Designation: E903 − 20

Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres[1]

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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.9 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

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 6101[3]

ASHRAE Standard 74-1988[4]

CIE 38 Radiometric and Photometric Characteristics of Materials and their Measurement[5]

CIE 44 Absolute Methods for Reflection Measurement[5]

NIST SP 250-48 Spectral Reflectance[6]

[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 Optical Materials for Solar Applications.

Current edition approved Oct. 1, 2020. Published October 2020. Originally approved in 1982. Last previous edition approved in 2012 as E903–12. DOI: 10.1520/E0903-20.

[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.

[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] Online, Available: https://www.nist.gov/publications/spectral-reflectance

NIST SP 250-69 Regular Spectral Transmittance[7]

3. Terminology

3.1 For definitions of terms used in this test method, refer to Terminology E772.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *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.

3.2.2 *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.

3.2.3 *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.

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

3.2.5 *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.

3.2.5.1 *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*.

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

4. Summary of Test Method

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

4.2 The solar transmittance, reflectance, or absorptance 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 absorptance, 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 absorptance, 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 propogate 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:*

[7] Online, Available: https://www.nist.gov/publications/nist-measurement-services-regular-spectral-transmittance

6.1.1 *Integrating Sphere 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 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 center-mount type (Edwards type) such that the specimen is mounted in the center of the sphere for reflectance and absorptance measurements.

6.1.1.2 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 3—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.

6.1.1.3 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 4—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.

6.1.1.4 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.

6.1.1.5 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 5—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 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.

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 6—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.

[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.

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 7—Identified suitable working standards are tablets of pressed tetrafluoroethylene polymer, $BaSO_4$, $BaSO_4$-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 8—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 9—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 10—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 11—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 12—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 13—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 14—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 over the range 300 mm to 2500 mm 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, ρ(λ), for the specimen, at wavelength λ using:

$$\rho(\lambda) = (S_\lambda - Z_\lambda)/(100_\lambda - Z_\lambda)\rho'(\lambda) \tag{1}$$

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

8.2.3 *Reflectance of Opaque Specimen in an Absolute Sphere:*

$$\rho(\lambda) = (S_\lambda - Z_\lambda)/(100_\lambda - Z_\lambda) \tag{2}$$

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 16—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 17). Record spectral curves without specimen in place. Record spectral curves with the specimen over the specimen beam entrance port of the sphere over the range 300 mm to 2500 mm. Calculate the spectral transmittance as:

$$\tau(\lambda) = (S_\lambda - Z_\lambda)/(100_\lambda - Z_\lambda) \tag{3}$$

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

8.2.6 *Absorptance*—For opaque samples record the reflectance spectrum as in 8.2.2. The solar absorptance 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:

$$\alpha_s + \tau_s + \rho_s = 1 \tag{4}$$

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 absorptance 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 τ(λ) + ρ(λ) is measured directly. Then use 8.3 and the Kirchoff relationship to determine the solar absorptance.

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 ρ(λ), α(λ), and τ(λ) respectively and form the product η(λ) = ρ(λ)α(λ)τ(λ) 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:

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

Solar transmittance τ_s or absorptance α_s, is obtained from a similar expression with ρ(λ) replaced by τ(λ) or α(λ) 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:

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

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

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:

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

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:

$$E_{ph} = hc/\lambda \tag{8}$$

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:

$$N_{ph,\lambda} = \lambda E_\lambda / hc \tag{9}$$

8.3.5.3 In the photovoltaic solar method, obtain the photovoltaic solar reflectance ρ_{pv} (λ_g) as follows:

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

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 No material specific information is presented about either the precision or bias of this test method. The reproducibility and repeatability of this test method are not provided at this time because an ASTM Interlaboratory Study (ILS) has never been run. While there have been several attempts to run an ILS since 1982 (the year this standard was originally approved), due to a repeated lack of laboratories willing to participate in a measurement-based ILS one has never been conducted

10.2 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

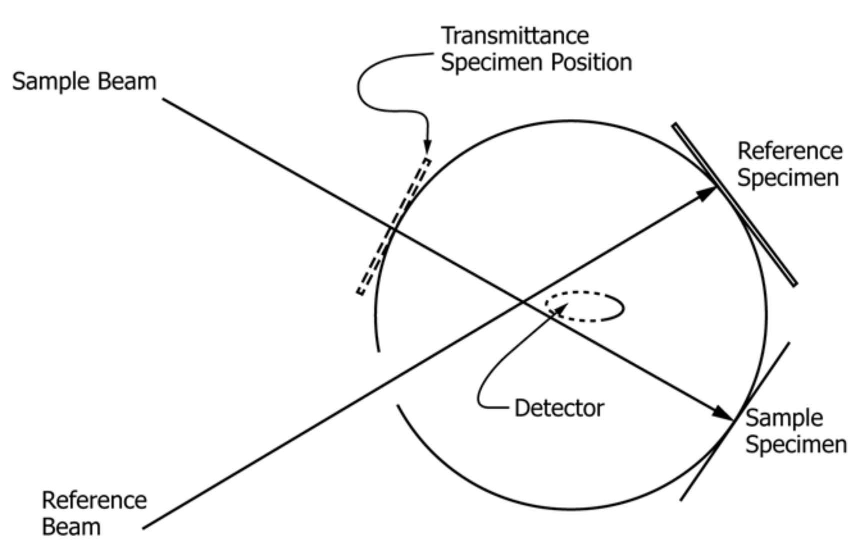

FIG. X1.1 Four-port, Comparison-type Integrating Sphere (Most Common)