



Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells¹

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1. Scope

1.1 These test methods cover the electrical performance of photovoltaic modules and arrays under natural or simulated sunlight using a calibrated reference cell.

1.1.1 These test methods allow a reference module to be used instead of a reference cell provided the reference module has been calibrated using these test methods against a calibrated reference cell.

1.2 Measurements under a variety of conditions are allowed; results are reported under a select set of reporting conditions (RC) to facilitate comparison of results.

1.3 These test methods apply only to nonconcentrator terrestrial modules and arrays.

1.4 The performance parameters determined by these test methods apply only at the time of the test, and imply no past or future performance level.

1.5 These test methods apply to photovoltaic modules and arrays that do not contain series-connected photovoltaic multijunction devices; such module and arrays should be tested according to Test Methods E2236.

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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.8 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

¹ These test methods are under the jurisdiction of ASTM Committee E44 on Solar, Geothermal and Other Alternative Energy Sources and are the direct responsibility of Subcommittee E44.09 on Photovoltaic Electric Power Conversion.

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2. Referenced Documents

2.1 ASTM Standards:²

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

E772 Terminology of Solar Energy Conversion

E927 Specification for Solar Simulation for Photovoltaic Testing

E941 Test Method for Calibration of Reference Pyranometers With Axis Tilted by the Shading Method (Withdrawn 2005)³

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 Nonconcentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum

E1362 Test Methods for Calibration of Non-Concentrator Photovoltaic Non-Primary Reference Cells

E2236 Test Methods for Measurement of Electrical Performance and Spectral Response of Nonconcentrator Multijunction Photovoltaic Cells and Modules

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 these test methods may be found in Terminology E772.

3.2 *Definitions of Terms Specific to This Standard:*

² For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

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

3.2.1 *nominal operating cell temperature, NOCT, n* —the temperature of a solar cell inside a module operating at an ambient temperature of 20°C, an irradiance of 800 Wm⁻², and an average wind speed of 1 ms⁻¹.

3.2.2 *reporting conditions, RC, n* —the device temperature, total irradiance, and reference spectral irradiance conditions that module or array performance data are corrected to.

3.3 Symbols:

3.3.1 The following symbols and units are used in these test methods:

- α_r —temperature coefficient of reference cell I_{SC} , °C⁻¹,
- α —current temperature coefficient of device under test, °C⁻¹,
- $\beta(E)$ —voltage temperature function of device under test, °C⁻¹,
- C —calibration constant of reference cell, Am²W⁻¹,
- C' —adjusted calibration constant of reference cell, Am²W⁻¹,
- C_f —NOCT Correction factor, °C,
- $\delta(T)$ —voltage irradiance correction function of device under test, dimensionless,
- ΔT —NOCT cell-ambient temperature difference, °C,
- E —irradiance, Wm⁻²,
- E_o —irradiance at RC, Wm⁻²,
- FF —fill factor, dimensionless,
- I —current, A,
- I_{mp} —current at maximum power, A,
- I_o —current at RC, A,
- I_r —short-circuit current of reference cell (or module, see 1.1.1 and 4.3.4), A,
- I_{sc} —short-circuit current, A,
- M —spectral mismatch parameter, dimensionless,
- P —electrical power, W,
- P_m —maximum power, W,
- T —temperature, °C,
- T_a —ambient temperature, °C,
- T_c —temperature of cell in module, °C,
- T_o —temperature at RC, °C,
- T_r —temperature of reference cell, °C,
- v —wind speed, ms⁻¹,
- V —voltage, V,
- V_{mp} —voltage at maximum power, V,
- V_o —voltage at RC, V, and
- V_{oc} —open-circuit voltage, V.

4. Summary of Test Methods

4.1 Measurement of the performance of a photovoltaic module or array illuminated by a light source consists of determining at least the following electrical characteristics: short-circuit current, open-circuit voltage, maximum power, and voltage at maximum power.

4.2 These parameters are derived by applying the procedure in Section 8 to a set of current-voltage data pairs (I - V data) recorded with the test module or array operating in the power-producing quadrant.

4.3 Testing the performance of a photovoltaic device involves the use of a calibrated photovoltaic reference cell to determine the total irradiance.

TABLE 1 Reporting Conditions

	Total Irradiance, Wm ⁻²	Spectral Irradiance	Device Temperature, °C
Standard reporting conditions	1000	G173	25
Nominal operating conditions	800	...	NOCT

4.3.1 The reference cell is chosen according to the spectral distribution of the irradiance under which it was calibrated, for example, the direct normal or global spectrum. These spectra are defined by Tables G173. The reference cell therefore determines to which spectrum the test module or array performance is referred.

4.3.2 The reference cell must match the device under test such that the spectral mismatch parameter is 1.00 ± 0.05, as determined in accordance with Test Method E973.

4.3.3 Recommended physical characteristics of reference cells are described in Specification E1040.

4.3.4 A reference module may be used instead of a reference cell throughout these test methods provided 4.3.2 is satisfied and the short-circuit current of the reference module has been determined according to the procedures in these test methods using a reference cell. The reference module must also meet the module package design requirements in Specification E1040, with the exception of the electrical connector requirement. Ideally, electrical connections to an individual cell in the reference module should be provided to allow for spectral responsivity measurement according to Test Method E1021.

4.4 The spectral response of the module or array is usually taken to be that of a representative cell from the module or array tested in accordance with Test Method E1021. The representative cell should be packaged such that the optical properties of the module or array packaging and the representative cell package are similar.

4.5 The tests are performed using either natural or simulated sunlight. Solar simulation requirements are stated in Specification E927.

4.5.1 If a pulsed solar simulator is used as a light source, the transient responses of the module or array and the reference cell must be compatible with the test equipment.

4.6 The data from the measurements are translated to a set of reporting conditions (see 5.3) selected by the user of these test methods. The actual test conditions, the test data (if available), and the translated data are then reported.

5. Significance and Use

5.1 It is the intent of these procedures to provide recognized methods for testing and reporting the electrical performance of photovoltaic modules and arrays.

5.2 The test results may be used for comparison of different modules or arrays among a group of similar items that might be encountered in testing a group of modules or arrays from a single source. They also may be used to compare diverse designs, such as products from different manufacturers. Repeated measurements of the same module or array may be used for the study of changes in device performance.

5.3 Measurements may be made over a range of test conditions. The measurement data are numerically translated from the test conditions to standard RC, to nominal operating conditions, or to optional user-specified reporting conditions. Recommended RC are defined in [Table 1](#).

5.3.1 If the test conditions are such that the device temperature is within $\pm 2^{\circ}\text{C}$ of the RC temperature and the total irradiance is within $\pm 5\%$ of the RC irradiance, the numerical translation consists of a correction to the measured device current based on the total irradiance during the *I-V* measurement.

5.3.2 If the provision in [5.3.1](#) is not met, performance at RC is obtained from four separate *I-V* measurements at temperature and irradiance conditions that bracket the desired RC using a bilinear interpolation method.⁴

5.3.2.1 There are a variety of methods that may be used to bracket the temperature and irradiance. One method involves cooling the module under test below the reference temperature and making repeated measurements of the *I-V* characteristics as the module warms up. The irradiance of pulsed light sources may be adjusted by using neutral density mesh filters of varying transmittance. If the distance between the simulator and the test plane can be varied then this adjustment can be used to change the irradiance. In natural sunlight, the irradiance will change with the time of day or if the solar incidence angle is adjusted.

5.4 These test methods are based on two requirements.

5.4.1 First, the reference cell (or module, see [1.1.1](#) and [4.3.4](#)) is selected so that its spectral response is considered to be close to the module or array to be tested.

5.4.2 Second, the spectral response of a representative cell and the spectral distribution of the irradiance source must be known. The calibration constant of the reference cell is then corrected to account for the difference between the actual and the reference spectral irradiance distributions using the spectral mismatch parameter, which is defined in Test Method [E973](#).

5.5 Terrestrial reference cells are calibrated with respect to a reference spectral irradiance distribution, for example, [Tables G173](#).

5.6 A reference cell made and calibrated as described in [4.3](#) will indicate the total irradiance incident on a module or array whose spectral response is close to that of the reference cell.

5.7 With the performance data determined in accordance with these test methods, it becomes possible to predict module or array performance from measurements under any test light source in terms of any reference spectral irradiance distribution.

5.8 The reference conditions of [5.3.1](#) must be met if the measured *I-V* curve exhibits “kinks” or multiple inflection points.

⁴ Marion, B., Rummel, S., and Anderberg, A., “Current-Voltage Curve Translation by Bilinear Interpolation,” *Prog. Photovolt: Res. Appl.* 2004, 12:593–607.

6. Apparatus

6.1 *Photovoltaic Reference Cell*—A calibrated reference cell is used to determine the total irradiance during the electrical performance measurement.

6.1.1 The reference cell shall be matched in its spectral response to a representative cell of the test module or array such that the spectral mismatch parameter as determined by Test Method [E973](#) is 1.00 ± 0.05 .

6.1.2 Specification [E1040](#) provides recommended physical characteristics of reference cells.

6.1.3 Reference cells may be calibrated in accordance with Test Methods [E1125](#) or [E1362](#), as appropriate for a particular application.

6.1.4 A current measurement instrument (see [6.7](#)) shall be used to determine the I_{sc} of the reference cell when illuminated with the light source (see [6.4](#)).

6.2 *Test Fixture*—The device to be tested is mounted on a test fixture that facilitates temperature measurement and four-wire current-voltage measurements (Kelvin probe, see [6.3](#)). The design of the test fixture shall prevent any increase or decrease of the device output due to reflections or shadowing. Arrays installed in the field shall be tested as installed. See [7.2.3](#) for additional restrictions and reporting requirements.

6.3 *Kelvin Probe*—An arrangement of contacts that consists of two pairs of wires attached to the two output terminals of the device under test. One pair of wires is used to conduct the current flowing through the device, and the other pair is used to measure the voltage across the device. A schematic diagram of an *I-V* measurement using a Kelvin Probe is given in Fig. 1 of Test Method [E948](#).

6.4 *Light Source*—The light source shall be either natural sunlight or a solar simulator providing Class A, B, or C simulation as specified in Specification [E927](#).

6.5 *Temperature Measurement Equipment*—The instrument or instruments used to measure the temperature of both the reference cell and the device under test shall have a resolution of at least 0.1°C , and shall have a total error of less than $\pm 1^{\circ}\text{C}$ of reading.

6.5.1 Temperature sensors, such as thermocouples or thermistors, suitable for the test temperature range shall be attached in a manner that allows measurement of the device temperature. Because module and array temperatures can vary spatially under continuous illumination, multiple sensors distributed over the device should be used, and the results averaged to obtain the device temperature.

6.5.2 When testing modules or arrays for which direct measurement of the cell temperature inside the package is not feasible, sensors can be attached to the rear side of the devices. The error due to temperature gradients will depend on the thermal characteristics of the packaging, especially under continuous illumination. Modules with glass back sheets will have higher gradients than modules with thin polymer backs, for example.

6.6 *Variable Load*—An electronic load, such as a variable resistor, a programmable power supply, or a capacitive sweep

circuit, used to operate the device to be tested at different points along its I - V characteristic.

6.6.1 The variable load should be capable of operating the device to be tested at an I - V point where the voltage is within 1 % of V_{oc} in the power-producing quadrant.

6.6.2 The variable load should be capable of operating the device to be tested at an I - V point where the current is within 1 % of I_{sc} in the power-producing quadrant.

6.6.3 The variable load should allow the device output power (the product of device current and device voltage) to be varied in increments as small as 0.2 % of the maximum power.

6.6.4 The electrical response time of the variable load should be fast enough to sweep the required range of I - V operating points during the measurement period. It is possible that the response time of the device under test may limit how fast the range of I - V points can be swept, especially when pulsed simulators are used. For these cases, it may be necessary to make multiple measurements over smaller portions of the I - V curve to obtain the entire recommended range.

6.7 *Current Measurement Equipment*—The instrument or instruments used to measure the current through the device under test and the I_{sc} of the reference cell shall have a resolution of at least 0.05 % of the maximum current encountered, and shall have a total error of less than 0.2 % of the maximum current encountered.

6.8 *Voltage Measurement Equipment*—The instrument or instruments used to measure the voltage across the device under test shall have a resolution of at least 0.05 % of the maximum voltage encountered, and shall have a total error of less than 0.2 % of the maximum voltage encountered.

7. Procedures

7.1 *Momentary Illumination Technique:*

7.1.1 This technique is valid for use with pulsed solar simulators, shuttered continuous solar simulators, or shuttered sunlight. For testing under continuous illumination see 7.2.

7.1.2 Determine the spectral mismatch parameter, M , using Test Method E973.

7.1.3 Mount the reference cell and the device to be tested in the test fixture coplanar within $\pm 2^\circ$, and normal to the illumination source within $\pm 10^\circ$. If an array or module cannot be aligned to within $\pm 10^\circ$, the solar angle of incidence, the device orientation and its tilt angle must be reported with the data.

7.1.4 Connect the four-wire Kelvin probe to the module or array output terminals.

7.1.5 Expose the module or array to the light source.

7.1.6 If the temporal instability of the light source (as defined in Specification E927) is less than 0.1 %, the total irradiance may be determined with the reference cell prior to the performance measurement. In this case, measure the short-circuit current of the reference cell, I_r .

7.1.7 Measure the I - V characteristic of the test device by changing the operating point with the variable load so that the provisions of 6.6 are met. At each operating point along the I - V characteristic, measure the device voltage, the device current, and I_r .

7.1.7.1 If the provision of 7.1.6 is met, it is not necessary to measure I_r at each operating point.

7.1.8 Measure the temperature of the reference cell, T_r , and the temperature of the test device, T_c . Temperature changes during the test shall be less than 2°C .

7.2 *Continuous Illumination Technique:*

7.2.1 This technique is valid for testing in continuous solar simulators or natural sunlight.

7.2.2 Determine the spectral mismatch parameter, M , using Test Method E973.

7.2.3 Mount the reference cell and the device to be tested in the test fixture coplanar within $\pm 2^\circ$, and normal to the illumination source within $\pm 10^\circ$. If an array or module cannot be aligned to within $\pm 10^\circ$, the solar angle of incidence, the device orientation and its tilt angle must be reported with the data.

7.2.4 Connect the four-wire Kelvin probe to the module or array output terminals.

7.2.5 Expose the test device to the illumination source for a period of time sufficient for the device to achieve thermal equilibrium.

7.2.6 If the temporal instability of the light source (as defined in Specification E927) is less than 0.1 %, the total irradiance may be determined with the reference cell prior to the performance measurement. In this case, measure the short-circuit current of the reference cell, I_r .

7.2.7 Obtain the average temperature, T_c , of a cell in the module or array using one of the following two methods:

7.2.7.1 For outdoor measurements in natural sunlight if the NOCT correction factors are known (see Annex A1), measure the ambient air temperature and the wind speed. The average wind speed for 5 min preceding the test and during the test should not exceed 1.75 ms^{-1} .

7.2.7.2 Measure the temperature of the sensors, following the provisions of 6.5.

7.2.8 Measure the reference cell temperature, T_r .

7.2.9 Measure the I - V characteristic of the test device by changing the operating point with the variable load so that the provisions of 6.6 are met. At each operating point along the I - V characteristic, measure the device voltage, the device current, and I_r .

7.2.9.1 If the provision of 7.2.6 is met, it is not necessary to measure I_r at each operating point.

7.2.10 Immediately following the I - V recording, repeat the temperature measurements and verify that temperature changes during the test were less than 2°C .

7.3 If the provision of 5.3.1 is not met, repeat 7.1 or 7.2 three times to obtain a total of four I - V characteristics as required by 5.3.2.

8. Calculation of Results

8.1 Adjust the reference cell calibration constant using:

$$C' = \frac{C}{M} [1 + \alpha_r(T_r - T_o)] \quad (1)$$

8.2 Calculate the total irradiance during the performance measurement(s) using the following equation (if I_r was measured at each operating point, use the average value of I_r):