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INTERNATIONAL

Designation: ~~E948 – 15~~ E948 – 16

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.~~reporting conditions. In either case, the chosen reporting conditions are abbreviated as RC.

1.2.1 The ~~SRC or user-specified conditions~~ 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 ~~response over the range of interest.~~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 and health practices and determine the applicability of regulatory limitations prior to use.*

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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 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 ~~*cell temperature, °C,*~~ *effective irradiance, n*—the ~~temperature of the semiconductor junction of a photovoltaic cell.~~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.

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[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.

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TABLE 1 Standard Reporting Conditions

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

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

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

3.2.3 ~~*light source,*~~*test cell, n*—~~a source of radiant energy used for cell performance measurements that simulates natural sunlight.~~ the photovoltaic cell to be tested, or cell under test, using the method described herein.

3.3 ~~*Symbols:*~~*Symbols*

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

~~*A*—cell area, m^2~~

~~α_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}~~

~~*η*—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~~

~~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~~—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).

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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 ~~suitable light source.~~solar simulator and with its temperature sufficiently controlled.

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

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~~ 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 ~~SRC~~RC is corrected using the ~~total~~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 ~~cell temperature~~ test-cell and reference-cell temperatures from the ~~SRC~~RC is minimized by maintaining the cell ~~temperature~~ temperatures sufficiently close to the required ~~value (see~~RC value. ~~7.10).~~ 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 ~~It is the intent of this test method to provide a recognized method~~ 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 ~~cell based upon the output power~~ photovoltaic cell 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.~~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.

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6. Apparatus

6.1 *~~Photovoltaic~~ Reference Cell*—A ~~calibrated reference~~ 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 ~~such as~~ using high-altitude balloon and low-earth orbit flights are being used to calibrate such reference cells.

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

6.1.3 A current measurement instrument (see 6.3) shall be used to determine the ~~I~~short-circuit~~sc~~ current of the reference cell under the ~~light source.~~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 ~~cell to be tested~~ test cell and the reference cell are mounted in a fixture that meets the following ~~requirements.~~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~~ test cell (see ~~7.10~~7.11).

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

6.2.4 A four-terminal connection (also known as a Kelvin connection, see Fig. 1) from the test 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 test 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~~ current measurement equipment shall measure data points simultaneously with the voltage (see ~~6.9~~6.4) and ~~voltage~~ short-circuit current (see ~~6.4~~6.9) measurement equipment, to within 10 µs.

6.4 *Voltage Measurement Equipment*—Electrical instrumentation used to measure the voltage across the test 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.

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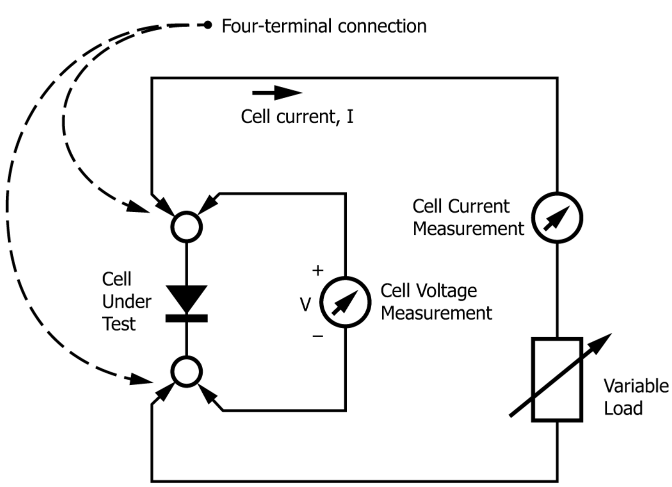

FIG. 1 I-V Measurement Schematic

6.4.1 The ~~instrumentation shall be capable of simultaneously measuring data points~~ 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 ~~cell to be tested~~ test cell at different points along its I-V characteristic.

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

6.5.2 The variable load shall be capable of operating the ~~cell to be tested~~ 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 ~~must~~shall allow an output power (the product of cell current and cell voltage) resolution of at least 0.2 % of ~~*the*~~ P_{MP} ~~*maximum*~~ .~~power.~~

6.5.4 The electrical response time of the variable load ~~must~~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 ~~cell to be tested~~ 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 ~~*Light Source*—~~*Solar Simulator*—Requirements of the solar ~~simulation~~simulator used to illuminate the ~~cell to be tested~~ 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 ~~cell to be tested,~~ test cell, and the monitor ~~solar~~ cell shall have a resolution of at least ~~0.1°C,~~ 0.2 °C, and shall have a total ~~error~~uncertainty of less than ±1°C of reading.

6.7.1 Sensors used for the temperature measurement(s) ~~must~~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 ~~must~~shall 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~~solar simulator during the performance measurement of the ~~cell to be tested.~~ test cell. The monitor ~~solar~~ cell is used to measure the effective 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~~ test cell for temporal instability of the ~~light source.~~solar simulator.

6.8.1 The monitor ~~solar~~ cell may be positioned anywhere in the test plane of the ~~light source,~~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 ~~solar~~ cell is unimportant, but the wavelength range of its responsivity should include that of the ~~cell to be tested.~~ test cell. 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~~ its temperature measurement resolution 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~~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*~~*Short-Circuit Current Measurement Equipment*—Instrumentation used to measure the ~~I~~short-circuit~~sc~~ current of the ~~photovoltaic~~ reference cell and the monitor ~~solar~~ cell.

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

6.9.2 The ~~instrumentation shall be capable of simultaneously measuring~~ 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 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.~~

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

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7.2 ~~*Special Case*—If the cell to be tested also qualifies as a reference cell according to~~ Determine short-circuit current of the reference cell at 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.~~the RC using:

~~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.~~

$$I_{SC,R0} = C_R E_0 \quad (1)$$

7.3 Determine the spectral ~~mismatch~~ 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 ~~under test~~ and the reference cell, the spectral irradiance distribution of the ~~light source,~~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 ~~(required~~ at its calibration temperature (that is, T_R, required as part of its calibration ~~data),~~data) and the reference spectral irradiance distribution (selected or specified beforehand in 1.2).

7.3.3 ~~Measure~~Determine the ~~spectral responsivity~~quantum efficiency of the ~~cell to be tested~~ test cell at the temperature corresponding to the selected RC (that is, T) according to ~~7.1~~7.4 of Test Method E973.

7.3.4 ~~The~~ Measure the spectral irradiance ~~of the light source~~ distribution of the solar simulator according to 7.5 of Test Method E973. The measurement should be ~~measured~~performed within the last 50 h of lamp time unless the ~~solar simulator's~~ 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 ~~7.3~~6.1.4, ~~by definition~~ M ~~will be~~ is equal to ~~one, and the~~ 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 ~~7.4.3~~7.3.3 and ~~7.4.4~~7.3.4 are not ~~necessary.~~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.

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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.

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7.5 Mount the reference cell in the test fixture. Connect it to the short-circuit current measurement equipment, and ~~expose~~illuminate it ~~to~~with the ~~light source.~~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*—~~If possible,~~While measuring $I_{SC,R}$, adjust the ~~total~~effective irradiance ~~of the~~so that ~~*light*~~$I_{SC,R}$ ~~source until it~~ is equal to ~~C × E~~the reference cell's~~o.~~ calibrated short-circuit current corrected for spatial non-uniformity of irradiance and spectral mismatch, that is,

$$I_{SC,R} = \frac{S}{M} I_{SC,R0} \quad (2)$$

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, $T_{\sout{r}R}$.

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

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

NOTE 6—The reference cell's ~~I~~short-circuit~~sc~~ current is a convenient way to verify the temporal instability of the ~~light source.~~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 ~~cell to be tested.~~test cell.

7.8.3 Measure the temperature of the ~~cell under~~test cell, ~~*test.*~~T.