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# Standard Test Method for CALIBRATION OF NON-CONCENTRATOR TERRESTRIAL PHOTOVOLTAIC PRIMARY REFERENCE CELLS UNDER DIRECT IRRADIANCE[1]

This standard is issued under the fixed designation E 1144; 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 calibrates and characterizes primary (Type I) non-concentrator terrestrial photovoltaic reference cells to a desired reference spectral irradiance distribution. The physical requirements for this reference cell are described in Practice E 1040. Reference cells are principally used in the determination of the electrical performance of photovoltaic devices.

1.2 Primary photovoltaic cells shall be calibrated in natural sunlight under specific atmospheric conditions by reference to a previously calibrated pyrheliometer.

1.3 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 in accordance with Test Method E 1143.

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

1.5 The values given in SI units are to be regarded as the standard.

1.6 *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems 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:*

E 816 Method for Calibration of Secondary Reference Pyrheliometers and Pyrheliometers for Field Use[2]

E 891 Standard for Terrestrial Direct Normal Solar Spectral Irradiance Tables for Air Mass 1.5[2]

E 948 Test Method for Electrical Performance of Non-Concentrator Terrestrial Photovoltaic Cells Using Reference Cells[2]

E 1021 Methods for Measuring the Spectral Response of Photovoltaic Cells[2]

E 1040 Practice for Physical Characteristics of Non-Concentrator Terrestrial Photovoltaic Reference Cells[2]

E 1143 Test Method for Determining the Linearity of a Photovoltaic Device Parameter With Respect to a Test Parameter[2]

## 3. Terminology

3.1 *Definitions:*

3.1.1 *calibration constant, photovoltaic reference cell*—a number that expresses the calibration of a reference cell in terms of short-circuit current per unit incidence irradiance.

*Discussion*—For a calibrated reference cell, the calibration constant expresses the short-circuit current of the reference cell, when illuminated by a reference spectral irradiance distribution (Standard E 891) divided by the total irradiance of that standard spectral irradiance.

[1] This test method is under the jurisdiction of ASTM Committee E-44 on Solar and Other Renewable Energy Conversion and is the direct responsibility of Subcommittee E44.09 on Photovoltaic Electric Power Systems.

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

3.1.2 *cell voltage*—electrical potential (in volts) across the positive and negative terminals of a photovoltaic cell.

3.1.3 *fill factor*—ratio of maximum power of the cell to the product of open-circuit voltage and short-circuit current, or:

$$FF = P_m/((V_{oc})(I_{sc}))$$

3.1.4 *irradiance, effective*—product of spectral irradiance $E(\lambda)$ and spectral response $R(\lambda)$ of a receiver integrated over all wavelengths and normalized to the receiver's response under the total irradiance $E_{ot}$ from a reference light source, or:

$$E_f = E_{ot}\{\int R(\lambda)E(\lambda)d\lambda/\int R(\lambda)E_o(\lambda)d\lambda\}$$

3.1.5 *photovoltaic device*—any photovoltaic cell or collection of cells (module, panel, or array) under consideration.

3.1.6 *photovoltaic reference cell*—a photovoltaic cell whose short-circuit current output is calibrated against the total irradiance from a reference light source.

NOTE—The reference light source is defined by a tabular direct spectrum or a global spectrum.

3.1.7 *photovoltaic reference cell, primary*—a photovoltaic cell calibrated in natural sunlight and used to measure the effective irradiance on a photovoltaic device under test.

3.1.8 *precipitable water vapor*—water in the gas phase suspended in the atmosphere.

*Discussion*—The depth of liquid water that this vapor would form if condensed is the common method of quantification.

3.1.9 *short-circuit current*—current measured between the positive and the negative terminals of the photovoltaic device when no voltage appears across these terminals.

3.1.10 *spectral correction factor*—a number that corrects calibration constant data measured under an arbitrary set of atmospheric conditions to a set of reference atmospheric conditions.

*Discussion*—The spectral correction factor, *K*, is defined as follows:

$$K = \frac{\int E(\lambda)R_r(\lambda)\,d\lambda \int E_{ref}(\lambda)\,d\lambda}{\int E(\lambda)\,d\lambda \int E_{ref}(\lambda)\,R_r(\lambda)\,d\lambda}$$

where:

$R_r(\lambda)$ = spectral response of the cell,
$E(\lambda)$ = spectral irradiance under which the calibration constant is measured, and
$E_{ref}(\lambda)$ = reference spectral irradiance distribution.

3.1.10.1 The corrected calibration constant is obtained by dividing the measured calibration constant by *K*.

3.1.11 *spectral irradiance*—spectral distribution of a light source over a specified wavelength range incident on a receiver and expressed in watts per square metre per nanometre or micrometre.

3.1.12 *spectral response*—a wavelength dependent short-circuit current density per unit irradiance.

*Discussion*—Spectral response can be discussed in terms of wavelength band.

3.1.13 *spectral response, absolute*—current density per unit irradiance at a given wavelength, or over a narrow (usually no more than 10 nm) waveband centered on a given wavelength.

*Discussion*—It may be reported as a single value at a given wavelength or plotted as a function of wavelength over a much broader spectral range.

3.1.14 *spectral response, relative*—normalized current density per unit irradiance at a given wavelength, or over a narrow (usually no more than 10 nm) waveband centered on a given wavelength.

*Discussion*—It may be reported as a single value at a given wavelength band (relative to some reference wavelength), or plotted as a function of wavelength over a much broader spectral range. The normalization is accomplished by dividing the spectral response at each wavelength by the spectral response at some convenient reference wavelength. Relative spectral response is used where the absolute magnitude of the spectral response is unimportant, simplifying the measurement procedure by eliminating the need to accurately calibrate the irradiance detector.

3.1.15 *temperature coefficient*—coefficient that correlates changes in a reference cell's short-circuit current with temperature variations in units per °C.

3.1.16 *turbidity*—turbidity is defined by the function as follows:

$$\tau = \beta\lambda^{-\alpha_\tau}$$

where:

$\beta$ = turbidity coefficient,
$\lambda$ = wavelength at which $\tau$ is evaluated, and
$\alpha_\tau$ = wavelength exponent.

3.2 *Symbols:*

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

| Symbol | Parameter | Unit |
|---|---|---|
| $\lambda$ | Wavelength | nm or µm |
| $R(\lambda)$ | Spectral response | . . . |
| $R_a(\lambda)$ | Absolute | A/W |
| $R_r(\lambda)$ | Relative | . . . |
| $E$ | Irradiance | $W/m^2$ |
| $E_t$ | Total irradiance | $W/m^2$ |
| $E_f$ | Effective irradiance | $W/m^2$ |
| $E(\lambda)$ | Spectral irradiance | $(W/m^2)/nm$ or $(W/m^2)/\mu m$ |
| $I$ | Current | A |
| $I_{sc}$ | Short-circuit current | A |
| $T$ | Temperature | °C |
| $\alpha$ | Temperature coefficient of reference cell | $°C^{-1}$ |
| $C$ | Calibration constant | $A/(W/m^2)$ |
| $\theta$ | Zenith angle | degrees |
| | Turbidity | |
| $\tau$ | Optical depth | . . . |
| $\beta$ | Turbidity coefficient | . . . |
| $\alpha_r$ | Wavelength exponent | . . . |
| $P$ | Atmospheric pressure | kPa |
| $P_o$ | Standard atmospheric pressure (101.325 kPa) | kPa |
| $K$ | Spectral correction factor | . . . |
| $S$ | Standard deviation | . . . |

## 4. Summary of Test Method

4.1 The calibration of a photovoltaic reference cell consists of measuring the short-circuit current of the cell under natural sunlight while using a calibrated pyrheliometer or active cavity radiometer to measure the incident irradiance. Error in the short-circuit current measurement due to the spectral irradiance of the natural sunlight being other than the desired spectral irradiance is corrected by dividing the short-circuit current by a spectral correction factor. In addition to the short-circuit current, the relative spectral response and the temperature coefficient of the cell being calibrated must be determined. The test methods employed in the calibration procedure are as follows:

4.1.1 The cell's spectral response is characterized using either discrete narrow band filters, a continuously variable monochromator, or other suitable technique. The spectral response of the cell shall be determined in accordance with Methods E 1021.

4.1.2 The reference 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 shall be established in accordance with Test Method E 1143 for short-circuit current versus irradiance.

4.1.4 A primary reference cell's calibration constant is determined under natural sunlight with specific atmospheric conditions by comparison to a pyrheliometer. The reference spectral irradiance distribution is defined in Standard E 891. The pyrheliometer shall be calibrated in accordance with Method 816.

4.1.5 The spectral correction factor is calculated following determination of the optical air mass, barometric pressure, aerosol turbidity, and precipitable water vapor existing in the atmosphere during measurement of the cell's short-circuit current.

## 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 measure the effective irradiance with a calibrated reference cell which closely matches the spectral response of the device under test. It is the intent of this test method to provide a recognized procedure for calibrating, and reporting the calibration data for primary photovoltaic reference cells under direct irradiance.

5.2 A primary reference cell should be checked or recalibrated, or both, at periodic intervals in accordance with good engineering and instrumentation practices.

5.3 Physical characteristics of reference cells are specified in Practice E 1040.

## 6. Apparatus

6.1 *Pyrheliometer*—A pyrheliometer that is calibrated in accordance with Method E 816 or an active cavity radiometer.

6.2 *Normal Incidence Tracking Platform*—The tracking platform shall be able to hold a pyrheliometer, the reference cell being calibrated, a collimator for the reference cell, and the water vapor/turbidity measurement equipment. The tracker shall be able to track the sun to within ±0.5° during the calibration procedure.

6.3 *Temperature Measuring Equipment*—A measurement instrument capable of determining the temperature of the reference cell and the air to within ±1°C.

6.4 *Collimator*—A collimator fitted to the reference cell during calibration shall have the same field of view as the pyrheliometer used as the irradiance monitor. The collimator design is given in Annex A1.

6.5 *Current Measurement Equipment*—A measurement instrument capable of determining the short-circuit current of the reference cell with an error of less than ±0.2 % of the short-circuit current. This error shall include all errors produced by electronic data acquisition systems and the precision of the load resistor in use.

6.5.1 The equipment for the measurement of short-circuit current shall produce a cell voltage of less than 20 mV across the reference cell.

6.6 *Voltage Measurement Equipment*—A measurement instrument capable of determining the cell voltage, pyrheliometer voltage, or other device voltages with an error of less than ±0.2 % of the actual voltage. This error shall include all errors produced by electronic data acquisition systems in use.

6.7 *Water Vapor/Turbidity Measurement Equipment*—A calibrated sun photometer[3] or other suitable device used to measure turbidity and water vapor during the calibration of primary reference cells. The device shall be able to measure turbidity to within ±10 % and water vapor to within ±15 %.[4,5,6]

6.8 *Spectral Response Measurement Equipment*—Discrete narrow-band interference filters, continuously variable monochromators, or other instruments capable of covering the appropriate spectrum shall be used to determine the relative spectral response (optionally the absolute spectral response) of the photovoltaic cell in accordance with Methods E 1021. The wavelength interval between spectral response data points shall be a maximum of 50 nm.

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

6.10 *Barometer*—An instrument to measure atmospheric pressure to within ±1 % shall be used.

## 7. Procedures

7.1 *Characterization*—Characterize the cells being calibrated by the following test methods:

7.1.1 *Spectral Response*—Determine the relative spectral response (optionally the absolute spectral response) of the cell being calibrated in accordance with Methods E 1021.

7.1.2 *Temperature Coefficient*—Determine the temperature coefficient, $\alpha$, of the cell to a precision of ±20 % using the following procedure.

7.1.2.1 Measure the $I_{sc}$ to a precision of ±1 % at four or more temperatures over at least a 50°C temperature range centered around 35°C. The irradiance shall be at least 750 W/m$^2$.

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

7.1.2.3 Determine the temperature coefficient by performing a least-squares fit of the data to a straight line.

7.1.2.4 Divide the slope of the line by the interpolated value at 25°C to establish 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 E 1143 for the irradiance range from 750 to 1100 W/m$^2$.

7.1.4 *Fill Factor*—Determine the fill factor of the cell being calibrated from the I-V curve of the device, which shall be measured in accordance with Test Method E 948.

7.2 *Calibration of Primary Photovoltaic Reference Cells*—Perform the calibration of primary photovoltaic reference cells in natural sunlight under the following conditions:

7.2.1 *Test Condition Requirements:*

7.2.1.1 *Irradiance*—The direct solar irradiance shall be greater than 750 W/m$^2$ at the time of the test, as measured by the pyrheliometer.

7.2.1.2 *Irradiance Stability*—The irradiance shall be sufficiently stable so that the variation in short-circuit current of the cell being calibrated is less than ±0.5 % over a period at least twice the pyrheliometer response time.

7.2.1.3 *Clouds and Haze*—The sky must be clear with no observable cloud formations within a 15° half-angle cone surrounding the sun.

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[3] Suitable sun photometers may be purchased from Dr. Frederick E. Volz, 24 Tyler Rd., Lexington, MA 02173, or from Sonotek Ltd., Mississauga, Ontario, Canada, or from EKO, Japan.

[4] Shaw, Glen E., "Sun Photometry," *Bulletin American Meteorological Society,* Vol 64, No. 1, January 1983, pp. 4–10.

[5] Bird, R. E., and Hulstrom, R. L., "Precipitable Water Measurements with Sun Photometers," *Journal of Applied Meteorology,* Vol 21, 1982, pp. 1196–1201.

[6] Bird, R. E., and Hulstrom, R. L., Reply to "Comments on 'Precipitable Water Measurements with Sun Photometers'," *Journal of Climate and Applied Meteorology,* Vol 22, No. 11, November 1983.

7.2.1.4 *Turbidity*—The optical depth to turbidity, $\tau$, shall be between 0.05 and 0.30 evaluated at a wavelength, $\lambda$, of 0.5 $\mu$m.

7.2.1.5 *Air Mass*—The optical air mass shall be between 1.00 and 2.00.

7.2.1.6 *Water Vapor*—The precipitable water vapor shall be between 0.5 and 2.0 cm.

7.2.2 *Test Procedures:*

7.2.2.1 Fit the cell being calibrated with a collimator such that the cell's field of view is the same as the pyrheliometer used as the irradiance monitor.

7.2.2.2 Mount the cell/collimator assembly, pyrheliometer, and water vapor/turbidity measuring equipment in a parallel plane on the same tracking mount. All equipment must track the sun to within ±0.5°.

7.2.2.3 Determine the test site longitude and latitude.

7.2.2.4 Measure the meterological conditions: air mass, turbidity, water vapor, barometric pressure, and air temperature.

7.2.2.5 Verify direct normal irradiance is ≥750 W/m$^2$.

7.2.2.6 Record the date and local standard time.

7.2.2.7 Measure the pyrheliometer output.

7.2.2.8 Measure the $I_{sc}$ of the cell being calibrated.

7.2.2.9 Measure the temperature of the cell being calibrated.

7.2.2.10 Repeat 7.2.2.4 through 7.2.2.9 at least five times while meeting the requirements of 7.2.1.

7.2.2.11 Perform 7.2.2.10 on at least two separate days.

7.2.2.12 Calculate the calibration constant for the cell being calibrated using the formula contained in Section 8.

## 8. Calculation and Interpretation of Results

8.1 All data shall be corrected to a reference temperature of 25°C.

8.2 *Temperature Coefficient*—The temperature coefficient shall be determined in accordance with the procedure contained in 7.1.2.

8.3 *Linearity*—The cell's linearity shall be determined in accordance with Test Method E 1143.

8.4 *Spectral Correction Factor*—The spectral correction factor, $K$, shall be determined for each measured $I_{sc}$ of the cell being calibrated in accordance with Annex A2.

8.5 *Cell Calibration Constant*—For each time 7.2.2.4 through 7.2.2.9 are performed, calculate as follows:

$$C_i = \frac{I_{sc_i}[1 - \alpha(T_i - 25)]}{K_i E_{t_i}}$$

where:

$I_{sc_i}$ = measured short-circuit current of cell being calibrated for i$^{th}$ data point,
$E_{t_i}$ = total irradiance for i$^{th}$ data point,
$T_i$ = measurement temperature,
$\alpha$ = temperature coefficient,
$K_i$ = spectral correction factor, and
$C_i$ = calibration constant.

8.5.1 Compute the average calibration constant as follows:

$$C = \frac{1}{n} \sum_{i=1}^{n} C_i$$

where:

$n$ = total number of $C_i$ measurements.

8.6 *Standard Deviation of Calibration Constant*—The standard deviation of the calibration constant is calculated as follows:

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

8.6.1 The value of $S$ shall be 1 % or less of the average calibration constant, $C$.

## 9. Reports

9.1 The calibration report for a primary reference cell shall include as a minimum the following information:

9.1.1 *Linearity Verification*—As calculated in accordance with Test Method E 1143.

9.1.2 *Spectral Response*—As determined by Methods E 1021.

9.1.3 Test conditions for each data point in the data set shall include the following:

9.1.3.1 Air mass,

9.1.3.2 Water vapor,

9.1.3.3 Turbidity at 0.5 $\mu$m,

9.1.3.4 Barometric pressure,

9.1.3.5 Air temperature,

9.1.3.6 Test site longitude and latitude,

9.1.3.7 Date and local standard time of measurements,

9.1.3.8 Minimum and maximum temperature of cell during calibration,

9.1.3.9 Total irradiance, and

9.1.3.10 Spectral correction factor.

9.1.4 Primary Reference Cell Calibration Data, shall include the following:

9.1.4.1 Calibration constant at 25°C,

9.1.4.2 Standard deviation,

9.1.4.3 Reference irradiance used,

9.1.4.4 Serial number,

9.1.4.5 Pyrheliometer (type, manufacturer, serial number, calibration constant, primary reference, date of calibration),

9.1.4.6 Fill factor, and

9.1.4.7 Temperature coefficient.

## 10. Precision and Bias

10.1 Estimates for precision and bias provided in this test method are intended for guidance only. The estimates are based on good engineering judgement and will have to be refined eventually by interlaboratory determinations of precision and bias.

10.2 *Precision:*

10.2.1 The factors collected in Table 1 may cause variability in the measurements made according to this test method. Each factor is assigned an estimated index of precision given as one standard deviation percentage of the quantity measured. The index of precision is an error introduced by the statistical nature of the measurement process.

10.2.2 The total index of precision of the reported calibration constant can be calculated as the square root of the sum of the squares of the individual contributions. The measurement procedures determine which of the contributions listed in Table 1 have to be considered in the calculation according to which ones are involved in generating the calibration constant.

10.3 *Bias:*

10.3.1 Bias of the results is influenced by several systematic factors that are discussed in 10.3.5 through 10.5, and Table 2. The estimated systematic error is given as a percentage of the true value (see 10.4).

10.3.2 Loading of the cell by the electrical measurement instruments, that is, nonzero input impedance of the ammeter (for short-circuit current measurement) will result in somewhat smaller values for this quantity. This situation can occur unless the voltage can be forced actively to zero in short-circuit current measurement.

10.3.3 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 the source illumination. This may result in a value for short-circuit current that is slightly too high.

10.3.4 It is assumed that the instruments used in the measurements are calibrated at regular intervals, however, to account for drift of the instruments between calibrations a combined bias from all instruments of 0.1 % is assumed.

10.3.5 Reproduction of the reference spectral irradiance distribution can only be accomplished with natural sunlight when the atmospheric conditions are exactly as required. To be practical, the test method must allow for a "window" on each atmospheric parameter, (see 7.2.1) and the various combinations of these allowable conditions will cause errors in the short-circuit current of the primary reference cell under calibration relative to the pyrheliometer measurement. The purpose of the spectral correction factor is to reduce these errors. Annex A2 provides spectral correction factors for correcting the short-circuit current measured for a generic crystalline silicon solar cell, and provides a listing of a FORTRAN computer program that can be used to calculate a spectral correction factor for other photovoltaic devices.

10.3.6 A bias of 0.25 % for terrestrial solar radiometric measurement has been determined by a series of international comparisons of active cavity radiometers.[7] An additional bias of 1 % when calibrating a pyrheliometer with an active cavity radiometer is to be expected when using the procedures of Method E 816.

10.4 A summary of the estimated bias is given as a percentage of the quantity measured, for the factors discussed in 10.3.2 through 10.3.6.

10.5 The total bias associated with the reported calibration constant can be calculated as the square root of the sum of the squares of the individual contributions. The measurement procedures determine which of the contributions listed in Table 2 have to be considered in the calculation according to which ones are involved in generating the calibration constant.

[7] Estey, R. S., and Seaman, C. H., "Four Absolute Cavity Radiometer (Pyrheliometer) Intercomparisons at New River, Arizona," *JPL Publication*, 81-60, Jet Propulsion Laboratory, Pasadena, CA, July 1981.