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Standard Table for
Reference Solar Spectral Distributions: Direct and Diffuse on 20° Tilted and Vertical Surfaces[1]

This standard is issued under the fixed designation G197; 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.

INTRODUCTION

This table of solar spectral irradiance distributions has been developed to meet the need for weighting functions to be used in evaluating the broadband transmittance of fenestration systems or the performance of technologies such as building-integrated photovoltaic devices. To compare the relative optical performance of spectrally sensitive products by theoretical simulation, or to compare the performance of products by actual testing under laboratory conditions, separate reference standard solar spectral distributions for direct and diffuse irradiance are required. This table was prepared using version 2.9.2 of the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) atmospheric transmission code (**1, 2**).[2] SMARTS uses parameterizations of version 4.0 of the Air Force Geophysical Laboratory (AFGL) Moderate Resolution Transmission model, MODTRAN (**3, 4**). An extraterrestrial spectrum differing only slightly from the extraterrestrial spectrum in ASTM E490 is used to calculate the resultant spectra. The directional beam and diffuse hemispherical (2π steradian acceptance angle) spectral irradiances on planes tilted 20° (representative of a pitched roof slope) and 90° (tilt of a typical wall) to the horizontal are tabulated. The wavelength range for the spectra extends from 280 nm to 4000 nm, covering the spectral range for which windows or solar collectors respond to shortwave energy. The input parameters used in conjunction with SMARTS for each set of conditions are tabulated. The SMARTS model and documentation are available as an adjunct to this standard.

1. Scope

1.1 This table provides terrestrial solar spectral irradiance distributions that may be employed as weighting functions to *(1)* calculate the broadband solar or light transmittance of fenestration from its spectral properties; or *(2)* evaluate the performance of building-integrated technologies such as photovoltaic electricity generators. Most of these systems are installed on vertical walls, but some are also installed on pitched roofs or on other tilted structures, such as sunspaces. Glazing transmittance calculations or measurements require information on both the direct and diffuse components of irradiance. The table provides separate information for direct and diffuse irradiance, and for two different tilt angles, 20° and 90° relative to the horizontal. All distributions are provided at 2002 wavelengths within the spectral range 280–4000 nm. The data contained in this table reflect reference spectra with uniform wavelength interval (0.5 nanometer (nm) below 400 nm, 1 nm between 400 and 1700 nm, an intermediate wavelength at 1702 nm, and 5 nm intervals from 1705 to 4000 nm). The data table represents reasonable cloudless atmospheric conditions favorable for the computerized simulation, comparative rating, or experimental testing of fenestration systems.

1.2 The data contained in this table were generated using the SMARTS version 2.9.2 atmospheric transmission model developed by Gueymard (**1, 2**).

1.3 The selection of the SMARTS radiative model to generate the spectral distributions is chosen for compatibility with previous standards (ASTM G173 and G177). The atmospheric and climatic conditions are identical to those in ASTM G173. The environmental conditions are also identical, with only one exception (see sections 4.3 and X1.2).

1.4 The table defines four solar spectral irradiance distributions:

1.4.1 Separate direct and diffuse solar spectral irradiance incident on a sun-facing, 20° tilted surface in the wavelength region from 280–4000 nm for air mass 1.5, at sea level.

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[1] These tables are under the jurisdiction of ASTM Committee G03 on Weathering and Durability and is the direct responsibility of Subcommittee G03.09 on Radiometry.

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

1.4.2 Separate direct and diffuse solar spectral irradiance incident on a sun-facing, 90° (vertical) tilted surface in the wavelength region from 280–4000 nm for air mass 1.5, at sea level.

1.5 The diffuse spectral distribution on a vertical surface facing away from the sun (i.e., shaded), or at any prescribed azimuth away from the sun, may be computed using the model to obtain representative results (i.e., results that fall within an acceptable range of variance).

1.6 The climatic, atmospheric, and geometric parameters selected reflect the conditions to provide a realistic set of spectral distributions appropriate for building applications under very clear-sky conditions, representative of near-maximum solar heat gains in buildings.

1.7 A wide variety of orientations or local environmental conditions is possible for exposed surfaces. The availability of the SMARTS model (as an adjunct to this standard) used to generate the standard spectra allows users to evaluate spectral differences relative to the spectra specified here.

2. Referenced Documents

2.1 *ASTM Standards:*[3]

E490 Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables

E772 Terminology of Solar Energy Conversion

G173 Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

G177 Tables for Reference Solar Ultraviolet Spectral Distributions: Hemispherical on 37° Tilted Surface

2.2 *ASTM Adjuncts:*

ADJG173CD—SMARTS, Simple Model of the Atmospheric Radiative Transfer of Sunshine, Terrestrial Solar Spectral Modeling Code[4]

3. Terminology

3.1 *Definitions*—Definitions of terms used in this specification not otherwise described below may be found in Terminology E772.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *aerosol optical depth (AOD)*—the wavelength-dependent total extinction (scattering and absorption) by aerosols in the atmosphere. This optical depth (also called "optical thickness") is defined here at 500 nm.

3.2.2 *air mass zero (AM0)*—describes solar radiation quantities outside the Earth's atmosphere at the mean Earth-Sun distance (1 Astronomical Unit). See ASTM E490.

3.2.3 *albedo*—also called reflectance, a measure of the reflective characteristics of a surface relative to incident irradiance.

3.2.3.1 *Discussion*—For this standard, the albedo refers to the spectral reflectance of the ground relative to hemispherical irradiance. Two different albedos are considered by the model, and both only affect diffuse irradiance. The first albedo corresponds to the average surface reflectance of the far-field area around the site, within a radius of 5–50 km. The second albedo is that of the foreground (or near-field) immediately adjacent to the tilted surface, to a distance of 10–100 m. The two albedos can be identical or different, but the foreground albedo's effect significantly increases with tilt angle, whereas the far-field albedo's effect on diffuse irradiance decreases with tilt angle.

3.2.4 *integrated irradiance* $E_{\lambda 1\text{-}\lambda 2}$—spectral irradiance integrated over a specific wavelength interval from λ_1 to λ_2, measured in $W{\cdot}m^{-2}$; mathematically:

$$E_{\lambda 1-\lambda 2} = \int_{\lambda 1}^{\lambda 2} E_\lambda \, d\lambda \quad (1)$$

3.2.5 *shading*—condition that results in partial obscuration of the sky, including the sun or not.

3.2.5.1 *Discussion*—For this standard, no shading of the sky is considered. However, the standard also applies to cases when the 20° or 90° tilted surfaces are shaded from the sun only, due to their relative geometry or other circumstances. This cancels the direct irradiance component, so that the total hemispherical irradiance reduces to the diffuse component.

3.2.6 *solar irradiance, spectral* E_λ—solar irradiance E per unit wavelength interval at a given wavelength λ (unit: Watts per square meter per nanometer, $W{\cdot}m^{-2}{\cdot}nm^{-1}$)

$$E_\lambda = \frac{dE}{d\lambda} \quad (2)$$

3.2.7 *spectral interval*—the distance in wavelength units between adjacent spectral irradiance data points.

3.2.8 *spectral passband*—the effective wavelength interval within which spectral irradiance is allowed to pass, as through a filter or monochromator. The convolution integral of the *spectral passband* (normalized to unity at maximum) and the incident spectral irradiance produces the effective transmitted irradiance.

3.2.8.1 *Discussion*—Spectral passband may also be referred to as the *spectral bandwidth* of a filter or device. Passbands are usually specified as the interval between wavelengths at which one half of the maximum transmission of the filter or device occurs, or as *full-width at half-maximum*, FWHM.

3.2.9 *spectral resolution*—the minimum wavelength difference between two wavelengths that can be identified unambiguously.

3.2.9.1 *Discussion*—In the context of this standard, the spectral resolution is simply the interval, Δλ, between spectral data points, or the *spectral interval*.

3.2.10 *spectral solar irradiance, diffuse* $E_{d\lambda}$—on a given plane, the solar radiant flux at wavelength λ received from within the 2π steradian field of view of a tilted plane from the portion of the sky dome and the foreground included in the plane's field of view, excluding direct solar radiation.

[3] 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.

[4] Available on CD-ROM from ASTM International Headquarters. Order Adjunct No. ADJG173CD.

3.2.11 *spectral solar irradiance, direct* $E_{D\lambda}$—on a given plane, the solar radiant flux at wavelength λ received directly from the sun, excluding diffuse solar radiation.

3.2.11.1 *Discussion*—In practice, instruments measuring direct solar irradiance have a larger acceptance angle than the apparent diameter of the sun. Consequently, it is virtually impossible to measure $E_{D\lambda}$ without the contribution of diffuse radiation emanating from the sun's aureole. This contribution is referred to as "circumsolar radiation." Contrarily to ASTM G173, the data in Table 3 use the ideal definition of direct irradiance, and therefore ignore the circumsolar contribution. The sum of direct and diffuse irradiance is the hemispherical solar irradiance, $E_{H\lambda}$.

3.2.12 *total ozone*—the depth of a column of pure ozone equivalent to the total of the ozone in a vertical column from the ground to the top of the atmosphere. (unit: atmosphere-cm)

3.2.13 *total precipitable water*—the depth of a column of water (with a section of 1 cm^2) equivalent to the condensed water vapor in a vertical column from the ground to the top of the atmosphere. (unit: cm or g/cm^2)

3.2.14 *wavenumber*—a unit of frequency, í, in units of reciprocal centimeters (symbol cm^{-1}) commonly used in place of wavelength, λ (units of length, typically nanometers). To convert wavenumbers to nanometers, λ nm = $1 \cdot 10^7$/í cm^{-1}.

4. Technical Bases for the Tables

4.1 These tables are modeled data generated using an air mass zero (AM0) spectrum based on the extraterrestrial spectrum of Gueymard (**1, 2**) derived from Kurucz (**5**), the United States Standard Atmosphere of 1976 (USSA) reference Atmosphere (**6**), the Shettle and Fenn rural aerosol profile (**7**), and the SMARTS version 2.9.2 radiative transfer code. Further details are provided in ASTM G173.

4.2 The 20° tilted surface closely represents the geometry of pitched roofs or tilted glazed structures, which are common elements of buildings. The 90° (vertical) surface represents the norm for building walls.

4.3 The tabulated diffuse irradiance is a combination of scattered irradiance from the sky and reflected irradiance from far-field and near-field ground surfaces. Dry soil conditions have been chosen for both surfaces. This is a darker, less reflective surface than what was used in ASTM G173 or G177.

4.4 The documented USSA atmospheric profiles utilized in the MODTRAN spectral transmission model (**6**) have been used to provide atmospheric properties and concentrations of absorbers.

4.5 To provide spectral data with a uniform spectral step size, the AM0 spectrum used in conjunction with SMARTS to generate the terrestrial spectrum is slightly different from the ASTM extraterrestrial spectrum, ASTM E490. Because ASTM E490 and SMARTS both use the data of Kurucz (**5**), the SMARTS and E490 spectra are in excellent agreement although they do not have the same spectral resolution.

4.6 The current spectra reflect improved knowledge of atmospheric aerosol optical properties, transmission properties, and radiative transfer modeling (**8**).

4.7 The terrestrial solar spectral in the tables have been computed with a spectral bandwidth equivalent to the spectral resolution of the tables, namely 0.5 nm to 5 nm (see 1.1).

4.8 The SMARTS model code and documentation is available as an adjunct standard. Request ASTM Stock number ADJG173CD.

5. Significance and Use

5.1 This standard does not purport to address the mean spectral irradiance incident on tilted or vertical fenestration or building-integrated systems over a day, a season, or a year. The spectral irradiance distributions have been chosen to represent a reasonable near-upper limit for solar radiation when these systems are exposed to clear-sky conditions similar to those used to calculate solar heat loads of buildings. The diffuse spectral irradiance distributions can also be used to represent conditions when these systems are shaded from the direct sun.

5.2 Absorptance, reflectance, and transmittance of solar radiation are important factors in studies of light transmission through semi-transparent plates. These properties are normally functions of wavelength, which require that the spectral distribution of the solar flux be known before the solar-weighted property can be calculated.

5.3 To compare the relative performance of competitive products by computerized simulations, or to compare the performance of products subjected to experimental tests in laboratory conditions, a reference standard solar spectral distribution for both direct and diffuse irradiance is desirable.

5.4 The table provides appropriate standard spectral irradiance distributions for determining the relative optical performance of semi-transparent materials and other systems. The table may be used to evaluate components and materials for the purpose of solar simulation where the direct and the diffuse spectral solar irradiances are needed separately.

5.5 The selected air mass value of 1.5 for a plane-parallel atmosphere above a flat earth corresponds to a zenith angle of 48.19°. The SMARTS2 computation of air mass accounts for atmospheric curvature and the vertical density profile of molecules, which results in a solar zenith angle of 48.236°, or an equivalent plane-parallel-atmosphere air mass of 1.50136. The angle of incidence computed by SMARTS for the direct beam irradiance incident on a 20°-tilted plane facing the sun is thus 28.236°. It is 41.764° for a 90°-tilted surface facing the sun.

5.6 A plot of the SMARTS model output for the reference direct radiation on a 20° and 90° tilted surfaces is shown in Fig. 1. A similar plot, but for diffuse radiation, is shown in Fig. 2.

5.7 The input needed by SMARTS to generate the spectra for the prescribed conditions and the 20°-tilted surface is provided in Table 1. The input file for the 90°-tilted surface differs only by one line. This modified line appears in Table 2.

5.8 The total irradiance, integrated over the spectral range 280–4000 nm, is 791.07, 93.02, 97.96, and 889.03 W·m^{-2} for direct, sky diffuse, total diffuse and global radiation incident on the 20° tilted surface, respectively. It is 669.74, 58.66, 140.56,