Designation: E2481 – 12

# Standard Test Method for
# Hot Spot Protection Testing of Photovoltaic Modules[1]

## 1. Scope

1.1 This test method provides a procedure to determine the ability of a photovoltaic (PV) module to endure the long-term effects of periodic "hot spot" heating associated with common fault conditions such as severely cracked or mismatched cells, single-point open circuit failures (for example, interconnect failures), partial (or non-uniform) shadowing or soiling. Such effects typically include solder melting or deterioration of the encapsulation, but in severe cases could progress to combustion of the PV module and surrounding materials.

1.2 There are two ways that cells can cause a hot spot problem; either by having a high resistance so that there is a large resistance in the circuit, or by having a low resistance area (shunt) such that there is a high-current flow in a localized region. This test method selects cells of both types to be stressed.

1.3 This test method does not establish pass or fail levels. The determination of acceptable or unacceptable results is beyond the scope of this test method.

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

1.5 *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]

E772 Terminology of Solar Energy Conversion
E927 Specification for Solar Simulation for Photovoltaic Testing
E1036 Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells
E1799 Practice for Visual Inspections of Photovoltaic Modules
E1802 Test Methods for Wet Insulation Integrity Testing of Photovoltaic Modules

## 3. Terminology

3.1 *Definitions*—definitions of terms used in this test method may be found in Terminology E772.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *hot spot*—a condition that occurs, usually as a result of shadowing, when a solar cell or group of cells is forced into reverse bias and must dissipate power, which can result in abnormally high cell temperatures.

## 4. Significance and Use

4.1 The design of a photovoltaic module or system intended to provide safe conversion of the sun's radiant energy into useful electricity must take into consideration the possibility of partial shadowing of the module(s) during operation. This test method describes a procedure for verifying that the design and construction of the module provides adequate protection against the potential harmful effects of hot spots during normal installation and use.

4.2 This test method describes a procedure for determining the ability of the module to provide protection from internal defects which could cause loss of electrical insulation or combustion hazards.

4.3 Hot-spot heating occurs in a module when its operating current exceeds the reduced short-circuit current (Isc) of a shadowed or faulty cell or group of cells. When such a condition occurs, the affected cell or group of cells is forced into reverse bias and must dissipate power, which can cause overheating.

NOTE 1—The correct use of bypass diodes can prevent hot spot damage from occurring.

4.4 Fig. 1 illustrates the hot-spot effect in a module of a series string of cells, one of which, cell $Y$, is partially shadowed. The amount of electrical power dissipated in $Y$ is equal to the product of the module current and the reverse voltage developed across $Y$. For any irradiance level, when the

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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.

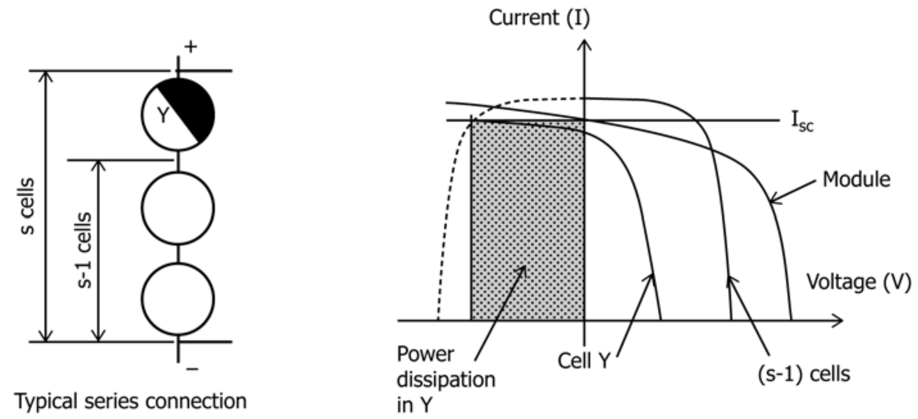

FIG. 1 Hot Spot Effect

reverse voltage across *Y* is equal to the voltage generated by the remaining (*s*-1) cells in the module, power dissipation is at a maximum when the module is short-circuited. This is shown in Fig. 1 by the shaded rectangle constructed at the intersection of the reverse I-V characteristic of *Y* with the image of the forward I-V characteristic of the (*s*-1) cells.

4.5 By-pass diodes, if present, as shown in Fig. 2, begin conducting when a series-connected string in a module is in reverse bias, thereby limiting the power dissipation in the reduced-output cell.

NOTE 2—If the module does not contain bypass diodes, check the manufacturer's instructions to see if a maximum number of series modules is recommended before installing bypass diodes. If the maximum number of modules recommended is greater than one, the hot spot test should be preformed with that number of modules in series. For convenience, a constant current power supply may be substituted for the additional modules to maintain the specified current.

4.6 The reverse characteristics of solar cells can vary considerably. Cells can have either high shunt resistance where the reverse performance is voltage-limited or have low shunt resistance where the reverse performance is current-limited. Each of these types of cells can suffer hot spot problems, but in different ways.

4.6.1 *Low-Shunt Resistance Cells:*

4.6.1.1 The worst case shadowing conditions occur when the whole cell (or a large fraction) is shadowed.

4.6.1.2 Often low shunt resistance cells are this way because of localized shunts. In this case hot spot heating occurs because a large amount of current flows in a small area. Because this is a localized phenomenon, there is a great deal of scatter in performance of this type of cell. Cells with the lowest shunt resistance have a high likelihood of operating at excessively high temperatures when reverse biased.

4.6.1.3 Because the heating is localized, hot spot failures of low shunt resistance cells occur quickly.

4.6.2 *High Shunt Resistance Cells:*

4.6.2.1 The worst case shadowing conditions occur when a small fraction of the cell is shadowed.

4.6.2.2 High shunt resistance cells limit the reverse current flow of the circuit and therefore heat up. The cell with the highest shunt resistance will have the highest power dissipation.

4.6.2.3 Because the heating is uniform over the whole area of the cell, it can take a long time for the cell to heat to the point of causing damage.

4.6.2.4 High shunt resistance cells define the need for bypass diodes in the module's circuit, and their performance characteristics determine the number of cells that can be protected by each diode.

4.7 The major technical issue is how to identify the highest and lowest shunt resistance cells and then how to determine the

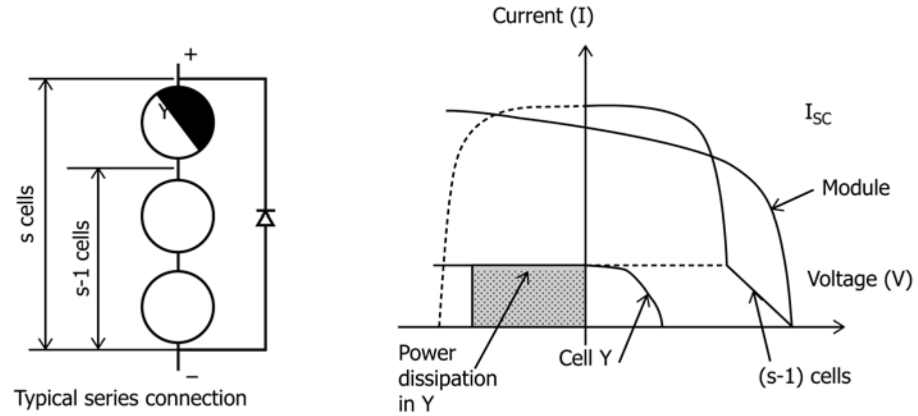

FIG. 2 Bypass Diode Effect

worst case shadowing for those cells. If the bypass diodes are removable, cells with localized shunts can be identified by reverse biasing the cell string and using an IR camera to observe hot spots. If the module circuit is accessible the current flow through the shadowed cell can be monitored directly. However, many PV modules do not have removable diodes or accessible electric circuits. Therefore a non-intrusive method is needed that can be utilized on those modules.

4.8 The selected approach is based on taking a set of I-V curves for a module with each cell shadowed in turn. Fig. 3 shows the resultant set of I-V curves for a sample module. The curve with the highest leakage current at the point where the diode turns on was taken when the cell with the lowest shunt resistance was shadowed. The curve with the lowest leakage current at the point where the diode turns on was taken when the cell with the highest shunt resistance was shadowed.

4.9 If the module to be tested has parallel strings, each string must be tested separately.

4.10 This test method may be specified as part of a series of qualification tests including performance measurements and demonstration of functional requirements. It is the responsibility of the user of this test method to specify the minimum acceptance criteria for physical or electrical degradation.

## 5. Apparatus

5.1 In addition to the apparatus required for the electrical performance (I-V) measurements of Test Methods E1036, the following apparatus is required:

5.1.1 *Illumination Source*—natural sunlight or Class C (or better) steady-state solar simulator as defined in Specification E927.

5.1.2 Set of opaque covers for test cell shadowing. The area of the covers shall be based on the area of the cells in the module being tested, in 5 % increments.

5.1.3 Appropriate temperature detectors to measure ambient temperature and module surface temperature.

5.1.4 Appropriate meter(s) to measure module voltage and current.

## 6. Procedure

6.1 Measure the electrical performance (I-V characteristics) of the module according to Test Methods E1036.

6.2 Perform visual inspection per Practice E1799.

6.3 Perform insulation test per Test Methods E1802.

6.4 Expose the module to an irradiance of 800 to 1000 Wm$^{-2}$ using either:

6.4.1 A pulsed simulator where the module temperature will be close to room temperature (25 ± 5°C),

6.4.2 A steady-state simulator where the module temperature must be stabilized within ±5°C before beginning the measurements, or

6.4.3 Natural sunlight where the module temperature must be stabilized within ±5°C before beginning the measurements.

6.5 After thermal stabilization is attained, determine the maximum power current $I_{MP1}$ according to Test Methods E1036. It is not necessary to correct the value to standard test conditions (STC).

6.6 Completely cover each cell in turn, measure the resultant I-V curve and prepare a set of curves like Fig. 3.

6.6.1 Select the three cells with the lowest shunt resistance (highest leakage current).

6.6.2 Select the cell with the highest shunt resistance (lowest leakage current).

NOTE 3—It is important to ensure that individual cells are completely covered during the I-V curve characterization procedure. Leaving even 1% of a cell uncovered may cause the wrong cell to be selected for the stress testing.

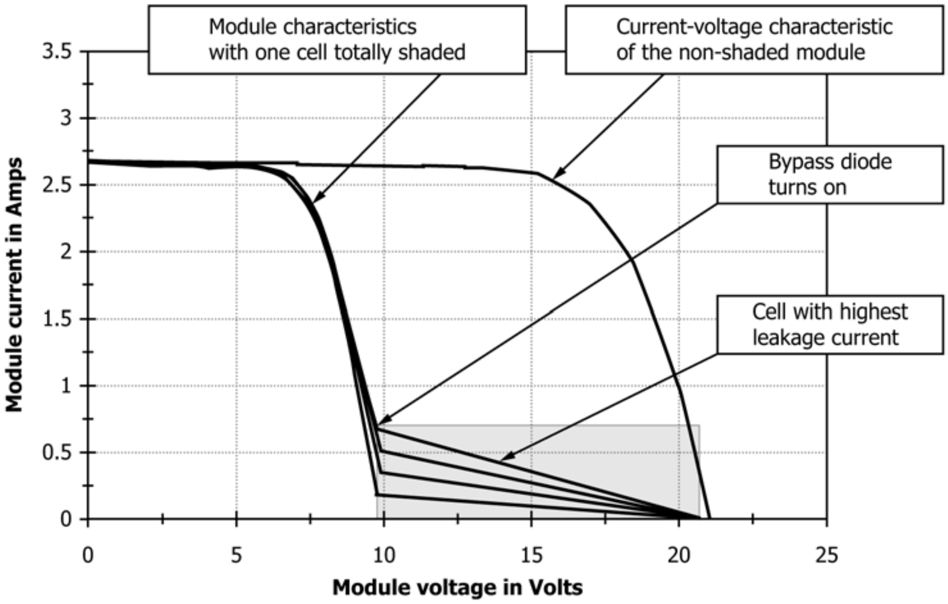

FIG. 3 Module I-V Characteristics with Different Cells Totally Shadowed

6.7 For each of the selected cells determine the worst case covering condition by taking a set of I-V curves with each of the test cells covered at different levels as shown in Fig. 4. The worst case covering condition occurs when the "kink" in the I-V curve of the shadowed covered module coincides with $I_{MP1}$. (line "c" in Fig. 4)

6.8 Select one of the three lowest shunt resistance cells selected in 6.6. Cover that cell to the worst case condition as determined in 6.7. Short-circuit the module.

6.9 Expose the module to the illumination source. Irradiance must be between 800 and 1200 Wm$^{-2}$. Record the value of short circuit current $I_{SC}$, irradiance, ambient temperature and module temperature.

6.10 Maintain this condition for a total exposure time of 1 h.

6.11 Repeat 6.8 – 6.10 for the other two low shunt resistance cells selected in 6.6.

6.12 Cover the highest shunt resistance cell to the worst case condition as determined in 6.7. Short-circuit the module.

6.13 Expose the module to the illumination source. Irradiance must be between 800 and 1200 Wm$^{-2}$. Record the value of short circuit current $I_{SC}$, irradiance, ambient temperature and module temperature.

6.14 Measure the irradiance every 5 min until the total radiant exposure reaches 180 MJm$^{-2}$. (This is equivalent to 50 h at 1000 Wm$^{-2}$.)

6.14.1 If using a steady-sate solar simulator, remove the module from the illumination source for a minimum of 1 h after every 5 h of exposure.

6.15 Measure the electrical performance (I-V characteristics) of the module according to Test Methods E1036.

6.16 Perform visual inspection per Practice E1799

6.17 Perform insulation test per Test Methods E1802

## 7. Report

7.1 The report shall include the following items as a minimum:

7.1.1 Module manufacturer and complete test specimen identification,

7.1.2 Description of module construction,

7.1.3 Description of electrical measurement equipment,

7.1.4 Module I-V measurement results before and after the hot spot exposure,

7.1.5 Ambient conditions during the test,

7.1.6 Measured values of module current and temperature,

7.1.7 A description of any apparent changes as a result of the testing. For example, indications of shorting, arcing, excessive heating, damage to module materials, or other failures which result in accessibility of live parts,

7.1.8 Identification of areas of the module where problems were found, and

7.1.9 Any deviations from the test procedure.

## 8. Precision and Bias

8.1 The procedures described by these test methods do not produce numeric results that would be subject to ASTM requirements for evaluating the precision and bias of these test methods. However, the precision and bias of the electrical measurements, when performed in accordance with Test Methods E1036, are subject to the provisions of that document.

## 9. Keywords

9.1 solar; energy; photovoltaics; modules; electrical testing; hot spot

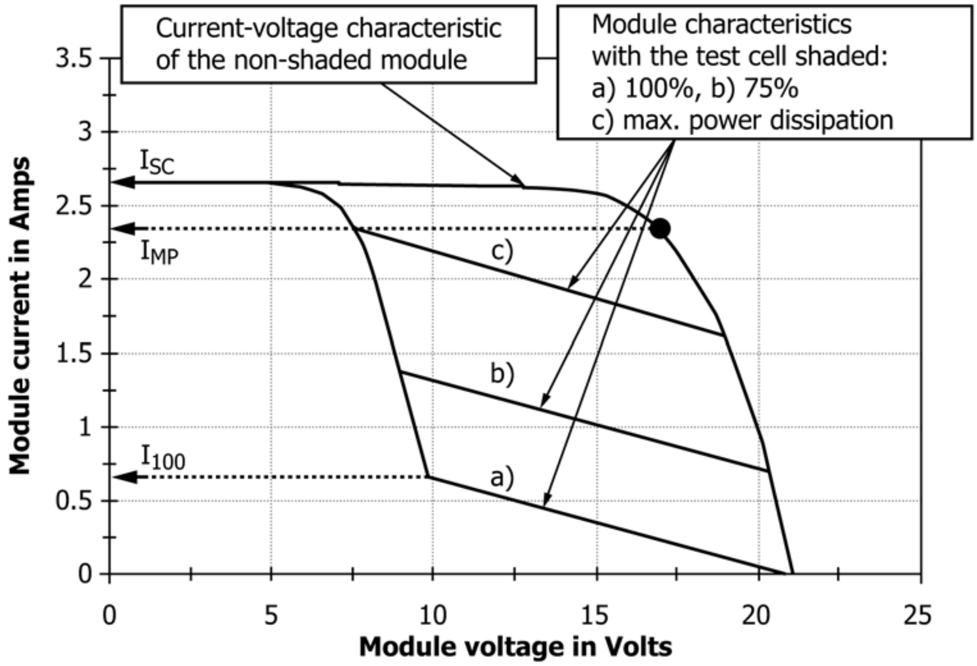

FIG. 4 Module I-V Characteristics with the Test Cell Shadowed at Different Levels

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