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

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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

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

where:

$L_b(\lambda, T)$ = 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_2 = 1.4388×10^{-2} m·K,
T = absolute temperature, K,
λ = wavelength, m,
$\int_0^\infty L_b(\lambda,T)d\lambda$ = σT^4, and
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, 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 *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 three different types of instruments are, or have been, commercially available for performing this measurement. One type measures radiant energy reflected from the specimen (Test Method A), a second type measures radiant energy emitted from the specimen (Test Method 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*—Test Method A can best 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 $\varepsilon_N = 1 - \rho_N$. 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.

[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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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:

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

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

[2] The boldface numbers in parentheses refer to a list of references at the end of this standard.

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 ε(θ). 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):

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

3. Limitations

3.1 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 spectral response of the optical system and that emitted by a 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 (**1**).

3.3 Test Method 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.

3.6 Test Method B is subject to several possible significant errors. These may be due to (*1*) variation of the test surface temperature during measurements, (*2*) differences in temperature between the calibrating standards and the test surfaces, (*3*) changes in orientation of the sensing component between calibration and measurement, (*4*) errors due to irradiation of the specimen with thermal radiation by the sensing component, and (*5*) errors due to specimen curvature. Variations in test surface temperature severely limit accuracy when specimens that are thin or have low thermal conductivity are being measured. Great care must be taken to maintain the same temperature on the test surface and calibrating standards. Meter readings are directly proportional to the radiant flux emitted by the test surface, which in turn is proportional to the fourth power of temperature. Changes in orientation of the sensing component between calibration and test measurement introduce errors due to temperature changes of the thermopile. The relatively poor vaccuum around the thermopile results in variations in convection heat transfer coefficients which are affected by orientation.

3.7 The emittance measured by Test Method B is an intermediate value between total-normal and total-hemispherical emittance because of the relationship between the thermocouple sensing elements and the test surface. The close proximity of the thermopile to the relatively large test surface allows it to receive radiation emitted over a significant angle (up to 80°). This error (the difference between total-normal and total-hemispherical) emittance can be as large as 10 % on certain types of specimens (such as specular metal surfaces). Since the angular response is unknown, ε_N values must rely on reference samples that have been calibrated for ε_N values.

3.8 Critical to Test Method C is the degree to which the interior of the sphere, hemi-sphere, ellipsoid or hemi-ellipsoid is uniform. Errors will arise for the direct method when measuring samples that may have a significant specular component if the interior is not uniform. For the reciprocal method errors due to non-uniformity of the interior also arise because the hemispherical illumination of the sample will not be uniform.

3.9 FTIR devices are very sensitive to vibration in Test Method C. Errors in the measured spectrum, and hence errors in the calculated emittance, may arise if the FTIR is not securely placed or in a location that is subject to significant vibration.

3.10 Test Method C, when done in the relative mode, is limited in accuracy by the degree to which the reflectance/emittance properties of the calibrating standards are known. In addition, for measurements conducted at angles larger than near-normal the reflectance/emittance properties of the calibrating standards as a function of angle need to be carefully characterized. Reference samples may be provided to NIST[3] for careful calibration of their reflectance characteristics at both near-normal as well as angular incidence. In addition, a method of testing instrument accuracy is by use of a secondary reference (**8**) which is a material of well known optical properties that can be tested on the FTIR based device and the resultant data compared to the known optical properties. Ideally, such a secondary reference will have certain spectral features that can be distinguished by the FTIR and used to judge instrument accuracy.

3.11 Due to the long optical path-length of the FTIR, Test Method C is subject to error due to the spectral absorption of many common atmospheric gases such as water vapor and

[3] National Institute of Standards and Technology, Gaithersburg, MD, 20899.

CO_2. Establishing a dry air or dry Nitrogen purge into the integrating sphere, hemi-sphere, ellipsoid or hemi-ellipsoid will help to mitigate these effects. Many integrating sphere, hemisphere, ellipsoid and hemi-ellipsoid attachments feature a purge connection where purge gas may be directed into the measurement volume. The longer the length of purge before the test begins the less absorption features will be present.

3.12 Measuring emittance at various angles to obtain total hemispherical emittance is subject to errors to the extent that the incident angles are accurately known. Fine control over angular movements, or positioning, or both, are necessary.

3.13 When using Test Method C for hemispheres and hemi-ellipsoids that test in the relative mode, errors will arise if the test surface and the calibrating reference surface are not at the identical height. This leads to differences in the incident angle of the incident radiation. When testing in the relative mode, the incident angle on the test surface must be identical to the incident angle on the calibrating reference.

4. Procedure

4.1 The type A absolute measurement instrument requires only an appropriate warm-up before measurements. However, calibration samples are recommended to determine instrument health. In Test Method A relative measurement, hemispheric infrared reflectance properties of calibrating standards must be known, and for Test Method B normal emittance values of ε_N standards are utilized.

4.1.1 For Test Methods A and B relative measurements following an appropriate warm-up time, calibrate the readout meter. Adjust the meter to give the correct reading when measuring both high and low emittance (or reflectance) standards. Repeat calibration of the meter several times until the correct readings can be obtained near each end of the scale. Typical high and low emittance (low and high reflectance) standards may consist of black paint (or preferably a blackbody cavity) and polished high-purity aluminum, respectively. In all cases, it is recommended that the samples or instrument be rotated to determine unusual directional reflectance/emittance properties.

4.2 In Test Method B care must be taken to prevent stray radiant energy from entering the sensor. This can occur if the test surface is not sufficiently flat or is not opaque.

4.3 In Test Method B the test surfaces and calibrating standards must be maintained at the same temperature. If thin (less than about 0.7 mm thick) conducting specimens are to be measured, they should be bonded to a thick metallic substrate. Specimen temperature changes can be noted by observing whether the indicated meter reading drifts with time.

4.4 In Test Method B the orientation of the sensor must be the same for both calibration and test surface measurements.

4.5 After the meter has been properly calibrated, place the test surface over the aperture of the measuring instrument. The resulting meter reading of the relative Test Method A is then the infrared reflectance for blackbody radiant energy at near room temperature, or in Test Method B, a meter reading that can be converted to emittance using the manufacturer's emittance/meter reading conversion data. In Test Method A, obtain the emittance by subtracting the reflectance from unity. It is recommended that the instrument be recalibrated as soon as possible after measuring the test surface. If the meter calibration has changed, repeat the entire calibration and readout procedure. It is recommended that at least three readings be taken for each test specimen, and the results averaged, to minimize statistical errors. It is also recommended that both laboratory and working emittance (or reflectance) standards be maintained, and that they be kept clean.

4.6 The absolute type of measurement of Test Method A provides a direct measurement of near-normal directional total hemispherical reflectance.

4.7 For Test Method C, allow suitable time for the source of infrared radiation to reach its nominal operating temperature and become stable.

4.8 For Test Method C, establish the purge flow.

4.9 For Test Method C, if using the relative mode, place the calibration reference and the test sample in the proper location. For integrating spheres in relative mode with only one (1) aperture for placing the sample or reference, the reference is placed first then a calibration background is scanned. If the device requires a "zero" or "dark" scan to set the instrument zero block the source radiation and scan the "zero" level. Then the reference is replaced with the sample and the sample is scanned. For all other devices scan the reference followed by the "zero" if required, then scan sample. For instruments that utilize the absolute mode scan the 100 % level, then scan the "zero" if required, then scan the sample.

4.10 For Test Method C, for instruments using the absolute mode, divide the sample scan by the 100 % scan. If a "zero" scan is required then divide the "zero" scan by the 100 % scan. Subtracting the second quotient from the first yields the sample reflectance/emittance. Run the resultant reflectance/emittance spectrum through the approximation program for the integration shown in 2.1.3. For instruments that use the relative mode, replace the 100 % scan with the calibration reference scan and multiply both of the quotients above by the known spectral reflectance of the reference.

4.11 Using Test Method C at various incidence angles, if determining total hemispherical emittance, repeat steps 4.8 and 4.9 at a suitable variety of incident angles. Then perform an approximation to the hemispherical integration shown in 2.1.3.

5. Report

5.1 Report the following information:

5.1.1 Name and other pertinent identification of the test material and test type,

5.1.2 Name and other pertinent identification or traceability of the surfaces used for calibration,

5.1.3 Emittance (or reflectance) values assumed for calibration surfaces,

5.1.4 Locations on the surface area at which emittance (or reflectance) measurements were performed (not applicable for small individual test specimens nor for the reciprocal Test Method C), 5.1.5 Ambient temperature,

5.1.6 For Test Method A, the indicated meter reading (reflectance) shall be recorded for three successive measurements. An average of the three values shall than be calculated and subtracted from one to obtain the emittance,

5.1.7 For Test Method B, the indicated meter reading shall be recorded for three successive measurements. These meter readings shall be converted to emittance using the manufacturer's data, and then averaged,

5.1.8 For Test Method C, the measured reflectance, the calculated total near-normal emittance, the calculated total emittance (at each angle, if measured), and the calculated total hemispherical emittance, if applicable, and

5.1.9 Date and time the measurements were taken.

6. Keywords

6.1 emittance; infrared emittance; material radiative property; normal emittance; radiative heat transfer; spacecraft thermal control; thermal radiation

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