivity and blackbody require uniform temperature.

Measuring temperature by measuring radiated energy therefore requires a reference blackbody that has known and certifiable emissivity. As a practical matter, most commercial IR thermometers are calibrated with "homemade" blackbodies of unknown and uncertified emissivities. Although the errors introduced by emissivity uncertainty are insignificant for many industrial applications, for medical use they are not negligible at all.

The design presented here for a water-immersible certified-emissivity blackbody (CEBB) is intended to provide a simple and inexpensive, but accurate reference for emissivity, one that is

referenced to recognized standards and proven mathematical constructions. The emissivity for this design is certified at:

$$0.9993 < \varepsilon_{bb} < 0.9997$$

For the maximum range of medical clinical thermometry applications (42°C target and 16°C ambient), the above uncertainty results in a maximum temperature uncertainty of ±0.01 C.

Historical Note

In 1665, Sir Isaac Newton became the first to split sunlight into colors with a prism, thus demonstrating the existence of light as radiated energy of differing wavelengths. About 135 years later, another English astronomer/scientist, William Herschel, measured the heat content of each of the colors of Newton's spectrum and was shocked to discover that his thermometer registered the greatest heat beyond the red—in an area of the spectrum he could not see. He coined the term *infrared* to describe this heat energy.

Herschel demonstrated that IR heat radiation and light are simply two forms of electromagnetic energy. Our eyes see light energy because we are equipped to detect the wavelengths of visible light but not the longer IR wavelengths (see Figure 1).
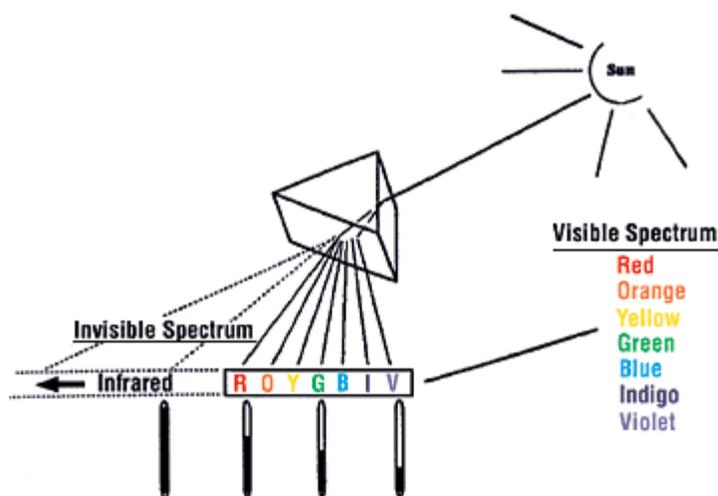

Figure 1. Herschel's experiment demonstrated that heat is generated beyond the visible spectrum.

One example of a special IR sensing adaptation in the animal world is the pit viper (see Figure 2), which can use the IR-sensing organs located in pits below its eyes to locate warm-blooded animals in the dark. An IR sensor, like Herschel's thermometer and the pit viper's organs, detects the longer wavelengths of IR energy by detecting the long-wave radiation's heating of the measuring element.

At the turn of the twentieth century, Max Planck discovered the correct mathematical formulation of the relationship between temperature and IR radiation, thus paving the way for its use as a noncontact way to measure temperature. An unanticipated result of Planck's work was the

discovery of quantum physics, arguably the century's most important scientific development.

Recent advances in the technology of IR temperature measurement have stimulated the development of devices billions of times more sensitive than Herschel's thermometer. Medical applications of this technology have enabled the design of devices capable of making noninvasive measurements at the temporal artery and at other body sites where speed and accuracy are required.
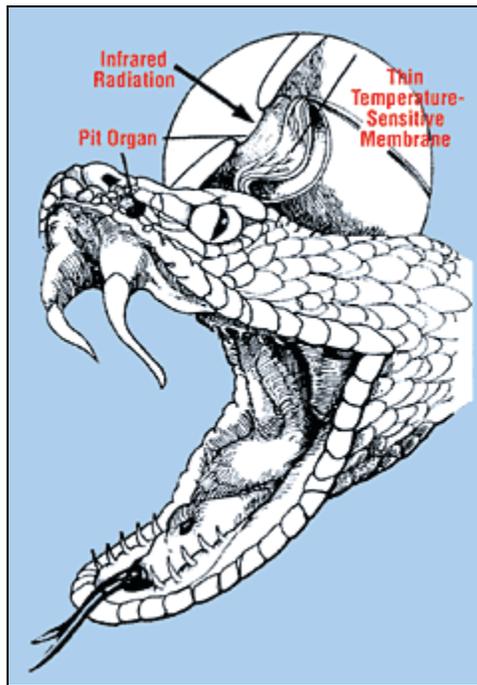

Figure 2. Members of the pit viper family of snakes use their infrared sensing pit organs below their eyes to locate warm-blooded prey.

The Principles of Emissivity

Emissivity is a surface characteristic that determines how well an object's temperature can be measured by an IR device. Along with background thermal radiation, emissivity is the primary source of error in IR temperature measurement. Simply stated, emissivity is the opposite of reflectivity. A perfect mirror has a reflectivity of unity and an emissivity of zero. A perfect blackbody has an emissivity of unity and a reflectivity of zero. In actuality, all real bodies (including human ones) have an emissivity between these two limits.

Mirrors figure prominently in any discussion of heat radiation and emissivity. Since heat and light radiation behave in much the same way, we can use what we see with our eyes as examples of what the IR instrument sees. When you look in the mirror, you see only reflections and nothing of the mirror itself. If the mirror is perfect, it has 100% reflectivity. Because it reflects everything, it emits nothing. For this condition, the emissivity is zero.

If we consider an imperfect mirror, the eye then sees mostly reflection but also some of the imperfections on the mirror surface. If, for example, we saw 90% of the mirror as a perfect

Poor Emitter
Emissivity = 0.1
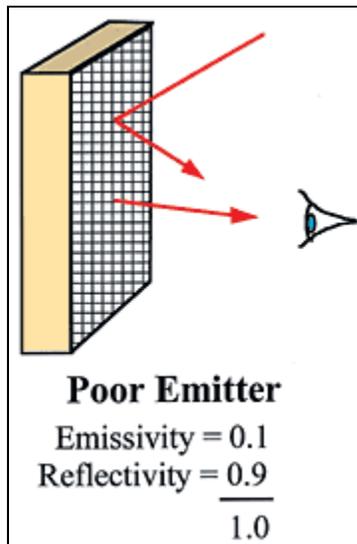$$\text{Reflectivity} = \frac{0.9}{1.0}$$

Figure 3. A poor emitter is characterized by high reflectivity.

reflector and 10% as imperfections, 90% of the mirror would reflect; the remaining 10% would emit. Therefore, the emissivity equals 0.1 (see Figure 3).

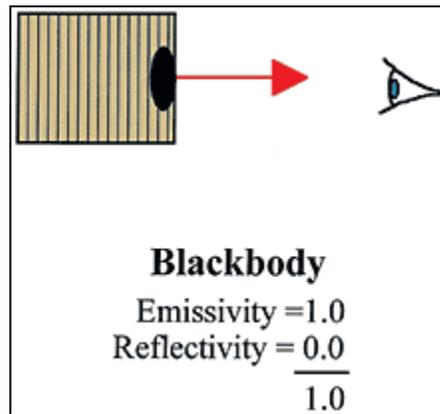Now consider the exact opposite of a perfect mirror—a perfect emitter. The eye looks at a perfect emitter and sees no reflection at all, only the emitting surface. Such an object emits 100% of the energy and reflects 0% of the energy. This type of object is called a blackbody (see Figure 4).

Blackbody
Emissivity = 1.0
Reflectivity = 0.0
____
1.0

Figure 4. A blackbody emits but does not reflect.

Good Emitter
Emissivity = 0.9
Reflectivity = 0.1
____
1.0
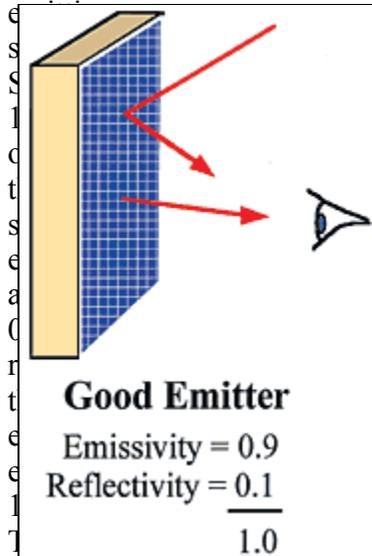
Figure 5. A good emitter emits with little reflection.

And, finally, consider a good emitter. The eye sees a small amount of reflecting interspersed with a large amount of emitting. If, for example, 10% of the surface reflected instead of emitting, the emissivity would equal 0.9 (see Figure 5). Accordingly, we can state the following rule of emissivity: *The emissivity of the surface is simply the percentage of the surface that emits. The remaining percentage of the surface reflects*.

The Mathematics of Emissivity
Emissivity is derived from the basic physics of thermal radiation, in which the mathematical description of the energy distribution follows a formula called the Planck function:

$$q_\lambda = \varepsilon \frac{2\pi hc^2 \lambda^{-5}}{e^{ch/k\lambda T} - 1} \tag{1}$$

where:

$q\lambda$	= radiated energy at a given wavelength
ε	= emissivity
T	= absolute target temperature

λ = wavelength
h, c, K, and e = various physical constants

The Planck function integrates to the more familiar Stefan-Boltzmann equation:

$$\text{radiated energy} = q = \int_0^\infty q_\lambda d\lambda = \varepsilon \sigma T^4 \tag{2}$$

where:

T = Stefan-Boltzmann law when all wave lengths are measured.

It is important to note that if the radiation being measured does not extend over all wavelengths, the exact form of the Stefan-Boltzmann equation does not strictly apply. An approximate description based on the integrated Planck function is:

filtered radiated energy =

$$\int_{\lambda_1}^{\lambda_2} q_\lambda d\lambda \approx \varepsilon \sigma T^x \tag{3}$$

where:

$x \neq 4$

Accordingly, corrections for spectral effects must be checked before using the Stefan-Boltzmann equation if the detection system incorporates filters that restrict the wavelengths measured. Equation 4 gives the results of calculations of the spectral effect shift for several common wavelength bands, normalized to a 100 F (37.8°C) target:

spectral factor =

$$\left[\frac{\int_{\lambda_1}^{\lambda_2} q_\lambda d\lambda}{\int_0^\infty q_\lambda d\lambda} \right]_{T1} \Bigg/ \left[\frac{\int_{\lambda_1}^{\lambda_2} q_\lambda d\lambda}{\int_0^\infty q_\lambda d\lambda} \right]_{T0} \tag{4}$$

As is evident from Table 1, the spectral correction must be included if calibrations are to be checked over a wide target temperature range, and the spectral characteristics must be known.

TABLE 1

Spectral Correction Factors

Temperature (°F)	6-14µ	2-20µ	8-14µ	0.5-50µ
65	0.939	0.960	0.969	0.997
70	0.949	0.966	0.975	0.997
75	0.958	0.972	0.980	0.998
80	0.967	0.978	0.985	0.998
85	0.976	0.984	0.989	0.999
90	0.984	0.989	0.993	0.999
95	0.992	0.995	0.997	1.000
100	1.000	1.000	1.000	1.000
105	1.007	1.005	1.003	1.000
110	1.015	1.010	1.006	1.001

To account for the effect of reflected energy, Kirchoff's law is applied:

emitted + reflected + transmitted energy = 1
or
$$\varepsilon + \rho + \tau = 1 \tag{5}$$

Since for opaque surfaces $\square = 0$, then $\varepsilon + \rho = 1$. For the case of a blackbody aperture, the reflected energy has as its source the ambient radiation field surrounding the aperture. For poor blackbodies (ε <0.99) the reflected ambient energy cannot be neglected. The source of the reflected ambient energy for the case of a probe inserted into the blackbody *is the probe itself* (see Figure 6). Accordingly, if an emissivity correction is required, the probe geometry and temperature must be known.
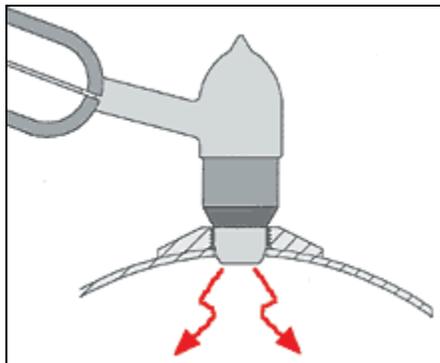

Figure 6. Because of radiation emitted by the probe into the blackbody, its geometry and temperature should be known for any small corrections.

Linear Approximation

For convenience in analysis, a linear approximation of Equation 2 may be used when comparing emissivities if the temperature is held within a narrow range. Deriving the relationship:

$$q = \varepsilon\sigma T^4$$
$$\text{let } \Delta q = c\Delta T$$
$$\text{then } \frac{c\Delta T}{q_1 - q_2} = \frac{c(T_1 - T_2)}{\varepsilon\sigma(T_1^4 - T_2^4)}$$
$$\frac{\partial q}{\partial T} = 4\varepsilon\sigma T_m^3 = c \tag{6}$$
$$\text{then } \frac{c\Delta T}{q_1 - q_2} = \frac{4T_m^3(T_1 - T_2)}{(T_1^4 - T_2^4)}$$

If the target blackbody temperatures are held to within 0.5°C, the nonlinearity is:

$$\frac{c\Delta T}{q_1 - q_2} = \frac{4T_m^3(T_1 - T_2)}{(T_1^4 - T_2^4)}$$

$$= \frac{4(273 + 37.25)^3(37.5 - 37)}{(273 + 37.5)^4 - (273 + 37)^4}$$

$$= 0.99999935$$

With the linearity assumption valid to one part in 10^6 for small temperature differences, linear forms can be used to conveniently perform the calculations for emissivity variations (see Figure 7).
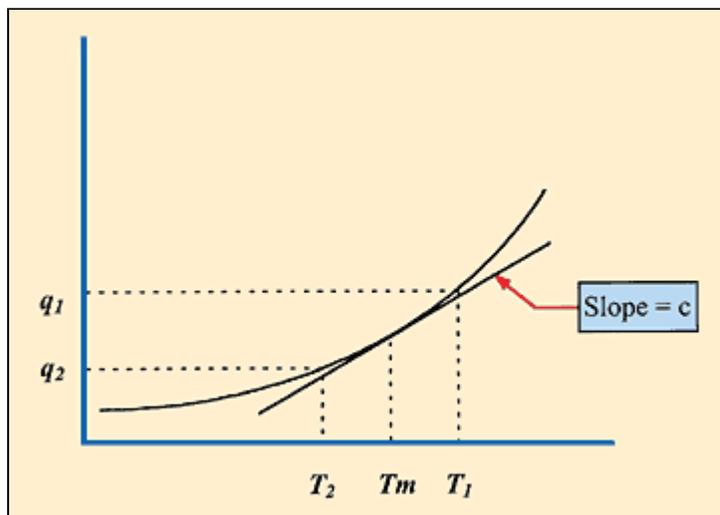

Figure 7. In calculating emissivity variations, linearity may be assumed for small temperature variations.

Accordingly, the change in emissivity of a blackbody, or from one blackbody to another at the same temperature, may be given as:

$$\varepsilon_{BB1} - \varepsilon_{BB2} = \frac{(T'_{BB1} - T'_{BB2})}{(T_{BB} - T_A)} \qquad (7)$$

where:

T' = effective temperature of radiation at the probe in the aperture, measured by the same probe at the same temperature T_A. Note the importance of instrument probe temperature, since as $T_A \Rightarrow T_{BB}$, emissivity change cannot be evaluated.

Certified Blackbody Emissivity Analysis
The spherical cavity shape has been selected for certification, since it is the only geometry for which an exact analytical solution can be calculated for emissivity [1].

Following the method of Bedford, the effective emissivity of spherical CEWIBB-1 may be simply looked up in [1]. For the ratio **R_a/R_s** (aperture-to-sphere radius) of 0.1 for the actual device, and wall emissivity of 0.9 (nominal value for the anodized aluminum

walls), the effective emissivity is 0.9997, which we can term the "nominal" value from which errors can be assessed to provide a tolerance range:

$$0.7 < \varepsilon_w < 0.9$$
$$0.9989 < \varepsilon_{BB} < 0.9997 \qquad (8)$$

The emissivity of the anodized walls of the sphere has been estimated by [2] and by test (using a reflective cup technique [3]) to lie in the range $0.9 + 0.02$, $0.9 - 0.1$. Accordingly, the emissivity can be immediately interpolated from Equation 8 as:

$$0.8 < \varepsilon_w < 0.92$$
$$0.9993 < \varepsilon_{BB} < 0.9997$$

All other errors due to departures from spherical geometry, and from the small seam between hemispheres, are negligible since the area ratio is negligible (no proof given).

Errors due to nonuniformity of the temperature of the water bath used to ensure that the entire sphere is at the same temperature are independent of the sphere's properties, but will be on the same order as the nonuniformities, i.e., very small. If nonuniformities are maintained to <0.01°C, apparent emissivity error can be evaluated by Equation 7:

$$\varepsilon_{BB1} - \varepsilon_{BB2} = \frac{\left(T'_{BB1} - T'_{BB2}\right)}{\left(T_{BB} - T_A\right)}$$

$$= \frac{0.01}{37 - 23} = 0.0007$$

In preparing an emissivity certification of other devices from the master CEWIBB-1, the water bath must be checked for uniformity, and the cross certification can be no more accurate than the temperature nonuniformity.

We have described a design for an inexpensive, certified-emissivity blackbody that is both accurate and traceable by recognized standards and mathematics.

References
1. *Theory and Practice of Radiation Thermometry*. 1988. D.P. Dewitt and G.D. Nutter Eds., Wiley & Sons.

2. M.Q. Brewster. 1992. *Thermal Radiative Transfer & Properties*. Wiley & Sons.

3. F. Pompei. U.S. Patent No. 4,636,091.

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For further reading on this and related topics, see these *Sensors* articles.

"The New IRt/c: Real-World Performance Accuracy," September 2001
"Smart Infrared Temperature Sensors: Making Sense of the New Generation," November 2000
"The New Generation of Infrared Thermometers," Part 1 and Part 2, October and November 1999
"IR Thermometry Gets Smart," August 1998

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