



Standard Test Method for Calibration of Non-Concentrator Photovoltaic Secondary Reference Cells¹

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1. Scope

1.1 This test method covers calibration and characterization of secondary terrestrial photovoltaic reference cells to a desired reference spectral irradiance distribution. 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 a photovoltaic device.

1.2 Secondary reference cells are calibrated indoors using simulated sunlight or outdoors in natural sunlight by reference to a primary reference cell previously calibrated to the same desired reference spectral irradiance distribution.

1.3 Secondary reference cells calibrated according to this test method will have the same radiometric traceability as the of the primary reference cell used for the calibration. Therefore, if the primary reference cell is traceable to the World Radiometric Reference (WRR, see Test Method E816), the resulting secondary reference cell will also be traceable to the WRR.

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

1.5 This test method applies only to the calibration of a photovoltaic cell that has been fabricated using a single photovoltaic junction.

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

1.7 *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.*

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. Referenced Documents

2.1 ASTM Standards:²

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

E691 Practice for Conducting an Interlaboratory Study to Determine the Precision of a Test Method

E772 Terminology Relating to 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

E1039 Test Method for Calibration of Silicon Non-Concentrator Photovoltaic Primary Reference Cells Under Global Irradiation³

E1040 Specification for Physical Characteristics of Non-concentrator Terrestrial Photovoltaic Reference Cells

E1125 Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum

E1143 Test Method for Determining the Linearity of a Photovoltaic Device Parameter with Respect To a Test Parameter

E1328 Terminology Relating to Photovoltaic Solar Energy Conversion

G173 Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

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 Withdrawn. The last approved version of this historical standard is referenced on www.astm.org.

3. Terminology

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

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *junction temperature, n* —synonym for **cell temperature**. E1328

3.2.2 *test light source, n* —a source of radiant energy used for the secondary reference cell calibration, either natural sunlight or a solar simulator.

3.3 *Symbols:*

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

C —calibration constant, Am^2W^{-1} ,

E —irradiance, Wm^{-2} ,

E_t —total irradiance, Wm^{-2} ,

I —current, A,

I_p —primary reference cell short-circuit current, A,

I_s —secondary reference cell short-circuit current, A,

I_{sc} —short-circuit current, A,

L —collimator length, m,

M —spectral mismatch parameter,

n —total number of data points,

r —collimator receiving aperture radius, m,

R —collimator opening aperture radius, m,

R_a —absolute spectral response, AW^{-1} ,

R_r —relative spectral response,

S —standard deviation,

T —temperature, $^{\circ}\text{C}$,

α —temperature coefficient of reference cell, $^{\circ}\text{C}^{-1}$,

θ_o —collimator opening angle, $^{\circ}$, and

λ —wavelength, nm or μm .

3.3.2 Symbolic quantities that are functions of wavelength appear as $X(\lambda)$.

4. Summary of Test Method

4.1 The calibration of a secondary photovoltaic reference cell consists of measuring the short-circuit current of the cell under natural or simulated sunlight using a primary reference cell to measure the incident irradiance. In addition to the short-circuit current, the relative spectral response of the cell to be calibrated and the relative spectral irradiance of the light source must be determined. Errors in the short-circuit current due to the spectral irradiance of the light source and the spectral response of the primary reference cell are then corrected by dividing the short-circuit current by the spectral mismatch parameter. Also, if the temperature of the cell is not $25 \pm 1^{\circ}\text{C}$, the temperature coefficient for the short-circuit current is needed. The list of necessary test methods is as follows:

4.1.1 The spectral response of the cell to be calibrated is determined in accordance with Test Methods E1021.

4.1.2 The cell's short-circuit current temperature coefficient is determined experimentally by measuring short-circuit current at various temperatures and computing the temperature coefficient.

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

4.1.4 The relative spectral distribution of the light source is determined using a spectral irradiance measurement instrument as specified in Test Method E973.

5. Significance and Use

5.1 The electrical output of photovoltaic devices is dependent on the spectral content of the source illumination and its intensity. To make 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 primary reference cell is not identical to the spectral response of the cell to be calibrated. 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 M (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 secondary photovoltaic reference cells.

5.2 A secondary reference cell is calibrated to the same reference spectral irradiance distribution as the primary reference cell used during the calibration. Primary reference cells can be calibrated by use of Test Method E1125 or Test Method E1039.

NOTE 1—No standards for calibration of reference cells to the extra-terrestrial spectral irradiance distribution presently exist.

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

5.4 Recommended physical characteristics of reference cells are provided 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 *Normal Incidence Tracking Platform (for calibrations conducted in natural sunlight)*—A tracking platform used to follow the sun that holds both the primary reference cell and the cell to be calibrated. The tracker shall be able to track the sun to within $\pm 0.5^{\circ}$ during the calibration procedure.

6.1.1 When the calibration is performed in direct natural sunlight, each cell and the spectral irradiance measurement (see 6.7) shall have collimators that meet the requirements of Annex A1 of Test Method E1125.

6.1.2 When the calibration is performed in global normal conditions, no significant energy reflected from surrounding buildings or any other surfaces in the vicinity of the test stand shall be allowed onto the reference cells for the duration of the calibration period. Care shall be taken to conduct the calibration in a location or manner such that a condition of high ground reflectance is avoided. If significant reflection can occur, provision shall be made on the tracker to shield the reference cells by the use of a horizon shield. This horizon shield shall consist of a black nonreflecting surface, and shall,

as viewed by each reference cell, block the view downward from the local horizon to the lowest extremes of the field of view.

6.2 Solar Simulator—A light source that meets the requirements of a Class A solar simulator in terms of the nonuniformity and temporal instability of the total irradiance, and meets the requirements of a Class B solar simulator in terms of the spectral distribution of irradiance performance, as specified in Specification **E927**.

6.3 Temperature Measurement Equipment—An instrument or instruments used to measure the cell temperature of both the primary reference cell and the 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.

6.3.1 Sensors used for the temperature measurements must be located in a position that minimizes any temperature gradients between the sensor and the photovoltaic device junction.

6.4 Current Measurement Equipment—Instruments used to measure the I_{sc} of the reference cell to be calibrated and the primary reference cell that has a resolution of at least 0.02 % of the maximum current encountered, and a total error of less than 0.1 % of the maximum current encountered.

6.5 Temperature Control Block (optional)—A device to maintain the temperature of the reference cells at $25 \pm 1^\circ\text{C}$ for the duration of the calibration.

6.6 Spectral Response Measurement Equipment, as required by Test Methods **E1021**.

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

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

7. Characterization

7.1 Cells being calibrated shall be characterized by the following methods:

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

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

7.1.2.1 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.

7.1.2.2 Divide each value of I_{sc} by the normalized instantaneous irradiance level at the time of each measurement, and plot the resulting data versus measurement temperature.

NOTE 2—The normalized instantaneous irradiance can be determined by dividing a reference cell's I_{sc} by its calibration constant.

7.1.2.3 Determine the temperature coefficient by performing a least-squares fit of the data to a straight line. The slope of the line divided by the interpolated I_{sc} value at 25°C is the temperature coefficient.

7.1.3 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} .

7.1.3.1 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.

7.1.4 Fill Factor—Determine the fill factor of the cell to be calibrated from the I - V curve of the device, which shall be measured in accordance with Test Method **E948**.

8. Procedure

8.1 Mount the primary reference cell and the cell to be calibrated coplanar in close proximity. For natural sunlight measurements, orient the cells to within $\pm 0.5^\circ$ of normal to the sun's direct beam.

8.2 Verify that the following test condition requirements are met:

8.2.1 Total Irradiance—The total irradiance shall be $>750 \text{ Wm}^{-2}$ and $<1100 \text{ Wm}^{-2}$ at the time of the calibration, as measured by the primary reference cell.

8.2.2 Irradiance Stability—The irradiance shall be sufficiently stable so that variation in the primary reference cell short-circuit current is less than $\pm 1 \%$ during the calibration.

8.2.3 Clouds and Haze—For natural sunlight measurements, the sky must be clear with no observable cloud formations within a 30° half-angle cone surrounding the sun.

8.3 Measure the I_{sc} of both the primary reference cell and the cell being calibrated during the same time period. During this time period, measure the incident spectral irradiance in accordance with Test Method **E973**.

NOTE 3—For calibrations using solar simulation, it is not necessary to measure the spectral irradiance at the same time as the short-circuit current if it has been determined that the average relative spectral irradiance will not change more than $\pm 3 \%$ over any 100-nm wavelength interval between the two measurements.

8.4 Measure the temperature of both cells.

8.5 Perform **8.2**, **8.3**, and **8.4** at least three times. One data point will be obtained for each time **8.2**, **8.3**, and **8.4** are performed.

9. Calculation of Results

9.1 Spectral Mismatch—Determine the spectral mismatch parameter M for each data set in accordance with Test Method **E973**.

9.1.1 Reject any data points where the spectral mismatch parameter is not 1.00 ± 0.20 .

9.2 Reference Cell Calibration Constant—For each data point, calculate:

$$C_i = \frac{I_{si}}{M_i} \cdot \frac{C_p}{I_{pi}} \cdot \frac{1 - \alpha_p(T_{pi} - 25)}{1 - \alpha_s(T_{si} - 25)} \quad (1)$$

where the i subscripts refer to the i th data point, the s subscripts refer to the secondary reference cell to be calibrated, and the p subscripts refer to the primary reference cell.

NOTE 4—The temperature correction terms may be deleted if the temperature control block (see **6.5**) is employed.

9.2.1 Calculate the average calibration constant using the following:

$$C = \frac{1}{n} \sum_{i=1}^n C_i \quad (2)$$

9.3 *Standard Deviation of Calibration Constant*—Calculate the standard deviation of the calibration constant using the following:

$$S = \left[\frac{\left[\sum_{i=1}^n C_i^2 \right] - nC^2}{n-1} \right]^{1/2} \quad (3)$$

9.3.1 The value of S shall be 1 % or less of the calibration constant C .

10. Report

10.1 Report, as a minimum, the following information:

10.1.1 *Secondary Reference Cell Calibration*:

10.1.1.1 Calibration constant at 25°C,

10.1.1.2 Reference spectral irradiance distribution used for calibration, (for example, Tables E490 or G173),

10.1.1.3 Linearity Verification (Report s/m as calculated using Test Method E1143),

10.1.1.4 Spectral Response, as required by Test Methods E1021,

10.1.1.5 Date of calibration,

10.1.1.6 Serial number,

10.1.1.7 Temperature coefficient, and

10.1.1.8 Fill factor.

10.1.2 *Primary Reference Cell*:

10.1.2.1 Calibration constant,

10.1.2.2 Serial number,

10.1.2.3 Calibration date, and

10.1.2.4 Temperature coefficient.

10.1.3 Description of the light source used for calibration.

10.1.4 Description of the spectral irradiance measurement instrument.

10.1.5 Data for each point in calibration, which shall include the following:

10.1.5.1 Temperature of both cells,

10.1.5.2 Short-circuit current of both cells, and

10.1.5.3 Spectral mismatch parameter.

11. Precision and Bias

11.1 *Interlaboratory Test Program*—An interlaboratory study of secondary reference cell calibrations was conducted in

1992 through 1994. Seven laboratories calibrated ten reference cells that circulated among the participants. The design of the experiment, similar to that of Practice E691, and a between analysis of the data are given in an ASTM Research Report.⁴

11.2 *Test Result*—The precision information given below in percentage points of the calibration constant submitted by each laboratory. Within-laboratory precision is not given because each participant reported a single calibration, each of which is the average of three measurements.

11.3 *Precision*:

95 % reproducibility limit (between-laboratory)

5.7 %

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

11.4.1 Loading of the cell by the current measurement instruments (due to nonzero input impedance) can result in somewhat smaller values for the short-circuit current. This situation can be eliminated by forcing the cell voltage to zero during the current measurement.

11.4.2 Measurement of the cell temperature at a point away from the junction may introduce an offset in the measured short-circuit current.

11.4.3 It is assumed that all instruments are calibrated at regular intervals. However, bias will still affect any instrumentation even after careful calibration.

11.4.4 Because the calibration of secondary reference cells employs a primary reference cell to measure the incident total irradiance, any bias associated with the primary reference cell's calibration constant is transferred to the secondary reference cell. The primary reference cell's calibration constant will most likely be dominated by the instrument (pyranometer or pyrliometer) used for total irradiance measurement during the calibration. Under normal conditions, the bias contribution from the primary reference cell will dominate the total bias for the secondary reference cell's calibration constant.

12. Keywords

12.1 calibration; photovoltaic; reference cell; secondary

⁴ Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:E44-1004.

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