Designation: E927 − 19

An American National Standard

Standard Classification for Solar Simulators for Electrical Performance Testing of Photovoltaic Devices[1]

This standard is issued under the fixed designation E927; 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 classification provides means for assessing the suitability of solar simulators for indoor electrical performance testing of photovoltaic cells and modules, that is, for measurement current-voltage curves under artificial illumination.

1.2 Solar simulators are classified according to their ability to reproduce a reference spectral irradiance distribution (see Tables G138 and E490), the uniformity of total irradiance across the test plane, and the stability of total irradiance over time.

1.3 A solar simulator usually consists of three major components: *(1)* light source(s) and associated power supplies; *(2)* optics and filters required to modify the irradiance at the test plane; and *(3)* controls to operate the simulator, including irradiance adjustment.

1.4 This classification is applicable to both pulsed and steady-state solar simulators.

1.5 Many solar simulators also include integral data acquisition systems for photovoltaic performance testing; these data acquisition systems are outside of the scope of this classification.

1.6 Light sources for weathering, durability, or conditioning of photovoltaic devices are outside of the scope of this classification.

1.7 This classification is not applicable to solar simulators intended for testing photovoltaic concentrator devices.

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

1.9 The following precautionary caveat pertains only to the hazards portion, Section 6, of this classification. *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.*

1.10 *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

E772 Terminology of Solar Energy Conversion

E948 Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight

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

E1036 Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells

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

E2236 Test Methods for Measurement of Electrical Performance and Spectral Response of Nonconcentrator Multijunction Photovoltaic Cells and Modules

G113 Terminology Relating to Natural and Artificial Weathering Tests of Nonmetallic Materials

G138 Test Method for Calibration of a Spectroradiometer Using a Standard Source of Irradiance

G173 Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface

[1] This classification 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.

3. Terminology

3.1 Definitions of terms used in this classification may be found in Terminologies E772 and G113.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *field of view*—the maximum angle between any two incident irradiance rays from the simulator at any arbitrary point in the test plane.

3.2.2 *multi-pulse solar simulator*—a solar simulator whose effective irradiance at the test plane consists of a series of short duration, periodic light pulses.

3.2.2.1 *Discussion*—The irradiance of a multi-pulse solar simulator is not required to be zero between pulses.

3.2.2.2 *Discussion*—A steady-state solar simulator (see 3.2.9) that fails the 5 % maximum effective irradiance variation requirement can be identified as a multi-pulse solar simulator if its temporal irradiance variations are periodic.

3.2.3 *single-pulse solar simulator*—a solar simulator whose effective irradiance at the test plane consists of a single short duration light pulse of 100 ms or less.

3.2.4 *solar simulator*—equipment used to illuminate photovoltaic devices with radiation similar to that of the sun (that is, solar radiation) for the purpose of electrical performance measurements.

3.2.5 *spatial matrix*—the discrete positions in the test plane at which the spatial non-uniformity of irradiance is evaluated.

3.2.6 *spatial non-uniformity of irradiance*—the variation of effective irradiation of a solar simulator, as determined from the short-circuit current of a detector solar cell at discrete positions in a two-dimensional spatial matrix in the test plane.

3.2.7 *spectral match*—the ratio of integrated spectral irradiance produced by a solar simulator in a particular wavelength band to that of the target spectral irradiance in the same wavelength band.

3.2.8 *spectrally adjustable solar simulator*—a solar simulator, primarily intended for testing the electrical performance of photovoltaic multijunction devices (see Test Methods E2236), that allows the spectral irradiance to be adjusted in discrete wavelength bands by the user of the solar simulator.

3.2.9 *steady-state solar simulator*—a solar simulator whose effective irradiance at the test plane does not vary more than 10 % for time periods greater than 100 ms.

3.2.10 *target spectral irradiance*—the reference spectral irradiance distribution that the solar simulator is intended to simulate; the distribution may be normal or hemispherical as defined in Tables G173, or extraterrestrial as defined in E490.

3.2.11 *temporal instability of irradiance*—the variation of effective irradiance during the time period of data acquisition, as determined from the short-circuit current of a detector solar cell in the test plane.

3.2.12 *test plane*—the plane of the solar simulator in which a device under test will be illuminated, as designated by the user of this classification.

3.2.13 *test plane area*—the area of the test plane (see 3.2.12).

3.2.14 *time period of data acquisition*—a designated period of time over which electrical performance is acquired from a photovoltaic device under test.

3.3 The following symbols and units are used in this classification:

3.4 *Symbols:*

3.4.1 A_{TP}—area, spatial non-uniformity test position (m^2).

3.4.2 $\mathbf{I}_S$—array of normalized short-circuit currents for spatial non-uniformity, detector solar cell (dimensionless).

3.4.3 I_{SC}—short-circuit current, detector solar cell (A).

3.4.4 $\mathbf{I}_T$—array of measured short-circuit currents for temporal instability, detector solar cell (A).

3.4.5 R_{SM}—spectral match ratio (dimensionless).

3.4.6 S_{NE}—spatial non-uniformity of irradiance (%).

3.4.7 t_{DAQ}—time period of data acquistion(s).

3.4.8 T_{IE}—temporal instability of irradiance (%).

3.4.9 Δt—time between successive short-circuit current data point(s).

3.4.10 σ_{NE}—sample standard deviation of spatial non-uniformity (%).

3.4.11 λ—wavelength (nm).

4. Significance and Use

4.1 This classification is applicable to: *(1)* simulator manufacturers to specify the performance of their products; and *(2)* testing laboratories to document the performance of their measurement equipment.

4.2 Test methods that employ solar simulators as defined in this classification include Test Methods E948, E1036, E1362, and E2236; these standards provide procedures that minimize errors associated with imperfections in solar simulators, such as the simulator's spectral irradiance.

4.3 It is important to recognize that the classification of a solar simulator cannot provide any information about the magnitude of measurement errors that may be encountered with its use. These errors depend on additional factors including the data acquisition instrumentation, the measurement procedures that are used, and the photovoltaic devices tested with the solar simulator.

4.4 A solar simulator is classified without regard to the physical and electrical characteristics of any photovoltaic device. As a result, the parameters and limits associated with the A-B-C classification scheme are generic. However, classification alone does not provide all information needed to assess a solar simulator's suitability. This is especially true of the spatial non-uniformity of irradiance classification.

4.4.1 It is the responsibility of the user of this classification to identify the test plane over which the spatial non-uniformity of irradiance will be measured.

4.4.2 The test for spatial non-uniformity of irradiance involves mapping of the test plane with a detector solar cell. Thus, the mapping cannot resolve spatial variations smaller than the area of the detector solar cell. How this smoothing might affect errors introduced by the spatial non-uniformity of the solar simulator into a given photovoltaic current-voltage performance measurement cannot be determined in advance.

4.4.3 If a solar simulator is intended for testing photovoltaic devices modules composed of uniformly sized solar cells, then using a detector solar cell with the same size should be considered for spatial non-uniformity test.

4.4.4 It is common for devices tested in a solar simulator to be smaller than the test plane identified for this classification. In such cases it may be advantageous for the user of the solar simulator to place a test device in a position where the spatial non-uniformity of irradiance is minimized, using the spatial non-uniformity mapping.

4.4.5 It is possible (and potentially useful) to map the spatial non-uniformity using detector solar cells of different sizes; this can provide maps of greater detail at the expense of longer testing times. Although the spatial non-uniformity classification requires testing with only one size of detector solar cell, results with multiple sizes may be reported.

4.5 Temporal instability of irradiance can only be measured over a pre-determined time period, which in this classification is the time period of data acquisition. Thus, the temporal instability of a solar simulator packaged without an integral data acquisition system may not reflect its performance in actual use.

4.5.1 It is the responsibility of the user of this classification to identify the time period of data acquisition that will be used to determine the temporal instability of irradiance.

4.6 The variations of spatial non-uniformity of irradiance and temporal instability of irradiance are expressed as functions of the minimum and maximum values measured (see Eq 1 and Eq 2); these functions are equal to one-half of the standard expression for percent difference between two values. In this manner, Eq 1 and Eq 2 differ from the expressions for irradiance variations in Practice E491.

4.7 No information about statistical variations of the classification parameters is provided, except the standard deviation of spatial non-uniformity.

4.8 Several important solar simulator characteristics are not included in the A-B-C classification scheme; these include the solar simulator type, test plane size, field of view, standard deviation of the spatial non-uniformity, and the maximum and minimum irradiance capability. These additional properties are to be listed in the reporting requirements (see Section 7).

4.9 The classification of a solar simulator is likely to vary over time. It is common for bulbs in xenon arc lamps to darken with extended use, and the optical properties of mirrors and lenses to degrade over time, all of which can affect the spectral irradiance. Bulb replacement usually includes the need to align it with the solar simulator optics to restore the spatial uniformity in the test plane. It is also common for the temporal instability of irradiance in xenon arc lamps to worsen over time as the bulb ages. It is the responsibility of the user of this classification to identify any appropriate re-classifcation interval or intervals (see 7.4).

4.10 It is common for the spectral irradiance of single- and multi-pulse solar simulators to vary significantly during a single pulse; this classification provides no information about the magnitude of these variations.

4.11 It is not practicable to specify the spectral match at ultraviolet wavelengths less than 350 nm, for several reasons:

4.11.1 The uncertainty of spectral irradiance measurements is high due to the low irradiance of the calibration lamps and low signal-to-noise ratios (see Test Method G138).

4.11.2 The spectral irradiance of common solar simulators in the ultraviolet, especially xenon, is highly variable with time due to bulb aging.

4.11.3 For safety considerations and prevention of ozone generation, it is advantageous to filter all light below 350 nm.

4.12 Determination of the spectral match classification is made at a single location in the test plane. No information is provided by this classification about possible variations of spectral irradiance at other locations. If the existence of such variations is suspected, the spectral match classification should be performed at multiple locations in the test plane area.

4.13 A history of how this classification has developed over time is provided in Appendix X1.

5. Basis of Classification

5.1 A solar simulator is classified according to the following criteria:

5.1.1 Steady-state, single-pulse, or multi-pulse, as defined in 3.2.9, 3.2.3, and 3.2.2.

5.1.2 Spectrally adjustable, as defined in 3.2.8.

5.1.3 Temporal instability of irradiance, T_{IE}, as measured from 7.1 and in accordance with Table 1:

Class A—$T_{IE} \leq 2$ %
Class B—$T_{IE} \leq 5$ %
Class C—$T_{IE} \leq 10$ %
Class U—$T_{IE} > 10$ % (unclassified)

5.1.4 Spatial non-uniformity of irradiance, S_{NE}, as measured from 7.2 and in accordance with Table 1:

Class A—$S_{NE} \leq 2$ %
Class B—$S_{NE} \leq 5$ %
Class C—$S_{NE} \leq 10$ %
Class U—$S_{NE} > 10$ % (unclassified)

5.1.5 Spectral match, R_{SM}, as measured from 7.3 and in accordance with Table 1, for direct normal (Tables G173), hemispherical (Tables G173), or extraterrestrial (Standard E490):

Class A—$0.75 \leq R_{SM} \leq 1.25$, for all wavelength intervals in Table 2

Class B—$0.60 \leq R_{SM} \leq 1.40$, for all wavelength intervals in Table 2

TABLE 1 Solar Simulator Classifications

Classification	Characteristics		
	Spectral Match, All Intervals	Spatial Non-uniformity of Irradiance	Temporal Instability of Irradiance
Class A	$0.75 \leq R_{SM} \leq 1.25$	$S_{NE} \leq 2$ %	$T_{IE} \leq 2$ %
Class B	$0.60 \leq R_{SM} \leq 1.40$	$S_{NE} \leq 5$ %	$T_{IE} \leq 5$ %
Class C	$0.40 \leq R_{SM} \leq 2.00$	$S_{NE} \leq 10$ %	$T_{IE} \leq 10$ %
Class U	$R_{SM} > 2.00$	$S_{NE} > 10$ %	$T_{IE} > 10$ %

TABLE 2 Integrated Target Spectral Irradiance Ratios

Wavelength Interval, nm	Ratio of Interval Irradiance to all Intervals, %		
	Direction Normal Tables G173	Hemispherical Tables G173	Extraterrestrial Standard E490
350 ≤ λ < 400	not used	not used	4.67
400 ≤ λ < 500	16.75	18.21	16.80
500 ≤ λ < 600	19.49	19.73	16.68
600 ≤ λ < 700	18.36	18.20	14.28
700 ≤ λ < 800	15.08	14.79	11.31
800 ≤ λ < 900	12.82	12.39	8.98
900 ≤ λ < 1100	16.69	15.89	13.50
1100 ≤ λ < 1400	not used	not used	12.56
Normalization Interval	400 ≤ λ < 1100	400 ≤ λ < 1100	350 ≤ λ < 1400

Class C—$0.40 \leq R_{SM} \leq 2.00$, for all wavelength intervals in Table 2

Class U—$R_{SM} > 2.00$ (unclassified)

Class N—spectrally adjustable (see 3.2.8 and 5.6)

5.2 A solar simulator may have different classifications for each performance category. For example, a simulator might be Class A for spatial non-uniformity and Class B for spectral match. Classification for all three characteristics must be defined and reported.

5.2.1 When a simulator is identified with a group of three letters, such as Class ABB, it shall be unambiguous as to which classification parameter the individual letters correspond.

5.3 The user of this classification shall identify the test plane of the solar simulator over which the spatial non-uniformity was defined and measured.

5.4 The user of this classification shall identify the time period of data acquisition over which the temporal instability was defined and measured.

5.4.1 For single- or multi-pulse solar simulators, the time period of data acquisition shall be specified with respect to a well-defined reference time, such as the initiation of a pulse.

5.4.2 For steady-state solar simulators, the time period of data acquisition shall be specified after a defined time of warm-up and stabilization, such as the number of minutes after start.

5.5 The user of this classification shall identify the target spectral irradiance to which the spectral match refers (see 5.1.5).

5.6 Because a spectrally adjustable solar simulator does not have a fixed spectral irradiance, the spectral match is not a constant parameter and thus cannot be classified. However, it is possible to perform the spectral match classification for a given adjustment state while recognizing that the spectral match is not constant.

6. Hazards

6.1 The use of a solar simulator involves several safety hazards. A partial description of potential hazards follows:

6.1.1 Electrical hazards due to high voltages that may be associated with starting, flashing or operating solar simulators.

6.1.2 Ultraviolet radiation from solar that can be very harmful to skin and eyes, and which generates ozone.

6.1.3 Very high lamp temperatures.

6.1.4 Many lamps may be under pressure. Even at non-operating conditions, the lamp may be pressurized to several atmospheres.

7. Test Methods and Retest

7.1 *Temporal Instability of Irradiance:*

7.1.1 Identify the time period of data acquisition, t_{DAQ}.

7.1.2 Select a detector solar cell: this will be a silicon cell, or for a single-pulse solar simulator with very short pulses (<50 ms), a III-V solar cell such as GaAs or GaInP.

7.1.3 Mount the detector solar cell in the test plane of the solar simulator.

7.1.4 Connect the detector solar cell to short-circuit measurement equipment, as required for Test Method E948.

7.1.5 Expose the detector solar cell to light from the solar simulator. The temperature of the detector solar cell shall be held constant during temporal instability measurement.

7.1.6 Determine the short-circuit current of the detector solar cell, I_{SC}, as a function of time, as follows:

7.1.6.1 Divide t_{DAQ} by a minimum of 20; this is the time between successive I_{SC} data points, Δt.

7.1.6.2 During the t_{DAQ}, at intervals equal to Δt, make successive I_{SC} measurements using the short-circuit current measurement equipment.

7.1.6.3 For single- or multi-pulse solar simulators, repeat 7.1.6.2 for a minimum of 20 successive pulses.

7.1.6.4 Form an array of all measured I_{SC} values, $\mathbf{I}_T$.

7.1.7 Calculate the temporal instability of irradiance for the solar simulator:

$$T_{IE} = 100 \frac{\max \mathbf{I}_T - \min \mathbf{I}_T}{\max \mathbf{I}_T + \min \mathbf{I}_T} \quad (1)$$

7.1.8 *Classification*—Select the classification category in 5.1.3 that best describes T_{IE}; this is the temporal instability of irradiance classification of the solar simulator.

7.2 *Spatial Non-uniformity of Irradiance:*

7.2.1 Identify the test plane of the solar simulator and its area.

7.2.2 Determine the spatial matrix of positions at which the spatial non-uniformity will be evaluated; this may be done either of two ways: *(1)* dividing the test plane into equal-area test positions and then selecting a detector solar cell that fits into test positions; or *(2)* selecting a detector solar cell and then dividing the test plane into test positions equal to the area of the detector solar cell.