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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 to be used 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 spectral response of the cell, the relative spectral distribution of the sunlight, and a tabulated reference spectral irradiance distribution.

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 a technique that may be used instead of the procedures found in Test Method E1362. This test method offers convenience in its ability to characterize a reference cell under any spectrum for which tabulated data are available. The selection of the specific reference spectrum is left to the user.

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]

E772 Terminology of Solar Energy Conversion
E816 Test Method for Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers
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
E1328 Terminology Relating to Photovoltaic Solar Energy Conversion (Withdrawn 2012)[3]
E1362 Test Method for Calibration of Non-Concentrator Photovoltaic Secondary Reference Cells
G173 Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

3. Terminology

3.1 *Definitions*—Definitions of terms used in this test method may be found in Terminology E772 and Terminology E1328.

3.2 *Symbols:*

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

λ—Wavelength, nm or µm,

[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.

[3] The last approved version of this historical standard is referenced on www.astm.org.

I_{sc}—Short-circuit current, A,
E—Irradiance, Wm^{-2},
E_t—Total irradiance, Wm^{-2},
$E(\lambda)$—Spectral irradiance, $Wm^{-2}\mu m^{-1}$,
$R(\lambda)$—Spectral response, AW^{-1} ,
$R_r(\lambda)$—Reference cell spectral response, AW^{-1},
T—Temperature, °C,
α—Temperature coefficient of reference cell I_{sc}, $°C^{-1}$,
n—Total number of data points,
C—Calibration constant, Am^2W^{-1},
M—Spectral mismatch parameter,
F—Spectral correction factor, and
S—Standard deviation.

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 total solar irradiance using a pyrheliometer. The ratio of the short-circuit current of the cell to the irradiance, divided by a correction factor similar to the spectral mismatch parameter defined in Test Method E973, is the calibration constant for the reference cell. Also, if the temperature of the cell is not 25 ± 1°C, the short-circuit current must be corrected to 25°C.

4.1.1 The relative spectral irradiance of the sunlight is measured using a spectral irradiance measurement instrument as specified in Test Method E973.

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 spectral response of the cell is determined in accordance with Test Methods E1021.

4.2.2 The cell's short-circuit current temperature coefficient is determined experimentally by measuring the short-circuit current at various temperatures and computing the temperature coefficient (see 7.2.2).

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, it is necessary to account for the error in the short-circuit current that occurs if the relative spectral response of the reference cell is not identical to the spectral response 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), 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.

5.3 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 Because silicon solar cells made on p-type substrates are susceptible to a loss of I_{sc} upon initial exposure to light, it is required that newly manufactured reference cells be light soaked at an irradiance level greater than 850 W/m^2 for 2 h prior to initial characterization in Section 7.

6. Apparatus

6.1 *Pyrheliometer*— A secondary reference pyrheliometer that is calibrated in accordance with Test Method E816. An absolute cavity radiometer may also be used. Because secondary reference pyrheliometers are calibrated against an absolute cavity radiometer, the total uncertainty in the primary reference cell calibration constant will be reduced if an absolute cavity radiometer is used.

6.2 *Collimator*—A collimator fitted to the reference cell during calibration that has the same field-of-view as the pyrheliometer. An acceptable collimator design is described in Annex A1.

6.3 *Spectral Irradiance Measurement Equipment,* as required by Test Method E973.

6.3.1 The spectral range of the spectral irradiance measurement shall be wide enough to include the spectral response of the cell to be calibrated.

6.3.2 The spectral range of the spectral irradiance measurement shall include 98 % of the total irradiance to which the pyrheliometer is sensitive.

6.3.3 If the spectral irradiance measurement is unable to measure the entire wavelength range required by 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 model.

6.3.4 The spectral irradiance measurement equipment shall have the same field-of-view as the pyrheliometer and the reference cell collimator.

6.4 *Normal Incidence Tracking Platforms*—Tracking platforms used to follow the sun during the calibration and to hold the reference cell to be calibrated, the pyrheliometer, the collimator, and spectral irradiance measurement equipment. The pyrheliometer and the collimator must be parallel within

±0.25°. The platforms shall be able to track the sun within ±0.5° during the calibration procedure.

6.5 *Temperature Measurement Equipment*—An instrument or instruments used to measure the temperature of the reference cell to be calibrated, that has a resolution of at least 0.1°C, and a total error of less than ±1°C of reading.

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 I_{sc} of the cell to be calibrated and the pyrheliometer output, that have a resolution of at least 0.02 % of the maximum current or voltage encountered, and a total error of less than 0.1 % of the maximum current or voltage encountered.

6.7 *Spectral Response Measurement Equipment,* as required by Test Method E1021.

6.7.1 The wavelength interval between spectral response data points shall be a maximum of 50 nm.

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 Prior to the characterization measurements, illuminate the reference cell to be calibrated at 1000 Wm^{-2} for 2 h. This is necessary to stabilize any light-induced degradation of the cell prior to calibration.

7.2 Characterize the reference cell being calibrated by the following methods:

7.2.1 *Spectral Response*—Determine the relative spectral response, *R(λ)*, (optionally the absolute spectral response) of the cell to be calibrated in accordance with Test Methods E1021.

7.2.2 *Temperature Coefficient*—Determine the temperature coefficient, *α*, of the cell to be calibrated as follows:

7.2.2.1 Using the electrical measurement equipment, measure I_{sc} at four or more temperatures over at least a 50°C temperature range centered around 35°C. The irradiance shall be at least 750 Wm^{-2} and less than 1100 Wm^{-2}, as measured with a second reference cell. Measure the temperature of the being calibrated at the same time.

7.2.2.2 Divide each value of I_{sc} by the normalized instantaneous irradiance level at the time of each measurement.

NOTE 1—The normalized instantaneous irradiance can be determined by dividing the second reference cell's I_{sc} by its calibration constant.

7.2.2.3 Determine the temperature coefficient by performing a least-squares fit of the I_{sc} versus *T* data to a straight line. The slope of the line divided by the value of the current from the least-squares fit at 25°C is the temperature coefficient, *α*.

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 Mount the reference cell to be calibrated, the collimator, the pyrheliometer, and the spectral irradiance measurement equipment on the tracking platforms.

8.2 Measure the relative spectral irradiance of the sun, *E(λ)*, using the spectral irradiance measurement instrument (see 6.6) and the procedure of Test Method E973. During the spectral irradiance measurement, perform the following:

8.2.1 Measure the pyrheliometer output, E_t, and verify that the total irradiance is between 750 Wm^{-2} and 1100 Wm^{-2}.

8.2.2 Measure the short-circuit current of the reference cell, I_{sc}.

8.2.3 Measure the reference cell temperature, *T*.

8.2.4 Repeat 8.2.1 and 8.2.2 at least four times. These repetitions must be distributed in time during the spectral irradiance measurement. To assure temporal stability, the short-circuit current of the reference cell shall not vary by more than ±0.2 % during the repetitions.

8.2.5 Average the short-circuit current and total irradiance values from 8.2.4 to obtain the I_{sc} and E_t that corresponds to the spectral irradiance measurement.

8.3 Perform a minimum of five replications of 8.2.

8.3.1 The five replications must be performed on at least three separate days. Therefore, five replications all performed on the same day would not be an acceptable data set for the calibration.

8.3.2 In order to reduce precision errors through averaging, it is recommended that at least 30 replications of 8.2 be performed.

9. Calculation of Results

9.1 Each spectral irradiance measurement obtained in 8.2 defines one data point. The total number of these data points is denoted as *n*.

9.1.1 For each data point, calculate the spectral correction factor, *F*, using the spectral mismatch parameter calculation, 8.1, of Test Method E973. To perform this calculation, replace the reference cell spectral response $R_r(\lambda)$ with unity (this represents the spectral response of the pyrheliometer), and replace *M* with *F*.

9.2 Calculate the calibration constant for each data point, using the following:

$$C_i = \frac{I_{sc}}{E_t}\frac{1}{F}\frac{1}{1-\alpha(25-T)} \quad (1)$$

NOTE 2—The temperature correction term may be deleted if the measured reference cell temperature is 25 ± 1°C.

9.3 Calculate the average calibration constant with the following: