Designation: G 173 – 03^{ε1}

Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface[1]

This standard is issued under the fixed designation G 173; 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.

ε[1] NOTE—The reference to ADJG0173CD was added editorially in March 2006.

INTRODUCTION

A wide variety of solar spectral energy distributions occur in the natural environment and are simulated by artificial sources during product, material, or component testing. To compare the relative optical performance of spectrally sensitive products a reference standard solar spectral distribution is required. These tables replace ASTM standard G 159, which has been withdrawn. The solar spectral energy distribution presented in this standard are not intended as a benchmark for ultraviolet radiation in weathering exposure testing of materials. The spectra are based on version 2.9.2 of the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS) atmospheric transmission code (**1**,**2**).[2] SMARTS uses empirical parameterizations of version 4.0 of the Air Force Geophysical Laboratory (AFGL) Moderate Resolution Transmission model, MODTRAN (**3**,**4**) for some gaseous absorption processes, and recent spectroscopic data for others. An extraterrestrial spectrum differing only slightly from the extraterrestrial spectrum in ASTM E 490 is used to calculate the resultant spectra (**5**). The hemispherical tilted spectrum is similar to the hemispherical spectrum in use since 1987, but differs from it because: (*1*) the wavelength range for the current spectrum has been extended deeper into the ultraviolet; (*2*) uniform wavelength intervals are now used; (*3*) more representative atmospheric conditions are represented,; and (*4*) SMARTS Version 2.9.2 has been used as the generating model. For the same reasons, and particularly the adoption of a remarkably less turbid atmosphere than before, significant differences exist in the reference direct normal spectrum compared to previous versions of this standard. The input parameters used in conjunction with SMARTS for the selected atmospheric conditions are tabulated. The SMARTS model and documentation are available as an adjunct (ADJG0173[3]) to this standard.

1. Scope

1.1 These tables contain terrestrial solar spectral irradiance distributions for use in terrestrial applications that require a standard reference spectral irradiance for hemispherical solar irradiance (consisting of both direct and diffuse components) incident on a sun-facing, 37° tilted surface or the direct normal spectral irradiance. The data contained in these tables 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 tables represent reasonable cloudless atmospheric conditions favorable for photovoltaic (PV) energy production, as well as weathering and durability exposure applications.

1.2 The 37° slope of the sun-facing tilted surface was chosen to represent the average latitude of the 48 contiguous United States. A wide variety of orientations is possible for exposed surfaces. The availability of the SMARTS model (as an adjunct, ADJG0173CD[3]) to this standard) used to generate the standard spectra allows users to evaluate differences relative to the surface specified here.

1.3 The air mass and atmospheric extinction parameters are chosen to provide (*1*) historical continuity with respect to previous standard spectra, (*2*) reasonable cloudless atmospheric conditions favorable for photovoltaic (PV) energy production or weathering and durability exposure, based upon modern broadband solar radiation data, atmospheric profiles, and improved knowledge of aerosol optical depth profiles. In

[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.

[3] Available from ASTM International Headquarters. Order Adjunct No. ADJ**G0173CD**.

nature, an extremely large range of atmospheric conditions can be encountered even under cloudless skies. Considerable departure from the reference spectra may be observed depending on time of day, geographical location, and changing atmospheric conditions. The availability of the SMARTS model (as an adjunct (ADJG0173CD[3])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:* [4]

E 490 Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables

E 772 Terminology Relating to Solar Energy Conversion

G 113 Terminology Relating to Natural and Artificial Weathering Tests of Nonmetallic Materials

2.2 *ASTM Adjunct:*[3]

ADJG0173CD Simple Model for Atmospheric Transmission of Sunshine

3. Terminology

3.1 *Definitions*—Definitions of most terms used in this specification may be found in Terminology E 772.

3.2 The following definition differs from that in Terminology E 772, representing information current as of this revision.

3.2.1 *solar constant*—the total solar irradiance at normal incidence on a surface in free space at the earth's mean distance from the sun. (1 astronomical unit, or AU = 1.496×10^{11} m).

3.2.1.1 *Discussion*—The solar constant is now known within about ± 1.5 W·m^{-2}. Its current accepted values are 1366.1 W·m^{-2} (ASTM E 490) or 1367.0 W·m^{-2} (World Meteorological Organization, WMO), and are subject to change. Due to the eccentricity of the earth's orbit, the actual extraterrestrial solar irradiance varies by ± 3.4 % about the solar constant as the earth-sun distance varies through the year. Throughout this standard the solar constant is defined as 1367.0 W·m^{-2}.

3.3 *Definitions of Terms Specific to This Standard:*

3.3.1 *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.

3.3.1.1 *Discussion*—See Appendix X1.

3.3.2 *air mass zero (AM0)*—describes solar radiation quantities outside the Earth's atmosphere at the mean Earth-Sun distance (1 Astronomical Unit). See ASTM E 490.

3.3.3 *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·m^{-2}; mathematically:

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

3.3.4 *solar irradiance, hemispherical* E_H—on a given plane, the solar radiant flux 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, including both diffuse and direct solar radiation.

3.3.4.1 *Discussion*—For the special condition of a horizontal plane the hemispherical solar irradiance is properly termed global solar irradiance, E_G. Incorrectly, global tilted, or total global irradiance is often used to indicate hemispherical irradiance for a tilted plane. In case of a sun-tracking receiver, this hemispherical irradiance is commonly called global normal irradiance. The adjective global should refer only to hemispherical solar radiation on a horizontal, not a tilted, surface.

3.3.5 *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·m^{-2}·nm^{-1}):

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

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

3.3.7 *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.

3.3.7.1 *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.

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

3.3.8.1 *Discussion*—In the context of this standard, the spectral resolution is simply the interval, $\Delta\lambda$, between spectral data points, or the *spectral interval*.

3.3.9 *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 or atm-cm).

3.3.10 *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).

3.3.11 *wavenumber*—a unit of frequency, ν, in units of reciprocal centimeters (symbol cm^{-1}) commonly used in place of wavelength, λ (units of length, typically nanometers). To convert wavenumber to nanometers, λ nm = $1 \cdot 10^7 / \nu$ cm^{-1}. See X1.2.

4. Significance and Use

4.1 Absorptance, reflectance, and transmittance of solar energy are important factors in material degradation studies, solar thermal system performance, solar photovoltaic system performance, biological studies, and solar simulation activities. These optical properties are normally functions of wavelength, which require the spectral distribution of the solar flux be known before the solar-weighted property can be calculated.

[4] 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.

To compare the relative performance of competitive products, or to compare the performance of products before and after being subjected to weathering or other exposure conditions, a reference standard solar spectral distribution is desirable.

4.2 These tables provide appropriate standard spectral irradiance distributions for determining the relative optical performance of materials, solar thermal, solar photovoltaic, and other systems. The tables may be used to evaluate components and materials for the purpose of solar simulation where either the direct or the hemispherical (that is, direct beam plus diffuse sky) spectral solar irradiance is desired. However, these tables are not intended to be used as a benchmark for ultraviolet radiation used in indoor exposure testing of materials using manufactured light sources.

4.3 The total integrated irradiances for the direct and hemispherical tilted spectra are 900.1 $W \cdot m^{-2}$ and 1000.4 $W \cdot m^{-2}$, respectively. Note that, in PV applications, no amplitude adjustments are required to match standard reporting condition irradiances of 1000 $W \cdot m^{-2}$ for hemispherical irradiance.

4.4 Previously defined global hemispherical reference spectrum (G 159) for a sun-facing 37°-tilted surface served well to meet the needs of the flat plate photovoltaic research, development, and industrial community. Investigation of prevailing conditions and measured spectra shows that this global hemispherical reference spectrum can be attained in practice under a variety of conditions, and that these conditions can be interpreted as representative for many combinations of atmospheric parameters. Earlier global hemispherical reference spectrum may be closely, but not exactly, reproduced with improved spectral wavelength range, uniform spectral interval, and spectral resolution equivalent to the spectral interval, using inputs in X1.4.

4.5 Reference spectra generated by the SMARTS Version 2.9.2 model for the indicated conditions are shown in Fig. 1. The exact input file structure required to generate the reference spectra is shown in Table 1.

4.6 The availability of the adjunct (ADJG0173CD[3]) standard computer software for SMARTS allows one to (*1*) reproduce the reference spectra, using the above input parameters; (*2*) compute test spectra to attempt to match measured data at a specified FWHM, and evaluate atmospheric conditions; and (*3*) compute test spectra representing specific conditions for analysis vis-à-vis any one or all of the reference spectra.

4.7 Differences from the previous standard spectra (G 159) can be summarized as follows:

4.7.1 Extended spectral interval in the ultraviolet (down to 280 nm, rather than 305 nm),

4.7.2 Better resolution (2002 wavelengths, as compared to 120),

4.7.3 Constant intervals (0.5 nm below 400 nm, 1 nm between 400 and 1700 nm, and 5 nm above),

4.7.4 Better definition of atmospheric scattering and gaseous absorption, with more species considered,

4.7.5 Better defined extraterrestrial spectrum,

4.7.6 More realistic spectral ground reflectance, and

4.7.7 Lower aerosol optical depth, yielding significantly larger direct normal irradiance.

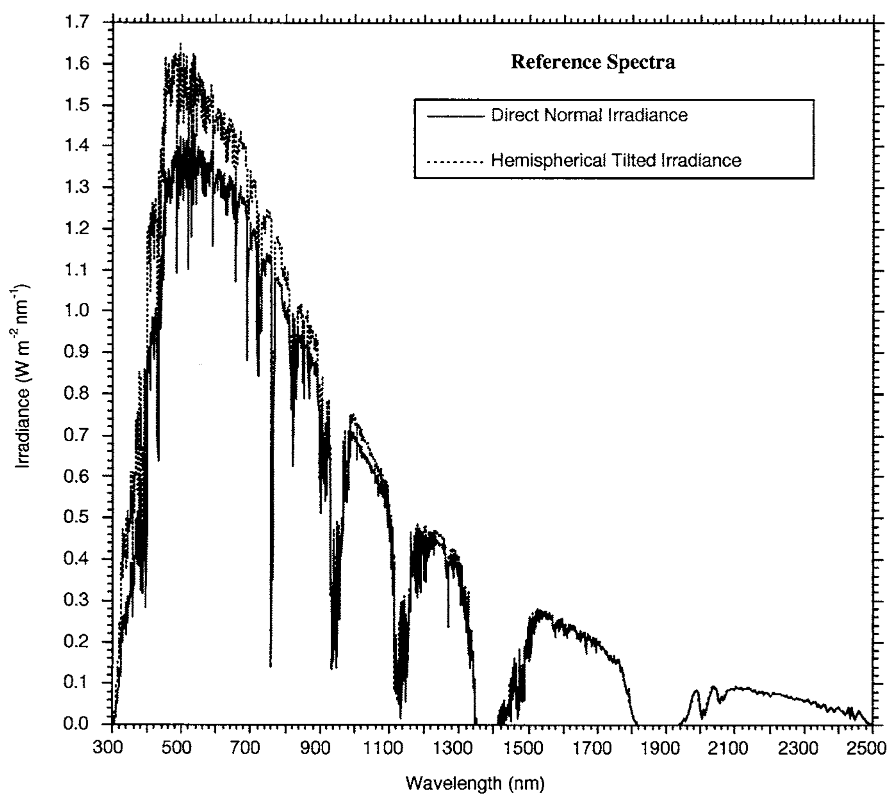

FIG. 1 Plot of Direct Normal Spectral Irradiance (Solid Line) and Hemispherical Spectral Irradiance on 37° Tilted Sun-Facing Surface (Dotted Line) Computed Using Smarts Version 2.9.2 Model With Input File in Table 1