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Standard Test ~~Method~~Methods for Calibration of Non-Concentrator Photovoltaic ~~Secondary~~Non-Primary Reference Cells[1]

This standard is issued under the fixed designation E1362; 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~~These test ~~method covers~~methods cover calibration and characterization of ~~secondary~~non-primary 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~~Non-primary 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.~~previously calibrated reference cell, which is referred to as the calibration source device.

1.2.1 The non-primary calibration will be with respect to the same reference spectral irradiance distribution as that of the calibration source device.

1.2.2 The calibration source device may be a primary reference cell calibrated in accordance with Test Method E1125, or a non-primary reference cell calibrated in accordance with these test methods.

1.2.3 For the special case in which the calibration source device is a primary reference cell, the resulting non-primary reference cell is also referred to as a secondary reference cell.

1.3 ~~Secondary~~Non-primary reference cells calibrated according to ~~this~~these test ~~method~~methods will have the same radiometric traceability as ~~the of the primary reference cell used for the calibration.~~ that of the calibration source device. Therefore, if the ~~primary reference cell~~calibration source device 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~~These test ~~method applies~~methods apply 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~~These test ~~method applies~~methods apply 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.*

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 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

[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.

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 Irradiation (Withdrawn 2004)[3]~~
E1040 Specification for Physical Characteristics of Nonconcentrator 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 (Withdrawn 2012)[3]~~
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~~these test ~~method~~methods may be found in Terminology E772 ~~and in Terminology E1328~~.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 ~~*junction temperature,*~~ *calibration source device, photovoltaic, n*—~~synonym for~~the reference cell ~~temperature.~~used to measure the incident irradiance during the calibration. ~~E1328~~

3.2.2 *monitor solar cell, n*—a solar cell used to measure the irradiance of the solar simulator during the calibration; prior to the calibration procedure, the monitor solar cell is compared against the calibration source device using a transfer-of-calibration procedure.

3.2.3 *non-primary reference cell, photovoltaic, n*—a photovoltaic reference cell calibrated against another reference cell in accordance with Test Method E1362. E772

3.2.4 *primary reference cell, photovoltaic, n*—a photovoltaic reference cell calibrated in sunlight in accordance with Test Method E1125. E772

3.2.5 *secondary reference cell, photovoltaic, n*—a photovoltaic reference cell calibrated against a primary reference cell in accordance with Test Method E1362. E772

3.2.6 *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~~these test ~~method:~~methods:

A—active area, reference cell (m^2),
C—calibration constant, Am^2W^{-1},
C_T—transfer calibration ratio (dimensionless),
D—as a subscript, refers to the reference cell to be calibrated,
E—irradiance, ~~Wm~~(Wm^{-2}),
$E_{\lambda 0}$—total irradiance, ~~Wm~~reference spectral irradiance distribution (Wm^{-2}),
~~*I*~~E_0~~—current, A,~~(λ)—reference spectral irradiance distribution ($Wm^{-2}\mu m^{-1}$ or $Wm^{-2}nm^{-1}$),
~~*I*~~i_p~~—primary reference cell short-circuit current, A,~~—as a subscript, refers to the *i*th calibration data point,
I or I_{sSC}~~—secondary reference cell short-circuit current, A,~~—short-circuit current, (A),
I_{seM}—short-circuit current, ~~A,~~monitor solar cell (A),
~~*L*—collimator length, m,~~
M—spectral mismatch ~~parameter,~~parameter (dimensionless),
n—total number of calibration data points,
~~*r*~~*Q*(λ,*T*)~~—collimator receiving aperture radius, m,~~—quantum efficiency (electrons/photon or %),
~~*R*—collimator opening aperture radius, m,~~—as a subscript, refers to the calibration source device,
$R_{\alpha A}(\lambda)$—absolute spectral ~~response, AW~~response (AW^{-1}),
~~*R*~~s_r~~—relative spectral response,~~—standard deviation,
~~*S*—standard deviation,~~
T—temperature, ~~°C,~~(°C),
~~α~~T_0~~—temperature coefficient of reference cell, °C~~—calibration temperature, (°C),~~$^{-1}$~~,~~
~~θ~~ΔT_o~~—collimator opening angle, °, and~~—temperature difference, (°C),
~~λ—wavelength, nm or μm.~~—wavelength (nm or μm), and
Θ(λ)—partial derivative of quantum efficiency with respect to temperature (electrons per photon·°C^{-1} or %·°C^{-1}).
~~3.3.2 Symbolic quantities that are functions of wavelength appear as *X*(λ).~~

4. Summary of Test Method

4.1 The calibration constant, C, of a photovoltaic refererence cell is defined as the ratio of its short-circuit current to the total irradiance when illuminated with a reference spectral irradiance distribution (such as Standard E490 or Tables G173). In integral form, the calibration constant is:

$$C = \frac{I_{SC}}{E_0} = \frac{A\int R_A(\lambda)E_0(\lambda)d\lambda}{\int E_0(\lambda)d\lambda} \quad (1)$$

4.2 A reference cell is used to measure irradiance through Eq 2:

$$E = I_{SC}/C \quad (2)$$

4.3 Errors and difficulties associated with measuring A and $R_A(\lambda)$ in Eq 1 can be avoided by comparing the short-circuit current of a reference cell to be calibrated (I_D) against that of a previously calibrated reference cell (that is, the calibration source device, I_R), while both cells are illuminated with a test light source. The calibration constant of the calibration source device transforms short-circuit current to total irradiance so that Eq 1 becomes:

$$C_D = \frac{I_D}{I_R/C_R} \quad (3)$$

4.4 For calibrations in natural sunlight, the calibration source device and the cell to be calibrated are placed on a normal incidence tracking platform, and the short-circuit currents of both devices are measured simultaneously.

4.5 For calibrations in simulated sunlight, the calibration source device is first placed in the test plane, and a transfer-of-calibration procedure is performed to a monitor solar cell. The calibration source device is then replaced with the cell to be calibrated in the same location, and the non-primary calibration is then performed.

4.6 *Calibration Temperature*—These procedures assume the calibration temperatures, T_0, of both the calibration source device and the cell to be calibrated are 25°C; other calibration temperatures may be substituted if desired.

4.7 *Calibration Data Collection*—Raw calibration constant data are corrected for spectral and temperature differences using the spectral mismatch parameter, M (see 5.2 and Test Method E973).

4.8 *Light Soaking*—Newly manufactured reference cells must be light soaked at an irradiance level greater than 850 W/m^2 for 20 h prior to initial characterization.

4.9 *Characterization*—~~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 ± 1°C, the temperature coefficient for the short-circuit current is needed. The list of necessary test methods is as follows:~~Prior to calibration, the non-primary cell is characterized using the following procedures:

4.9.1 ~~The spectral response of the cell to be~~Quantum efficiency at the calibration temperature, $Q(\lambda,T_0$ ~~calibrated is~~), determined in accordance with Test Methods E1021.

4.9.2 ~~The cell's short-circuit current temperature coefficient~~Partial derivative of quantum efficiency with respect to temperature $\Theta_D(\lambda)=\partial Q_D/\partial T$ ~~is determined experimentally by measuring short-circuit current at various temperatures~~(λ), determined in accordance with Annex A1 of Test Methods E973~~and computing the temperature coefficient.~~.

4.9.3 Linearity of short-circuit current versus ~~irradiance is~~ irradiance, 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 It is the intent of these test methods to provide a recognized procedure for calibrating, characterizing, and reporting the calibration data for non-primary photovoltaic reference cells that are used during photovoltaic device performance measurements.

5.2 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.~~ device under test. 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~~ quantified with 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.~~).

5.2.1 Test Method E973 requires four quantities for spectral mismatch calculations:

5.2.1.1 The quantum efficiency of the reference cell to be calibrated (see 7.1.1),
5.2.1.2 The quantum efficiency of the calibration source device (required as part of its calibration),

NOTE 1—See 10.10 of Test Method E1021 for the identity that converts spectral responsivity to quantum efficiency.

5.2.1.3 The spectral irradiance of the light source (measured with the spectral irradiance measurement equipment), and,
5.2.1.4 The reference spectral irradiance distribution to which the calibration source device was calibrated (see G173).
5.2.2 *Temperature Corrections*—Test Method E973 provides means for temperature corrections to short-circuit current using the partial derivative of quantum efficiency with respect to temperature.

5.3 A ~~secondary~~non-primary reference cell is calibrated in accordance with these test methods is with respect to the same reference spectral irradiance distribution as ~~the primary reference cell used during the calibration.~~ that of the calibration source device. Primary reference cells ~~can~~may be calibrated by use of Test Method E1125 ~~or Test Method E1039~~.

NOTE 2—No ASTM standards for calibration of primary reference cells to the extraterrestrial spectral irradiance distribution presently exist.

5.4 A ~~secondary~~non-primary reference cell should be recalibrated yearly, or every six months if the cell is in continuous use outdoors.

5.5 Recommended physical characteristics of reference cells are provided in Specification E1040.

5.6 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~~soaked, see [2] ~~for 2 h prior to initial charcterization in Section 7~~4.8.

5.7 The choice of natural sunlight versus solar simulation for the test light source involves tradeoffs between the advantages and disadvantages of either source. Natural sunlight provides excellent spatial uniformity over the test plane but the total and spectral irradiances vary with the apparent motion of the sun and changes of atmospheric conditions such as clouds. Calibrations in a solar simulator can be done at any time and provide a stable spectral irradiance. Disadvantages of solar simulators include spatial non-uniformity and short-time variations in total irradiance. The procedures in these test methods have been designed to overcome these disadvantages.

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~~ platform that holds the calibration source device, the cell to be ~~calibrated. The tracker shall be able to track the sun to within ±0.5°~~ calibrated, and the spectral irradiance measurement equipment (see 6.7) coplanar during the calibration procedure. Using two orthogonal axes, such as azimuth and elevation, the platform must follow the apparent motion of the sun such that the angle between the sun vector and the normal vector is less than 0.5°.

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

6.1.2 ~~When the calibration is~~ For calibrations performed in ~~global normal conditions, no significant~~ hemispherical sunlight conditions, energy reflected from surrounding buildings or any other surfaces in the vicinity of the ~~test stand~~tracking platform shall be ~~allowed onto the reference cells~~ blocked 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.~~Such conditions can result in spatially non-uniform illumination between the cell to be calibrated and the calibration source device.

6.1.2.1 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, a horizon shield shall be used. This horizon shield shall consist of a black nonreflecting surface, and shall block the view downward from the local horizon to the lowest extremes of the field of view.

6.2 *Solar ~~Simulator~~—Simulator* (for calibrations conducted in simulated sunlight)—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~~ BAA solar simulator per Specification E927.

6.3 *Temperature Measurement Equipment*—An instrument or instruments used to measure the cell ~~temperature~~temperatures of ~~both the primary reference cell~~the calibration source device and 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.

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

6.3.2 Specification E1040 requires packaged reference cells to have embedded temperature sensors.

6.3.3 Time constants associated with these measurements must be less than 500 ms.