Designation: E2481 − 12 (Reapproved 2023)

An American National Standard

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

This standard is issued under the fixed designation E2481; 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 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 nonuniform) 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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.6 *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]

E772 Terminology of Solar Energy Conversion

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

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 (I_{SC}) of a shadowed or faulty cell or group of cells. When such a

[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.

Current edition approved Aug. 1, 2023. Published August 2023. Originally approved in 2006. Last previous edition approved in 2018 as E2481 – 12 (2018). DOI: 10.1520/E2481-12R23.

[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.

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 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 Bypass 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 performed 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 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

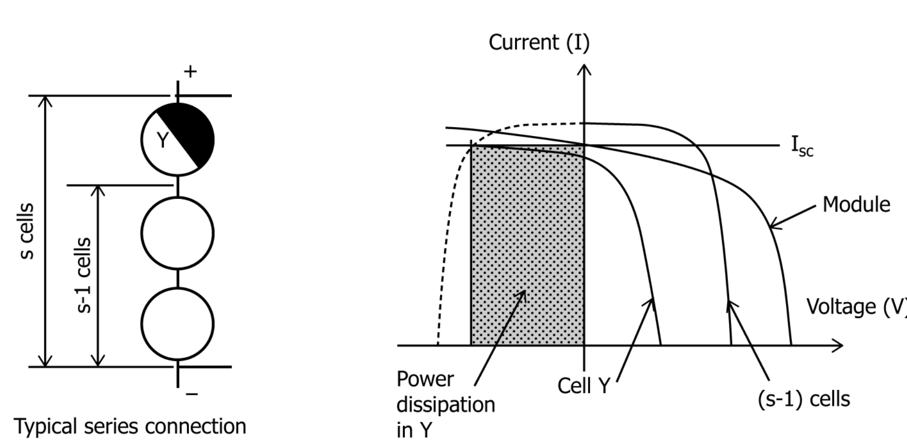

FIG. 1 Hot Spot Effect

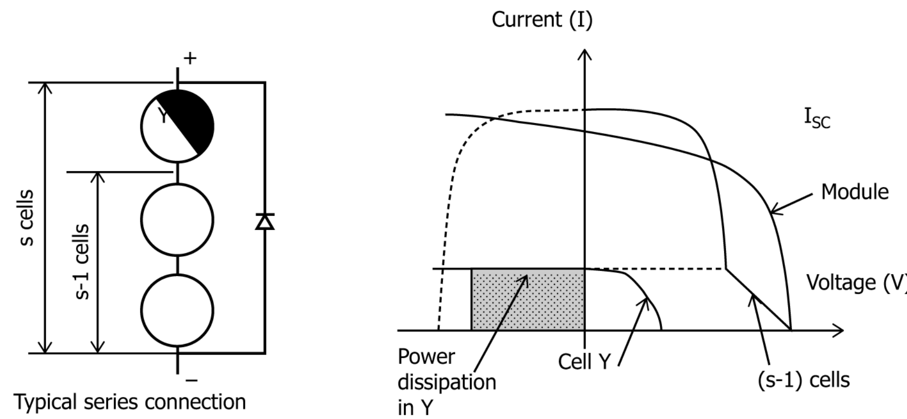

FIG. 2 Bypass Diode Effect

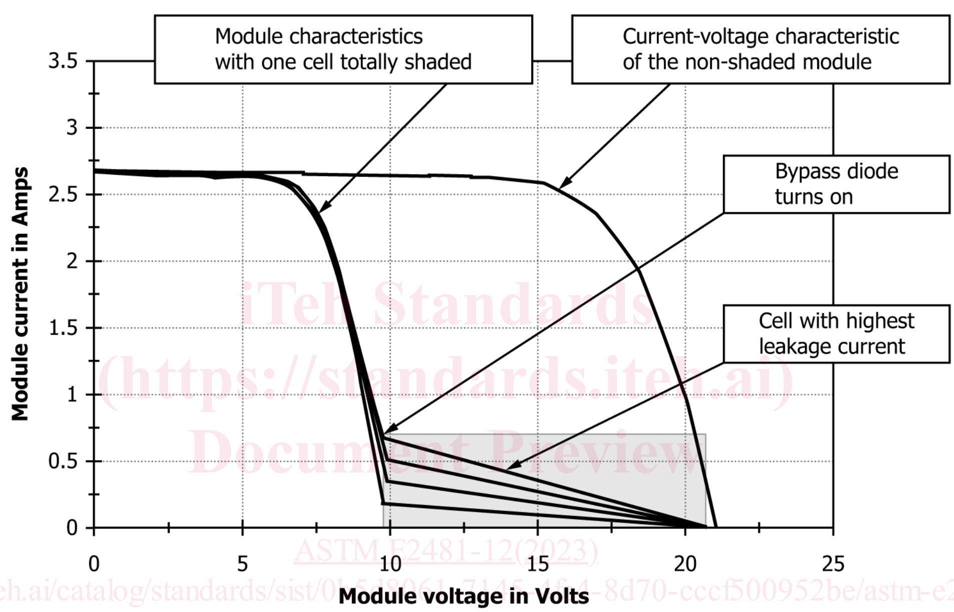

FIG. 3 Module I-V Characteristics with Different Cells Totally Shadowed

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 Classification 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.