Designation: E948 – 15

# 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 conditions.

1.2.1 The SRC or user-specified conditions 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 response over the range of interest.

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 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

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 Specification for Solar Simulation for Photovoltaic Testing

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 Method for Calibration of Non-Concentrator Photovoltaic Secondary 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 in this test method may be found in Terminology E772.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *cell temperature, °C, n*—the temperature of the semiconductor junction of a photovoltaic cell.

3.2.2 *junction temperature, n*—synonym for *cell temperature*.

3.2.3 *light source, n*—a source of radiant energy used for cell performance measurements that simulates natural sunlight.

3.3 *Symbols:*

3.3.1 The following symbols and units are used in this test method:

$A$—cell area, $m^2$

$\alpha_r$—temperature coefficient of reference cell, $°C^{-1}$

$C$—calibration constant of reference cell, $Am^2W^{-1}$

$C_T$—transfer calibration ratio, dimensionless

$E$—irradiance, $Wm^{-2}$

$E_o$—standard reporting irradiance, $Wm^{-2}$

$\eta$—efficiency, %

$FF$—fill factor, %

$I$—current, A

$I_m$—monitor solar cell short-circuit current, A

$I_o$—current with respect to SRC, A

$I_r$—reference cell short-circuit current, A

$I_{sc}$—short-circuit current, A

$M$—spectral mismatch parameter, dimensionless

[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 ($Wm^{-2}$) | Temperature (°C) |
|---|---|---|
| Tables G173 Direct Normal | 1000 | 25 |
| Tables G173 Hemispherical | 1000 | 25 |
| Tables E490 | 1366.1 | 25 |

$P_m$—maximum power, W
$R_s$—series resistance, Ω
$T$—temperature,° C
$T_o$—standard reporting temperature, °C
$T_r$—temperature of reference cell, °C
$V$—voltage, V
$V_o$—voltage with respect to SRC, V
$V_{oc}$—open-circuit voltage, V

## 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 suitable light source.

4.2 A calibrated photovoltaic reference cell (see 6.1) is used to determine the total irradiance during the test and to account for the spectral distribution of the light source.

4.3 Simulated sunlight is used as the light source 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 standard reporting conditions, or to optional user-specified reporting conditions. The standard reporting conditions are defined in Table 1.[3]

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

4.4.2 Measurement error caused by deviation of the cell temperature from the SRC is minimized by maintaining the cell temperature close to the required value (see 7.10).

## 5. Significance and Use

5.1 It is the intent of this test method to provide a recognized method 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 cell based upon the output power at a single instant of time. It does not provide for integrating the output power over a given period of time and conditions to predict an energy output.

5.4 This test method requires a 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 *Photovoltaic Reference Cell*—A calibrated reference 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 such as high-altitude balloon and low-earth orbit flights are being used to calibrate such reference cells.

6.1.2 The calibration constant, $C$, of the reference cell must be with respect to the reference spectral irradiance distribution of the desired SRC (see 1.2).

6.1.3 A current measurement instrument (see 6.3) shall be used to determine the $I_{sc}$ of the reference cell under the light source.

6.2 *Test Fixture*—Both the cell to be tested 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 cell to be tested (see 7.10).

NOTE 2—When using pulsed or shuttered light sources, 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 simulated sunlight, shall ensure that the field-of-view of both the reference cell and the cell to be tested 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 cell to be tested and the reference cell have similar reflectance and cosine-response characteristics.

6.2.4 A four-terminal connection (also known as a Kelvin connection, see Fig. 1) from the cell to be tested 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 cell under test 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 instrumentation shall be capable of simultaneously measuring data points with the short-circuit current (see 6.9) and voltage (see 6.4) measurement equipment, to within 10 µs.

[3] Wehrli, C., Extraterrestrial Solar Spectrum, Publ. No. 615, Physikalisch-Meteorologisches Observatorium and World Radiation Center, Davos Switzerland, 1985.

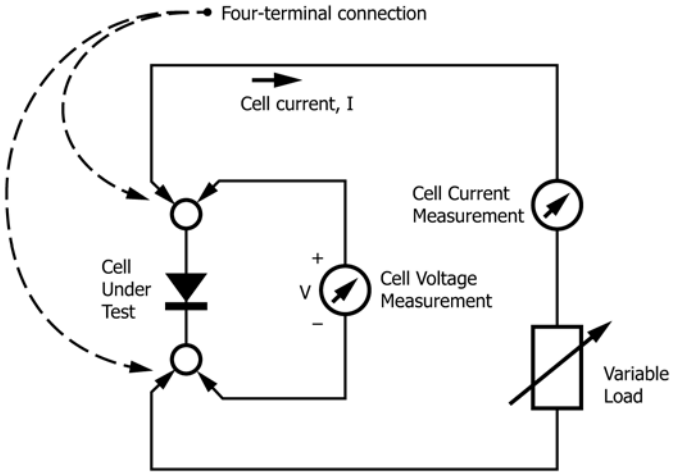


**FIG. 1 I-V Measurement Schematic**

6.4 *Voltage Measurement Equipment*—Electrical instrumentation used to measure the voltage across the cell under test 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 instrumentation shall be capable of simultaneously measuring data points 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 cell to be tested at different points along its I-V characteristic.

6.5.1 The variable load shall be capable of operating the cell to be tested 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 cell to be tested 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 must allow an output power (the product of cell current and cell voltage) resolution of at least 0.2 % of the maximum power.

6.5.4 The electrical response time of the variable load must 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 cell to be tested 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 *Light Source*—Requirements of the solar simulation used to illuminate the cell to be tested are defined in Specification E927 (terrestrial applications) and Practice E491 (space applications).

6.7 *Temperature Measurement Equipment*—Instrumentation used to measure the cell temperatures of the reference cell, the cell to be tested, and the monitor solar cell shall have a resolution of at least 0.1°C, and shall have a total error of less than ±1°C of reading.

6.7.1 Sensors used for the temperature measurement(s) must 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 must be less than 500 ms.

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

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

6.8.2 The spectral responsivity 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 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.

6.9 *Short-circuit Current Measurement Equipment*—Instrumentation used to measure the $I_{sc}$ of the photovoltaic reference cell and the monitor solar cell.

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

6.9.2 The instrumentation shall be capable of simultaneously measuring current data points with the current (see 6.3) and voltage (6.4) measurement equipment, to within 10 µs.

## 7. Procedure

7.1 Determine the series resistance, $R_s$, of the cell to be measured. An acceptable method is described in Annex A1.

7.1.1 If the total irradiance during the performance measurement as measured by the reference cell is within ±2 % of the standard reporting total irradiance, the series resistance is not needed.

7.2 Measure the cell area, $A$, using the definition of **area, photovoltaic cell** in Terminology E772.

7.3 *Special Case*—If the cell to be tested also qualifies as a reference cell according to 6.1 so that its $C$ is known prior to test, the cell may be used to measure irradiance 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.

7.3.1 Set the spectral mismatch parameter, $M$, to one.

7.3.2 Mount the cell to be tested in the test fixture.

7.3.3 Proceed to 7.6.