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An American National Standard

Standard ~~Specification~~Classification for Solar ~~Simulation for Photovoltaic Testing~~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 specification provides means for classifying solar simulators intended for indoor testing of photovoltaic devices (solar cells or modules), according to their spectral match to a reference spectral irradiance, non-uniformity of spatial irradiance, and temporal instability of irradiance.~~

~~1.2 Testing of photovoltaic devices may require the use of solar simulators. Test Methods that require specific classification of simulators as defined in this specification include Test Methods E948, E1036, and E1362.~~

~~1.3 This standard is applicable to both pulsed and steady state simulators and includes recommended test requirements used for classifying such simulators.~~

~~1.4 A solar simulator usually consists of three major components: *(1)* light source(s) and associated power supply; *(2)* any optics and filters required to modify the output beam to meet the classification requirements in Section 4; and *(3)* the necessary controls to operate the simulator, adjust irradiance, etc.~~

~~1.5 A light source that does not meet all of the defined requirements for classification presented in this document may not be referred to as a solar simulator.~~

~~1.6 Spectral irradiance classifications are provided for Air Mass 1.5 direct and global (as defined in Tables G173), or Air Mass 0 (AM0, as defined in Standard E490).~~

~~1.7 The classification of a solar simulator is based on the size of the test plane; simulators with smaller test plane areas have tighter specifications for non-uniformity of spatial irradiance.~~

~~1.8 The data acquisition system may affect the ability to synchronize electrical measurements with variations in irradiance and therefore may be included in this specification. In all cases, the manufacturer must specify with the temporal instability classification: *(1)* how the classification was determined; and *(2)* the conditions under which the classification was determined.~~

~~1.9 The classification of a solar simulator does not provide any information about electrical measurement errors that are related to photovoltaic performance measurements obtained with a classified solar simulator. Such errors are dependent on the actual instrumentation and procedures used.~~

~~1.10 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.~~

~~1.11 The following precautionary caveat pertains only to the hazards portion, Section 6, of this specification. *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.*~~

~~1.12 *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~~

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[1] This ~~specification~~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.

E772 Terminology of Solar Energy Conversion
E948 Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight
E1036 Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells
E1328 Terminology Relating to Photovoltaic Solar Energy Conversion (Withdrawn 2012)[3]
E1362 Test Methods for Calibration of Non-Concentrator Photovoltaic Non-Primary Reference Cells
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

2.2 *IEC Standard:*
IEC 60904-9 Photovoltaic Devices—Part 9: Solar Simulator Performance Requirements

3. Terminology

3.1 *Definitions*—Definitions of terms used in this specification may be found in Terminologies E772 and E1328.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *solar simulator*—equipment used to simulate solar radiation. Solar simulators shall be labeled by their mode of operation during a test cycle (steady state, single pulse or multi-pulse) and by the size of the test plane area. A solar simulator must fall into at least the C classification.

3.2.2 *simulator classification*—a solar simulator may be one of three classes (A, B, or C) for each of three categories: spectral match, spatial non-uniformity, and temporal instability. The simulator is rated with three letters in order of spectral match, spatial non-uniformity and temporal instability (for example: Class ABA). Large area and small area simulators are classified according to the appropriate table. The simulator classification may be abbreviated by a single letter characterization. A simulator characterized by a single letter is indicative of a simulator with all three classes being the same (for example: a Class A simulator is the same as a Class AAA simulator).

3.2.3 *test plane area, A*—the area of the plane intended to contain the device under test.

3.2.4 *small area solar simulator*—a simulator whose test plane is equal to or less than 30 cm by 30 cm or a diameter of less than 30 cm if the test area is circular.

3.2.5 *large area solar simulator*—a simulator whose test plane is greater than 30 cm by 30 cm or a diameter of greater than 30 cm if the test area is circular.

3.2.6 *steady-state simulator*—a simulator whose irradiance output at the test plane area does not vary more than 5 % for time periods of greater than 100 ms.

3.2.7 *single-pulse simulator*—a simulator whose irradiance output at the test plane area consists of a short duration light pulse of 100 ms or less.

3.2.8 *multi-pulse simulator*—a simulator whose irradiance output at the test plane area consists of a series of short duration, periodic light pulses. Note that the light pulses do not necessarily have to go to zero irradiance between pulses; a steady-state simulator that fails the 5 % requirement in 3.2.6 can be classified as a multi-pulse simulator if the irradiance variations are periodic.

3.2.9 *time of data acquisition*—the time required to obtain one data point (irradiance, current, and voltage) if there is a simultaneous measurement of irradiance at each current-voltage data point. If no simultaneous measurement of the irradiance is made during the test, the time of data acquisition is the time to obtain the entire current-voltage (I-V) curve.

3.2.10 *solar spectrum*—the spectral distribution of sunlight at Air Mass 1.5 Direct (as defined in Tables G173), Air Mass 1.5 Global (as defined in Tables G173), or Air Mass 0 (as defined in Standard E490).

3.2.11 *spectral match*—ratio of the actual percentage of total irradiance to the required percentage specified in Table 3 for each wavelength interval.

3.2.12 *spatial non-uniformity of irradiance (in percent):*

$$S_{NE} = 100\,\% \times \frac{E_{max} - E_{min}}{E_{max} + E_{min}} \tag{1}$$

where E_{max} and E_{min} are measured with the detector(s) over the test plane area.

3.2.13 *temporal instability of irradiance (in percent):*

$$T_{IE} = 100\,\% \times \frac{E_{max} - E_{min}}{E_{max} + E_{min}} \tag{2}$$

where E_{max} and E_{min} are measured with the detector at any particular point on the test plane during the time of data acquisition.

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

TABLE 1 Classification of Small Area Simulator Performance

Classification	Characteristics		
	Spectral Match to all Intervals	Spatial Non-uniformity of Irradiance	Temporal Instability of Irradiance
Class A	0.75 to 1.25	2 %	2 %
Class B	0.6 to 1.4	5 %	5 %
Class C	0.4 to 2.0	10 %	10 %

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	$R_{SM} > 2.00$	$S_{NE} > 10$ %	$T_{IE} > 10$ %

4. Significance and Use

4.1 In any photovoltaic measurement, the choice of simulator Class should be based on the needs of that particular measurement. For example, the spectral distribution requirements need not be stringent if devices of identical spectral response from an assembly line are being sorted according to current at maximum power, which is not a strong function of spectral distribution.

4.2 Classifications of simulators are based on the size of the test area and the probable size of the device being measured. It has been shown that when measuring modules or other larger devices the spatial non-uniformity is less important, and up to 3 % non-uniformity may not introduce unacceptable error for some calibration procedures.[4] Accurate measurements of smaller area devices, such as cells, may require a tighter specification on non-uniformity or characterization of the non-uniformity by the user. When measuring product it is recommended that the irradiance be measured with a reference device similar to the devices that will be tested on the simulator to minimize spatial non-uniformity errors.

4.3 It is the intent of this specification to provide guidance on the required data to be taken, and the required locations for this data to be taken. It is not the intent to define the possible methods to measure the simulator spectrum or the irradiance at every location on the test plane.

4.4 Note that the letter classification scheme (see 3.2.2) does not include a number of important properties, especially the test plane size, the field of view, nor the steady state or the pulsed classifications (see 3.2.3 through 3.2.8, and 3.2.14). These additional properties are included in the reporting requirements (see Section 9). It is also recommended that they be included in product specification sheets or advertising.

4.5 Because of the transient nature of pulsed solar simulators, considerations must be given to possible problems such as the response time of the device under test versus the time of data acquisition and the rise time of the pulsed irradiance. If a pulsed solar simulator includes a data acquisition system, the simulator manufacturer should provide guidance concerning such possible problems that may affect measurement results on certain test devices.

4.6 The simulator manufacturer should provide I-V data showing the repeatability of multiple measurements of a single device. This data should include a description of how the repeatability was determined.

5. Classification

5.1 A solar simulator may be either steady state or pulsed, and its performance for each of three determined categories (spectral match, spatial non-uniformity, and temporal instability) may be one of three Classes (A, B, or C). A simulator may be classified to multiple Classes, depending on its characteristics in each of the performance categories. For example, a simulator may be Class A related to spatial uniformity and Class B related to spectral distribution. Classification for all three performance characteristics must be defined and provided by the manufacturer.

5.2 The manufacturer shall provide test area information to assist in proper usage of the simulator. Tables 1 and 2 give performance requirements for small and large area simulators for the three performance categories: spectral match to the reference spectrum at all intervals, non-uniformity of irradiance, and temporal instability of irradiance. Table 3 gives the spectral match requirements for spectral distribution of irradiance for Direct AM1.5, Global AM1.5, and AM0. The simulator irradiance is divided into the same wavelength intervals and compared with the reference spectrum. All intervals must agree within the spectral match ratio in Table 1 to obtain the respective Class.

TABLE 2 Classification of Large Area Simulator Performance

Classification	Characteristics		
Spectral Match to all Intervals	Spatial Non-uniformity of Irradiance	Temporal Instability of Irradiance	
Class A	0.75 to 1.25	3 %	2 %
Class B	0.6 to 1.4	5 %	5 %
Class C	0.4 to 2.0	10 %	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

TABLE 3 Spectral Distribution of Irradiance Performance Requirements (Small and Large Area Simulators)

Wavelength interval, µm	Percent of Total Irradiance		
	Direct AM 1.5	Global AM 1.5	AM 0
0.3 to 0.4	Not Specified	Not Specified	8.0
0.4 to 0.5	16.9	18.4	16.4
0.5 to 0.6	19.7	19.9	16.3
0.6 to 0.7	18.5	18.4	13.9
0.7 to 0.8	15.2	14.9	11.2
0.8 to 0.9	12.9	12.5	9.0
0.9 to 1.1	16.8	15.9	13.1
1.1 to 1.4	Not Specified	Not Specified	12.2

5.3 A reference device should be used for determining the spatial uniformity of the simulator. The reference device must have a spectral response appropriate for the simulator; a silicon device is typically a good choice. A map of simulator spatial uniformity must be supplied with the simulator to assist the user in simulator operation and to clearly define different areas in the test plane that may have different classifications.

5.4 For the evaluation of temporal instability, the data acquisition system may be considered an integral part of the solar simulator. When the data acquisition system of the solar simulator measures data simultaneously (irradiance, voltage, and current data measured within 10 nanoseconds of each other), then the temporal instability may be rated A for this classification but the range of irradiance variation during an entire I-V measurement, including times between points, must be reported and less than 5 %. If a solar simulator does not include the data acquisition system, then the simulator manufacturer must specify the time of data acquisition as related to the reported temporal instability classification.

5.4.1 For a steady-state simulator without an integral data acquisition system this rating must be given for a period of 1 second, and actual instability data must be reported for 100 milliseconds, 1 minute, and 1 hour.

5.4.2 In the case of a pulsed solar simulator with a data acquisition system that measures irradiance, current, and voltage sequentially, temporal instability must be evaluated.

5.4.3 The user of a pulsed simulator should verify that the device under test has reached final electrical output levels when data acquisition has begun and that the device under test has a fast enough response to follow the rapidly-changing irradiance.

5.4.4 The ultimate test of the stability of the simulator and system is the actual measurement of data on the total system. For simulators that include an integral data acquisition system, a repeatability measurement should be made on the significant measured parameters such as voltage, fill factor, and current to verify the correction being applied on each data pair is repeatable from measurement to measurement. The manufacturer should specify how repeatability was measured and report the results.

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 the high voltage associated with starting, flashing or operating xenon arc lamps.

6.1.2 Ultraviolet radiation from xenon arc lamps that can be very harmful to bare skin and especially to eyes.

6.1.3 The very high temperature of the bulb.

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

6.1.5 Generation and possible buildup of ozone due to the ultraviolet content of the light.

7. Performance Requirements

7.1 *Spectral Match:*

7.1.1 The data comparison shall indicate the spectral match classification as per the following:

7.1.1.1 *Class A*—Spectral match within 0.75 to 1.25 for each wavelength interval, as specified in Table 3.

7.1.1.2 *Class B*—Spectral match within 0.6 to 1.4 for each wavelength interval, as specified in Table 3.

7.1.1.3 *Class C*—Spectral match within 0.4 to 2.0 for each wavelength interval, as specified in Table 3.

7.1.2 All intervals listed in Table 3 must fall within the range of ratios for spectral match listed in Table 1 or Table 2 for the simulator to qualify for the associated spectral match classification.

7.2 *Non-uniformity of Spatial Irradiance:*

7.2.1 A map of simulator spatial uniformity must be supplied with the simulator to assist the user in testing and to clearly define different areas with different classifications.

7.2.2 The class of the simulator for spatial non-uniformity is given by Table 1 or Table 2 depending on the size of the simulator.

7.2.2.1 *Class A*—Spatial non-uniformity 2 % or 3 %, as specified in Table 1 or Table 2.

7.2.2.2 *Class B*—Spatial non-uniformity 5 %, as specified in Table 1 or Table 2.

7.2.2.3 *Class C*—Spatial non-uniformity 10 %, as specified in Table 1 or Table 2.

7.3 *Temporal Instability of Irradiance:*

7.3.1 The class of the simulator for temporal instability is given by the following:

7.3.1.1 *Class A*—Class A: Temporal instability 2 %, as specified in Table 1 or Table 2.

7.3.1.2 *Class B*—Class B: Temporal instability 5 %, as specified in Table 1 or Table 2.

7.3.1.3 *Class C*—Class C: Temporal instability 10 %, as specified in Table 1 or Table 2.

8. Classification Parameters

8.1 The following requirements specify the parameters needed to determine the classification of a solar simulator.

8.1.1 Because of the large number of possible test methods and the varieties of different solar simulator configurations and uses, it is beyond the scope of this specification to provide specific test methods for the measurements necessary for simulator classification. It is therefore the responsibility of the simulator manufacturer to provide upon request information about the test methods used for the determination of the performance in each classification. Another source of test methods may be found in the suggested procedures section of IEC 60904-9.

8.2 *Spectral Irradiance:*

8.2.1 A spectroradiometer calibrated according to Test Method G138 is an acceptable instrument for simulator spectral irradiance measurements.

8.2.2 The spectral irradiance data are then integrated over the wavelength intervals defined in Table 3, and also integrated over all the wavelength intervals to obtain the total irradiance. The integration results in each of the wavelength bands are then normalized by the total irradiance and compared with the percentages in Table 3. Spectral irradiance deviation limits for Classes A, B, and C are given in Tables 1 and 2.

8.3 *Non-uniformity of Spatial Irradiance:*

8.3.1 A uniformity device is used for determining the non-uniformity of spatial irradiance of the simulator by measuring the irradiance. The linearity and time response of the uniformity device must be appropriate for the characteristics of the simulator being measured.

8.3.2 Divide the defined test area into at least 36 equally sized (by area) test positions. Using the uniformity device, determine the irradiance in each of the test positions.

8.3.2.1 The uniformity device shall be no larger than the area of the individual test positions.

8.3.2.2 The uniformity device shall be at least large enough that the area of the device times the number of test positions is greater than 25 % of the total defined test area.

8.3.2.3 It is recommended that a single cell be used for a uniformity device.

8.3.3 While the uniformity device may be centered in the test positions inside the perimeter of the test area, it must be placed to the outer edge of the test area for those test positions on the test area perimeter.

8.3.4 At least one measurement of the irradiance must be made in each location, and the spatial non-uniformity is determined according to 3.2.12.

8.3.5 Simulator manufacturers are encouraged to take more than the 36 measurements specified as a minimum number in this procedure.

8.3.6 The uniformity device must have a spectral response appropriate for the simulator, and a silicon device is typically a good choice.

8.4 *Temporal Instability of Irradiance*—Separate cases for pulsed and steady-state simulators are provided. Note that temporal instability of irradiance cannot be determined for a pulse simulator without a data acquisition system.

8.4.1 *Pulse Simulator, with Data Acquisition System:*

8.4.1.1 *Simultaneous Data Sampling*—If three separate data inputs simultaneously measure values of irradiance, current, and voltage within 10 nanoseconds of each other, and the irradiance does not vary by more than 5 %, then the temporal instability is Class A. If this condition is not met, the temporal instability of irradiance must be determined using 8.4.1.2.

(1) Multi-pulse Simulator—The 5 % limit must be determined with measurements of irradiance at each pulse for the number of pulses in a typical I-V curve measurement.

(2) Single-pulse Simulator—The 5 % limit must be determined with multiple measurements of irradiance during the I-V curve data acquisition period of a single pulse.

8.4.1.2 *Sequential Data Sampling*—If the data acquisition system measures irradiance, current, and voltage in succession, determine the temporal instability using these steps:

(1) Measure at least 10 irradiance data points evenly spaced in time during the portion of the pulse that is used for I-V measurements.

(2) Determine the maximum and minimum irradiance for this data measured in 8.4.1.1.

(3) Calculate the temporal instability according to 3.2.13.

8.4.2 *Steady State Simulator:*

8.4.2.1 *Simultaneous Data Sampling*—If three separate data inputs simultaneously measure values of irradiance, current, and voltage within 10 nanoseconds of each other, and the irradiance does not vary by more than 5 % during the I-V curve measurement period, including times between irradiance, current, and voltage data sets, then the temporal instability is Class A. If this condition is not met, the temporal instability of irradiance must be determined using 8.4.2.2.

8.4.2.2 For steady state simulators either not including the data acquisition system, or without simultaneous measurement of irradiance, current and voltage, and the irradiance does not vary by more than 5 %, the following procedure is used to determine temporal instability.

(1) Measure the simulator irradiance over a period of one second, taking at least 20 measurements evenly spaced in time over the one second time period. The instrumentation used to measure irradiance should have a frequency bandwidth of at least 100 kHz to minimize high frequency filtering of simulator instability.

(2) Determine maximum and minimum irradiances from the data recorded in 8.4.2.2*(1)*.

(3) Calculate the temporal instability according to 3.2.13.

(4) For reporting purposes only, also record the irradiance variations for the additional periods required by 5.4.1.

9. Reporting Requirements

9.1 The following information shall be supplied, as a minimum, by the simulator manufacturer:

9.1.1 Date of issue,

9.1.2 Manufacturer of simulator,

9.1.3 Type of simulator (single pulse, multi-pulse, or steady state),

9.1.4 Date(s) of measurements used to determine simulator classification,

9.1.5 Defined test area size,

9.1.6 Distance between test plane and light source,

9.1.7 Test plane depth (allowable distance from test plane),

9.1.8 Classes for all three characteristics: spectral match, spatial non-uniformity, and temporal instability,

9.1.9 Maximum and minimum irradiances used for 3.2.12,

9.1.10 Spectral distribution data,

9.1.11 Repeatability data,

9.1.12 Map of non-uniformity of irradiance measured over the specified test area,

9.1.13 Summary of temporal instability determination, including:

9.1.13.1 Case used for determination, 8.4.1.1, 8.4.1.2, 8.4.2.1, or 8.4.2.2,

9.1.13.2 Maximum and minimum irradiances used for 3.2.13,

9.1.13.3 Irradiance variations over the additional periods specified in 5.4.1, if required by 8.4.2.2*(4)*,

9.1.14 Measurement methods used to determine classification categories,

9.1.15 Percentage of the total irradiance of the simulator that falls within a 30° field of view, and

9.1.16 Recommended time interval for verification of classification.

10. Keywords

10.1 photovoltaic; solar simulation; solar; testing

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.