Designation: E1125 – 16

Standard Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum[1]

This standard is issued under the fixed designation E1125; 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 is intended for calibration and characterization of primary terrestrial photovoltaic reference cells to a desired reference spectral irradiance distribution, such as Tables G173. The recommended physical requirements for these reference cells are described in Specification E1040. Reference cells are principally used in the determination of the electrical performance of photovoltaic devices.

1.2 Primary photovoltaic reference cells are calibrated in natural sunlight using the relative quantum efficiency of the cell, the relative spectral distribution of the sunlight, and a tabulated reference spectral irradiance distribution. Selection of the reference spectral irradiance distribution is left to the user.

1.3 This test method requires the use of a pyrheliometer that is calibrated according to Test Method E816, which requires the use of a pyrheliometer that is traceable to the World Radiometric Reference (WRR). Therefore, reference cells calibrated according to this test method are traceable to the WRR.

1.4 This test method is used to calibrate primary reference cells; Test Method E1362 may be used to calibrate secondary and non-primary reference cells (these terms are defined in Terminology E772).

1.5 This test method applies only to the calibration of a photovoltaic cell that shows a linear dependence of its short-circuit current on irradiance over its intended range of use, as defined in Test Method E1143.

1.6 This test method applies only to the calibration of a reference cell fabricated with a single photovoltaic junction.

1.7 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

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

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E490 Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables
E772 Terminology of Solar Energy Conversion
E816 Test Method for Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers
E927 Specification for Solar Simulation for Photovoltaic Testing
E948 Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight
E973 Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell
E1021 Test Method for Spectral Responsivity Measurements of Photovoltaic Devices
E1040 Specification for Physical Characteristics of Nonconcentrator Terrestrial Photovoltaic Reference Cells
E1143 Test Method for Determining the Linearity of a Photovoltaic Device Parameter with Respect To a Test Parameter
E1362 Test Methods for Calibration of Non-Concentrator Photovoltaic Non-Primary Reference Cells
E2554 Practice for Estimating and Monitoring the Uncertainty of Test Results of a Test Method Using Control Chart Techniques
G138 Test Method for Calibration of a Spectroradiometer Using a Standard Source of Irradiance
G173 Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

[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 E44.09 on Photovoltaic Electric Power Conversion.

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[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.

G183 Practice for Field Use of Pyranometers, Pyrheliometers and UV Radiometers

2.2 *WMO Document:*[3]

WMO-No. 8 Guide to Meteorological Instruments and Methods of Observation, Seventh ed., 2008.

3. Terminology

3.1 *Definitions*—Definitions of terms used in this test method may be found in Terminology E772.

3.2 The following symbols and units are used in this test method:

3.3 *Symbols:*

3.3.1 A_x—collimator aperture identifiers (non-numeric).

3.3.2 *C*—calibration value, reference cell (Am^2W^{-1}).

3.3.3 **C**—array of calibration values, reference cell (Am^2W^{-1}).

3.3.4 *D*—as a subscript, refers to the reference cell to be calibrated; as a variable, distance from collimator entrance aperture to reference cell top surface, or to spectroradiometer entrance optics (m).

3.3.5 *E*—total irradiance, measured with pyrheliometer (Wm^{-2}).

3.3.6 **E**—array of measured total irradiance values (Wm^{-2}).

3.3.7 $E(\lambda)$—spectral irradiance ($Wm^{-2}\mu m^{-1}$ or $Wm^{-2}nm^{-1}$).

3.3.8 $E_S(\lambda)$—measured solar spectral irradiance ($Wm^{-2}\mu m^{-1}$ or $WM^{-2}nm^{-1}$).

3.3.9 $E_0(\lambda)$—reference spectral irradiance distribution ($Wm^{-2}\mu m^{-1}$ or $WM^{-2}nm^{-1}$).

3.3.10 *F*—spectral correction factor (dimensionless).

3.3.11 *FOV*—field-of-view (°).

3.3.12 *I*—short-circuit current, reference cell (A).

3.3.13 **I**—array of measured short-circuit currents, reference cell (A).

3.3.14 *i* —as a subscript, refers to the *i*th current and irradiance data point (dimensionless).

3.3.15 *j* —as a subscript, refers to the *j*th calibration value data point (dimensionless).

3.3.16 *L*—collimator length (m).

3.3.17 *n*—number of current and irradiance data points measured during calibration time period (dimensionless).

3.3.18 *m*—number of calibration value data points (dimensionless).

3.3.19 *M*—spectral mismatch parameter (dimensionless).

3.3.20 $O_D(\lambda,T)$—quantum efficiency, reference cell (%).

3.3.21 r_x—collimator inner aperture radius (m).

3.3.22 *R*—collimator entrance aperture radius (m).

3.3.23 R_E—pyrheliometer to integrated spectral irradiance ratio (dimensionless).

3.3.24 *RNG*—as a subscript, refers to the minimum-to-maximum range of an array of values.

3.3.25 *s*—sample standard deviation, reference cell calibration value (Am^2W^{-1}).

3.3.26 *T*—temperature (°C).

3.3.27 T_0—calibration temperature, reference cell (25°C).

3.3.28 $Z_P(\lambda)$—pyrheliometer spectral transmittance function (dimensionless).

3.3.29 λ—wavelength (µm or nm).

3.3.30 θ_O—collimator opening angle (°).

3.3.31 θ_S—collimator slope angle (°).

3.3.32 $\Theta_D(\lambda)$—partial derivative of quantum efficiency with respect to temperature ($\%\cdot°C^{-1}$).

4. Summary of Test Method

4.1 The calibration of a primary photovoltaic reference cell consists of measuring the short-circuit current of the cell when illuminated with natural sunlight, along with the direct solar irradiance using a pyrheliometer (see Terminology E772). The ratio of the short-circuit current of the cell to the irradiance is called the responsivity, which, when divided by a spectral correction factor similar to the spectral mismatch parameter defined in Test Method E973, is the calibration value for the reference cell. The spectral correction factor also corrects the calibration value to 25°C (see 4.2.2).

4.1.1 The relative spectral irradiance of the sunlight is measured using a spectroradiometer as specified in Test Method G138 and Test Method E973.

4.1.2 A pyrheliometer measures direct solar irrradiance by restricting the field-of-view (FOV) to a narrow conical solid angle, typically 5°, that includes the 0.5° cone subtended by the sun. This calibration method requires that the same irradiance measured by the pyrheliometer also illuminate the primary reference cell to be calibrated and the spectroradiometer simultaneously. Thus, both are required to have collimators (see 6.2).

4.1.3 Multiple calibration values determined from *I*, *E*, and $E(\lambda)$ measurements made on a minimum of three different days, are averaged to produce the final calibration result. Each data point corresponds to a single $E(\lambda)$ spectral irradiance.

4.2 The following is a list of measurements that are used to characterize reference cells and are reported with the calibration data:

4.2.1 The relative quantum efficiency of the cell is determined in accordance with Test Methods E1021.

4.2.2 Temperature sensitivity of the cell's short-circuit current is determined experimentally by measuring the partial derivative of quantum efficiency with respect to temperature, as specified in Test Method E973.

4.2.3 Linearity of short-circuit current versus irradiance is determined in accordance with Test Method E1143.

4.2.4 The fill factor of the reference cell is determined using Test Method E948. Providing the fill factor with the calibration data allows the reference cell to be checked in the future for electrical degradation or damage.

[3] Available from World Meteorological Organization (WMO), 7bis, avenue de la Paix, Case Postale No. 2300, CH-1211 Geneva 2, Switzerland, http://www.wmo.int.

5. Significance and Use

5.1 The electrical output of a photovoltaic device is dependent on the spectral content of the illumination source, its intensity, and the device temperature. To make standardized, accurate measurements of the performance of photovoltaic devices under a variety of light sources when the intensity is measured with a calibrated reference cell, it is necessary to account for the error in the short-circuit current that occurs if the relative quantum efficiency of the reference cell is not identical to the quantum efficiency of the device to be tested. A similar error occurs if the spectral irradiance distribution of the test light source is not identical to the desired reference spectral irradiance distribution. These errors are accounted for by the spectral mismatch parameter (described in Test Method E973), which is a quantitative measure of the error in the short-circuit current measurement. It is the intent of this test method to provide a recognized procedure for calibrating, characterizing, and reporting the calibration data for primary photovoltaic reference cells using a tabular reference spectrum.

5.2 The calibration of a reference cell is specific to a particular spectral irradiance distribution. It is the responsibility of the user to specify the applicable irradiance distribution, for example Tables G173. This test method allows calibration with respect to any tabular spectrum.

5.2.1 Tables G173 do not provide spectral irradiance data for wavelengths longer than 4 µm, yet pyrheliometers (see 6.1) typically have response in the 4–10 µm region. To mitigate this discrepancy, the Tables G173 spectra must be extended with the data provided in Annex A2.

5.3 A reference cell should be recalibrated at yearly intervals, or every six months if the cell is in continuous use outdoors.

5.4 Recommended physical characteristics of reference cells can be found in Specification E1040.

5.5 High-quality silicon primary reference cells are expected to be stable devices by nature, and as such can be considered control samples. Thus, the calibration value data points (see 9.3) can be monitored with control chart techniques according to Practice E2554, and the test result uncertainty estimated. The control charts can also be extended with data points from previous calibrations to detect changes to the reference cell or the calibration procedures.

6. Apparatus

6.1 *Pyrheliometer*— A secondary reference pyrheliometer that is calibrated in accordance with Test Method E816, or an absolute cavity radiometer. See also World Radiometric Reference in Terminology E772 and the World Meteorological Organization (WMO) guide WMO-No.8, Chapter 7. Practice G183 provides guidance to the use of pyrheliometers for direct solar irradiance measurements.

6.1.1 Because secondary reference pyrheliometers are calibrated against an absolute cavity radiometer, the total uncertainty in the primary reference cell calibration value will be reduced if an absolute cavity radiometer is used.

6.1.2 The spectral transmittance function of the pyrheliometer must be considered. For an absolute cavity radiometer without a window, $Z_P(\lambda)$ can be assumed to be one over a very wide wavelength range. Secondary reference pyrheliometers typically have a window at the entrance aperture, so $Z_P(\lambda)$ can be assumed to be the spectral transmittance of the window material.

6.1.2.1 Test Method E816 requires absolute cavity radiometers to be "nonselective over the range from 0.3 to 10 µm", and secondary reference pyrheliometers to be "nonselective over the range from 0.3 to 4 µm."

6.1.2.2 Commercially available secondary pyrheliometers use a variety of different window materials, and many do not meet the 0.3 to 4 µm requirement of Test Method E816. The transmittance of fused silica (SiO_2), for example, has significant variations in the 2 to 4 µm region that depend on the grade of the material (ultraviolet or infrared grade). Sapphire (Al_2O_3) transmits beyond 4 µm, but its transmittance is not entirely flat over 0.4 to 4 µm. Crystalline quartz (SiO_2) is very flat over 0.25 to 2.5 µm, but the transmittance falls to zero by 4 µm. The pyrheliometer manufacturer should be consulted to obtain the window transmittance data.

6.1.2.3 The calibration procedure in Test Method E816 places restrictions on allowable atmospheric conditions and does not adjust calibration results with spectral information: all pyrheliometers are calibrated with the same procedure regardless of the window material.

6.2 *Collimators*—Tubes with internal baffles, intended for pointing toward the sun, that restrict the FOV and are fitted to the reference cell to be calibrated and the spectroradiometer (see 6.3); an acceptable collimator design is provided in Annex A1. The collimators must match the FOV of the pyrheliometer (see A1.4.1).

6.2.1 Eliminate or minimize any stray light entering the collimators at the bottoms of the tubes.

6.2.2 The receiving aperture of the reference cell collimator shall be sized such that the entire optical surface of the primary reference cell to be calibrated is completely illuminated, including the window (see Specification E1040). Thus, for a reference cell with a 50 mm square window, the collimator would require a receiving aperture radius equal to:

$$\sqrt{50^2 + 50^2} / 2 = 35.4 \text{ mm}$$

6.3 *Spectroradiometer,* as required by Test Methods G138 and E973 for direct normal solar spectral irradiance measurements.

6.3.1 The wavelength range of the spectral irradiance measurement shall be wide enough to span the wavelength range of the quantum efficiency of the cell to be calibrated (see 6.7.3) and the spectral sensitivity function of the pyrheliometer (see 6.1.2).

6.3.2 If the spectral irradiance measurement is unable to measure the entire wavelength range required by 6.3.1 and 6.3.2, it is acceptable to use a reference spectrum, such as Tables G173, to supply the missing wavelengths. The reference spectrum is scaled to match the measured spectral irradiance data over a convenient wavelength interval within the wavelength range of the spectral irradiance measurement equipment. It is also acceptable to calculate the missing spectral irradiance data using a numerical spectral irradiance model.

6.3.2.1 Note that the reference spectrum is also required to include the wavelengths specified by 6.3.1: see 5.2.1.

6.4 *Normal Incidence Tracking Platforms*—A platform or platforms that hold the reference cell to be calibrated, the pryheliometer, and the spectroradiometer during the calibration procedure. Using two orthogonal axes, such as azimuth and elevation (that is, altazimuthal mount), the platforms must follow the apparent motion of the sun such that the angle between the sun vector and the normal vector is less than 0.1° (that is, the tracking error). The collimators (including that of the pyrheliometer) define the normal vector and shall be parallel to each other within ±0.25°.

6.4.1 The tracking error tolerance is dependent on the FOV and slope angle of the pyrheliometer and the collimators (see A1.4.1); WMO-No. 8 states that 0.1° is acceptable for the recommended FOV of 5° and slope angle of 1°.

6.5 *Temperature Measurement Equipment*—The instrument or instruments used to measure the temperature of the reference cell to be calibrated must have a resolution of at least 0.1°C, and a total uncertainty of less than ±1°C of reading when such uncertainty is combined with the uncertainty of the sensors themselves.

6.5.1 Sensors such as thermocouples or thermistors used for the temperature measurements must be located in a position that minimizes any temperature gradients between the sensor and the photovoltaic device junction.

6.6 *Electrical Measurement Equipment*—Voltmeters, ammeters, or other suitable electrical measurement instruments, used to measure the short-circuit current, I, of the cell to be calibrated and the pyrheliometer output, E, must have a resolution of at least 0.02 % of the maximum current or voltage encountered, and a total uncertainty of less than 0.1 % of the maximum current or voltage encountered.

6.6.1 The electrical measurement equipment should be able to record a minimum of 50 to 100 data points during the calibration time period (see 8.1).

6.7 *Quantum Efficiency Measurement Equipment,* as required by Test Method E1021 for spectral responsivity measurements and the following additional requirements:

6.7.1 The wavelength interval between successive quantum efficiency data points shall be 10 nm or less.

6.7.2 For reference cells made with direct bandgap semiconductors such as GaAs, it is recommended that the wavelength interval be no greater than 5 nm.

6.7.3 The low- and high-wavelength endpoints of the quantum efficiency measurement shall span all wavelengths for which the measured quantum efficiency are greater than 1 % of the maximum quantum efficiency.

6.7.4 The full-width-at-half maximum bandwidth fo the monochromatic light source shall be 10 nm or less.

6.8 *Temperature Control Block (Optional)*—A device to maintain the temperature of the reference cell at 25 ± 1°C for the duration of the calibration.

7. Characterization

7.1 Because some silicon solar cells are susceptible to a loss of short-circuit current upon initial exposure to light, newly manufactured reference cells shall be light soaked prior to initial characterization, as follows:

7.1.1 Measure the short-circuit current and the cell area of the reference cell to be calibrated according to Test Method E948, with respect to standard reporting conditions corresponding to the reference spectral irradiance distribution (see 5.2 and Table 1 of Test Method E948).

7.1.2 Connect the reference cell to the electrical measurement equipment (see 6.6) and prepare to record short-circuit current versus time.

7.1.3 Illuminate the reference cell with either natural sunlight or a solar simulator (see Specification E927); the spectral irradiance is not critical, nor is the cell temperature.

7.1.4 Record the short-circuit current of the reference cell when the current is greater than 85 % of the current measured in 7.1.1.

7.1.5 Integrate the short-circuit currents recorded in 7.1.4 with time to calculate the total charge generated.

7.1.6 Discontinue the illumination when 22 MCm^{-2} have been generated. For an Si solar cell with a short-circuit current density of 300 Am^{-2} at 1000 Wm^{-2}, this amount of charge requires approximately 20 h of illumination.

7.2 Characterize the reference cell to be calibrated by the following methods:

7.2.1 *Quantum Efficiency*—Determine the relative quantum efficiency (optionally the absolute quantum efficiency) of the reference cell to be calibrated at 25°C in accordance with Test Methods E1021 and the requirements of 6.7.

7.2.1.1 Repetition of 7.2.1 is optional if the quantum efficiency has been previously measured in accordance with 7.2.1.

7.2.2 *Partial Derivative of Quantum Efficiency with Respect to Temperature*—Determine the working temperature range of the reference cell to be calibrated and measure its $\Theta_D(\lambda)$ according to Annex A1 of Test Methods E973.

NOTE 1—Test Method E973 requires all quantum efficiency measurements needed for $Q_D(\lambda,T_0)$ and $\Theta_D(\lambda)$ be measured with the same multiplicative calibration or scaling factors.

7.2.2.1 Repetition of 7.2.2 is optional if $\Theta_D(\lambda)$ has been previously measured in accordance with 7.2.2.

7.2.3 *Linearity*—Determine the short-circuit current versus irradiance linearity of the cell being calibrated in accordance with Test Method E1143 for the irradiance range 750 to 1100 Wm^{-2}.

7.2.3.1 For reference cells that use single-crystal silicon solar cells, or for reference cells that have been previously characterized, the short-circuit current versus irradiance linearity determination is optional.

7.2.4 *Fill Factor*— Determine the fill factor of the cell to be calibrated from the I-V curve of the device, as measured in accordance with Test Methods E948.

8. Procedure

8.1 Select the time period for a single calibration data point. Two factors must be considered: *(1)* the response time of the pyrheliometer, and *(2)* the time required for the spectroradiometer to measure a single spectral irradiance.

8.1.1 Pyrheliometers have response times (defined as the time required for the instrument to indicate 95 % of a step change of input irradiance) on the order of 1 to 30 s. It is recommended that the calibration time period span the manufacturer's specified response time by a factor of at least five.

8.1.1.1 Absolute cavity radiometers are self-calibrating instruments that rely on periodically blocking all light with shutters; the blocked periods must be considered when selecting the calibration time period.

8.1.2 Spectroradiometers that use mechanically rotated diffraction gratings can require as much as 60 s to scan a single spectral irradiance, while those that employ photodiode arrays can reduce the measurement time to tens of milliseconds.

8.1.3 Use the larger of either 8.1.1 or 8.1.2 as the calibration time period.

8.2 Mount the reference cell to be calibrated, the pyrheliometer, and the spectroradiometer on the tracking platforms, and orient the collimating tubes parallel to the sun vector within the tracking limits of the platforms (see 6.4).

8.3 Collect data for a single calibration data point during the calibration time period as follows:

8.3.1 Measure an array of reference cell short-circuit current values, where n is the number of current values:

$$\mathbf{I} = [I_1\ I_2\ ...\ I_n] \tag{1}$$

8.3.2 Measure an array of the pyrheliometer output values, where n is the number of irradiance values:

$$\mathbf{E} = [E_1\ E_2\ ...\ E_n] \tag{2}$$

8.3.3 Depending on the speed of the electrical measurement equipment (see 6.6), the numbers of current and irradiance values obtained in 8.3.1 and 8.3.2 might not be identical, and they are not required to be identical. However, the time periods over which the values are obtained must be identical.

8.3.4 Measure the spectral irradiance for the calibration time period using the spectroradiometer.

8.3.4.1 If the spectroradiometer measurement time is less than the calibration time period, collect multiple spectra and average them to obtain a single spectral irradiance.

8.3.5 Measure the reference cell temperature, T_D.

8.4 Perform a minimum of six replications of 8.3 on at least three separate days; more repetitions are recommended.

9. Calculation of Results

9.1 Each spectral irradiance measurement obtained in 8.3 defines one data point; denote the total number of these points as m.

9.2 For each data point, where j=1...m:

9.2.1 Compute the mean short-circuit current, where n is the number of current values measured in each repetition of 8.3.1:

$$I_j = \langle \mathbf{I}_j \rangle = \frac{1}{n}\sum_{i=1}^{n} I_i \tag{3}$$

9.2.2 Compute the mean irradiance, where n is the number of current values measured in each repetition of 8.3.2:

$$E_j = \langle \mathbf{E}_j \rangle \tag{4}$$

9.2.3 Compute the short-circuit current range in percent:

$$I_{RNGj} = 200\frac{\max\mathbf{I}_j - \min\mathbf{I}_j}{\max\mathbf{I}_j + \min\mathbf{I}_j} \tag{5}$$

9.2.4 Compute the irradiance range in percent:

$$E_{RNGj} = 200\frac{\max\mathbf{E}_j - \min\mathbf{E}_j}{\max\mathbf{E}_j + \min\mathbf{E}_j} \tag{6}$$

9.2.5 Discard any data points for which E_j is <750 Wm^{-2} or >1100 Wm^{-2}.

9.2.6 Discard any data points for which I_{RNGj} is >1 %.

9.2.7 Discard any data points for which E_{RNGj} is >0.5 %.

9.2.8 The range limits in 9.2.5, 9.2.6, and 9.2.7 have been found useful for rejecting questionable data points and may be adjusted as needed. The smaller limit for E_{RNGj} reflects the difference between the time constant of the pyrheliometer and the nearly instantaneous response time of a solar cell; if the irradiance changes by more then 0.5 % during the calibration time period, then it is likely that the pyrheliometer is not in thermal equilibrium.

9.2.9 Calculate the spectral correction factor, F_j, using the following equation:

$$F_j = \frac{\int_{\lambda 1}^{\lambda 2}\lambda Q_D(\lambda,T_0)E_{Sj}(\lambda)d\lambda + (T_{Dj} - T_0)\int_{\lambda 1}^{\lambda 2}\lambda\Theta_D(\lambda)E_{Sj}(\lambda)d\lambda}{\int_{\lambda 3}^{\lambda 4}Z_P(\lambda)E_{Sj}(\lambda)d\lambda} \times \frac{\int_{\lambda 3}^{\lambda 4}Z_P(\lambda)E_0(\lambda)d\lambda}{\int_{\lambda 1}^{\lambda 2}\lambda Q_D(\lambda,T_0)E_0(\lambda)d\lambda} \tag{7}$$

where:

T_0	=	25°,
$Q_D(\lambda,T_0)$	=	the quantum efficiency of the reference cell to be calibrated (see 7.2.1),
$E_{Sj}(\lambda)$	=	spectral irradiance,
T_{Dj}	=	the measured cell temperature (see 8.3.4),
$\Theta_D(\lambda)$	=	the partial derivative of quantum efficiency with respect to temperature (see 7.2.2), and
$Z_P(\lambda)$	=	the spectral transmittance of the pyrheliometer (see 6.2.1).

9.2.9.1 Eq 7 is similar to the spectral mismatch parameter, M, as expressed in Eq 1 of Test Method E973. Rather than an expression of four short-circuit current densities (see Appendix X1 of Test Method E973), Eq 7 is instead the ratio of two responsivities.

9.2.9.2 The wavelength integration limits λ1 and λ2 shall correspond to the spectral response limits of the photovoltaic device (see 6.7.1).

9.2.9.3 The wavelength integration limits λ3 and λ4 shall correspond to those of the spectral transmittance function of the pyrheliometer, $Z_P(\lambda)$ (see 6.1.2).

9.2.9.4 If necessary (see 5.2.1), extend the reference spectral irradiance distribution with the data provided in Annex A2.

9.2.9.5 If $|T_{Dj}-T_0|\leq 1°C$, the temperature correction integral containing $\Theta_D(\lambda)$ may be assumed to be zero and eliminated from the calculation of F_j.

9.2.10 Calculate the calibration value:

$$C_j = \frac{I_j}{E_j}\cdot\frac{1}{F_j} \tag{8}$$

9.2.11 Calculate the pyrheliometer to integrated spectral irradiance ratio:

$$R_{Ej} = \frac{E_j}{\int_{\lambda 3}^{\lambda 4} Z_P(\lambda) E_{Sj}(\lambda) d\lambda} \quad (9)$$

9.2.11.1 The irradiance ratio, R_{Ej}, will depend on the spectroradiometer's calibraton and thus is not necessarily equal to one; this is not an error in the reference cell calibration value because the spectral correction factor does not require absolute spectral quantities (see Test Method E973). However, the R_{Ej} values should be used as rejection criteria through comparison and monitoring to detect possible problems with individual data points.

9.3 Construct an array of calibration values using the results obtained in 9.2.10.

$$\mathbf{C} = [C_1\ C_2\ ...\ C_m] \quad (10)$$

9.4 Compute the mean calibration value:

$$C = \langle \mathbf{C} \rangle \quad (11)$$

9.5 Compute the sample standard deviation of the calibration value:

$$s = \sqrt{\frac{\mathbf{C} \bullet \mathbf{C} - mC^2}{m - 1}} \quad (12)$$

9.6 Compute the range of the calibration value:

$$C_{RNG} = 2\frac{\max\mathbf{C} - \min\mathbf{C}}{\max\mathbf{C} + \min\mathbf{C}} \quad (13)$$

9.7 *Optional*—If the number of data points collected on any one day is greater than those from the other days (see 8.4), separate the data points according to day and compute the mean calibration value using Eq 10 for each day. Then compute the final mean calibration value using the daily mean values. This prevents coloration of the results by the atmospheric conditions on a single day.

10. Report

10.1 Report, as a minimum, the following information:

10.1.1 Reference cell serial number.

10.1.2 Date of calibration.

10.1.3 Reference spectral irradiance distribution, $E_0(\lambda)$.

10.1.4 *Reference Cell:*

10.1.4.1 Quantum efficiency, $Q_D(\lambda, T_0)$, as required by Test Method E973.

10.1.4.2 Partial derivative of quantum efficiency with respect to temperature, $\Theta_D(\lambda)$ as required by Test Method E973.

10.1.4.3 Fill factor.

10.1.4.4 Linearity verification, as required by Test Method E1143.

10.1.4.5 Calibration value, C.

10.1.4.6 Calibration value standard deviation, s.

10.1.4.7 Calibration range, C_{RNG}.

10.1.5 Pyrheliometer type, manufacturer, serial number, calibration value, data last calibrated.

10.1.6 Complete description of measurement system.

10.1.7 Any deviations from the standard calibration procedure.

10.1.8 Any unusual occurrences during calibration.

10.1.9 Data for each point in calibration, that shall include the following:

10.1.9.1 Cell temperature, T_{Dj},

10.1.9.2 Irradiance, E_j,

10.1.9.3 Irradiance range, E_{RNGj},

10.1.9.4 Short-circuit current, I_j,

10.1.9.5 Short-circuit current range, I_{RNG},

10.1.9.6 Pyrheliometer to integrated spectral irradiance ratio, R_{Ej}, and

10.1.9.7 Spectral correction factor, F_j.

11. Precision and Bias

11.1 *Precision*—It is not possible to specify the precision of the reference cell calibration test method using the results of an interlaboratory study because no laboratories were willing to participate in such a study. The restrictions placed on the apparatus and the calibration conditions have been selected to minimize precision errors in the reference cell calibration value. Factors that contribute to the total precision error include:

11.1.1 Temporal variations of the solar spectral and total irradiance during the calibration time periods (see 8.3) will introduce errors.

11.1.2 The discussion of precision of spectral measurements in 9.1 of Test Method E973 is applicable to the reference cell calibration test method.

11.1.3 Temperature variations of the reference cell being calibrated within the 25 ± 1°C band will introduce small errors in the calibration value if the temperature corrections are not employed (see 9.2.9.5). The partial derivative of quantum efficiency with respect to temperature (see 7.2.1) controls the magnitude of these errors.

11.1.4 Electronic instrumentation used to measure the reference cell short-circuit current, the total irradiance, and the cell temperature will contribute precision errors to the calibration value.

11.2 *Bias*—The contribution of bias to the total error will depend upon the bias of each individual factor used for the determination of the calibration value. Possible individual contributions of bias include:

11.2.1 The slope of the cell's I–V curve near zero volts, and loading of the cell by the current measurement instrument due to nonzero input impedance can result in somewhat smaller values of the short-circuit current. This situation can be minimized by forcing the reference cell voltage as close to zero as possible during the short-circuit current measurement.

11.2.2 Measurement of the cell temperature at the back of the device will give a value that is lower than the junction temperature during exposure of the cell to sunlight. This may result in slightly too high a value for short-circuit current. Because the short-circuit current temperature coefficient is usually small, this source of bias tends to be small.

11.2.3 Each measurement instrument will introduce bias into the final calibration in varying amounts. It is assumed that all instruments are calibrated at regular intervals. However, bias will still affect any instrumentation even after careful calibration.

11.2.4 An absolute accuracy of 0.25 % for terrestrial solar radiometric measurements has been established for absolute cavity radiometers that have been compared with the World Radiometric Reference. If a secondary reference pyrheliometer is used, a 1 % transfer error from the cavity radiometer should be expected when utilizing the procedures of Test Method E816.

11.2.5 The discussion of bias in spectral measurements in 9.2 of Test Method E973 is applicable to the reference cell calibration test method.

12. Keywords

12.1 calibration; electrical performance; photovoltaic devices; primary terrestrial photovoltaic reference cells; spectral irradiance; spectral response; terrestrial photovoltaic reference cells

ANNEXES

(Mandatory Information)

A1. COLLIMATOR DESIGN

A1.1 Fig. A1.1 shows a cross section through the center of the tubular collimator assembly. Five apertures are used: A_1 is the entrance aperture, and A_2, A_3, A_4, and A_5 are the inner apertures, with their respective radii being R and r_2 through r_5. The apertures block light from outside the conical solid angle of the field-of-view (FOV).

A1.2 Three parameters determine the dimensions of the collimator; these are the FOV, the receiving aperture radius, r, and the slope angle, θ_S.

A1.2.1 The FOB and θ_S are selected to be the same as those of the pyrheliometer.

A1.2.2 The receiving aperture radius, r, defines the circular illumination area, which needs to encompass the size of the largest reference cell that will be calibrated, or the entrance optics of the spectroradiometer.

A1.2.3 Note that D is the distance to the top surface of the reference cell (or the spectroradiometer entrance optics) and not the distance to the final inner aperture, L_5. As a result, if the reference cell is positioned away from A_5, that is, $D > L_5$, the illumination area will be smaller than the area of the final inner aperture, and the FOV will be reduced. To ensure that all reference cells are calibrated with the same FOV, it is recommended that the collimator and test fixture be designed to allow adjustment of $D–L_5$ for difference reference cell package geometries.

A1.3 With the FOV, θ_S, and r known, the design dimensions are calculated using geometry.

A1.3.1 Opening angle:

$$\theta_O = \frac{1}{2}\text{FOV} \tag{A1.1}$$

A1.3.2 Entrance aperture radius:

$$R + \frac{r}{\left(1 - \frac{\tan\theta_S}{\tan\theta_O}\right)} \tag{A1.2}$$

A1.3.3 Collimator length:

$$D = \frac{R}{\tan\theta_O} \tag{A1.3}$$

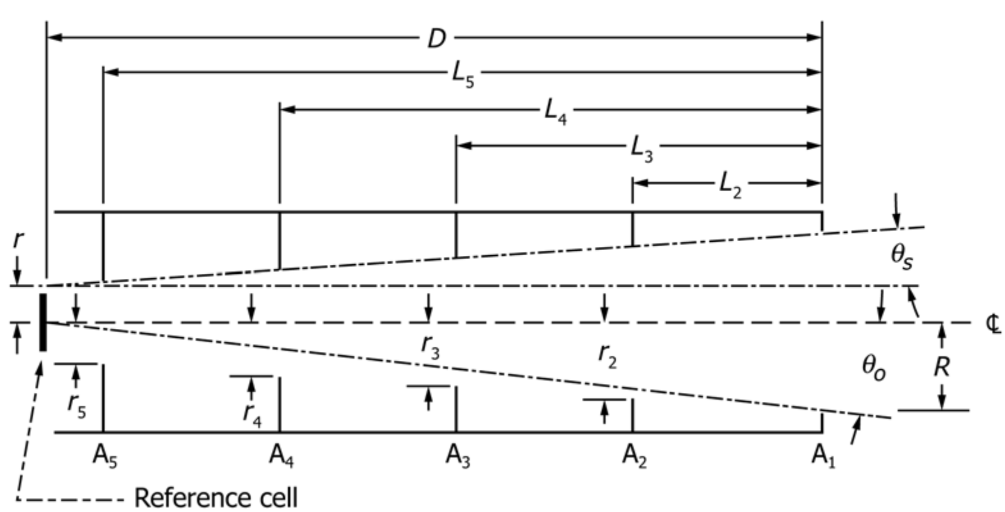

FIG. A1.1 Collimator Design Cross Section

A1.3.4 Positions of the inner aperture are not critical, but can be selected to minimize stray light from off-angle reflections from reaching the receiving aperture. Table A1.1 lists the recommended inner aperture positions normalized to the receiving aperture radius.

A1.3.5 Inner aperture radii (x=2,3,4, and 5):

$$r_x = r + (D - L_x)\tan\theta_S \quad (A1.4)$$

A1.4 *Additional Design Considerations*:

A1.4.1 The World Meteorological Organization (WMO) recommends in WMO-No. 8 that all solar pyrheliometers have a FOV of 5° and a slope angle of 1°, and most (if not all) instrument manufacturers now adhere to this recommendation. Using these angles and a receiving aperture radius equal to 1 in arbitrary units, the normalized design dimensions are obtained; these are listed in Table A1.2. A complete collimator design for use with a WMO-compliant pyrheliometer can then be obtained by multiplying the values in Tables Table A1.1 and Table A1.2 by the receiving aperture needed.

A1.4.2 *Internal Reflections:*

A1.4.2.1 The apertures should be beveled at 45° angles to minimize reflections off the edges.

A1.4.2.2 Inner surfaces of the collimator should be non-reflective, materials such as anodized aluminum can be highly reflective in the infrared, rendering them unsuitable despite their dark appearance to the eye.

TABLE A1.1 Recommended Inner Aperture Positions

L_2/r	L_3/r	L_4/r
10.5	21.5	28.5

TABLE A1.2 Collimator Design Using WMO Pyrheliometer Parameters

FOV	θo	θs	R/r	D/r	r_2/r	r_3/r	r_4/r
5°	2.5°	1°	1.6661	38.159	1.4828	1.2908	1.1686

A2. INFRARED SPECTRAL IRRADIANCE EXTENSION TO TABLES G173

An absolute cavity radiometer that meets the requirements of Test Method E816 will have a nonselective response in the infrared to at least 10 µm. However, the direct normal and hemispherical tilted reference spectral irradiance distributions in Tables G173 provide no information for wavelengths greater than 4 µm.

A2.2 Integrated between 4 and 10 µm, the extraterrestrial spectral irradiance contains a total of 10.9 Wm^{-2} (see Table 3 of Standard E490), and a portion of this irradiance is transmitted through the atmosphere to the ground. However, the reference spectral irradiance distributions in Tables G173 end at 4 µm, which leads to a potential source of error in the spectral correction factor (see Eq 7) if the pyrheliometer responds to wavelengths in the 4–10 µm region

A2.3 A similar error occurs if the measured spectral irradiance $E_S(\lambda)$ does not include all the wavelengths to which the pyrheliometer responds.

A2.4 The spectral correction factor is the ratio of two responsivities, which are ratios of short-circuit current to total irradiance (see 4.1). One responsivity represents the calibration value of the reference cell to be calibrated as measured in sunlight, and the other the calibration value under the reference spectral irradiance distribution.

A2.5 The wavelength integration limits λ3 and λ4 in Eq 7 are required to be those of the spectral transmittance function of the pyrheliometer, $Z_P(\lambda)$ in 9.2.9.4. If the tabular spectral irradiance data, $E_0(\lambda)$ or $E_S(\lambda)$, do not include all wavelengths between λ3 and λ4, then the two definite integrals with these limits in Eq 7 will be smaller, and will not represent the irradiance measured by the pyrheliometer. As a result, the requirement of 9.2.9.4 will not be met.

A2.6 Examination of the direct normal and hemispherical tilted distributions in Tables G173 shows that the two spectra are nearly identical over the 3–4 µm wavelength range, which is an indication that the diffuse spectral irradiance is very small in this region. By assuming the same is true of the 4–10 µm range, it is possible to calculate the spectral irradiance for both using a direct-only atmospheric transmittance model. This has been done using the Tables G173 atmospheric parameters and the MODTRAN computer code (see references 3 and 4 in Tables G173) at 20 nm wavelength resolution; the results are listed in Table A2.1.

A2.7 The third column of Table A2.1 lists the cumulative integrated total irradiance from 4 µm, thus the 4–10 µm total irradiance is 2.9 Wm^{-2}. For the hemispherical tilted spectral irradiance of Tables G173, which integrates to a total irradiance of 1000.4 Wm^{-2}, the discrepancy is 0.29 %.

TABLE A2.1 Infrared Spectral Irradiance Extension to Tables G173 (4-10 µm)

Wavelength, (nm)	Spect. Irrad. ($Wm^{-2}nm^{-1}$)	Total Irrad. (Wm^{-2})	Wavelength, (nm)	Spect. Irrad. ($Wm^{-2}nm^{-1}$)	Total Irrad. (Wm^{-2})	Wavelength, (nm)	Spect. Irrad. ($Wm^{-2}nm^{-1}$)	Total Irrad. (Wm^{-2})
4020	7.567E–3	0.147	6020	0.000E+0	2.405	8020	3.020E–4	2.485
4040	7.329E–3	0.296	6040	0.000E+0	2.405	8040	3.174E–4	2.491
4060	7.054E–3	0.439	6060	0.000E+0	2.405	8060	3.291E–4	2.498
4080	6.707E–3	0.577	6080	0.000E+0	2.405	8080	3.375E–4	2.504
4100	6.308E–3	0.707	6100	0.000E+0	2.405	8100	3.424E–4	2.511
4120	5.860E–3	0.829	6120	0.000E+0	2.405	8120	3.415E–4	2.518
4140	5.247E–3	0.940	6140	0.000E+0	2.405	8140	3.359E–4	2.525
4160	3.777E–3	1.030	6160	0.000E+0	2.405	8160	3.275E–4	2.531
4180	3.653E–5	1.068	6180	0.000E+0	2.405	8180	3.227E–4	2.538
4200	0.000E+0	1.069	6200	0.000E+0	2.405	8200	3.199E–4	2.544
4220	0.000E+0	1.069	6220	0.000E+0	2.405	8220	3.189E–4	2.551
4240	0.000E+0	1.069	6240	0.000E+0	2.405	8240	3.210E–4	2.557
4260	0.000E+0	1.069	6260	0.000E+0	2.405	8260	3.265E–4	2.564
4280	0.000E+0	1.069	6280	0.000E+0	2.405	8280	3.341E–4	2.570
4300	0.000E+0	1.069	6300	0.000E+0	2.405	8300	3.420E–4	2.577
4320	0.000E+0	1.069	6320	0.000E+0	2.405	8320	3.450E–4	2.584
4340	0.000E+0	1.069	6340	0.000E+0	2.405	8340	3.462E–4	2.591
4360	0.000E+0	1.069	6360	0.000E+0	2.405	8360	3.462E–4	2.598
4380	5.758E–8	1.069	6380	0.000E+0	2.405	8380	3.439E–4	2.605
4400	1.364E–6	1.069	6400	0.000E+0	2.405	8400	3.399E–4	2.611
4420	9.014E–6	1.069	6420	0.000E+0	2.405	8420	3.353E–4	2.618
4440	7.038E–5	1.070	6440	0.000E+0	2.405	8440	3.309E–4	2.625
4460	4.278E–4	1.075	6460	0.000E+0	2.405	8460	3.274E–4	2.631
4480	1.379E–3	1.093	6480	0.000E+0	2.405	8480	3.242E–4	2.638
4500	2.552E–3	1.132	6500	0.000E+0	2.405	8500	3.214E–4	2.644
4520	3.339E–3	1.191	6520	0.000E+0	2.405	8520	3.204E–4	2.651
4540	3.766E–3	1.262	6540	0.000E+0	2.405	8540	3.214E–4	2.657
4560	3.947E–3	1.339	6560	0.000E+0	2.405	8560	3.217E–4	2.664
4580	3.953E–3	1.418	6580	0.000E+0	2.405	8580	3.214E–4	2.670
4600	3.870E–3	1.496	6600	0.000E+0	2.405	8600	3.222E–4	2.677
4620	3.694E–3	1.572	6620	0.000E+0	2.405	8620	3.233E–4	2.683
4640	3.453E–3	1.643	6640	0.000E+0	2.405	8640	3.228E–4	2.689
4660	3.204E–3	1.710	6660	0.000E+0	2.405	8660	3.211E–4	2.696
4680	2.922E–3	1.771	6680	0.000E+0	2.405	8680	3.168E–4	2.702
4700	2.498E–3	1.825	6700	0.000E+0	2.405	8700	3.127E–4	2.709
4720	2.164E–3	1.872	6720	0.000E+0	2.405	8720	3.095E–4	2.715
4740	2.017E–3	1.914	6740	0.000E+0	2.405	8740	3.059E–4	2.721
4760	1.885E–3	1.953	6760	0.000E+0	2.405	8760	3.011E–4	2.727
4780	1.740E–3	1.989	6780	0.000E+0	2.405	8780	2.964E–4	2.733
4800	1.630E–3	2.023	6800	0.000E+0	2.405	8800	2.920E–4	2.739
4820	1.507E–3	2.054	6820	0.000E+0	2.405	8820	2.891E–4	2.745
4840	1.477E–3	2.084	6840	0.000E+0	2.405	8840	2.878E–4	2.750
4860	1.576E–3	2.115	6860	0.000E+0	2.405	8860	2.861E–4	2.756
4880	1.660E–3	2.147	6880	0.000E+0	2.405	8880	2.837E–4	2.762
4900	1.645E–3	2.180	6900	0.000E+0	2.405	8900	2.815E–4	2.768
4920	1.542E–3	2.212	6920	0.000E+0	2.405	8920	2.797E–4	2.773
4940	1.322E–3	2.240	6940	0.000E+0	2.405	8940	2.781E–4	2.779
4960	1.145E–3	2.265	6960	0.000E+0	2.405	8960	2.767E–4	2.784
4980	1.054E–3	2.287	6980	0.000E+0	2.405	8980	2.748E–4	2.790
5000	9.104E–4	2.307	7000	0.000E+0	2.405	9000	2.725E–4	2.795
5020	7.955E–4	2.324	7020	0.000E+0	2.405	9020	2.706E–4	2.801
5040	8.385E–4	2.340	7040	0.000E+0	2.405	9040	2.691E–4	2.806
5060	8.233E–4	2.357	7060	0.000E+0	2.405	9060	2.677E–4	2.811
5080	6.223E–4	2.371	7080	0.000E+0	2.405	9080	2.666E–4	2.817
5100	4.066E–4	2.382	7100	0.000E+0	2.405	9100	2.656E–4	2.822
5120	2.606E–4	2.388	7120	0.000E+0	2.405	9120	2.649E–4	2.827
5140	1.911E–4	2.393	7140	1.034E–9	2.405	9140	2.638E–4	2.833
5160	1.673E–4	2.396	7160	1.562E–9	2.405	9160	2.623E–4	2.838
5180	1.265E–4	2.399	7180	2.930E–9	2.405	9180	2.604E–4	2.843
5200	5.800E–5	2.401	7200	6.853E–9	2.405	9200	2.579E–4	2.848
5220	2.928E–5	2.402	7220	1.811E–8	2.405	9220	2.548E–4	2.854
5240	2.532E–5	2.403	7240	4.096E–8	2.405	9240	2.500E–4	2.859
5260	2.797E–5	2.403	7260	6.909E–8	2.405	9260	2.441E–4	2.864
5280	2.441E–5	2.404	7280	1.073E–7	2.405	9280	2.352E–4	2.868
5300	2.139E–5	2.404	7300	1.912E–7	2.405	9300	2.249E–4	2.873
5320	1.648E–5	2.404	7320	3.731E–7	2.405	9320	2.086E–4	2.877
5340	8.335E–6	2.405	7340	8.102E–7	2.405	9340	1.904E–4	2.881
5360	4.342E–6	2.405	7360	1.756E–6	2.405	9360	1.591E–4	2.885
5380	2.478E–6	2.405	7380	3.324E–6	2.405	9380	1.282E–4	2.888
5400	9.771E–7	2.405	7400	5.323E–6	2.405	9400	9.639E–5	2.890
5420	1.731E–7	2.405	7420	7.654E–6	2.405	9420	6.888E–5	2.892
5440	2.976E–8	2.405	7440	1.019E–5	2.405	9440	5.040E–5	2.893
5460	1.623E–8	2.405	7460	1.280E–5	2.406	9460	3.771E–5	2.894
5480	2.606E–8	2.405	7480	1.618E–5	2.406	9480	2.948E–5	2.894

TABLE A2.1 *Continued*

Wavelength, (nm)	Spect. Irrad. ($Wm^{-2}nm^{-1}$)	Total Irrad. (Wm^{-2})	Wavelength, (nm)	Spect. Irrad. ($Wm^{-2}nm^{-1}$)	Total Irrad. (Wm^{-2})	Wavelength, (nm)	Spect. Irrad. ($Wm^{-2}nm^{-1}$)	Total Irrad. (Wm^{-2})
5500	3.700E–8	2.405	7500	2.023E–5	2.406	9500	2.565E–5	2.895
5520	1.483E–8	2.405	7520	2.421E–5	2.407	9520	2.315E–5	2.895
5540	1.339E–9	2.405	7540	2.656E–5	2.407	9540	2.302E–5	2.896
5560	0.000E+0	2.405	7560	2.905E–5	2.408	9560	2.386E–5	2.896
5580	0.000E+0	2.405	7580	3.341E–5	2.408	9580	2.448E–5	2.897
5600	0.000E+0	2.405	7600	4.256E–5	2.409	9600	2.486E–5	2.897
5620	0.000E+0	2.405	7620	5.923E–5	2.410	9620	2.512E–5	2.898
5640	0.000E+0	2.405	7640	8.505E–5	2.412	9640	2.514E–5	2.898
5660	0.000E+0	2.405	7660	1.175E–4	2.414	9660	2.515E–5	2.899
5680	0.000E+0	2.405	7680	1.491E–4	2.416	9680	2.519E–5	2.899
5700	0.000E+0	2.405	7700	1.734E–4	2.420	9700	2.528E–5	2.900
5720	0.000E+0	2.405	7720	1.855E–4	2.423	9720	2.574E–5	2.900
5740	0.000E+0	2.405	7740	1.919E–4	2.427	9740	2.654E–5	2.901
5760	0.000E+0	2.405	7760	1.933E–4	2.431	9760	2.798E–5	2.901
5780	0.000E+0	2.405	7780	1.907E–4	2.435	9780	3.106E–5	2.902
5800	0.000E+0	2.405	7800	1.893E–4	2.438	9800	3.489E–5	2.903
5820	0.000E+0	2.405	7820	1.868E–4	2.442	9820	4.010E–5	2.903
5840	0.000E+0	2.405	7840	1.818E–4	2.446	9840	4.671E–5	2.904
5860	0.000E+0	2.405	7860	1.757E–4	2.449	9860	5.445E–5	2.905
5880	0.000E+0	2.405	7880	1.748E–4	2.453	9880	6.346E–5	2.906
5900	0.000E+0	2.405	7900	1.835E–4	2.457	9900	7.399E–5	2.908
5920	0.000E+0	2.405	7920	1.960E–4	2.460	9920	8.456E–5	2.909
5940	0.000E+0	2.405	7940	2.122E–4	2.464	9940	9.640E–5	2.911
5960	0.000E+0	2.405	7960	2.341E–4	2.469	9960	1.082E–4	2.913
5980	0.000E+0	2.405	7980	2.583E–4	2.474	9980	1.190E–4	2.915
6000	0.000E+0	2.405	8000	2.832E–4	2.479	10000	1.305E–4	2.918