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An American National Standard

Standard Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight[1]

This standard is issued under the fixed designation E948; 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 covers the determination of the electrical performance of a photovoltaic cell under simulated sunlight by means of a calibrated reference cell procedure.

1.2 Electrical performance measurements are reported with respect to a select set of standard reporting conditions (SRC) (see Table 1) or to user-specified reporting conditions. In either case, the chosen reporting conditions are abbreviated as RC.

1.2.1 The RC include the cell temperature, the total irradiance, and the reference spectral irradiance distribution.

1.3 This test method is applicable only to photovoltaic cells with a linear short-circuit current versus total irradiance response up to and including the total irradiance used in the measurement.

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

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

1.6 *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.*

1.7 *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.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

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

E491 Practice for Solar Simulation for Thermal Balance Testing of Spacecraft

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

E772 Terminology of Solar Energy Conversion

E927 Classification for Solar Simulators for Electrical Performance Testing of Photovoltaic Devices

E973 Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell

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

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

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 test method may be found in Terminology E772 and in Specification E927.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *effective irradiance, n*—the irradiance that a solar simulator produces as measured by a cell's short-circuit current relative to a reference value for the cell's short-circuit current at a particular RC.

3.2.1.1 *Discussion*—This reference value typically corresponds to a different spectral irradiance distribution than the solar simulator.

3.2.2 *reporting conditions, RC, n*—the reference spectral irradiance distribution, total irradiance, and cell temperature to which the photovoltaic current-voltage performance is measured and corrected.

[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.

TABLE 1 Standard Reporting Conditions

Reference Spectral Irradiance Distribution	Total Irradiance, E_0 (Wm^{-2})	Cell Temperature, T_0 (°C)
Tables G173 Direct Normal	900	25
Tables G173 Hemispherical	1000	25
Tables E490	1366.1	25

3.2.3 *test cell, n*—the photovoltaic cell to be tested, or cell under test, using the method described herein.

3.3 *Symbols*—The following symbols and units are used in this test method:

3.3.1 *0*—as a subscript, denotes a value under the specified RC.

3.3.2 A—area of the test cell, (m^2).

3.3.3 A_R—area of the reference cell, (m^2).

3.3.4 C_R—calibration constant of reference cell, (Am^2W^{-1}).

3.3.5 C_T—transfer calibration ratio, (dimensionless).

3.3.6 E—total irradiance, Wm^{-2}.

3.3.7 FF—fill factor, (%).

3.3.8 I—current of the test cell (A).

3.3.9 I_{MP}—current of the test cell at maximum power in the power-producing quadrant (A).

3.3.10 I_{SC}—short-circuit current of the test cell (A).

3.3.11 $I_{SC,R}$—short-circuit current of the reference cell (A).

3.3.12 $I_{SC,M}$—short-circuit current of the monitor cell (A).

3.3.13 M—spectral mismatch parameter (dimensionless).

3.3.14 P_{MP}—maximum power of the test cell in the power-producing quadrant (W).

3.3.15 R_S—series resistance of the test cell (Ω).

3.3.16 S—current correction factor due to spatial non-uniformity of irradiance (dimensionless).

3.3.17 T—temperature of the test cell (°C).

3.3.18 T_R—temperature of the reference cell (°C).

3.3.19 $\mathbf{U}_0$—ordered set of test cell current, voltage, and power values at RC (A, V, W).

3.3.20 V—voltage of the test cell (V).

3.3.21 V_{MP}—voltage of the test cell at maximum power in the power-producing quadrant (V).

3.3.22 V_{OC}—open-circuit voltage of the test cell (V).

3.3.23 η—efficiency (%).

4. Summary of Test Method

4.1 The performance test of a photovoltaic cell consists of measuring the electrical current versus voltage (I-V) characteristic of the cell while illuminated by a solar simulator and with its temperature sufficiently controlled.

4.2 A calibrated photovoltaic reference cell (see 6.1) is used to determine the effective irradiance during the test.

4.3 Simulated sunlight is used for the electrical performance measurement, and solar simulation requirements are defined in Specification E927 (terrestrial applications) and Practice E491 (space applications).

4.4 The data from the measurements are corrected to the desired RC. Three possible SRC are defined in Table 1.

4.4.1 Measurement error in test cell current caused by deviations of the irradiance conditions from the RC is corrected using the effective irradiance measured with the reference cell and the spectral mismatch parameter, M, which is determined in accordance with Test Method E973.

4.4.1.1 This test method does not apply corrections to cell voltage for irradiance deviations, thus the solar simulator irradiance must be sufficiently well controlled to accurately determine other parameters under RC, especially maximum power and open-circuit voltage. To this end, the effective irradiance during the measurement is restricted to be within ±2 % of the RC irradiance. However, there will still be measurement uncertainty due to irradiance variations in this range.

4.4.2 Measurement error caused by deviation of the test-cell and reference-cell temperatures from the RC is minimized by maintaining the cell temperatures sufficiently close to the required RC value. To this end, the test cell temperature during the measurement is restricted to be within ±1 °C of the RC temperature.

4.4.2.1 Test Method E973 provides for correction of test cell current through a temperature-dependent spectral mismatch parameter, $M(T)$; however, Test Method E973 allows the temperature correction to be bypassed if the temperature is within ±1 °C.

4.4.2.2 This test method does not apply corrections to cell voltage for temperature deviations, thus the test-cell temperature must be sufficiently well controlled to accurately determine other parameters under RC, especially maximum power and open-circuit voltage. However, there will still be measurement uncertainty due to temperature variations in this range.

4.4.3 The measurement procedure employs a reference cell-test cell substitution technique that is designed to minimize errors in short-circuit current caused by spatial non-uniformity of the solar simulator irradiance. A correction for spatial non-uniformity of irradiance may be applied to measured current data if the reference cell and test cell have different areas; the correction is defined as the ratio of the effective irradiance in the solar simulator over the area of the test cell to the effective irradiance over the area of the reference cell.

5. Significance and Use

5.1 This test method provides a procedure for testing and reporting the electrical performance of photovoltaic cells.

5.2 The test results may be used for comparison of cells among a group of similar cells or to compare diverse designs, such as different manufacturers' products. Repeated measurements of the same cell may be used to study changes in device performance.

5.3 This test method determines the electrical performance of a photovoltaic cell at a single instant of time and the results do no imply any past or future performance.

5.4 This test method requires a linear reference cell calibrated with respect to an appropriate reference spectral irradiance distribution, such as Tables E490, or G173. It is the responsibility of the user to determine which reference spectral irradiance distribution is appropriate for a particular application.

6. Apparatus

6.1 *Reference Cell*—A linear, calibrated, photovoltaic solar cell used to determine the total irradiance during the electrical performance measurement.

6.1.1 Reference cells may be calibrated in accordance with Test Methods E1125 or E1362, as is appropriate for a particular application.

NOTE 1—No reference cell calibration standards presently exist for space applications, although procedures using high-altitude balloon and low-earth orbit flights are being used to calibrate such reference cells.

6.1.2 The calibration constant, C_R, of the reference cell shall be with respect to the reference spectral irradiance distribution of the desired RC (see 1.2).

6.1.3 A current measurement instrument (see 6.3) shall be used to determine the short-circuit current of the reference cell under the solar simulator.

6.1.4 *Special Case*—If the test cell also qualifies as a reference cell in that its I_{SC} or calibration constant at the RC is known prior to test, the test cell may be used to measure irradiance by itself and the separate reference cell omitted. The self-irradiance measurement technique is typically used to determine the fill factor of a reference cell post-calibration, and as a check for damage or degradation.

6.2 *Test Fixture*—Both the test cell and the reference cell are mounted in a fixture that meets the following requirements:

6.2.1 The test fixture shall ensure a uniform lateral temperature distribution to within ±0.5°C during the performance measurement.

6.2.2 The test fixture shall include a provision for maintaining a constant cell temperature for both the reference cell and the test cell (see 7.11).

NOTE 2—When using pulsed or shuttered solar simulators, it is possible that the cell temperature will increase upon initial illumination, even when the cell temperature is controlled.

6.2.3 The test fixture, when placed in the solar simulator, shall ensure that the fields-of-view of both the reference cell and the test cell are identical.

NOTE 3—Some solar simulators may have significant amounts of irradiation from oblique or non-perpendicular angles to the test plane. In these cases, it is important that the test cell and the reference cell have similar reflectance and angular-response characteristics.

6.2.4 A four-terminal connection (also known as a Kelvin connection, see Fig. 1) from the test cell to the I-V measurement instrumentation (see 6.3 – 6.5) shall be used.

6.3 *Current Measurement Equipment*—Electrical instrumentation used to measure the current through the test cell during the performance measurement. The instrumentation shall have a resolution of at least 0.02 % of the maximum current encountered, and shall have a total error of less than 0.1 % of the maximum current encountered.

6.3.1 The current measurement equipment shall measure data points simultaneously with the voltage (see 6.4) and short-circuit current (see 6.9) measurement equipment, to within 10 µs.

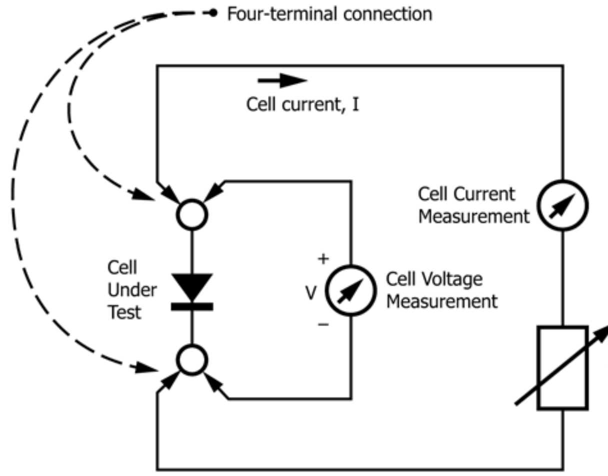

FIG. 1 I-V Measurement Schematic

6.4 *Voltage Measurement Equipment*—Electrical instrumentation used to measure the voltage across the test cell during the performance measurement. The instrumentation shall have a resolution of at least 0.02 % of the maximum voltage encountered, and shall have a total error of less than 0.1 % of the maximum voltage encountered.

6.4.1 The voltage measurement equipment shall measure data points simultaneously with the current (see 6.3) and short-circuit current (see 6.9) measurement equipment, to within 10 µs.

6.5 *Variable Load*—An electronic load, such as a variable resistor or a programmable power supply, used to operate the test cell at different points along its I-V characteristic.

6.5.1 The variable load shall be capable of operating the test cell at an I-V point where the voltage is within 1 % of V_{OC} in the power-producing quadrant.

6.5.2 The variable load shall be capable of operating the test cell at an I-V point where the current is within 1 % of I_{sc} in the power-producing quadrant.

6.5.3 The variable load shall allow an output power (the product of cell current and cell voltage) resolution of at least 0.2 % of P_{MP}.

6.5.4 The electrical response time of the variable load shall be fast enough to sweep the range of I-V operating points during the measurement period.

NOTE 4—It is possible that the response time of the test cell may limit how fast the range of I-V operating points can be swept, especially when pulsed solar simulators are used. For these cases, it may be necessary to measure smaller ranges of the I-V curve using multiple measurements to obtain the entire range required.

6.6 *Solar Simulator*—Requirements of the solar simulator used to illuminate the test cell are defined in Specification E927 (terrestrial applications) and Practice E491 (space applications).

6.6.1 The effective irradiance during the performance measurement shall be within ±2 % of the RC value.

NOTE 5—This tolerance is a reasonable choice for SRC. For very low irradiance measurements, a tighter tolerance on the effective irradiance may be required because of the increased dependence of V_{OC} on irradiance.

6.7 *Temperature Measurement Equipment*—Instrumentation used to measure the cell temperatures of the reference cell, the test cell, and the monitor cell shall have a resolution of at least 0.2 °C, and shall have a total uncertainty of less than ±1°C of reading.

6.7.1 Sensors used for the temperature measurement(s) shall be located in a position that minimizes any temperature gradients between the sensor and the photovoltaic device junction.

6.7.2 Time constants associated with these measurements shall be less than 500 ms.

6.8 *Monitor Cell (optional)*—An uncalibrated photovoltaic solar cell that is positioned in the test plane such that it is illuminated by the solar simulator during the performance measurement of the test cell. The monitor cell is used to measure the effective irradiance during the performance measurement following a transfer-of-calibration procedure from the reference cell. It is also used to correct current measurement data points of the test cell for temporal instability of the solar simulator.

6.8.1 The monitor 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. Placement locations close to the test cell may be preferable.

6.8.2 The spectral responsivity of the monitor cell is unimportant, but the wavelength range of its responsivity should include that of the test cell. Crystalline-Si solar cells are recommended.

6.8.3 The monitor cell shall be mounted on a test fixture that controls its cell temperature to within its temperature measurement resolution during the performance measurement. It is recommended that the monitor cell have its own test fixture.

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

6.8.5 The short-circuit current of the monitor cell, as a property of the cell, shall not increase or decrease for the duration of the performance measurement, to within the resolution of the short-circuit current measurement equipment (see 6.9).

6.8.6 The monitor cell shall be checked at least annually for sufficient performance and stability.

6.9 *Short-Circuit Current Measurement Equipment*—Instrumentation used to measure the short-circuit current of the reference cell and the monitor cell.

6.9.1 The short-circuit current measurement equipment shall hold the voltage across these cells to within 25 mV of zero.

6.9.2 The short-circuit current measurement equipment shall measure current data points simultaneously with the current (see 6.3) and voltage (6.4) measurement equipment, to within 10 µs.

7. Procedure

7.1 Measure the test cell area, A, using the definition of **area, photovoltaic cell** in Terminology E772.

7.2 Determine short-circuit current of the reference cell at the RC using:

$$I_{SC,R0} = C_R E_0 \tag{1}$$

7.3 Determine the spectral parameter, M, using Test Method E973, as follows:

7.3.1 Test Method E973 requires four spectral quantities: the spectral responsivities (or quantum efficiencies) of the test cell and the reference cell, the spectral irradiance distribution of the solar simulator, and the reference spectral irradiance distribution.

7.3.2 Two of these quantities will be known prior to the performance measurement: the reference cell spectral responsivity at its calibration temperature (that is, T_R, required as part of its calibration data) and the reference spectral irradiance distribution (selected or specified beforehand in 1.2).

7.3.3 Determine the quantum efficiency of the test cell at the temperature corresponding to the selected RC (that is, T) according to 7.4 of Test Method E973.

7.3.4 Measure the spectral irradiance distribution of the solar simulator according to 7.5 of Test Method E973. The measurement should be performed within the last 50 h of lamp time unless the spectral stability of the solar simulator has demonstrated that a longer period causes no discernible error.

7.3.5 *Special Case*—For the special case of 6.1.4, M is equal to one by definition if the test cell is within ±1 °C of temperature at which its I_{SC} was calibrated; in this case the spectral measurements in 7.3.3 and 7.3.4 are not necessary and may be omitted.

7.3.6 Notice that in Test Method E973, T and T_R may not be equal to each other, and are not required to be so. Also, because both cells are required to be held within ±1 °C of these temperatures (see 7.9.2.1 and 7.9.5.1), the temperature-dependent quantum efficiency terms for M in Test Method E973 may be omitted.

7.4 Determine the current correction factor due to spatial non-uniformity of irradiance, S, as follows:

7.4.1 For the special case of 6.1.4 in which the test cell is also the reference cell, set S equal to one and proceed to 7.5.

7.4.2 Obtain the area of the reference cell, A_R, either by measurement or from its calibration report.

7.4.3 Select the larger of A and A_R, and divide it by the smaller area. If this ratio is less than 3, set S equal to one and proceed to 7.5.

7.4.4 Use the procedure in Annex A2 to measure and compute S.

7.5 Mount the reference cell in the test fixture. Connect it to the short-circuit current measurement equipment, and illuminate it with the solar simulator.

7.5.1 For the special case of 6.1.4, the test cell is also the reference cell, thus $I_{SC,R}$ is equal to I_{SC} of the test cell throughout the remainder of the procedure.

7.6 *Solar Simulator with Adjustable Effective Radiance*—While measuring $I_{SC,R}$, adjust the effective irradiance so that $I_{SC,R}$ is equal to the reference cell's calibrated short-circuit current corrected for spatial non-uniformity of irradiance and spectral mismatch, that is,

$$I_{SC,R} = \frac{S}{M} I_{SC,R0} \tag{2}$$

7.6.1 Note that this adjustment can affect the eventual satisfaction of the provision in 6.6.1.

7.7 Measure the temperature of the reference cell, T_R.

7.7.1 T_R shall be within ±1 °C of the reference cell's calibration temperature, including temperature measurement uncertainty.

7.8 *Stable Solar Simulator*—If the temporal instability of the solar simulator (as defined in Specification E927) is less than 0.1 %, the effective irradiance may be determined with the reference cell prior to the performance measurement. In this case, use the following steps to measure the effective irradiance and the I-V characteristic. Otherwise, proceed to 7.9.

NOTE 6—The reference cell's short-circuit current is a convenient way to verify the temporal instability of the solar simulator.

7.8.1 Measure the short-circuit current of the reference cell, $I_{SC,R}$, using the short-circuit current measurement equipment.

7.8.1.1 For the special case of 6.1.4, connect the test cell to the variable load and proceed to 7.8.4.

7.8.2 Replace the reference cell with the test cell.

7.8.3 Measure the temperature of the test cell, T.

7.8.3.1 T shall be within ±1 °C of the applicable RC, including temperature measurement uncertainty.

7.8.4 Measure the I-V characteristic of the test cell by changing the operating point with the variable load so that the provisions of 6.5.1 – 6.5.3 are met. At each operating point on the I-V characteristic, simultaneously measure the test-cell voltage, (V), and test-cell current, (I), to within 10 µs.

7.8.5 *Optional*—Connect the test cell to the short-circuit current measurement equipment and measure its I_{SC}.

7.8.6 Proceed to 7.10.

7.9 *Unstable Solar Simulator:*

7.9.1 Mount the monitor cell in its test fixture and connect it to the short-circuit current measurement equipment.

7.9.2 *Transfer Calibration:*

7.9.2.1 Measure the short-circuit currents of the reference cell and the monitor cell simultaneously within 10 µs.

7.9.2.2 Repeat 7.9.2.1 a minimum of 10 times. The number of repetitions will vary according to the temporal instability of the solar simulator, and judgment should be used to establish the time needed for the transfer calibration.

7.9.2.3 Calculate the transfer calibration ratio using the following equation, where n is the number of repetitions:

$$C_T = \frac{1}{n}\sum_{i=1}^{n}\frac{I_{SC,R_i}}{I_{SC,M_i}} \tag{3}$$

7.9.3 For the special case of 6.1.4, proceed to 7.9.6.

7.9.4 Replace the reference cell with the test cell.

7.9.5 Measure the temperature of the test cell, T.

7.9.5.1 T shall be within ±1 °C of the applicable RC, including temperature uncertainty.

7.9.6 Measure the I-V characteristic of the test cell by changing the operating point with the variable load so that the provisions of 6.5.1 – 6.5.3 are met. At each operating point on the I-V characteristic, simultaneously measure the test-cell voltage, (V), test-cell current, (I), and the monitor cell short-circuit current ($I_{SC,M}$) to within 10 µs.

7.10 Measure the temperature of the test cell to verify that it is still within ±1 °C of the applicable RC, including temperature uncertainty.

7.11 *Optional*—Disconnect the variable load and measure the voltage across the test cell. With no current flowing through the cell, this voltage is the open-circuit voltage, V_{OC}. This measurement may also be performed prior to 7.8.4 or 7.9.6.

7.12 *Optional*—Determine the series resistance, R_S, of the test cell. An acceptable method is described in Annex A1.

7.13 Remove the test cell from the test fixture.

8. Calculation of Results

8.1 Determine the short-circuit current of the reference cell, $I_{SC,R}$, as follows:

8.1.1 *Stable Solar Simulator*—Use the reference cell short-circuit current measured prior to the I-V curve sweep (see 7.8.1).

8.1.2 *Unstable Solar Simulator*—Compute values of $I_{SC,R}$ from the monitor cell short-current values, $I_{SC,M}$, measured with each I-V data pair (see 7.9.6).

$$I_{SC,R} = C_T I_{SC,M} \tag{4}$$

8.2 Calculate the test cell current and voltage at RC from the measured I-V curve data pairs and the value or values of $I_{SC,R}$ from 8.1).

$$I_0 = \frac{S}{M}\frac{I_{SC,R0}}{I_{SC,R}}I, \quad V_0 = V \tag{5}$$

8.3 Form an ordered set of test cell current-voltage-power data points from each I_0-V_0 data pair, sorted from lowest to highest V_0, with the jth element as:

$$\mathbf{U}_0[j] = \{I_0, V_0, P_0\} = \{I_0, V_0, I_0 \cdot V_0\} \tag{6}$$

8.4 Determine the short-circuit current I_{SC}, using one of the following procedures:

8.4.1 Calculate the short-circuit current from I_0-V_0 data pairs in $\mathbf{U}_0$ where V_0 is close to zero using a 1st degree polynomial (straight-line) interpolation or least-squares regression.

8.4.1.1 Higher-degree polynomials may be preferable if there is significant curvature in the I-V curve near V_0=0.

8.4.2 If the optional measurement of 7.8.5 was performed, use this value of I_{SC}.

8.5 Determine the open-circuit voltage V_{OC} using one of the following procedures:

8.5.1 Calculate the open-circuit voltage from I_0–V_0 data pairs in $\mathbf{U}_0$ where I_0 is close to zero using a 1st degree polynomial (straight-line) interpolation or least-squares regression.

8.5.1.1 Higher-degree polynomials may be preferable if there is significant curvature in the I-V curve near I_0=0.

8.5.2 If the optional no-load measurement of 7.11 was performed, use this value of V_{OC}.

8.6 Determine the cell maximum power P_{MP}, as follows:

8.6.1 Select the elements in U_0 with the largest P_0 and designate the data points of this element as I_{MP}, V_{MP}, and P_{MP}.