



Standard Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum¹

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

1.9 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

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 Classification for Solar Simulators for Electrical Performance Testing of Photovoltaic Devices
- 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

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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.

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

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 $\mathbf{C}$ —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 $\mathbf{E}$ —array of measured total irradiance values (Wm^{-2}).

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

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

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

3.3.10 F —spectral correction factor (dimensionless).

3.3.11 FOV —field-of-view ($^\circ$).

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

3.3.13 $\mathbf{I}$ —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 ($^\circ\text{C}$).

3.3.27 T_o —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 ($^\circ$).

3.3.31 θ_s —collimator slope angle ($^\circ$).

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

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 irradiance 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**.

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>.

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.

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](#)).