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# Standard Test Methods for Calibration of Non-Concentrator Photovoltaic 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 These test methods cover calibration and characterization of 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 Non-primary reference cells are calibrated indoors using simulated sunlight or outdoors in natural sunlight by reference to a 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 Non-primary reference cells calibrated according to these test methods will have the same radiometric traceability as that of the calibration source device. Therefore, if the 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 These test 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 These test 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
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
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
G173 Tables for Reference Solar Spectral Irradiances: Direct

[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.

Normal and Hemispherical on 37° Tilted Surface

## 3. Terminology

3.1 *Definitions*—Definitions of terms used in these test methods may be found in Terminology E772.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *calibration source device, photovoltaic, n*—the reference cell used to measure the incident irradiance during the calibration.

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 these test 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, ($Wm^{-2}$),

$E_0$—total irradiance, reference spectral irradiance distribution ($Wm^{-2}$),

$E_0(\lambda)$—reference spectral irradiance distribution ($Wm^{-2}\mu m^{-1}$ or $Wm^{-2}nm^{-1}$),

$i$ —as a subscript, refers to the $i$th calibration data point,

$I$ or $I_{SC}$—short-circuit current, (A),

$I_M$—short-circuit current, monitor solar cell (A),

$M$—spectral mismatch parameter (dimensionless),

$n$—total number of calibration data points,

$Q(\lambda,T)$—quantum efficiency (electrons/photon or %),

$R$—as a subscript, refers to the calibration source device,

$R_A(\lambda)$—absolute spectral response ($AW^{-1}$),

$s$—standard deviation,

$T$—temperature, (°C),

$T_0$—calibration temperature, (°C),

$\Delta T$—temperature difference, (°C),

$\lambda$—wavelength (nm or µm), and

$\Theta(\lambda)$—partial derivative of quantum efficiency with respect to temperature (electrons per photon·$°C^{-1}$ or %·$°C^{-1}$).

## 4. Summary of Test Method

4.1 The calibration constant, $C$, of a photovoltaic reference 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*—Prior to calibration, the non-primary cell is characterized using the following procedures:

4.9.1 Quantum efficiency at the calibration temperature, $Q(\lambda,T_0)$, determined in accordance with Test Methods E1021.

4.9.2 Partial derivative of quantum efficiency with respect to temperature $\Theta_D(\lambda)=\partial Q_D/\partial T(\lambda)$, determined in accordance with Annex A1 of Test Methods E973.

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

## 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 reference cell is not identical to the spectral response of the 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 quantified with the spectral mismatch parameter *M* (Test Method E973).

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

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

5.4 A 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, see 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 platform that holds the calibration source device, the cell to be 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 For calibrations performed in direct sunlight, the cells and the spectral irradiance measurement equipment shall have collimators that meet the requirements of Annex A1 of Test Method E1125.

6.1.2 For calibrations performed in hemispherical sunlight conditions, energy reflected from surrounding buildings or any other surfaces in the vicinity of the tracking platform shall be blocked for the duration of the calibration period. 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* (for calibrations conducted in simulated sunlight)—A light source that meets the requirements of a Class BAA solar simulator per Specification E927.

6.3 *Temperature Measurement Equipment*—An instrument or instruments used to measure the cell temperatures of 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 positions that minimize any temperature gradients between the sensor and the photovoltaic device 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.

6.4 *Short-Circuit Current Measurement Equipment*—Electrical instrumentation used to measure short-circuit currents of the cell to be calibrated, the calibration source device, and the monitor solar cell.

6.4.1 The instrumentation shall have 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.

6.4.2 The instrumentation shall be capable of holding the voltage across these cells to within 25 mV of zero.

6.5 *Temperature Control Block*—A device to maintain the temperature of both reference cells at 25 ± 2°C for the duration of the calibration.

6.6 *Quantum Efficiency Measurement Apparatus*—as required by Test Methods E1021 for spectral responsivity measurements.

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

6.8 *Monitor Solar Cell* (for calibrations conducted in simulated sunlight)—A solar cell that is positioned in the test plane of the solar simulator such that it is illuminated during the non-primary calibration. The monitor solar cell is used to measure the irradiance following a transfer-of-calibration procedure from the calibration source device. It is also used to correct current measurement data points of the cell to be calibrated for temporal instability of the solar simulator.

6.8.1 The monitor solar cell may be positioned anywhere in the test plane of the solar simulator, but shall not be moved after the transfer-of-calibration procedure has been performed.

6.8.2 The quantum efficiency of the monitor solar cell is unimportant, but the wavelength range of its responsivity should include that of the cell to be tested. Crystalline-Si solar cells are recommended.

6.8.3 The monitor solar cell shall be mounted on a test fixture that controls its cell temperature constant to within ±1°C during the performance measurement. It is recommended that the monitor solar cell have its own test fixture.

6.8.4 The time constant of the monitor solar cell's temperature measurement must be less than 500 ms.

## 7. Characterization

7.1 The cell to be calibrated shall be characterized by the following methods:

7.1.1 *Quantum Efficiency*—Determine the relative quantum efficiency (optionally the absolute quantum efficiency) of the reference cell to be calibrated at 25°C in accordance with Test Methods E1021.

7.1.1.1 The wavelength interval between quantum efficiency data points shall be a maximum of 20 nm.

7.1.1.2 For reference cells made with direct bandgap semiconductors such as GaAs, it is recommended that the wavelength interval be no greater than 5 nm.

7.1.1.3 Repetition of 7.1.1 is optional if the quantum efficiency has been previously measured.

7.1.2 *Partial Derivative of Quantum Efficiency with Respect to Temperature*—Determine the working temperature range of the reference cell to be calibrated and measure its $\Theta_D(\lambda)$ according to Annex A1 of Test Methods E973.

NOTE 3—Test Methods E973 require all quantum efficiency measurements needed for $Q(\lambda,T_0)$ and $\Theta_D(\lambda)$ to be measured with the same multiplicative calibration constants or scaling factors.

7.1.2.1 Repetition of 7.1.2 is optional if $\Theta_D(\lambda)$ has been previously measured.

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 Repetition of 7.1.3 is optional if the linearity has been previously determined according to 7.1.3.

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. The fill factor may be measured either prior to or following the calibration procedure.

## 8. Conditioning

8.1 Light soak the cell to be calibrated at an irradiance greater than 850 $Wm^{-2}$ for 20 h, in either natural sunlight or a solar simulator.

8.1.1 Repetition of the light soaking is optional if the cell has been previously light-soaked in accordance with 8.1.

## 9. Procedure

9.1 *Natural Sunlight:*

9.1.1 Mount the calibration source device and the reference cell to be calibrated on the normal incidence tracking platform, and orient the cells to within ±0.5° of normal to the sun's direct beam.

9.1.2 Connect the calibration source device and the reference cell to be calibrated to the short-circuit current measurement equipment.

9.1.3 Adjust the temperature control block so that the temperatures of both reference cells are within 25 ± 2°C.

9.1.4 Prepare to measure the incident solar spectral irradiance using the spectral irradiance measurement equipment.

9.1.5 Verify that the following test conditions are met:

9.1.5.1 The total irradiance shall be >750 $Wm^{-2}$ and <1100 $Wm^{-2}$ at the time of the calibration, as measured with the calibration source device and Eq 2.

9.1.5.2 The sky should be clear with no observable cloud formations within a 30° half-angle cone surrounding the sun.

9.1.6 Simultaneously measure:

9.1.6.1 The short-circuit current of the calibration source device, $I_R$,

9.1.6.2 The short-circuit current of the reference cell to be calibrated, $I_D$,

9.1.6.3 The temperatures of both reference cells, $T_R$ and $T_D$, and

9.1.6.4 The incident solar spectral irradiance, $E(\lambda)$, according to 7.3 of E973.

9.1.7 If the time required to measure the solar spectral irradiance is greater than the short-circuit current measurement time, repeat 9.1.6.1 – 9.1.6.3, and average the results to obtain single values.

9.1.8 Repeat 9.1.6 at least three times; one data point will be obtained for each repetition.

9.2 *Simulated Sunlight:*

9.2.1 Measure the spectral irradiance of the solar simulator. This measurement spectral irradiance shall have been performed within 50 h of lamp time before or after the calibration measurement, unless the solar simulator's spectral stability has demonstrated that a longer period causes no discernable error.

9.2.2 If possible, adjust the total irradiance of the solar simulator so that it is within ±5% of the integrated total irradiance of the desired reference spectral irradiance, as measured with the calibration source device and Eq 2.

9.2.3 *Stable Solar Simulator*—If the temporal instability of the solar simulator (as defined in Specification E927) is less than 0.1 %, the short-circuit current of the calibration source device may be measured prior to that of the reference cell to be calibrated. In this case, use the following steps to measure the short-circuit currents. Otherwise, proceed to 9.2.4.

9.2.3.1 Place the calibration source device in the test plane, connect it to the short-circuit current measurement equipment, and expose it to the solar simulator's light.

9.2.3.2 Adjust the temperature control block so that the temperature of the calibration source device is within 25 ± 2°C.

9.2.3.3 Measure temperature of the calibration source device, $T_R$.

9.2.3.4 Measure the short-circuit current of the calibration source device, $I_R$.

9.2.3.5 Remove the calibration source device.

9.2.3.6 Place the reference cell to be calibrated in the test plane in the same spatial position (X-Y-Z) as that of the calibration source device, with the vertical positions those of the cell surfaces.

9.2.3.7 Connect the reference cell to be calibrated to the short-circuit current measurement equipment and expose it to the solar simulator's light.

9.2.3.8 Adjust the temperature control block so that the temperature of the reference cell to be calibrated is within 25 ± 2°C.

9.2.3.9 Measure temperature of the reference cell to be calibrated, $T_D$,

9.2.3.10 Measure the short-circuit current of the reference cell to be calibrated, $I_D$,

9.2.3.11 Proceed to 9.2.5.

9.2.4 *Unstable Solar Simulator:*

9.2.4.1 Place the calibration source device in the test plane, connect it to the short-circuit current measurement equipment, and expose it to the solar simulator's light.

9.2.4.2 Adjust the temperature control block so that the temperature of the calibration device is within 25 ± 2°C.

9.2.4.3 Measure temperature of the calibration source device, $T_R$.

9.2.4.4 Measure the short-circuit currents of the calibration source device and the monitor solar cell simultaneously within 1 ms; these data will be used for the calibration transfer (see 4.5).

9.2.4.5 Repeat 9.2.4.4 a minimum of 10 times. The number of needed repetitions will vary according to the temporal instability of the light source, and judgment should be used to establish the number needed for the transfer calibration.

9.2.4.6 Calculate the transfer calibration ratio using Eq 4, where $n$ is the number of repetitions:

$$C_T = \frac{1}{n}\sum_1^n \frac{I_R}{I_M} \tag{4}$$

9.2.4.7 Remove the calibration source device from the test plane.

9.2.4.8 Place the reference cell to be calibrated in the test plane in the same spatial position (X-Y-Z) as that of the calibration source device, with the vertical positions those of the cell surfaces.

9.2.4.9 Connect the cell to be calibrated to the short-circuit current measurement equipment and expose it to the solar simulator's light.

9.2.4.10 Adjust the temperature control block so that the temperature of the reference cell to be calibrated is within 25 ± 2°C.

9.2.4.11 Measure temperature of the reference cell to be calibrated, $T_D$.

9.2.4.12 Simultaneously measure the short-circuit currents of the reference cell to be calibrated and the monitor solar cell, $I_D$ and $I_M$.

9.2.4.13 Repeat 9.2.4.12 a minimum of 10 times; one data point will be obtained for each repetition.

9.2.5 Remove the reference cell to be calibrated from the test plane.

## 10. Calculation of Results

10.1 Determine the spectral mismatch parameter $M_i$ for each data set in accordance with Test Method E973.

10.1.1 *Natural Sunlight*—Reject any data points in which is $M_i$ is not 1.00 ± 0.20.

10.1.2 *Solar Simulation*—As only a single spectral irradiance was measured, $M$ will be identical for each data point.

10.1.3 If the measured temperature of the calibration source device, $T_R$, is within 25 ± 0.5°C, the temperature difference $\Delta T_R$ in Eq 1 of Test Method E973 may be assumed to be zero.

10.1.4 If the measured temperature of the reference cell to be calibrated, $T_D$, is within 25 ± 0.5°C, the temperature difference $\Delta T_D$ in Eq 1 of Test Method E973 may be assumed to be zero.

10.2 For each data point, calculate the calibration constant of the cell to be calibrated.

10.2.1 If the transfer calibration technique was used (see 4.5 and Eq 4), use Eq 5:

$$C_{Di} = I_{Di}\frac{C_R}{C_T \cdot I_{Mi}}\frac{1}{M_i} \tag{5}$$

10.2.2 Otherwise, use Eq 6:

$$C_{Di} = I_{Di}\frac{C_R}{I_{Ri}}\frac{1}{M_i} \tag{6}$$

10.3 Calculate the average calibration constant using Eq 7:

$$C_D = \frac{1}{n}\sum_{i=1}^{n} C_{Di} \tag{7}$$

10.4 Calculate the standard deviation of the calibration constant using Eq 8:

$$s = \left[\frac{\left[\sum_{i=1}^{n} C_{Di}^2\right] - nC_D^2}{n-1}\right]^{1/2} \tag{8}$$

10.4.1 The value of $s$ shall be 1 % or less of the calibration constant $C$.

## 11. Report

11.1 The calibration report, as a minimum, shall contain the following information:

11.1.1 *Non-Primary Reference Cell Calibration:*

11.1.1.1 Calibration constant $C_D$, from Eq 7,

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

11.1.1.3 Linearity verification as required by Test Method E1143),

11.1.1.4 Quantum efficiency, as required by Test Methods E1021,

11.1.1.5 Date of calibration,

11.1.1.6 Serial number,

11.1.1.7 $\Theta_D(\lambda)$ and the working temperature range, from 7.1.3,

11.1.1.8 Fill factor,

11.1.1.9 Calibration temperature, and

11.1.1.10 Standard deviation of calibration constant, *s*, from Eq 8.

11.1.2 *Calibration Source Device:*

11.1.2.1 Calibration constant,

11.1.2.2 Serial number,

11.1.2.3 Calibration date,

11.1.2.4 $\Theta_R(\lambda)$,

11.1.2.5 Calibration laboratory, and

11.1.2.6 Calibration path to a primary reference cell.

11.1.3 Description of the test light source used for calibration, that is, natural sunlight or the solar simulator.

11.1.4 Each calibration data point, which shall include the following:

11.1.4.1 Temperature of both cells,

11.1.4.2 Short-circuit current of both cells, and

11.1.4.3 Spectral mismatch parameter.

## 12. Precision and Bias

12.1 *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.[3]

12.2 *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.

12.3 *Precision:*

| | |
|---|---|
| 95 % reproducibility limit (between-laboratory) | 5.7 % |

12.4 *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:

12.4.1 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.

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

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

12.4.4 Because a non-primary reference cell calibration employs another reference cell to measure total irradiance, the bias associated with the calibration source reference is transferred to the reference cell to be calibrated. Therefore, the total bias is effectively the sum of the bias contributed by each reference cell in the chain back to the primary reference cell, and the total bias increases at each calibration step.

## 13. Keywords

13.1 calibration; non-primary; photovoltaic; radiometric; reference cell; secondary

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