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Standard Tables for Reference Solar Ultraviolet Spectral Distributions: Hemispherical on 37° Tilted Surface[1]

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ε^1 NOTE—The title to Table 2 was corrected editorially in August 2008.

INTRODUCTION

These tables of solar ultraviolet (UV) spectral irradiance values have been developed to meet the need for a standard ultraviolet reference spectral energy distribution to be used as a reference for the upper limit of ultraviolet radiation in the outdoor weathering of materials and related indoor exposure studies. 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, 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 required. These tables were prepared using version 2.9.2 of the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS2) atmospheric transmission code (**1**,**2**).[2] SMARTS2 uses empirical 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 hemispherical (2π steradian acceptance angle) spectral irradiance on a panel tilted 37° (average latitude of the contiguous United States) to the horizontal is tabulated. The wavelength range for the spectra extends from 280 to 400 nm, with uniform wavelength intervals. The input parameters used in conjunction with SMARTS2 for each set of conditions are tabulated. The SMARTS2 model and documentation are available as an adjunct ADJG173CD[3]) to this standard.

1. Scope

1.1 The table provides a standard ultraviolet spectral irradiance distribution that maybe employed as a guide against which manufactured ultraviolet light sources may be judged when applied to indoor exposure testing. The table provides a reference for comparison with natural sunlight ultraviolet spectral data. The ultraviolet reference spectral irradiance is provided for the wavelength range from 280 to 400 nm. The wavelength region selected is comprised of the UV-A spectral region from 320 to 400 nm and the UV-B region from 280 to 320 nm.

1.2 The table defines a single ultraviolet solar spectral irradiance distribution:

1.2.1 Total hemispherical ultraviolet solar spectral irradiance (consisting of combined direct and diffuse components) incident on a sun-facing, 37° tilted surface in the wavelength region from 280 to 400 nm for air mass 1.05, at an elevation of 2 km (2000 m) above sea level for the United States Standard Atmosphere profile for 1976 (USSA 1976), excepting for the ozone content which is specified as 0.30 atmosphere-centimeters (atm-cm) equivalent thickness.

1.3 The data contained in these tables were generated using the SMARTS2 Version 2.9.2 atmospheric transmission model developed by Gueymard (**1**,**2**).

1.4 The climatic, atmospheric and geometric parameters selected reflect the conditions to provide a realistic maximum ultraviolet exposure under representative clear sky conditions.

1.5 The availability of the SMARTS2 model (as an adjunct (ADJG173CD[3]) to this standard) used to generate the standard spectra allows users to evaluate spectral differences relative to the spectra specified here.

[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. ADJG173CD. Original adjunct produced in 2005.

2. Referenced Documents

2.1 *ASTM Standards:*[4]

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

E772 Terminology of Solar Energy Conversion

2.2 *ASTM Adjuncts:*

ADJG173CD Simple Model for Atmospheric Transmission of Sunshine[3]

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 *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.

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

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

3.2.3 *solar irradiance, hemispherical* E_H—on a given plane, the solar radiant flux received from the within the 2-π 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.

3.2.3.1 *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.

3.2.4 *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.

3.2.4.1 *Discussion*—See X1.1.

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

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

3.2.6 *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.

3.2.6.1 *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.

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

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

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

3.2.9 *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)

3.2.10 *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)

3.2.11 *wavenumber*—a unit of frequency, υ, in units of reciprocal centimeters (symbol cm^{-1}) commonly used in place of wavelength, λ. The relationship between wavelength and frequency is defined by $\lambda \upsilon = c$, where c is the speed of light in vacuum. To convert wavenumber to nanometers, $\lambda \cdot nm = 1 \cdot 10^7 / \upsilon \cdot cm^{-1}$.

4. Technical Basis for the Tables

4.1 These tables are modeled data generated using an air mass zero (AM0) spectrum based on the extraterrestrial spectrum of 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**), the SMARTS2 V. 2.9.2 radiative transfer code. Further details are provided in X1.3.

4.2 The 37° tilted surface was selected as it represents the average latitude of the contiguous forty-eight states of the continental U.S., and outdoor exposure testing often takes place at latitude tilt.

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

4.4 The SMARTS model Version 2.9.2 is available at Internet URL: http://rredc.nrel.gov/solar/models/SMARTS.

4.5 To provide spectral data with a uniform spectral step size, the AM0 spectrum used in conjunction with SMARTS2 to generate the terrestrial spectrum is slightly different from the ASTM extraterrestrial spectrum, ASTM E490. Because ASTM E490 and SMARTS2 both use the data of Kurucz (**5**), the SMARTS2 and E490 spectra are in excellent agreement although they do not have the same spectral resolution.

[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.

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.

5. Significance and Use

5.1 This standard does not purport to address the mean level of solar ultraviolet spectral irradiance to which materials will be subjected during their useful life. The spectral irradiance distributions have been chosen to represent a reasonable upper limit for natural solar ultraviolet radiation that ought to be considered when evaluating the behavior of materials under various exposure conditions.

5.2 Absorptance, reflectance, and transmittance of solar energy are important factors in material degradation studies. 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 The interpretation of the behavior of materials exposed to either natural solar radiation or ultraviolet radiation from artificial light sources requires an understanding of the spectral energy distribution employed. 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.

5.4 A plot of the SMARTS2 model output for the reference hemispherical UV radiation on a 37° south facing tilted surface is shown in Fig. 1. The input needed by SMARTS2 to generate the spectrum for the prescribed conditions are shown in Table 1.

5.5 SMARTS2 Version 2.9.2 is required to generate AM 1.05 UV reference spectra.

5.6 The availability of the adjunct standard computer software (ADJG173CD[5]) for SMARTS2 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.

6. Solar Spectral Irradiance

6.1 Table 2 presents the reference spectral irradiance data global hemispherical solar irradiance on a plane tilted at 37° toward the equator, for the conditions specified in Table 1.

6.2 The table contains:

6.2.1 Hemispherical solar spectral irradiance incident on an equator-facing[5] plane tilted to 37° from the horizontal in the wavelength range from 280 to 400 nm.

6.2.2 The columns in each table contain:

6.2.2.1 Column 1: Wavelength in nanometers (nm).

6.2.2.2 Column 2: Mean hemispherical spectral irradiance incident on surface tilted 37° toward the equator. E_λ, $W \cdot m^{-2} \cdot nm^{-1}$.

7. Validation

7.1 In part of the spectral region of interest, (295 to 400 nm) the SMARTS2 model has been verified against experimental data. SMARTS2 performance is adequate for the region from 295 to 400 nm. No reliable experimental data has been found to verify performance below 295 nm.

7.2 Comparisons of the SMARTS2 computer model with both MODTRAN model results and measured spectral data and other rigorous spectral models are reported in (**1,2**). Fig. 2 is a plot of the relative magnitude of the spectral differences observed between MODTRAN version 4.0 and SMARTS2 for identical conditions. Results indicate that the various models are within ~5 % in spectral regions where significant energy is present.

7.3 Comparison of these reference spectra with clear sky solar spectral irradiance data from various spectrometers under various atmospheric conditions approximating those chosen for this data are in reasonable agreement (**8**).

8. Keywords

8.1 global hemispherical; materials exposure; terrestrial; ultraviolet solar spectral irradiance

[5] South facing for the northern hemisphere, north facing for the southern hemisphere.