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Standard Test Methods for Total Normal Emittance of Surfaces Using Inspection-Meter Techniques[1]

This standard is issued under the fixed designation E408; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 These test methods cover determination of the total normal emittance (Note 1) of surfaces by means of portable, as well as desktop, inspection-meter instruments.

NOTE 1—Total normal emittance (ε_N) is defined as the ratio of the normal radiance of a specimen to that of a blackbody radiator at the same temperature. The equation relating ε_N to wavelength and spectral normal emittance [$\varepsilon_N(\lambda)$] is

$$\varepsilon_N = \int_0^\infty L_b(\lambda,T)\,\varepsilon_N(\lambda)\,d\lambda / \int_0^\infty L_b(\lambda,T)\,d\lambda \qquad (1)$$

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where:

~~$L_b(\lambda, T)$ = Planck's blackbody radiation function = $c_1\pi^{-1}\lambda^{-5}(e^{c_2}/\lambda T - 1)^{-1}$,~~
$L_b(\lambda, T)$ = Planck's blackbody radiation function = $c_1\lambda^{-5}(e^{c_2/\lambda T} - 1)^{-1}$,
~~c_1 = 3.7415 × 10−16 W·m 2,~~
c_1 = 3.7415×10^{-16}W·m 2,
c_2 = 1.4388×10^{-2} m·K,
T = absolute temperature, K,
λ = wavelength, m,
~~$\int_0^\infty L_b(\lambda,T)d\lambda$ = $\Delta\pi^{-1}T^4$, and~~
$\int_0^\infty L_b(\lambda,T)d\lambda$ = σT^4, and
~~Δ = Stefan-Boltzmann constant = 5.66961×10^{-8} W·m^2·K^{-4}~~
σ = Stefan-Boltzmann constant = 5.66961×10^{-8} W·m^{-2}·K^{-4}

1.2 These test methods are intended for measurements on large ~~surfaces~~ surfaces, or small samples, or both, when rapid measurements must be made and where a nondestructive test is desired. They are particularly useful for production control tests.

~~1.3 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.~~

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Summary of Test Methods

2.1 At least ~~two~~three different types of instruments ~~are~~ are, or have been, commercially available for performing this measurement. One type measures radiant energy reflected from the specimen (Test Method A), ~~and the other~~ a second type measures radiant energy emitted from the specimen (Test Method ~~B).~~ B), and a third type measures the near-normal spectral reflectance (that is, the radiant energy reflected from the specimen as a function of wavelength) and converts that to total near-normal emittance (Test Method C). A brief description of the principles of operation of each test method follows.

2.1.1 *Test Method A*—~~The theory employed in~~ Test Method A ~~has been described in detail by Nelson et al~~can best ~~and therefore is only briefly reviewed herein. The surface to be measured is placed against an opening (or aperture) on the portable sensing component. Inside the sensing component are two semi-cylindrical cavities that are maintained at different temperatures, one at~~

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[1] These test methods are under the jurisdiction of ASTM Committee E21 on Space Simulation and Applications of Space Technology and are the direct responsibility of Subcommittee E21.04 on Space Simulation Test Methods.

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~~near ambient and the other at a slightly elevated temperature. A suitable drive mechanism is employed to rotate the cavities alternately across the aperture. As the cavities rotate past the specimen aperture, the specimen is alternately irradiated with infrared radiation from the two cavities. The cavity radiation reflected from the specimen is detected with a vacuum thermocouple. The vacuum thermocouple views the specimen at near normal incidence through an optical system that transmits radiation through slits in the ends of the cavities. The thermocouple receives both radiation emitted from the specimen and other surfaces, and cavity radiation which is reflected from the specimen. Only the reflected energy varies with this alternate irradiation by the two rotating cavities, and the detection-amplifying system is made to respond only to the alternating signal. This is accomplished by rotating the cavities at the frequency to which the amplifier is tuned. Rectifying contacts coupled to this rotation convert the amplifier output to a d-c signal, and~~ be described as the reflectance method. When a surface is irradiated, the flux is either reflected, transmitted or absorbed. The normalized expression is $\rho + \tau + \alpha = 1$, where ρ is reflectance, τ is transmittance and α is absorptance. For opaque surfaces, transmittance is zero ($\tau = 0$) and the expression reduces to $\rho + \alpha = 1$. Kirchhoff's Law states that for similar angular and spectral regions, $\alpha = \varepsilon$. This enables the conversion of normal hemispherical reflectance to normal hemispherical emittance for a given temperature, or $\varepsilon_N = 1 - \rho_N$~~this signal is read with a millivoltmeter. The meter reading must be suitably calibrated with known reflectance standards to obtain reflectance values on the test surface. The resulting data can be converted to total normal emittance by subtracting the measured reflectance from unity.~~ . For this to be strictly valid, the spectral range must be that of the blackbody at that temperature.

2.1.1.1 Utilizing Test Method A places two important requirements on the instrument. The first is that the optical system must measure reflectance over a complete hemisphere. The second is that the spectral response of the instrument must match closely with the radiance of a blackbody at that temperature; usually 300°K, but in principle other temperatures are possible.

2.1.1.2 One instrument available for Test Method A utilizes an absolute type reflectance method. The instrument aperture is placed against the test specimen. The instrument illuminates the specimen with infrared radiance at a near-normal incident angle and collects and measures the reflected radiance over the complete hemisphere. A measurement is then performed on the same illuminating radiance beam, providing a 100 % reference. Since the radiance source, path length, and number of reflecting surfaces and detector are the same, the ratio of the two signals provides an absolute reflectance measurement of the specimen, obviating the need for frequent calibrations to known standards. A second instrument for testing to Test Method A utilizes a relative type reflectance technique wherein the sample is tested as above, but instead of a 100 % reference measurement the device collects the signal off a reference sample with known reflectance (usually vacuum deposited gold on a silica substrate) to determine the reflectance of the sample. For either technique, the emittance ε_N is then determined from the reflectance as illustrated previously.

2.1.1.3 Another instrument employed in Test Method A that involves a relative type reflectance measurement has been described in detail by Nelson et al (**1**)[2] and therefore is only briefly reviewed herein. The surface to be measured is placed against an opening (or aperture) on the portable sensing component. Inside the sensing component are two semi-cylindrical cavities that are maintained at different temperatures, one at near ambient and the other at a slightly elevated temperature. A suitable drive mechanism is employed to rotate the cavities alternately across the aperture. As the cavities rotate past the specimen aperture, the specimen is alternately irradiated with infrared radiation from the two cavities. The cavity radiation reflected from the specimen is detected with a vacuum thermocouple. The vacuum thermocouple views the specimen at near normal incidence through an optical system that transmits radiation through slits in the ends of the cavities. The thermocouple receives both radiation emitted from the specimen and other surfaces, and cavity radiation which is reflected from the specimen. Only the reflected energy varies with this alternate irradiation by the two rotating cavities, and the detection-amplifying system is made to respond only to the alternating signal. This is accomplished by rotating the cavities at the frequency to which the amplifier is tuned. Rectifying contacts coupled to this rotation convert the amplifier output to a dc signal, and this signal is read with a millivoltmeter. The meter reading must be suitably calibrated with known reflectance standards to obtain reflectance values on the test surface. The resulting data can be converted to total normal emittance by subtracting the measured reflectance from unity.

2.1.2 *Test Method B*—The theory of operation of Test Method B has been described in detail by Gaumer et al (**2**) and is briefly reviewed as follows: The surface to be measured is placed against the aperture on the portable sensing component. Radiant energy which is emitted and reflected from the specimen passes through a suitable transmitting vacuum window and illuminates a thermopile. The amount of energy reflected from the specimen is minimized by cooling the thermopile and the cavity walls which the specimen views. The output of the thermopile is amplified and sensed by a suitable meter. The meter reading is relative and must be calibrated with standards of known emittance.

2.1.3 *Test Method C*—With the advent of the FTIR and FTIR-based reflectometers/emissometers it is now feasible to collect a high resolution spectrum of reflectance ($\rho_N(\lambda)$), or ($\varepsilon_N(\lambda)$), or both, in a short amount of time. For opaque samples, the total near-normal emittance can be expressed as:

$$\varepsilon_N = 1 - \frac{\int_0^\infty \rho_N(\lambda) L_b(\lambda,T)\,d\lambda}{\int_0^\infty L_b(\lambda,T)\,d\lambda} = 1 - \rho_N \tag{2}$$

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[2] ~~Nelson, K. E., Leudke, E. E., and Bevans, J. T.,~~ The boldface numbers in parentheses refer to a list ~~Journal of Spacecraft and Rockets,~~of references at the ~~Vol 3, No. 5, 1966, p. 758.~~end of this standard.

A variety of accessories exist for use with the FTIR for determination of $\rho_N(\lambda)$ and emittance $\varepsilon_N(\lambda)$ for a large number of values of wavelengths λ. There are then various methods for approximating the above integrals. The most important feature of any accessory is the ability to collect the reflectance or emittance in the entire hemisphere above the sample. Accessories that collect just the specular component of reflectance or emittance will omit an often sizeable portion of the reflectance or emittance leading to large errors in the total near-normal emittance measurement. The most common type of attachments to achieve hemispherical collection are integrating spheres, ellipsoids, hemi-spheres or hemi-ellipsoids. For integrating sphere accessories the test sample is either placed at an aperture on the sphere or in a center mount (Edwards type). For ellipsoids the test sample is placed at an aperture created by cutting the ellipsoid perpendicular to the major axis at a focal point. For hemispheres the sample is placed with the test face pointing towards the zenith of the hemisphere at the origin of the sphere. For hemi-ellipsoid accessories the test sample is also placed with the test face pointing towards the zenith and at one focal point of the hemi-ellipsoid. The modes of operation of these attachments is either the direct method (illumination of the sample from one direction and collection of the scattered energy in the entire hemisphere above the sample) described in Method A or the reciprocal method (hemispherical illumination and directional detection). For illustration, we will briefly describe the direct method using an ellipsoid and the reciprocal method using a hemi-ellipsoid (such attachments are readily available; see Nicodemus et al **(3)**, Brandenberg et al **(4)** and Neu et al **(5)** for more detailed discussion). In the direct method, a source of infrared radiation is de-convolved by firmware in the FTIR and directed onto a sample placed over an aperature in a high specular reflective ellipsoid created by cutting the ellipsoid off perpendicular to the major axis at one focal point. The reflected energy is collected by a detector placed at the other focal point. To obtain the absolute reference, a mirror with matched specular reflectance (to the ellipsoid) directs the beam directly to the detector. The ratio at each wavelength yields $\rho_N(\lambda)$ for a large number of values of λ.

2.1.3.1 In the reciprocal method a source of Infrared radiation is situated at one focal point of the hemi-ellipsoid while the sample to be tested is positioned at the other focal point. Thus, infrared energy radiated from the source is focused by the hemi-ellipsoid down to the sample. An overhead mirror is positioned at a near-normal angle to the sample and the reflected energy off the sample is picked off by the overhead mirror and steered into the FTIR where firmware in the FTIR de-convolves the detected energy into the reflectance spectrum ($\rho_N(\lambda)$) of the sample. This can be conducted in the absolute mode or the relative mode where a reference standard of known reflectance is used to calibrate the instrument.

2.1.3.2 The resultant reflectance spectrum from these methods can then be used to approximate the integrals in the equations above to determine the total near-normal emittance.

2.2 The near-normal total emittance measurements covered by this standard and provided by the previously described instruments may be converted to total hemispherical emittance values where required. The conversion for metals is accomplished by using the Schmidt-Eckert **(6)** (hemispherical emissivity) and Foote **(7)** (normal emissivity) relations. For nonmetals (or insulators) the relation of normal and hemispherical emittance has been calculated and is also presented in the previous references. This can be incorporated within the instrument via internal software in some cases. Another method is to take measurements using Test Method C at a number of incidence angles, θ, yielding $\varepsilon(\theta)$. For example, in the reciprocal method using a hemi-ellipsoid described previously, the mirror that directs the reflected energy to the FTIR can be positioned at a range of incidence angles from near-normal to near-grazing. The resultant set of emittance as a function of angle can then be integrated hemispherically as shown below to yield the total hemispherical emittance (ε_H):

$$\varepsilon_H = 2\int_{\theta=0}^{\pi/2} \varepsilon_t(\theta)\sin(\theta)\cos(\theta)d\theta \tag{3}$$

3. Limitations

3.1 ~~Both~~ All of the test methods are limited in accuracy by the degree to which the emittance or reflectance properties of calibrating standards are known and by the angular emittance or reflectance characteristics of the surfaces being measured.

3.2 Test Method A is normally subject to a small non-gray error caused by the difference in wavelength distributions between the ~~radiant energy emitted by the two cavities at different temperatures,~~ spectral response of the optical system and that emitted by a ~~blackbody at the specimen temperature.~~ 300K blackbody. The absolute Type A instrument uses a source coating spectrally tailored to approximate a 300K black body, partially correcting for this error. Test Method B also has nongray errors since the detector is not at absolute zero temperature. The magnitude of this type of error is discussed by Nelson et ~~al.~~al **(1).**

3.3 Test Method ~~A~~ A, relative measurement, is subject to small errors that may be introduced if the orientation of the sensing component is changed between calibration and specimen measurements. This type of error results from minor changes in alignment of the optical system.

3.4 Test Method A is subject to error when curved specular surfaces of less than about 300-mm radius are measured. These errors can be minimized by using calibrating standards that have the same radius of curvature as the test surface.

3.5 Test Method A can measure reflectance on specimens that are either opaque or semi-transparent in the wavelength region of interest (about 4 to 50 µm). However, if emittance is to be derived from the reflectance data on a semi-transparent specimen, a correction must be made for transmittance losses.