



Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres¹

This standard is issued under the fixed designation E903; 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 This test method covers the measurement of spectral absorptance, reflectance, and transmittance of materials using spectrophotometers equipped with integrating spheres.

1.2 Methods of computing solar weighted properties from the measured spectral values are specified.

1.3 This test method is applicable to materials having both specular and diffuse optical properties.

1.4 This test method is applicable to material with applied optical coatings with special consideration for the impact on the textures of the material under test.

1.5 Transmitting sheet materials that are inhomogeneous, textured, patterned, or corrugated require special considerations with respect to the applicability of this test method. Test Method E1084 may be more appropriate to determine the bulk optical properties of textured or inhomogeneous materials.

1.6 For homogeneous materials this test method is preferred over Test Method E1084.

1.7 This test method refers to applications using standard reference solar spectral distributions but may be applied using alternative selected spectra as long as the source and details of the solar spectral distribution and weighting are reported.

1.8 *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. Referenced Documents

2.1 ASTM Standards:²

¹ This test method is under the jurisdiction of ASTM Committee E44 on Solar, Geothermal and Other Alternative Energy Sources and is the direct responsibility of Subcommittee E44.20 on Glass for Solar Applications.

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² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

- E275 Practice for Describing and Measuring Performance of Ultraviolet and Visible Spectrophotometers
- E424 Test Methods for Solar Energy Transmittance and Reflectance (Terrestrial) of Sheet Materials
- E490 Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables
- E772 Terminology of Solar Energy Conversion
- E971 Practice for Calculation of Photometric Transmittance and Reflectance of Materials to Solar Radiation
- E1084 Test Method for Solar Transmittance (Terrestrial) of Sheet Materials Using Sunlight
- E1175 Test Method for Determining Solar or Photopic Reflectance, Transmittance, and Absorptance of Materials Using a Large Diameter Integrating Sphere
- E2554 Practice for Estimating and Monitoring the Uncertainty of Test Results of a Test Method Using Control Chart Techniques
- G173 Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface
- G197 Table for Reference Solar Spectral Distributions: Direct and Diffuse on 20° Tilted and Vertical Surfaces

2.2 Other Documents:

- Federal Test Method Standard No. 141, Method 6101³
- ASHRAE Standard 74-1988⁴
- CIE 38 Radiometric and Photometric Characteristics of Materials and their Measurement⁵
- CIE 44 Absolute Methods for Reflection Measurement⁵
- NIST SP 250-48 Spectral Reflectance⁶
- NIST SP 250-69 Regular Spectral Transmittance⁷

3. Terminology

3.1 The following definitions are consistent with Terminology E772. Additional terms appropriate to this test method are included in Terminology E772.

³ Available from Standardization Documents, Order Desk, Building 4, Section D, 700 Robbins Ave., Philadelphia, PA 19111-5049, Attn: NPODS.

⁴ Available from American Society of Heating, Refrigeration, and Air-Conditioning Engineers, Inc., 191 Tullie Circle, NE, Atlanta GA 30329.

⁵ Available from U.S. National Committee of the CIE (International Commission on Illumination), C/o Thomas M. Lemons, TLA-Lighting Consultants, Inc., 7 Pond St., Salem, MA 01970, <http://www.cie-usnc.org>.

⁶ Available on line at <http://www.nist.gov/pml/div685/pub/upload/sp250-48.pdf>

⁷ Available on line at <http://www.nist.gov/calibrations/upload/SP250-69.pdf>

3.2 Definitions:

3.2.1 *absorbance*, α , n —the ratio of the absorbed radiant flux to the incident radiant flux.

3.2.2 *diffuse*, *adj*—indicates that flux propagates in many directions, as opposed to direct beam, which refers to collimated flux. When referring to reflectance, it is the directional-hemispherical reflectance less the specular reflectance.

3.2.3 *integrating sphere*, n —an optical device used to either collect flux reflected or transmitted from a sample into a hemisphere or to provide isotropic irradiation of a sample from a complete hemisphere. It consists of a cavity that is approximately spherical in shape with apertures for admitting and detecting flux and usually having additional apertures over which sample and reference specimens are placed.

3.2.4 *irradiance*, E , n —a radiometric term for the radiant flux that is incident upon a surface ($\text{W}\cdot\text{m}^{-2}$).

3.2.5 *near normal-hemispherical*, *adj*—indicates irradiance to be directional near normal to the specimen surface and the flux leaving the surface or medium is collected over an entire hemisphere for detection.

3.2.6 *photovoltaic solar*, *adj*—referring to an optical property; indicates a weighted average of the spectral property using the number of photons per second per unit area per unit wavelength derived from a standard solar irradiance distribution as the weighting function.

3.2.7 *radiant flux*, Φ , n —a radiometric term for the time rate of flow of energy in the form of electromagnetic energy (watts).

3.2.8 *reflectance*, ρ , n —the ratio of the reflected radiant flux to the incident radiant flux.

3.2.9 *smooth*, *adj*—having an even and level surface, having no roughness or projections. Free from inequalities or unevenness of surface.

3.2.10 *solar*, *adj*—(1) referring to radiometric quantities, indicates that the radiant flux involved has the sun as its source, or has the relative spectral distribution of solar flux, and (2) referring to an optical property, indicates a weighted average of the spectral property, with a standard solar spectral irradiance distribution as the weighting function.

3.2.11 *spectral*, *adj*—(1) for dimensionless optical properties, indicating that the property was evaluated at a specific wavelength, λ , within a small wavelength interval, $\Delta\lambda$ about λ , symbol wavelength in parentheses as $L(350\text{ nm})$, or as a function of wavelength, symbol $L(\lambda)$, and (2) for a radiometric quantity, the concentration of the quantity per unit wavelength (or frequency), indicated by the subscript λ , as $L_{\lambda} = dL/d\lambda$; at a specific wavelength, the wavelength at which the spectral concentration was evaluated may be indicated by the wavelength in parentheses following the symbol, $L_{\lambda}(350\text{ nm})$.

3.2.11.1 *Discussion*—The parameters of frequency, ν , wavenumber, κ , or photon energy may be substituted for wavelength, λ , in this definition.

3.2.12 *specular*, *adj*—indicates the flux leaves a surface or medium at an angle that is numerically equal to the angle of

incidence, lies in the same plane as the incident ray and the perpendicular, but is on the opposite side of the perpendicular to the surface.

3.2.12.1 *Discussion*—Diffuse has been used in the past to refer to hemispherical collection (including the specular component). This use is deprecated in favor of the more precise term *hemispherical*.

3.2.13 *textured*, *adj*—the nature of a surface other than smooth. Having some degree of unevenness, roughness or projections.

3.2.14 *transmittance*, τ , n —the ratio of the transmitted radiant flux to the incident radiant flux.

4. Summary of Test Method

4.1 Measurements of spectral near normal-hemispherical transmittance (or reflectance) are made over the spectral range from approximately 300 to 2500 nm with an integrating sphere spectrophotometer.

4.2 The solar transmittance, reflectance, or absorbance is obtained by calculating a weighted average with a standard or selected solar spectral irradiance as the weighting function by either direct calculation of suitable convolution integrals, or the weighted (see 8.3.3) or selected (see 8.3.4) ordinate method.

5. Significance and Use

5.1 Solar-energy absorbance, reflectance, and transmittance are important in the performance of all solar energy systems ranging from passive building systems to central receiver power systems. This test method provides a means for determining these values under fixed conditions that represent an average that would be encountered during use of a system in the temperate zone.

5.2 Solar-energy absorbance, reflectance, and transmittance are important for thermal control of spacecraft and the solar power of extraterrestrial systems. This test method also provides a means for determining these values for extraterrestrial conditions.

5.3 This test method is designed to provide reproducible data appropriate for comparison of results among laboratories or at different times by the same laboratory and for comparison of data obtained on different materials.

5.4 This test method has been found practical for smooth materials having both specular and diffuse optical properties. Materials that are textured, inhomogeneous, patterned, or corrugated require special consideration.

5.4.1 Surface roughness may be introduced by physical or chemical processes, such as pressing, rolling, etching, or deposition of films or chemical layers on materials, resulting in textured surfaces.

5.4.2 The magnitude of surface roughness with respect to the components of the spectrophotometer and attachments (light beam sizes, sphere apertures, sample holder configuration) can significantly affect the accuracy of measurements using this test method.

5.4.3 Even if the repeatability, or precision of the measurement of textured materials is good, including repeated measurements at various locations within or orientations of the

sample, the different characteristics of different spectrophotometers in different laboratories may result in significant differences in measurement results.

5.4.4 In the context of 5.4.3, the term ‘significant’ means differences exceeding the calibration or measurement uncertainty, or both, established for the spectrophotometers involved, through measurement of or calibration with standard reference materials.

5.4.5 The caveats of 5.4.3 and 5.4.4 apply as well to measurement of smooth inhomogeneous or diffusing materials, where incident light may propagate to the edge of the test material and be ‘lost’ with respect to the measurement.

5.5 This test method describes measurements accomplished over wider spectral ranges than the Photopic response of the human eye. Measurements are typically made indoors using light sources other than natural sunlight, though it is possible to configure systems using natural sunlight as the illumination source, as in Practice E424. Practice E971 describes outdoor methods using natural sunlight over the spectral response range of the human eye.

5.6 Light diffracted by gratings is typically significantly polarized. For polarizing samples, measurement data will be a function of the orientation of the sample. Polarization effects may be detected by measuring the sample with rotation at various angles about the normal to the samples.

6. Apparatus

6.1 Instrumentation:

6.1.1 *Spectrophotometer*—A spectrophotometer with an integrating sphere attachment capable of measuring the spectral characteristics of the test specimen or material over the solar spectral region from approximately 300 to 2500 nm is required. Double beam, ratio recording instruments are recommended because of their low sensitivity to drift in source brightness or amplifier gain. Recording spectrophotometers with integrating spheres that have been found satisfactory for this purpose are commercially available.

NOTE 1—For determining extraterrestrial solar optical properties using Standard E490, the spectral region should extend down to 250 nm.

NOTE 2—This test method is used primarily for solar thermal and some photovoltaic applications that require the full spectral range be covered. There are other applications for which a narrower range is sufficient and that could otherwise use the procedures of this test method. For example, some applications involving photovoltaic cells utilize a narrower spectral responsive range and some others pertain only to visible light properties that have an even narrower spectral range. In such cases, the user of the test method is permitted to use a narrower range. Similarly, a user with an application requiring a broader spectral range is permitted to use a broader range. Any deviations from the spectral range of this test method should be noted in the report.

6.1.1.1 The integrating sphere shall be either a wall-mounted type such that the specimen may be placed in direct contact with the rim of an aperture in the sphere wall for transmittance and reflectance measurements or an Edwards type such that the specimen is mounted in the center for reflectance and absorptance measurements.

NOTE 3—The interior of the integrating sphere shall be finished with a stable highly reflecting and diffusing coating. Sphere coatings having the required properties can be prepared using pressed tetrafluoroethylene

polymer powder, or other highly reflective, stable material.

NOTE 4—For high accuracy (better than ± 0.01 reflectance units) measurements with absolute sphere configuration, the ratio of the port area to the sphere wall plus port area should be less than 0.001 (1).⁸ In general, large spheres (> 200 mm) meet these requirements and are preferred while small spheres (< 100 mm) can give rise to large errors.

6.1.1.2 For the evaluation of near normal-hemispherical or hemispherical-near-normal reflectance, the direction of the incident radiation or the direction of viewing respectively shall be between 6 and 12° from the normal to the plane of the specimen so that the specular component of the reflected energy is not lost through an aperture. Ambient light must be prevented from entering the sphere by placing a ring of black or white material around the external rim of the specimen ports or by covering the entire sphere attachment with a light tight housing. Black backing or border material may result in significant light absorption or loss, while white backing material should be more representative of the sphere interior and affect measurement results to a lesser extent. Several acceptable system configurations are illustrated in Appendix X1.

NOTE 5—The hemispherical near-normal irradiation-viewing mode is also allowed under this test method since the Helmholtz reciprocity relationship which holds in the absence of polarization and magnetic fields guarantees equivalent results are obtainable.

6.1.1.3 Some commercial instruments have sample ports equipped with quartz windows. There is a possibility for multiple reflections to occur between sample and window surfaces and miss or inadvertently enter the sample port. In transmission measurement mode ensure that any light reflected from the sample is collected at the sample port. Best practice is to ensure that the sample does not interact with the optical system of the spectrophotometer.

6.1.1.4 In spectrophotometer systems with multiple gratings and multiple detectors, discontinuities in the spectral data due to changes in bandwidth, grating efficiency, or detector sensitivity may occur at grating and detector switch over points. If observed, the magnitude and cause of the discontinuity should be investigated. Careful calibration over the entire spectral band of interest should account for such discrepancies.

6.2 Standards:

6.2.1 In general, both reference and working (comparison) standards are required.

NOTE 6—Reference standards are the primary standard for the calibration of instruments and working standards. Reference standards that have high specular reflectance, high diffuse reflectance, and low diffuse reflectance were formerly available from the National Institute of Standards and Technology as Standard Reference Materials (SRM).⁹ See NIST Special Publications 250-48 and 250-69. However, the low demand and high cost of these materials has been replaced by offers of measurement services from National Metrology Institutions (NMI) such as NIST. These laboratories offer to measure customers samples and report spectral optical properties. These become NIST (or NMI) traceable reference standards for customers. The customers often include commercial

⁸ The boldface numbers in parentheses refer to the list of references at the end of this standard.

⁹ National Institute of Standards and Technology, Office of Standard Reference Materials, Room B311, Chemistry Bldg., Washington, DC 20234. Additional details covering the appropriate SRMs (2019–2022) are available on request.

firms which then produce SRMs and reference standards based on their NMI traceable standards and provide them to their customers along with traceability and uncertainty information. These SRMs and reference standards are permitted within the context of this standard. Example NMIs include the National Physical Laboratory (NPL) of the United Kingdom, the National Research Council (NRC) of Canada, the Physical Technical Bureau (PTB) of Germany, The National Laboratory of Metrology and Test (LNE-INM) of France, etc.

NOTE 7—As of 2012, NPL still offers spectral reflectance standard reference materials at: <http://www.npl.co.uk/optical-radiation-photonics/optical-characterisation-of-materials/products-and-services/reflectance-standards>

6.2.1.1 Working standards are used in the daily operation of the instrument to provide comparison curves for data reduction. In general, ceramic and vitrified enamel surfaces are highly durable and desirable. A working standard shall be calibrated by measuring its optical properties relative to the properties of the appropriate reference standard using procedures given in 8.2.

NOTE 8—Even the best standards tend to degrade with continued handling. They should be handled with care and stored in a clean, safe manner. Working standards should be recalibrated periodically and cleaned, renewed, or replaced if degradation is noticeable. Avoid touching the optical surfaces. Only clean soft cloth gloves should be worn for handling the standards. Only lens tissue or sterile cotton is recommended for cleaning. This is especially important for reference standards carrying NIST calibration.

6.2.2 For transmitting specimens, incident radiation shall be used as the standard relative to which the transmitted light is evaluated. For some applications calibrated transmittance standards are available.

6.2.3 For diffuse high-reflectance specimens, a working standard that has high reflectance and is highly diffusing over the range of the solar spectrum is required.

NOTE 9—Identified suitable working standards are tablets of pressed tetrafluoroethylene polymer, BaSO₄, BaSO₄-based paints, and white ceramic tile.

6.2.4 For specularly reflecting specimens, a working standard that is highly specular is required. Identified suitable working standards are vacuum-deposited thin opaque films of metals. All front surface metalized working standards shall be calibrated frequently with an absolute reflectometer or relative to a standard reference mirror traceable to a national standardizing laboratory reference before being acceptable in this test method. An acceptable working standard for low-specular reflectance is a flat piece of optically polished black glass. NIST no longer provides specular reflectance standard reference materials; but will measure user provided mirrors to provide traceable calibration data.

NOTE 10—Although aluminum is most often used because of its high reflectance and ease of deposition, it is very unstable and scratches easily. Other metals such as chromium, nickel, and rhodium are much more durable. High vacuum ($\geq 10^{10}$ torr) is required for obtaining pure films with the best optical properties (2).

6.2.5 For absorber materials, a working standard that has low reflectance over the range of the solar spectrum is required in order to obtain an accurate zero line correction.

NOTE 11—Black semi-matt porcelain enameled substrates, black

barbeque, stove, or wrought iron fence paints, and opaque black glass are suitable working standards. For very low-reflectance materials light traps reflecting < 0.005 can be fabricated to calibrate sphere performance.

NOTE 12—Light traps can be made from a stack of razor blades, a 60° black cone, or by forming an approximate exponential horn by drawing a glass tube and painting it with high-gloss black paint.

6.2.6 If an absolute sphere is completely free of the flux losses referred to in X3.1.2, no working standard is required. A comparison of the measured reflectance of a primary reference standard to its calibration value will give a good estimate of the error due to flux losses, if any, from a nearly absolute sphere such as described in Appendix X1, X1.1.2 and X1.1.3.

7. Test Specimens

7.1 Specimens for Wall-Mounting Spheres:

7.1.1 The size of test specimens required depends on the dimensions of the integrating sphere. For wall-mounted spheres the specimen must be large enough to cover the aperture of the sphere. There may be no limit on maximum dimension. For textured or patterned samples, either the specimen shall be large enough to make a number of measurements over different areas, or several specimens representing the different areas of the material shall be used.

7.1.2 Opaque specimens shall have at least one surface that is essentially planar over an area large enough to cover the aperture of the sphere.

7.1.3 The most accurate results may be obtained from transparent and slightly translucent specimens with two surfaces that are essentially smooth, or plane and parallel. In order to reduce light scattered out the edges of translucent specimen, the minimum distance between the edge of the beam and the edge of the aperture shall be ten times the thickness of the specimen. The caveats of 5.4.1 to 5.4.5 should be observed when measuring textured or highly diffusing materials.

7.1.4 The transmittance of highly scattering translucent samples is not easily measured with an integrating sphere instrument, because a significant portion of the incident flux will be scattered outside the aperture. For such materials the standard test method using the sun as a source (Test Methods E1084 or E1175) is preferred. Smith et al. (3) discuss diffuse material transmittance issues (side losses, etc.) and discuss 0.01 (reflectance) accuracy and considerations for beam and aperture geometry.

NOTE 13—If such a sample must be measured, the edge losses can be greatly reduced by using a circular sample of diameter slightly less than that of the aperture, and coating the edge with silver, using the wet mirror process. Alternatively, small stops can be cemented to the edges of the sample, so that it can be suspended in the aperture with about half of its thickness extending outside the aperture.

7.2 Specimens for Edwards Sphere—The area of the specimen shall be limited to 0.01 of the surface area of the sphere.

NOTE 14—For a 200-mm diameter sphere, the required specimen size would be less than or equal to 20 mm in radius.

8. Procedure

8.1 Calibration—Calibrate linearity and wavelength scales of the spectrophotometers as recommended by the manufacturer or in accordance with Practice E275. Check on calibration annually.

8.2 Measurement:

8.2.1 Correction for 100 % and Zero Line Errors:

8.2.1.1 Record 100 % and zero line curves at least twice a day during testing.

NOTE 15—Variations in signal from the two beams are normal, usually wavelength dependent, and give rise to nonideal 100 % lines. Similarly, beam cross talk, light scattering or leaks, and detector noise give rise to a nonideal zero line. These effects produce errors in the measured ratio of the flux reflected by the specimen and the working standard.

8.2.1.2 For spheres with separate sample and reference ports, record the 100 % line curves using identical high-reflectance specimens in both ports. The specimens are identical in reflectance if the recorded curve does not change when the two specimens are interchanged.

8.2.1.3 For reflectance measurements, record the zero line with a perfect absorber or light trap in the sample port.

NOTE 16—The practice of recording the zero line with the sample beam blocked at the entrance port is discouraged because the effect of scattered light incident on the sphere wall is not included.

8.2.1.4 For transmittance measurements, record the zero line with the sample beam blocked, preferably as far in front of the entrance port as convenient.

8.2.2 Reflectance of Opaque Specimen—Comparison Type Sphere:

8.2.2.1 Record the spectral 100 % and zero lines as indicated in 8.2.1.

8.2.2.2 Record the spectral reflectance of specimen relative to the working standard by placing the specimen on the sample port and the standard on the reference port. Include the specular component in the reflectance measurement.

8.2.2.3 Compute the spectral reflectance, $\rho(\lambda)$, for the specimen, at wavelength λ using:

$$\rho(\lambda) = (S_\lambda - Z_\lambda)/(100_\lambda - Z_\lambda)\rho'(\lambda) \quad (1)$$

where:

- S_λ = recorded specimen reading,
- Z_λ = zero line reading,
- 100_λ = 100 % line reading, and
- $\rho'(\lambda)$ = calibrated spectral reflectance for the working standard or reference, all at wavelength λ .

NOTE 17—Slightly different procedures may be required for other sphere designs.

8.2.3 Reflectance of Opaque Specimen in an Absolute Sphere:

$$\rho(\lambda) = (S_\lambda - Z_\lambda)/(100_\lambda - Z_\lambda) \quad (2)$$

where:

100_λ = 100 % correction obtained with the specimen port replaced by a sample having a coating and a curvature identical to the sphere wall. The zero line correction for an absolute sphere is usually so small that it can be neglected.

NOTE 18—Slightly different procedures may be required for other sphere designs.

8.2.4 For reflectance of transparent or translucent materials or specimens having transmittance greater than 0.001, back the specimen by a light trap or black material having a low reflectance (< 0.02) over the 300 to 2500-nm spectral range.

For these measurements, the zero line shall be recorded with the specimen removed but the light trap or backing still in place. Obtain the spectral reflectance following 8.2.2.

8.2.5 Transmittance—Cover the specimen and reference ports at the rear of the sphere with surfaces having the same coating and optical properties as the sphere walls when measuring transmittance (Note 19). Record spectral curves without specimen in place. Record spectral curves with the specimen over the specimen beam entrance port of the sphere. Calculate the spectral transmittance as:

$$\tau(\lambda) = (S_\lambda - Z_\lambda)/(100_\lambda - Z_\lambda) \quad (3)$$

where:

- S_λ = signal recorded with the specimen over the entrance port,
- Z_λ = zero line reading with the specimen beam blocked with an opaque material, and
- 100_λ = line recorded with no specimen over the specimen beam entrance port.

NOTE 19—The working standards, 6.2.3, could be used with only a small error.

8.2.6 Absorbance—For opaque samples record the reflectance spectrum as in 8.2.2. The solar absorbance is calculated by first obtaining the solar reflectance as in 8.3 and subtracting from 1, that is, $\tau_s = 0$ in the Kirchoff relationship:

$$\alpha_s + \tau_s + \rho_s = 1 \quad (4)$$

8.2.6.1 For non-opaque samples, either obtain both the solar reflectance and solar transmittance using the described techniques and calculate the solar absorbance by using the Kirchoff relationship, or use an Edwards-type integrating sphere instrument with the specimen mounted so that the beam that exits through the back of the specimen is free to fall on the sphere wall. In this case the sum $\tau(\lambda) + \rho(\lambda)$ is measured directly. Then use 8.3 and the Kirchoff relationship to determine the solar absorbance.

8.3 Computation of Solar Properties—Solar energy transmittance or reflectance is computed by the weighted ordinate, 50 selected ordinate, 100 selected ordinate, or photovoltaic solar method.

8.3.1 Solar Spectral Irradiance Distribution:

8.3.1.1 For terrestrial applications, Tables G173 or a representative terrestrial spectrum, such as G197, or a specially selected and specified terrestrial spectrum, may be used. Calculate the optical properties using either the convolution integral of the selected spectrum and the measured property, the ordinate method in 8.3.3, or one of the selected ordinate methods described in section 8.3.4 and Appendix X2. For extraterrestrial applications, Standard E490 shall be used.

8.3.1.2 Calculate the optical properties using either the convolution integral of the selected spectrum and the measured property, the weighted ordinate method of 8.3.3, or one of the selected ordinate methods described in 8.3.4 and Appendix X2.

8.3.2 Product of Optical Properties—When calculating solar optical efficiency of a complicated system such as a reflecting concentrator with an absorber in a transparent envelope, the product of ρ , τ , and α is required. The appropriate procedure is to measure the spectral optical properties of each

component $\rho(\lambda)$, $\alpha(\lambda)$, and $\tau(\lambda)$ respectively and form the product $\eta(\lambda) = \rho(\lambda)\alpha(\lambda)\tau(\lambda)$ before solar weighting. Calculate η_s as described in 8.3.3 or 8.3.4. Calculation of η_s from individually weighted properties can lead to substantial error, that is, $\eta_s \neq \rho_s\alpha_s\tau_s$ (4). See also Section 7.2 of (5).

8.3.3 *Weighted Ordinates*—Obtain the solar reflectance ρ_s by integrating the spectral reflectance over the standard spectral irradiance distribution, E_{λ} , as follows:

$$\rho_s = \left(\sum_{i=1}^n \rho(\lambda_i) E_{\lambda_i} \Delta\lambda_i \right) / \left(\sum_{i=1}^n E_{\lambda_i} \Delta\lambda_i \right) \quad (5)$$

Solar transmittance τ_s or absorptance α_s , is obtained from a similar expression with $\rho(\lambda)$ replaced by $\tau(\lambda)$ or $\alpha(\lambda)$ respectively. Here n is the number of wavelengths for which E_{λ} is known. The $\Delta\lambda_i$ are not constant but are given by:

$$\Delta\lambda_i = (\lambda_{i+1} - \lambda_{i-1})/2 \quad (6)$$

For $i = 1$ and $i = n$, one assumes a $\Delta\lambda$ equal to the last interval, that is, $\Delta\lambda_1 = \lambda_2 - \lambda_1$ and $\Delta\lambda_n = \lambda_n - \lambda_{n-1}$.

8.3.4 *Selected Ordinates*:

8.3.4.1 In the selected ordinate method, the solar irradiance distribution is divided into n wavelength intervals each containing $1/n$ of the total irradiance. The spectral reflectance or transmittance of the sample is evaluated at the centroid λ_i of each interval, λ_i . The solar reflectance is then calculated as follows:

$$\rho_s = 1/n \sum_{i=1}^n \rho(\lambda_i) \quad (7)$$

8.3.4.2 The wavelengths λ_i , for the 50 and 100 selected ordinates derived from Tables G173 are provided in Appendix X2.

8.3.5 *Photovoltaic Solar*:

8.3.5.1 Photovoltaic solar energy conversion is effective only over a wavelength range shorter than the photovoltaic absorber's bandgap wavelength λ_g . Restricting the longest wavelength of the weighting function to λ_g yields an averaged value of an optical property that is more representative of a material's performance in a photovoltaic system than one averaged over a fixed wavelength interval.

8.3.5.2 In photovoltaic solar energy conversion, the current generated, and thus electrical power generated, depends on the number of photons absorbed in the absorber material. The number of photons in a wavelength interval depends on the spectral irradiance in that interval, E_{λ} , as well as the energy of photons in that interval; The energy of a photon of a given wavelength E_{ph} , is given by:

$$E_{ph} = hc/\lambda \quad (8)$$

where h is Planck's constant and c is the speed of light. The number of photons per second per unit area in the spectral interval, $N_{ph,\lambda}$ is given by:

$$N_{ph,\lambda} = \lambda E_{\lambda} / hc \quad (9)$$

8.3.5.3 In the photovoltaic solar method, obtain the photovoltaic solar reflectance $\rho_{pv}(\lambda_g)$ as follows:

$$\rho_{pv}(\lambda_g) = \frac{\left(\sum_{i=1}^m \rho(\lambda_i) \lambda_i E_{\lambda_i} \Delta\lambda \right)}{\left(\sum_{i=1}^m \lambda_i E_{\lambda_i} \Delta\lambda \right)} \quad (10)$$

Here m indicates the index of λ_i that is the wavelength equal or most nearly equal to λ_g .

Photovoltaic solar transmittance $\tau_{pv}(\lambda_g)$ or photovoltaic solar absorptance $\alpha_{pv}(\lambda_g)$ is obtained from a similar expression with $\rho(\lambda)$ replaced by $\tau(\lambda)$ or $\alpha(\lambda)$ respectively.

9. Report

9.1 The report shall include the following:

9.1.1 Complete identification of the material tested, specimen size and thickness, texture or surface contour if any, description of optical properties such as diffuse or specularly reflecting, clear or translucent transmitting, etc.

9.1.2 Solar transmittance, absorptance, or reflectance, or all three, determined to the nearest 0.001 unit or 0.1 %.

9.2 Estimated precision (repeatability) and estimated overall accuracy reported as uncertainty due to combined systematic and statistical (precision) errors. The accuracy and precision shall be reported in the same units as the optical property itself. The method by which the uncertainty was established shall be reported.

9.3 Identification of the instrument used. Manufacturer's name and model number including specifications, modifications and accessories is sufficient for a commercial instrument. Other instruments must be described in detail including estimations of their accuracy.

9.4 Solar spectral irradiance and weighting method used for computation of the solar optical property.

10. Precision and Bias

10.1 Uncertainties in the solar optical properties determined by the application of this test method arise from random errors associated with signal detection and electronic processing, errors introduced by the geometry of the integrating sphere system and the distribution of scattered or reflected light, errors in the values for standard reference materials, source illuminate beam configuration (size, orientation, and dispersion), sample orientation, positioning and configuration, and how correctly the spectral solar irradiance used in the calculation matches that at the actual location of system deployment. The contribution from each of these sources is discussed in Appendix X3. Experience has shown that high accuracy is relatively difficult to achieve and depends strongly on operator skill, experience, and care, as well as on equipment design and maintenance. Measurement results are required to be reported at a resolution of 0.1%, to permit resolution of incremental improvements in accuracy. However, it is extremely difficult to achieve absolute accuracy in any of the optical properties to better than 1 % to 2 %, or 10 to 20 times the required reporting resolution. References (6, 7, 8) discuss interlaboratory comparison results, on the order of 0.02 units, or 2 approximately 2 %.

11. Keywords

11.1 absorptance; diffuse; integrating sphere; reflectance; smooth; solar absorptance; solar reflectance; solar transmittance; spectral; spectrophotometer; specular; texture; transmittance

APPENDIXES

(Nonmandatory Information)

X1. INTEGRATING SPHERE GEOMETRIES

X1.1 A number of different integrating sphere geometries have been used over the years to obtain the optical reflectance and transmittance of materials. Each geometry has advantages for specific applications. For a thorough understanding of sphere applications and performance, Refs 1, 9, 10, and 11 should be consulted. Presented in X1.1.1 through X1.1.4 are the geometries felt to be most applicable for the use of this test method. Many of the comments on specific applications can be applied to more than one of the geometries. For a discussion of errors, see Section 10 and Refs 1 and 9.

X1.1.1 *Four-Port Sphere*—Because of its versatility, the four-port geometry shown in Fig. X1.1 is the most common sphere supplied with commercially available spectrophotometers. The reference and sample beams may either cross as shown or be parallel. The sphere gives the reflectance factor of the specimen relative to that of the reference material. Calibration with a reference standard is essential. In the transmittance mode the reference and sample ports are covered with matched references preferably of the same curvature and material as the sphere wall. The major problem with most commercial spheres of this type is that their size is small, usually less than 100 mm in diameter, so that the ratio of the total port area to the sphere wall area including the ports is large. This can introduce significant errors in a measurement due to flux loss. Large errors can also arise if the angular distribution of the light reflected from the specimen is different from that reflected by the standard. In transmittance measurements of translucent samples, this effect always occurs since the standard is the nonscattering open port. Careful baffle design can substantially reduce errors due to different light scattering distribution.

X1.1.1.1 Spheres of this type sometimes have specular ports with plugs that can be removed for measuring the diffuse reflectance with the specular component excluded.

X1.1.2 *Edwards Sphere*—A sphere of the Edwards type (Fig. X1.2) with a center-mounted sample allows ratio recording of absolute reflectance (12). This geometry is the only one in which the angular dependence of reflectance can be easily evaluated. By rotating the sample for normal incidence, the entrance port becomes a specular trap and diffuse reflectance with the specular component excluded can also be measured. Finally, since both reflected and transmitted light is collected by the sphere, absorptance of transmitting samples can be directly measured.

X1.1.2.1 The errors that can occur are related primarily to the uniformity and diffuseness of the sphere coating. A significant drawback is the small sample size required and the necessity of placing it inside the sphere.

X1.1.3 *Wall-Mount “Absolute”*—The sphere shown in Fig. X1.3 has a wall-mounted sample that is baffled from the view of the detector (11). The ratio signal obtained with this geometry is nearly absolute. Replacing a segment of the sphere wall with a black cavity that traps all the specularly reflected light permits the measurement of the diffuse component only. The addition of the light trap reduces the sphere’s efficiency and shifts the measurement further away from being absolute. After correction for changes in sphere efficiency (4), the specular component can be calculated from the difference in measurements with and without the light trap.

X1.1.4 *Transmittance Sphere*—Fig. X1.4 shows measurement geometry specifically for determining transmittance at

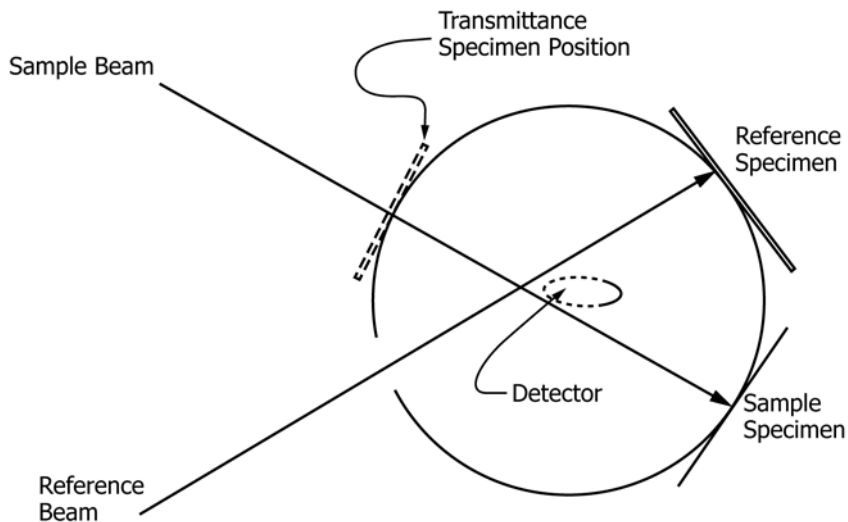


FIG. X1.1 Four-port, Comparison-type Integrating Sphere (Most Common)

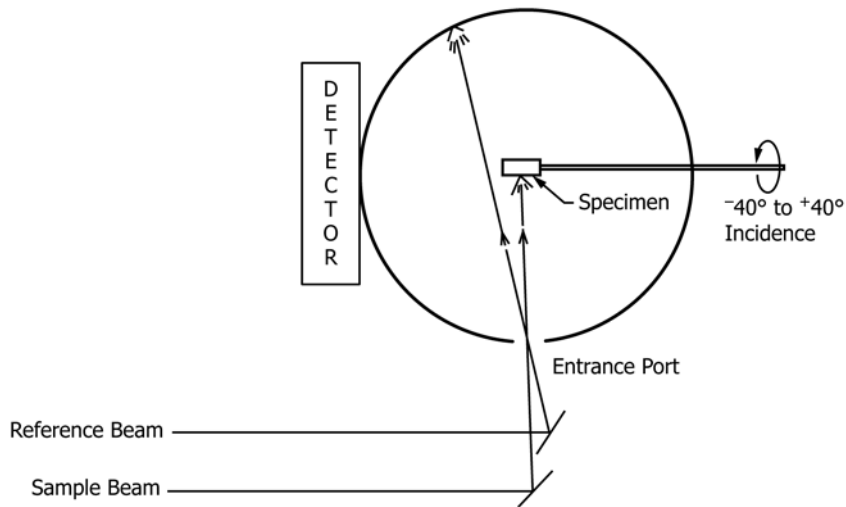


FIG. X1.2 Edwards-type, Absolute Integrating Sphere for Center-Mounted Specimen

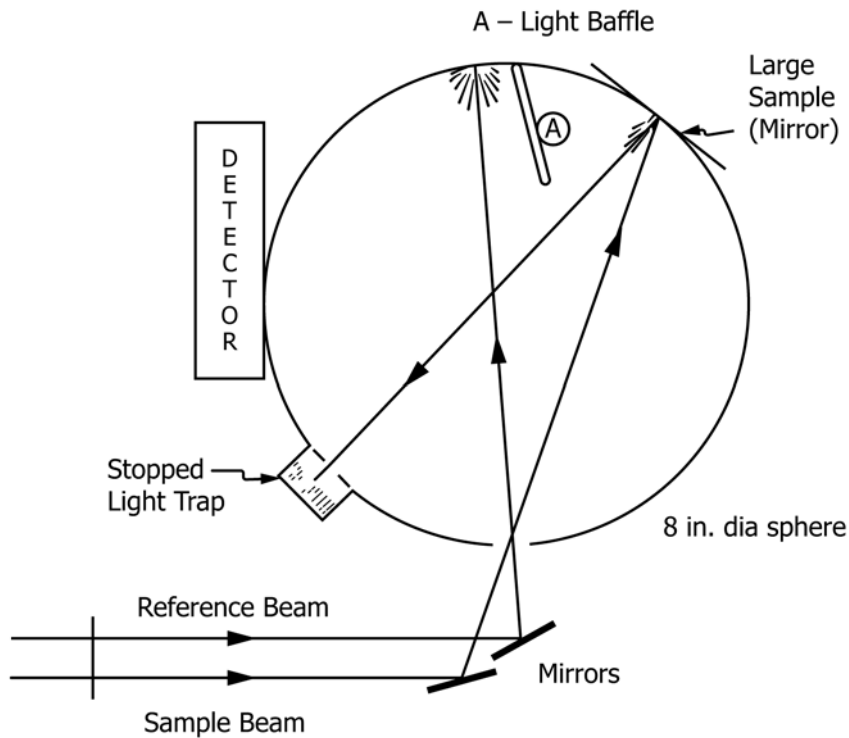


FIG. X1.3 Absolute Integrating Sphere for Wall-Mounted Specimen (11)

near-normal angles of incidence (4). The sphere has only three ports including the detector and collects nearly all of the transmitted flux. For maximum freedom from errors due to differences in specimen scattering properties, the detector shall be baffled from viewing the sample and either view all the remaining wall area with an isotropic 2π solid angle response

or view a very limited segment of the sphere wall that is also baffled from the sample port. In the latter case, low signal-to-noise would require long integration times for the detection circuit. All baffles should have high reflectance and can be coated with sphere wall material or they can be specular mirrors.

S₁ – Position for Near-Normal/Hemispherical Measurements
 S₂ – Position for Near-Normal/Near Normal Measurements

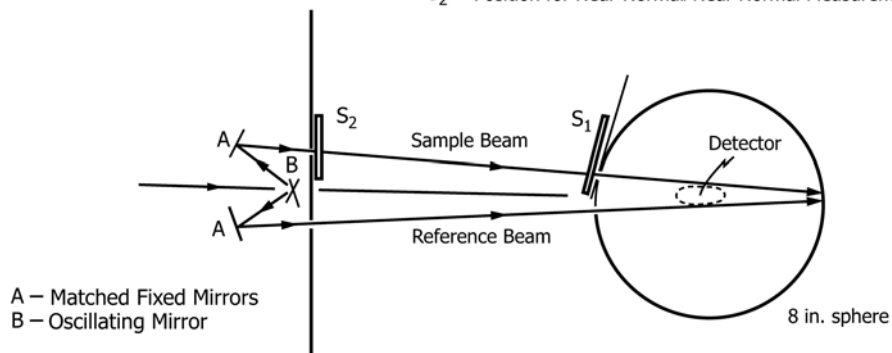


FIG. X1.4 Integrating Sphere for Transmittance Measurements (11)

X2. COMPUTATIONAL TECHNIQUE FOR TABULATED SELECTED ORDINATE VALUES

X2.1 Wavelength and equal energy values for the 100 and 50 selected ordinates are based on an interpolation procedure based on wavelength intervals bounding equal integrated power (energy), E_T , from the first value (E_o) to the last value (E_∞) under the spectral curves.

X2.1.1 The area between two adjacent wavelengths in the spectral curves of Tables G173 is computed using the trapezoid rule. The power P_i between wavelength λ_i and λ_{i+1} is computed from:

$$P_{i+1} = 0.5(\lambda_{i+1} - \lambda_i)(E_i + E_{i+1}) \quad (X2.1)$$

Where E_i is the power at wavelength λ_i .

X2.1.2 The cumulative power, $P_{c(i+1)}$ up to λ_{i+1} is the sum of all $P_i \leq P_{i+1}$: $P_{c(i+1)} = \sum_1^{i+1} P_i$

X2.1.3 For the m ($= 50$ or $m = 100$) selected ordinates, the proportion, F_K , of the total power, E_T , within each ordinate bin, K , is given by:

$$F_K = E_T(2K - 1)/(2m) \quad (X2.2)$$

X2.1.4 For theoretical purposes, the center wavelength for each equal power (energy) interval is derived from:

$$F_K = F_{i+1} - \frac{\Delta F}{\Delta \lambda_i} \Delta \lambda_K \quad (X2.3)$$

where:

$$F_i = P_{ci}/E_T$$

$$\Delta \lambda_K = \lambda_{i+1} - \lambda_i$$

F_K (defined by Eq X2.2) is between the values of F_i (at λ_i) and F_{i+1} (at λ_{i+1}), and $\Delta \lambda_i = \lambda_{i+1} - \lambda_i$.

X2.1.5 The equation for computing the central wavelength for the equal energy intervals, based on the above criteria is:

$$\lambda_K = \lambda_i + \frac{(F_K E_T - P_{ci})}{(P_{ci+1} - P_{ci})} (\lambda_{i+1} - \lambda_i) \quad (X2.4)$$

NOTE X2.1—The interpolation for the central wavelength of the equal energy interval is computed using the wavelengths and cumulative fraction of the total integrated energy bracketing the cumulative energy computed from Eq X2.2, from the high resolution spectral Table 2 in Tables G173.

X2.2 Summary of Weighted Ordinate Calculation Steps Using Selected Source Spectrum:

X2.2.1 From the original source spectrum, calculate the integral contribution between each adjacent wavelength according to Eq X2.1.

X2.2.2 For each successive wavelength interval, add the integral for that interval to that of the previous integral to produce the cumulative integral to each individual wavelength according to the equation in X2.1.2. The cumulative total at the final wavelength is the total integrated spectral power, E_T .

X2.2.3 Generate a table of m rows for the selected number, m of weighted ordinates. The first column contains the bin numbers, $1 - m$ inclusive. For the second column, compute the F_K for $k = 1 \dots m$ from Eq X2.2 for each bin k .

X2.2.4 The last column of the table will be the centroid wavelength for the band associated with each F_K computed in X2.2.3. To find that wavelength, compare the cumulative power, P_{ci} , in successive wavelength intervals for the original selected spectrum with the F_K for the selected bin. There will be two wavelengths, λ_i and λ_{i+1} where $P_{ci} \leq F_K \leq P_{c(i+1)}$ at those wavelengths. Use Eq X2.4 to interpolate between λ_i and λ_{i+1} to obtain the wavelength that matches the F_K value.

X2.3 Tables X2.1-X2.4 display the 100 and 50 selected ordinate data for direct normal spectral irradiance, and the 100 and 50 selected ordinate data for the global hemispherical 37° tilt spectral irradiance, respectively.

X2.4 For horizontal surface applications. Tables X2.5 and X2.6 display the 50 and 100 selected ordinate data for the global horizontal spectrum derived from the Tables G173 reference spectra, except that the air mass used is AM = 1.0, with the sun vertically overhead, and not AM 1.5. Note the integrated total global horizontal at AM 1.0 for the Tables G173 conditions is 1100.87 Wm⁻².

X2.5 Note that the selected ordinate approach may be used for any specified spectral distribution. The Tables G173 reference spectra in conjunction with the tables below can be used

TABLE X2.1 100 Selected Ordinates for G173 Direct Normal Irradiance AM 1.5

NOTE 1—Data given at the midpoint of the equal energy intervals.

k	F_K	$E_o \cdot \lambda_o$	λ_k	k	F_K	$E_o \cdot \lambda_o$	λ_k
1	0.005	4.50	338.04	51	0.505	454.57	745.21
2	0.015	13.50	365.63	52	0.515	463.57	753.17
3	0.025	22.50	385.00	53	0.525	472.57	764.51
4	0.035	31.50	401.14	54	0.535	481.57	773.88
5	0.045	40.51	411.34	55	0.545	490.58	782.24
6	0.055	49.51	420.86	56	0.555	499.58	790.83
7	0.065	58.51	430.56	57	0.565	508.58	799.77
8	0.075	67.51	439.68	58	0.575	517.58	808.83
9	0.085	76.51	447.56	59	0.585	526.58	819.13
10	0.095	85.51	454.65	60	0.595	535.58	829.82
11	0.105	94.51	461.58	61	0.605	544.58	839.89
12	0.115	103.52	468.00	62	0.615	553.59	849.61
13	0.125	112.52	475.25	63	0.625	562.59	858.23
14	0.135	121.52	481.84	64	0.635	571.59	869.88
15	0.145	130.52	487.20	65	0.645	580.59	880.07
16	0.155	139.52	495.49	66	0.655	589.59	890.52
17	0.165	148.52	502.20	67	0.665	598.59	903.30
18	0.175	157.52	508.88	68	0.675	607.59	917.32
19	0.185	166.53	515.53	69	0.685	616.60	921.65
20	0.195	175.53	522.56	70	0.695	625.60	961.68
21	0.205	184.53	529.29	71	0.705	634.60	978.10
22	0.215	193.53	535.85	72	0.715	643.60	991.67
23	0.225	202.53	542.56	73	0.725	652.60	1004.62
24	0.235	211.53	549.16	74	0.735	661.60	1005.35
25	0.245	220.53	555.71	75	0.745	670.60	1031.75
26	0.255	229.54	562.43	76	0.755	679.61	1045.92
27	0.265	238.54	569.13	77	0.765	688.61	1060.64
28	0.275	247.54	575.90	78	0.775	697.61	1076.11
29	0.285	256.54	582.62	79	0.785	706.61	1092.34
30	0.295	265.54	589.33	80	0.795	715.61	1112.29
31	0.305	274.54	596.31	81	0.805	724.61	1161.08
32	0.315	283.54	603.15	82	0.815	733.61	1183.50
33	0.325	292.55	609.89	83	0.825	742.61	1205.25
34	0.335	301.55	616.75	84	0.835	751.62	1226.32
35	0.345	310.55	623.63	85	0.845	760.62	1246.73
36	0.355	319.55	630.72	86	0.855	769.62	1269.05
37	0.365	328.55	637.70	87	0.865	778.62	1292.03
38	0.375	337.55	644.58	88	0.875	787.62	1318.67
39	0.385	346.55	651.68	89	0.885	796.62	1369.70
40	0.395	355.56	659.07	90	0.895	805.62	1524.51
41	0.405	364.56	666.18	91	0.905	814.63	1558.81
42	0.415	373.56	673.20	92	0.915	823.63	1595.85
43	0.425	382.56	680.29	93	0.925	832.63	1635.11
44	0.435	391.56	687.85	94	0.935	841.63	1677.49
45	0.445	400.56	695.97	95	0.945	850.63	1724.20
46	0.455	409.56	703.66	96	0.955	859.63	1788.69
47	0.465	418.56	711.22	97	0.965	868.63	2084.37
48	0.475	427.57	719.53	98	0.975	877.64	2190.64
49	0.485	436.57	728.65	99	0.985	886.64	2323.99
50	0.495	445.57	737.14	100	0.995	895.64	3502.26

as check on the implementation of the selected ordinate computation performed by a user.

TABLE X2.2 100 Selected Ordinates for G173 Global 37° Tilt Irradiance AM 1.5

NOTE 1—Data given at the midpoint of the equal energy intervals.

k	F_K	$E_o\lambda_o$	λ_k	k	F_K	$E_o\lambda_o$	λ_k
1	0.005	5.00	331.82	51	0.505		723.84
2	0.015	15.01	352.29	52	0.515	515.19	733.05
3	0.025	25.01	371.31	53	0.525	525.19	741.30
4	0.035	35.01	384.62	54	0.535	535.20	749.36
5	0.045	45.02	399.01	55	0.545	545.20	757.49
6	0.055	55.02	407.73	56	0.555	555.21	770.21
7	0.065	65.02	416.00	57	0.565	565.21	778.72
8	0.075	75.03	424.36	58	0.575	575.21	787.35
9	0.085	85.03	433.28	59	0.585	585.22	796.43
10	0.095	95.04	441.11	60	0.595	595.22	805.67
11	0.105	105.04	448.13	61	0.605	605.22	815.44
12	0.115	115.04	454.67	62	0.615	615.23	826.70
13	0.125	125.05	461.11	63	0.625	625.23	837.34
14	0.135	135.05	467.51	64	0.635	635.24	847.30
15	0.145	145.05	473.95	65	0.645	645.24	855.75
16	0.155	155.06	480.22	66	0.655	655.24	868.16
17	0.165	165.06	486.69	67	0.665	665.25	878.67
18	0.175	175.06	493.26	68	0.675	675.25	889.46
19	0.185	185.07	499.60	69	0.685	685.25	902.44
20	0.195	195.07	506.14	70	0.695	695.26	916.99
21	0.205	205.08	512.52	71	0.705	705.26	932.99
22	0.215	215.08	519.36	72	0.715	715.27	963.05
23	0.225	225.08	525.87	73	0.725	725.27	979.83
24	0.235	235.09	532.38	74	0.735	735.27	993.69
25	0.245	245.09	538.87	75	0.745	745.28	1007.35
26	0.255	255.09	545.46	76	0.755	755.28	1021.40
27	0.265	265.10	551.96	77	0.765	765.28	1035.91
28	0.275	275.10	558.48	78	0.775	775.29	1050.94
29	0.285	285.11	565.12	79	0.785	785.29	1066.66
30	0.295	295.11	571.85	80	0.795	795.29	1083.22
31	0.305	305.11	578.56	81	0.805	805.30	1101.50
32	0.315	315.12	585.14	82	0.815	815.30	1142.87
33	0.325	325.12	592.06	83	0.825	825.31	1175.18
34	0.335	335.12	598.93	84	0.835	835.31	1198.06
35	0.345	345.13	605.74	85	0.845	845.31	1220.96
36	0.355	355.13	612.51	86	0.855	855.32	1242.67
37	0.365	365.14	619.42	87	0.865	865.32	1265.55
38	0.375	375.14	626.40	88	0.875	875.32	1290.40
39	0.385	385.14	633.53	89	0.885	885.33	1318.50
40	0.395	395.15	640.45	90	0.895	895.33	1484.42
41	0.405	405.15	646.59	91	0.905	905.34	1529.65
42	0.415	415.15	654.58	92	0.915	915.34	1566.76
43	0.425	425.16	662.05	93	0.925	925.34	1607.96
44	0.435	435.16	630.37	94	0.935	935.35	1651.37
45	0.445	445.16	676.24	95	0.945	945.35	1698.68
46	0.455	455.17	683.41	96	0.955	955.35	1755.11
47	0.465	465.17	691.61	97	0.965	965.36	2039.94
48	0.475	475.18	699.41	98	0.975	975.36	2160.46
49	0.485	485.18	707.15	99	0.985	985.37	2298.17
50	0.495	495.18	714.82	100	0.995	995.37	3456.08

TABLE X2.3 50 Selected Ordinates for G173 Direct Normal Irradiance AM 1.5
TABLE X2.4 50 Selected Ordinates for G173 Global 37° Tilt Irradiance AM 1.5

NOTE 1—Data given at the midpoint of the equal energy intervals.

NOTE 1—Data given at the midpoint of the equal energy intervals.

k	F_K	$E_o-\lambda_o$	λ_k
1	0.01	9.00	353.19
2	0.03	27.00	394.13
3	0.05	45.01	416.10
4	0.07	63.01	435.39
5	0.09	81.01	451.07
6	0.11	99.02	464.98
7	0.13	117.02	478.57
8	0.15	135.02	491.82
9	0.17	153.02	505.58
10	0.19	171.03	519.18
11	0.21	189.03	532.52
12	0.23	207.03	545.84
13	0.25	225.03	559.06
14	0.27	243.04	572.54
15	0.29	261.04	585.89
16	0.31	279.04	599.72
17	0.33	297.05	613.29
18	0.35	315.05	627.16
19	0.37	333.05	641.13
20	0.39	351.05	655.24
21	0.41	369.06	669.68
22	0.43	387.06	683.86
23	0.45	405.06	697.77
24	0.47	423.07	715.05
25	0.49	441.07	733.08
26	0.51	459.07	749.17
27	0.53	477.07	769.68
28	0.55	495.08	786.47
29	0.57	513.08	804.30
30	0.59	531.08	824.60
31	0.61	549.08	844.73
32	0.63	567.09	864.67
33	0.65	585.09	885.28
34	0.67	603.09	909.93
35	0.69	621.10	948.68
36	0.71	639.10	985.19
37	0.73	657.10	1011.28
38	0.75	675.10	1038.78
39	0.77	693.11	1068.27
40	0.79	711.11	1101.51
41	0.81	729.11	1172.44
42	0.83	747.12	1215.87
43	0.85	765.12	1257.17
44	0.87	783.12	1304.37
45	0.89	801.12	1506.27
46	0.91	819.13	1577.10
47	0.93	837.13	1656.06
48	0.95	855.13	1751.98
49	0.97	873.14	2135.54
50	0.99	891.14	2433.69

k	F_K	$E_o-\lambda_o$	λ_k
1	0.01	10.00	342.08
2	0.03	30.01	377.07
3	0.05	50.02	403.35
4	0.07	70.03	361.98
5	0.09	90.03	437.21
6	0.11	110.04	451.36
7	0.13	130.05	464.26
8	0.15	150.06	477.01
9	0.17	170.06	490.04
10	0.19	190.07	501.89
11	0.21	210.08	515.80
12	0.23	230.09	529.22
13	0.25	250.09	542.23
14	0.27	270.10	555.19
15	0.29	290.11	568.46
16	0.31	310.11	581.89
17	0.33	330.12	595.52
18	0.35	350.13	609.11
19	0.37	370.14	622.85
20	0.39	390.14	637.01
21	0.41	410.15	651.03
22	0.43	430.16	665.62
23	0.45	450.17	679.81
24	0.47	470.17	695.58
25	0.49	490.18	710.97
26	0.51	510.19	728.55
27	0.53	530.20	745.34
28	0.55	550.20	765.26
29	0.57	570.21	783.02
30	0.59	590.22	800.02
31	0.61	610.23	821.17
32	0.63	630.23	842.31
33	0.65	650.24	862.84
34	0.67	670.25	884.05
35	0.69	690.26	909.30
36	0.71	710.26	949.90
37	0.73	730.27	986.97
38	0.75	750.28	1014.29
39	0.77	770.29	1043.35
40	0.79	790.29	1074.87
41	0.81	810.30	1113.08
42	0.83	830.31	1186.74
43	0.85	850.32	1231.88
44	0.87	870.32	1278.35
45	0.89	890.33	1341.00
46	0.91	910.34	1548.08
47	0.93	930.34	1629.15
48	0.95	950.35	1724.81
49	0.97	970.36	2099.04
50	0.99	990.37	2401.39

TABLE X2.5 50 Selected Ordinates for G173^A Global Horizontal Irradiance Air Mass = 1.0

NOTE 1—Data given at the midpoint of the equal energy intervals.

k	F_k	$E_o \lambda_o$	λ_k
1	0.01	11.01	333.32
2	0.03	33.03	363.96
3	0.05	55.04	388.74
4	0.07	77.06	407.56
5	0.09	99.08	422.25
6	0.11	121.10	437.50
7	0.13	143.11	450.52
8	0.15	165.13	462.48
9	0.17	187.15	474.51
10	0.19	209.17	486.51
11	0.21	231.18	498.85
12	0.23	253.20	511.29
13	0.25	275.22	524.22
14	0.27	297.23	536.85
15	0.29	319.25	549.68
16	0.31	341.27	562.59
17	0.33	363.29	575.73
18	0.35	385.30	588.93
19	0.37	407.32	602.67
20	0.39	429.34	616.38
21	0.41	451.36	630.54
22	0.43	473.37	644.82
23	0.45	495.39	659.87
24	0.47	517.41	674.72
25	0.49	539.43	690.52
26	0.51	561.44	706.84
27	0.53	583.46	724.35
28	0.55	605.48	742.53
29	0.57	627.50	761.05
30	0.59	649.51	781.73
31	0.61	671.53	801.07
32	0.63	693.55	822.57
33	0.65	715.56	844.93
34	0.67	737.58	867.53
35	0.69	759.60	890.81
36	0.71	781.62	919.92
37	0.73	803.63	965.52
38	0.75	825.65	997.06
39	0.77	847.67	1027.88
40	0.79	869.69	1061.04
41	0.81	891.70	1098.04
42	0.83	913.72	1168.99
43	0.85	935.74	1217.92
44	0.87	957.76	1266.86
45	0.89	979.77	1325.42
46	0.91	1001.79	1533.09
47	0.93	1023.81	1620.06
48	0.95	1045.83	1723.66
49	0.97	1067.84	2098.62
50	0.99	1089.86	2424.85

^A "G173" indicates that the same atmospheric conditions prescribed in G173 for Direct and Global tilt are used, ONLY the AIR MASS is changed to 1.0 rather 1.5. AM 1.0 is NOT a reference standard condition.

TABLE X2.6 100 Selected Ordinates for G173^A Global Horizontal Irradiance at Air Mass = 1.0

NOTE 1—Data given at the midpoint of the equal energy intervals.

k	F_K	$E_o\lambda_o$	λ_k	k	F_K	$E_o\lambda_o$	λ_k
1	0.00	5.50	324.27	51	0.50	555.9	702.80
2	0.01	16.51	341.03	52	0.51	566.9	710.90
3	0.02	27.52	356.44	53	0.52	577.9	719.68
4	0.03	38.53	369.80	54	0.53	588.9	729.17
5	0.04	49.54	381.70	55	0.54	599.9	738.12
6	0.05	60.55	394.87	56	0.55	610.9	746.85
7	0.06	71.56	403.75	57	0.56	621.9	755.58
8	0.07	82.57	411.35	58	0.57	633.0	767.85
9	0.08	93.57	418.59	59	0.58	644.0	777.10
10	0.09	104.58	425.88	60	0.59	655.0	786.40
11	0.10	115.59	434.00	61	0.60	666.0	796.13
12	0.11	126.60	441.06	62	0.61	677.0	806.07
13	0.12	137.61	447.51	63	0.62	688.0	816.68
14	0.13	148.62	453.53	64	0.63	699.0	828.37
15	0.14	159.63	459.52	65	0.64	710.0	839.53
16	0.15	170.63	465.45	66	0.65	721.0	850.46
17	0.16	181.64	471.53	67	0.66	732.0	861.79
18	0.17	192.65	477.47	68	0.67	743.0	873.24
19	0.18	203.66	483.33	69	0.68	754.0	884.90
20	0.19	214.67	489.72	70	0.69	765.1	897.23
21	0.20	225.68	495.80	71	0.70	776.1	912.19
22	0.21	236.69	502.00	72	0.71	787.1	927.10
23	0.22	247.70	508.20	73	0.72	798.1	953.93
24	0.23	258.70	514.41	74	0.73	809.1	973.89
25	0.24	269.71	521.07	75	0.74	820.1	989.72
26	0.25	280.72	527.49	76	0.75	831.1	1004.54
27	0.26	291.73	533.73	77	0.76	842.1	1019.96
28	0.27	302.74	540.05	78	0.77	853.1	1035.91
29	0.28	313.75	546.48	79	0.78	864.1	1052.47
30	0.29	324.76	552.86	80	0.79	875.1	1069.88
31	0.30	335.76	559.32	81	0.80	886.2	1088.20
32	0.31	346.77	565.86	82	0.81	897.2	1109.02
33	0.32	357.78	572.46	83	0.82	908.2	1155.02
34	0.33	368.79	579.06	84	0.83	919.2	1181.03
35	0.34	379.80	585.58	85	0.84	930.2	1205.75
36	0.35	390.81	592.44	86	0.85	941.2	1229.88
37	0.36	401.82	599.24	87	0.86	952.2	1253.88
38	0.37	412.83	606.05	88	0.87	963.2	1280.39
39	0.38	423.83	612.87	89	0.88	974.2	1308.29
40	0.39	434.84	619.87	90	0.89	985.2	1435.23
41	0.40	445.85	626.95	91	0.90	996.2	1512.43
42	0.41	456.86	634.14	92	0.91	1007.	1553.31
43	0.42	467.87	641.25	93	0.92	1018.	1596.78
44	0.43	478.88	648.46	94	0.93	1029.	1643.82
45	0.44	489.89	655.95	95	0.94	1040.	1695.32
46	0.45	500.90	663.59	96	0.95	1051.	1756.15
47	0.46	511.90	670.98	97	0.96	1062.	2033.97
48	0.47	522.91	678.48	98	0.97	1073.	2160.04
49	0.48	533.92	686.13	99	0.98	1084.	2310.08
50	0.49	544.93	694.64	100	0.99	1095.	3447.44

^A "G173" indicates that the same atmospheric conditions prescribed in Tables G173 for Direct and Global tilt are used, ONLY the AIR MASS is changed to 1.0 rather 1.5. AM 1.0 is NOT a reference standard condition.

X3. DISCUSSION OF SOURCES OF BIAS, PRECISION, AND UNCERTAINTY

X3.1 Uncertainties in the solar optical properties determined by the application of this test method arise from random errors associated with signal detection and electronic processing, errors introduced by the geometry of the integrating sphere system and the distribution of scattered or reflected light, errors in the values for standard reference materials, source illuminate beam configuration (size, orientation, and dispersion), sample orientation, positioning and configuration, and how correctly the spectral solar irradiance used in the calculation matches that at the actual location of system deployment. The contribution from each of these sources is subsequently discussed. Experience has shown that high accuracy is relatively difficult to achieve and depends strongly on operator skill, experience, and care, as well as on equipment design and maintenance.

X3.1.1 *Precision*—Random or precision uncertainty in the spectral reflectance or transmittance measured with an integrating sphere reflectometer (for repeated measurements of a sample in a single orientation) is due almost entirely to the signal-to-noise ratio of the detector-amplifier system. At wavelengths at which the signal to noise ratio is high, the repeatability of measurements made on the same sample with the same reflectometer is usually better than ± 0.005 of a full-scale value of 1.0. At the wavelengths near the limits of the spectral range of the detector, usually in the near infrared, the uncertainty due to this source may exceed ± 0.02 of a full-scale value of 1.0 at normal scanning speeds. These uncertainties can be reduced significantly by slow or stepwise scanning to average over longer times at each wavelength. However, since the spectral regions where large uncertainty in reflectance or transmittance occurs usually contain very little solar flux, carefully performed measurements can often be repeatable to ± 0.1 % or ± 0.001 units. Statistical analysis of multiple measurements (including multiple sample orientations or other variable parameters) such as described in Practice E2554 is needed to establish precision.

X3.1.2 *Bias*—The following discussion is based on reflectance measurements. Except where noted and in the case of the Edwards-type sphere, the same arguments pertain to the measurement of transmittance. Simple integrating sphere theory (1) is based on four assumptions:

- (1) the sphere coating is uniform in reflectance over the entire inner surface of the sphere,
- (2) the sphere coating is a perfectly lambertian reflector,
- (3) none of the reflected flux is lost out of the apertures of the spheres, and
- (4) none of the reflected flux reaches the detector without being reflected at least twice by the sphere wall.

None of these assumptions can be met rigorously, but they can be closely approached in a well-designed integrating sphere so that the resulting errors are small. Most commercially available integrating sphere reflectance attachments measure reflectance factor, which is the ratio of the flux reflected by a sample into a complete hemisphere to that reflected by a completely reflecting and perfectly diffusing

surface under identical conditions of irradiation and collection. Reflectance factor does not measure the reflectance which is the ratio of the flux reflected into a complete hemisphere to the flux incident on the sample from the monochromator.

The directional-hemispherical reflectance factor is proportional to the directional-hemispherical reflectance, with the constant of proportionality equal to the reflectance of the reference specimen in a comparison-type sphere or equal to one in an absolute sphere. The advantage of measuring reflectance factor rather than reflectance is that the ratio of the fluxes reflected by the sample and the comparison standard is automatically corrected for the major portion of the errors due to nonideal characteristics of the sphere.

An accurate evaluation of the errors present in a reflectance factor measurement requires a detailed knowledge of the geometrical distribution of light reflected from both the sample and the reference standard used in the measurement. Such information is almost never available. However, it is possible to compute the errors for the cases where the specimen and standard are perfectly diffuse or perfectly specular (9). In general, the errors will be of opposite sign when measuring a diffusely reflecting and a specularly reflecting sample with a diffusely reflecting comparison standard.

The integrating spheres of the Edwards- and wall-mounted absolute types use the sphere wall as the comparison standard. They measure the absolute reflectance factor with relatively small errors due to flux loss. For these spheres, the uniformity of the coating on the sphere wall becomes an important factor in the bias of the reflectance measurements.

X3.1.2.1 *Uncertainty Due to Sphere Parameters*—Uncertainty due to the deviations of the sphere from an ideal sphere satisfying the four assumptions in X3.1.2 is a function of sphere design (1) and the geometric distribution of the flux reflected or transmitted by the sample and the reference standard. If the specimen and reference standard have the same geometric distribution of reflected flux, the bias will be near zero. If they are markedly different, the errors due to this source can exceed ± 0.01 absolute. Best accuracy is achieved by using a specular reference standard when measuring a specular or near-specular sample, and a diffusely reflecting reference standard when measuring a diffusely reflecting sample. When measuring transmittance of a translucent material the errors can be significant since the open port which is completely specular is used as the standard. Well-designed light baffles in the sphere are essential to accurate measurements.

X3.1.2.2 *Uncertainty in Reflectance of Comparison Standard*—The uncertainty in the value assigned to a reference reflectance standard (13) should be ± 0.5 % although for a less carefully prepared specimen it may be as much as ± 2.0 %. This is due primarily to differences in the thickness of the material layer and in the degree of consolidation of the material produced in the pressing process. The uncertainty in BaSO₄ reference tablets is typically ± 2.0 %. Smoked MgO is no longer recommended as a comparison standard. The use of

National Institute of Standards and Technology (NIST) or other NMI produced standards to calibrate the working standard can reduce this uncertainty to less than $\pm 1.0\%$, since no separate comparison standard is used. This uncertainty is absent from measurements made in the “absolute” sphere geometries or for transmittance measurements.

X3.1.2.3 Uncertainties from Computation—The solar optical property is computed from the spectral curve by use of the weighted ordinate or the 50 selected ordinate method. A study of 19 typical solar materials (14) showed average deviations from the accurate weighted average method of 0.13 % for 100 point selected ordinates, 0.24 % for 50 point selected ordinates, and 0.39 % for 20 point selected ordinates with only two deviations greater than 0.6 %. There were 1.3 % deviations for a polycarbonate transmitter and an aluminized acrylic reflector when using the 20 point selected ordinate method.

X3.1.2.4 Uncertainties from Solar Spectral Irradiance—No single solar spectral irradiance is perfect for the variety of weather and geographical conditions in which solar collectors are deployed. The irradiance standard, Tables G173, adopted for computation of solar weighted optical properties, ensures a uniform procedure for reporting and comparing properties in the literature. However, the standard distribution is only a best

estimate of the average irradiance distribution in temperate zones. In actual deployment, the solar optical properties may vary slightly from the reported numbers at any particular time. Historically, the sensitivity of optical properties to various proposed solar spectral distribution has been explored (14) with the average deviations of slightly less than $\pm 1\%$ for materials over 4 different air masses ranging from AMO (extra terrestrial) to AM2 (Parry Moon) used in Test Methods E424. The deviation was highest, $\pm 1.1\%$, for spectrally selective surfaces and lowest, $\pm 0.4\%$, for reflectors which have relatively flat spectral properties.

X3.2 Summary—The total uncertainty in the reported value of solar weighted optical properties is dominated by uncertainties in the measurement of the spectral properties. The root-mean-square sum of errors due to measurement of the spectral properties and the calculation of the solar properties from the computational method give an expected uncertainty of $\pm 2\%$. The addition of the uncertainty in the spectral irradiance distribution gives a total uncertainty of ± 3 to 4% for the bias of the measured solar optical property for a particular site over a year’s average.

NOTE X3.1—This is better than the accuracy to which total system thermal performance generally can be measured.

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