Designation: E 892 – 87 (Reapproved 1992)

Standard Tables for Terrestrial Solar Spectral Irradiance at Air Mass 1.5 for a 37° Tilted Surface[1]

This standard is issued under the fixed designation E 892; 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

These tables utilize the recently revised **(1)**[2] extraterrestrial spectrum of Neckel and Labs **(2)** and replace the previous standard based on Standard E 490. In addition, refinements were made to absorption and scattering calculations in the computer code **(3, 4)** used to calculate the spectrum. These refinements consist of a change in the depolarization factor in the Rayleigh scattering calculation, a more accurate sampling technique for calculating scattered irradiance, and a better choice of wavelengths to perform the calculations. Comparisons with the previous standard based on Standard E 490 have shown that approximately a 5 % difference can exist in narrow band widths of the spectrum, but for the integrated total little difference is apparent.

1. Scope

1.1 These tables define an air mass 1.5 solar spectral irradiance distribution for use in all solar applications where a standard terrestrial spectral irradiance is required for that part of solar irradiance, diffuse, and direct, that is incident on a sun-facing, 37°-tilted surface. A similar standard for direct normal irradiance is given in Standard E 891.

1.2 These tables are modeled data that were generated using a zero air mass solar spectrum based on the revised extraterrestrial spectrum of Neckel and Labs **(1)**, the BRITE **(3, 4)** Monte Carlo radiative transfer code, and the 1962 U.S. Standard Atmosphere **(5)** with a rural aerosol **(6, 7, 8)**. Further details are presented in Appendix X1.

1.3 The air mass zero (AM0) spectrum that was used to generate the terrestrial spectrum was provided by C. Fröhlich and C. Wehrli **(1)** and is a revised and extended Neckel and Labs **(2)** spectrum. Neckel and Labs revised their spectrum by employing newer limb-darkening data to convert from radiance to irradiance, as reported by Fröhlich **(9)**, citing the study by Hardrop **(10)**. Comparisons by Fröhlich with calibrated sunphotometer data from Mauna Loa, Hawaii, indicate that this new extraterrestrial spectrum is the best currently available.

1.4 The development of the terrestrial solar spectrum data is based on work reported by Bird, Hulstrom, and Lewis **(11)**. In computing the terrestrial values using the BRITE Monte Carlo radiation transfer code, the authors cited took the iterations to 2.4500 µm only. We have extended the spectrum to 4.045 µm using sixteen $E\lambda_i$ values from the original Standard E 892 – 82. Irradiance values in Standard E 892 – 82 were computed from the extraterrestrial spectrum represented by Standard E 490. The additional data points were added to account for the solar irradiance in this region that account for approximately 1.5 % of the total irradiance between 0.305 and 4.045 µm. The errors propagated by doing so are insignificant.

1.5 An air mass of 1.5, a turbidity of 0.27, and a tilt of 37° were chosen for this standard because they are representative of average conditions in the 48 contiguous states of the United States.

2. Referenced Documents

2.1 *ASTM Standards:*

E 490 Standard Solar Constant and Air Mass Zero Solar Spectral Irradiance Tables[3]

E 772 Terminology Relating to Solar Energy Conversion[4]

E 891 Standard Tables for Terrestrial Direct Normal Solar Spectral Irradiance for Air Mass 1.5[4]

3. Terminology

3.1 *Definitions (from Terminology E 772):*

3.1.1 *air mass* (AM)—ratio of the mass of atmosphere in the actual observer-sun path to the mass that would exist if the observer were at sea level, at standard barometric pressure, and the sun were directly overhead.

NOTE—(Sometimes called air mass ratio.) Air mass varies with the zenith angle of the sun and the local barometric pressure, that changes with altitude. For sun zenith angle, Z, of 62° or less, and local atmospheric pressure, P, where P_o is standard atmospheric pressure, AM $\simeq \sec Z (P/P_o)$.

3.1.2 *solar irradiance, diffuse, E_s (d)*—downward scattered solar flux as received on a horizontal surface from a solid angle of 2π-steradian (hemisphere) with the exception of a conical solid angle with a 100 mrad (approximately 6°) included plane angle centered upon the sun's disk.

[1] This standard is under the jurisdiction of ASTM Committee E-44 on Solar, Geothermal, and other Alternative Energy Sources and is the direct responsibility of Subcommittee E44.02 on Environmental Parameters.

Current edition approved July 31, 1987. Published December 1987. Originally published as E 892 – 82. Last previous edition E 892 – 82.

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

[3] *Annual Book of ASTM Standards*, Vol 15.03.

[4] *Annual Book of ASTM Standards*, Vol 12.02.

3.1.3 *solar irradiance, direct, E_s*—solar flux coming from the solid angle of the sun's disk on a surface perpendicular to the axis of that solid angle.

3.1.3.1 *Discussion*—In conventional instruments the acceptance cone includes a plane angle of about 6°.

3.2 *Descriptions of Terms Specific to This Standard:*

3.2.1 *air mass zero* (AM0)—describing solar radiation quantities outside the Earth's atmosphere at the mean earth-sun distance.

3.2.2 *meteorological range*—distance V at which the threshold contrast, ϵ, between a black and white target is 0.02.

$$V = \frac{1}{\sigma} \ln \frac{1}{\epsilon}$$

Therefore, V is a function only of the atmospheric extinction coefficient σ.

3.2.3 *solar irradiance, spectral ($E\lambda$)*—solar irradiance per unit wavelength interval per unit wavelength λ. (Units $W \cdot m^{-2} \cdot \mu m^{-1}$.)

$$E\lambda = dE/d\lambda$$

4. Significance and Use

4.1 Absorptance, reflectance, and transmittance of terrestrial solar energy are important factors in solar thermal system performance, photovoltaic system performance, materials studies, biomass studies, and solar simulation activities. For each of the optical properties, the initial measurements are normally a function of wavelength, which requires that the spectral distribution of the solar flux be known before the solar weighted property can be calculated. In order to compare the performance of competitive products, a single standard solar spectral irradiance distribution is desired.

4.2 These tables provide an appropriate standard spectral irradiance distribution to be used in determining relative performance of solar thermal, photovoltaic, and other systems, components and materials where the direct plus diffuse irradiance components are desired.

5. Solar Spectral Irradiance (Air Mass 1.5)

5.1 Table 1 presents in tabular form that part of the solar spectral irradiance, diffuse and direct, from 0.305 to 4.045 μm that is incident on a surface tilted 37° from the horizontal toward the sun. The sun is at AM 1.5. The first column gives the wavelength (λ) in micrometres; the second gives the $\Delta\lambda$ integrating interval in micrometres; the third gives the direct irradiance in $W \cdot m^{-2} \cdot \mu m^{-1}$; the fourth gives the integrated solar irradiance in the wavelength range from 0.3 μm to λ_i in $W \cdot m^{-2}$; and the fifth gives the fraction of the direct normal solar irradiance in the wavelength range 0 to λ_i. There is an insignificant amount of radiation reaching the earth's surface below 0.3 μm. A plot of the results is shown in the Appendix.

6. Application

6.1 The output per unit area, O_s, of a device or system exposed to solar irradiance is the integral over wavelength of the product of the appropriate spectral response, $R(\lambda)$ (photovoltaic, photochemical, optical absorptance, reflectance, transmittance, etc.), and the solar spectral irradiance, $E\lambda$ as follows:

$$O_s = \int_0^\infty R(\lambda) E\lambda d\lambda \quad (1)$$

6.2 The solar response R_s of a device or system is the weighted average spectral response with the solar spectral irradiance as the weighting function as follows:

$$R_s = \frac{\int_0^\infty R(\lambda) E\lambda d\lambda}{\int_0^\infty E\lambda d\lambda} \quad (2)$$

6.3 Since the spectral response or property and the spectral irradiance are not known as algebraic expressions in general, the integration must be performed as summations so that Eqs 1 and 2 become, respectively,

$$O_s = \sum_{i=1}^{N} R(\lambda_i) E\lambda_i \Delta\lambda_i, \text{ and} \quad (3)$$

$$R_s = \sum_{i=1}^{N} R(\lambda_i) E\lambda_i \Delta\lambda_i \Big/ \sum_{i=1}^{N} E\, \lambda_i \Delta\lambda_i \quad (4)$$

where:

λ_i = wavelength of the *i*th point out of N for which the spectral data is known.

6.4 *Weighted Ordinate Method*—The summations are performed as indicated in Eqs 3 and 4 by using the values of λ_i, $\Delta\lambda_i$, and $E\lambda_i$ given in Tables 1 and 2. Interpolation between nearby values of the spectral response, $R(\lambda)$, is often required since the wavelengths of the digitally recorded response curves may differ from those given in the table.

6.5 *Selected Ordinate Method:*

6.5.1 In the selected ordinate method the solar spectral irradiance is divided into m wavelength intervals, each containing $1/m$ of the total solar irradiance, $E_{0-\infty}$ and having a centroid wavelength λ_i. This makes all the products $E\lambda_j \Delta\lambda_j$ equal to $E_{0-\infty}/m$, allowing them to be factored from the summation. Equations 3 and 4 respectively reduce to the following:

$$O_s = \frac{E_{0-\infty}}{m} \sum_{j=1}^{m} R(\lambda_i), \text{ and} \quad (5)$$

$$R_s = l/m \sum_{j=1}^{m} R(\lambda_i) \quad (6)$$

6.5.2 Appropriate values for the centroid wavelengths for 100 and 50 selected ordinates are provided in Tables 3 and 4. For devices with spectral responses that are relatively smooth, the 50-point selected ordinates are adequate. For devices with spectral responses that contain complex structure the 100-point selected ordinate or weighted ordinate method should be used.

7. Bias

7.1 In the spectral region of interest to most solar users (0.3 to 4.045 μm), the BRITE Monte Carlo computer code has not been adequately verified with experimental data. A comparison of the global irradiance resulting for this code (for example, Standard E 892) has been compared with other rigorous codes. The comparison indicates that the various models agree within ±5 % in spectral regions where there is significant radiation present. Almost all of the differences in the results of these rigorous codes can be traced to differences in the molecular absorption coefficients used as input to the codes.

TABLE 1 Solar Spectral Irradiance Standard Curve for Solar Irradiance, Diffuse, and Direct Incident on a 37° Tilted Surface Facing the Sun With a Ground Albedo of 0.2

λ_i	$E\lambda_i$	$E_0 - \lambda_i$	$F\lambda_i$	λ_i	$E\lambda_i$	$E_0 - \lambda_i$	$F\lambda_i$
0.3050	9.2	0.06	0.0081	1.0408	665.5	734.21	0.7618
0.3100	40.8	0.19	0.0002	1.0700	614.4	753.41	0.7817
0.3150	103.9	0.55	0.0006	1.1000	397.6	768.59	0.7975
0.3200	174.4	1.25	0.0013	1.1208	105.8	773.61	0.8027
0.3250	237.9	2.28	0.0024	1.1308	182.2	775.05	0.8042
0.3300	381.0	3.82	0.0040	1.1378	127.4	776.13	0.8053
0.3350	376.0	5.72	0.0059	1.1610	326.7	781.58	0.8110
0.3400	419.5	7.70	0.0080	1.1800	443.3	788.90	0.8186
0.3450	423.0	9.81	0.0102	0.2000	408.2	797.41	0.8274
0.3500	466.2	12.03	0.0125	1.2350	463.1	812.66	0.8432
0.3600	501.4	16.87	0.0175	1.2900	398.1	836.34	0.8678
0.3700	642.1	22.59	0.0234	1.3200	241.1	845.93	0.8777
0.3800	686.7	29.23	0.0303	1.3500	31.3	850.02	0.8820
0.3900	694.6	36.14	0.0375	1.3950	1.5	850.76	0.8828
0.4000	976.4	44.49	0.0462	1.4425	53.7	852.07	0.8841
0.4100	1116.2	54.96	0.0570	1.4625	101.3	853.62	0.8857
0.4200	1141.1	66.24	0.0687	1.4778	101.7	855.09	0.8872
0.4300	1033.0	77.11	0.0800	1.4978	175.5	857.86	0.8901
0.4400	1254.8	88.55	0.0919	1.5208	253.1	862.79	0.8952
0.4500	1470.7	102.18	0.1060	1.5390	264.3	867.70	0.9003
0.4600	1541.6	117.24	0.1217	1.5580	265.8	872.73	0.9056
0.4700	1523.7	132.57	0.1376	1.5780	235.7	877.74	0.9108
0.4800	1569.3	148.03	0.1536	1.5920	238.4	881.06	0.9142
0.4900	1483.4	163.30	0.1694	1.6100	220.4	885.19	0.9185
0.5000	1492.6	178.18	0.1849	1.6300	235.6	889.75	0.9232
0.5100	1529.0	193.29	0.2006	1.6460	226.3	893.44	0.9270
0.5200	1431.1	208.09	0.2159	1.6788	212.5	900.46	0.9343
0.5300	1515.4	222.82	0.2312	1.7408	165.3	912.18	0.9465
0.5400	1494.5	237.87	0.2468	1.8000	29.6	918.02	0.9525
0.5500	1504.9	252.87	0.2624	1.8600	1.9	918.97	0.9535
0.5700	1447.1	282.39	0.2930	1.9200	1.2	919.06	0.9536
0.5900	1344.9	310.30	0.3220	1.9600	20.4	919.49	0.9541
0.6100	1431.5	338.07	0.3508	1.9850	87.8	920.85	0.9555
0.6300	1382.1	366.20	0.3800	2.0050	25.8	921.98	0.9567
0.6500	1368.4	393.71	0.4085	2.0350	95.9	923.81	0.9586
0.6700	1341.8	420.81	0.4366	2.0650	58.2	926.12	0.9609
0.6900	1089.0	445.12	0.4619	2.1000	85.9	928.64	0.9636
0.7100	1269.8	468.70	0.4863	2.1480	79.2	932.60	0.9677
0.7180	973.7	477.67	0.4956	2.1980	68.9	936.30	0.9715
0.7244	1005.4	484.00	0.5022	2.2700	67.7	941.22	0.9766
0.7400	1167.3	500.95	0.5198	2.3600	59.8	946.96	0.9826
0.7525	1150.6	515.44	0.5348	2.4500	20.4	950.57	0.9863
0.7575	1132.9	521.15	0.5407	2.4940	17.8	951.41	0.9872
0.7625	619.8	525.53	0.5453	2.5370	3.1	951.86	0.9877
0.7675	993.3	529.56	0.5495	2.9410	4.2	953.33	0.9892
0.7800	1090.1	542.58	0.5630	2.9730	7.3	953.52	0.9894
0.8000	1042.4	563.91	0.5851	3.0050	6.3	953.73	0.9896
0.8160	818.4	578.79	0.6006	3.0560	3.1	953.97	0.9899
0.8237	756.5	584.86	0.6069	3.1320	5.2	934.29	0.9902
0.8315	883.2	591.25	0.6135	3.1560	18.7	954.58	0.9905
0.8400	925.1	598.94	0.6215	3.2040	1.3	955.06	0.9910
0.8600	943.4	617.62	0.6409	3.2450	3.1	955.15	0.9911
0.8800	899.4	636.05	0.6600	3.3178	12.6	955.71	0.9917
0.9050	721.4	656.31	0.6810	3.3440	3.1	955.92	0.9919
0.9150	643.3	663.13	0.6881	3.4500	12.8	956.77	0.9928
0.9250	665.3	669.68	0.6949	3.5730	11.5	958.26	0.9943
0.9300	389.0	672.31	0.6976	3.7650	9.4	960.27	0.9964
0.9370	248.9	674.55	0.6999	4.0450	7.2	962.39	0.9988
0.9480	302.2	677.58	0.7031	4.0950		963.75	1.0000
0.9650	507.7	684.46	0.7102				
0.9800	623.0	692.94	0.7190				
0.9935	719.7	702.00	0.7284				