Designation: E973 – 16

Standard Test Method for
Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell [1]

This standard is issued under the fixed designation E973; 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 for the determination of a spectral mismatch parameter used in performance testing of photovoltaic devices.

1.2 The spectral mismatch parameter is a measure of the error introduced in the testing of a photovoltaic device that is caused by the photovoltaic device under test and the photovoltaic reference cell having non-identical quantum efficiencies, as well as mismatch between the test light source and the reference spectral irradiance distribution to which the photovoltaic reference cell was calibrated.

1.2.1 Examples of reference spectral irradiance distributions are Tables E490 or G173.

1.3 The spectral mismatch parameter can be used to correct photovoltaic performance data for spectral mismatch error.

1.4 Temperature-dependent quantum efficiencies are used to quantify the effects of temperature differences between test conditions and reporting conditions.

1.5 This test method is intended for use with linear photovoltaic devices in which short-circuit is directly proportional to incident irradiance.

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

1.7 *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]

E490 Standard Solar Constant and Zero Air Mass Solar Spectral Irradiance Tables
E772 Terminology of Solar Energy Conversion
E948 Test Method for Electrical Performance of Photovoltaic Cells Using Reference Cells Under Simulated Sunlight
E1021 Test Method for Spectral Responsivity Measurements of Photovoltaic Devices
E1036 Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells
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
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
SI10 Standard for Use of the International System of Units (SI): The Modern Metric System

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 *test light source, n*—a source of illumination whose spectral irradiance will be used for the spectral mismatch calculation. The light source may be natural sunlight or a solar simulator.

3.3 *Symbols:* The following symbols and units are used in this test method:

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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.

3.3.1 λ—wavelength (µm or nm).

3.3.2 D—as a subscript, refers to the device to be tested.

3.3.3 R—as a subscript, refers to the reference cell.

3.3.4 S—as a subscript, refers to the test light source.

3.3.5 0—as a subscript, refers to the reference spectral irradiance distribution.

3.3.6 A—active area, (m^2).

3.3.7 E—irradiance ($W \cdot m^{-2}$).

3.3.8 $E_S(\lambda)$—spectral irradiance, test light source ($W \cdot m^{-2} \cdot \mu m^{-1}$ or $W \cdot m^{-2} \cdot nm^{-1}$).

3.3.9 $E_0(\lambda)$—spectral irradiance, to which the reference cell is calibrated ($W \cdot m^{-2} \cdot \mu m^{-1}$ or $W \cdot m^{-2} \cdot nm^{-1}$).

3.3.9.1 *Discussion*—Following normal SI rules for compound units (see Practice SI10), the units for spectral irradiance, the derivative of irradiance, with respect to wavelength, $dE/d\lambda$, would be $W \cdot m^{-3}$. However, to avoid possible confusion with a volumetric power density unit and for convenience in numerical calculations, it is common practice to separate the wavelength in the compound unit. This compound unit is also used in Tables G173.

3.3.10 I—short-circuit current (A).

3.3.11 J_L—light-generated photocurrent density ($A \cdot m^{-2}$).

3.3.12 M—spectral mismatch parameter (dimensionless).

3.3.13 $Q(\lambda,T)$—quantum efficiency (electrons per photon or %).

3.3.14 $\Theta(\lambda)$—partial derivative of quantum efficiency with respect to temperature (electrons per photon·°C^{-1} or %·°C^{-1}).

3.3.15 $R(\lambda)$—spectral responsivity ($A \cdot W^{-1}$).

3.3.16 T—temperature (°C).

3.3.17 T_{R0}—temperature, at which the reference cell is calibrated (°C).

3.3.18 T_{D0}—temperature, to which the short-circuit current of the device to be tested will be reported (°C).

3.3.18.1 *Discussion*—When reporting photovoltaic performance to Standard Reporting Conditions (SRC), it is common for $T_{R0} = T_{D0} = 25°C$.

3.3.19 q—electron charge (C).

3.3.20 h—Planck constant (J·s).

3.3.21 c—speed of light ($m \cdot s^{-1}$).

3.3.22 ΔT—temperature difference (°C).

3.3.23 ε—measurement error in short-circuit current (dimensionless).

4. Summary of Test Method

4.1 Spectral mismatch error occurs when a calibrated reference cell is used to measure total irradiance of a test light source (such as a solar simulator) during a photovoltaic device performance measurement, and the incident spectral irradiance of the test light source differs from the reference spectral irradiance distribution to which the reference cell is calibrated.

4.2 The magnitude of the error depends on how the quantum efficiencies of the photovoltaic reference cell and the device to be tested differ from one another; these quantum efficiencies vary with temperature.

4.3 Determination of the spectral mismatch parameter M requires six spectral quantities.

4.3.1 The spectral irradiance distribution of the test light source $E_S(\lambda)$.

4.3.2 The reference spectral irradiance distribution to which the photovoltaic reference cell was calibrated $E_0(\lambda)$.

4.3.3 *Photovolatic Reference Cell:*

4.3.3.1 The quantum efficiency at the temperature corresponding to its calibration constant, $Q_R(\lambda T_0)$

4.3.3.2 The partial derivative of the quantum efficiency with respect to temperature, $\Theta_R(\lambda) = \partial Q_R / \partial T(\lambda)$.

4.3.4 *Device to be Tested:*

4.3.4.1 The quantum efficiency at the temperature at which its performance will be reported, $Q_D(\lambda,T_{D0})$.

4.3.4.2 The derivative of the quantum efficiency with respect to temperature, $\Theta_R(\lambda) = \partial Q_D / \partial T(\lambda)$

4.4 Temperatures of both devices are measured, and M is calculated using Eq 1 and numerical integration.

5. Significance and Use

5.1 The calculated error in the photovoltaic device current determined from the spectral mismatch parameter can be used to determine if a measurement will be within specified limits before the actual measurement is performed.

5.2 The spectral mismatch parameter also provides a means of correcting the error in the measured device current due to spectral mismatch.

5.2.1 The spectral mismatch parameter is formulated as the fractional error in the short-circuit current due to spectral and temperature differences.

5.2.2 Error due to spectral mismatch is corrected by multiplying a reference cell's measured short-circuit current by M, a technique used in Test Methods E948 and E1036.

5.3 Because all spectral quantities appear in both the numerator and the denominator in the calculation of the spectral mismatch parameter (see 8.1), multiplicative calibration errors cancel, and therefore only relative quantities are needed (although absolute spectral quantities may be used if available).

5.4 Temperature-dependent spectral mismatch is a more accurate method to correct photovoltaic current measurements compared with fixed-value temperature coefficients.[3]

6. Apparatus

6.1 *Quantum Efficiency Measurement Apparatus*—As required by Test Method E1021 for spectral responsivity measurements.

6.2 *Spectral Irradiance Measurement Equipment*—A spectroradiometer as defined and required by Test Method G138 and calibrated according to Test Method G138.

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[3] Osterwald, C. R., Campanelli, M., Moriarty, T., Emery, K. A., and Williams, R., "Temperature-Dependent Spectral Mismatch Corrections," *IEEE Journal of Photovoltaics*, Vol 5, No. 6, November 2015, pp. 1692–1697. DOI:10.1109/JPHOTOV.2015.2459914

6.2.1 The wavelength resolution shall be no greater than 10 nm.

6.2.2 It is recommended that the wavelength pass-bandwith be no greater than 6 nm.

6.2.3 The wavelength range should be wide enough to include the quantum efficiencies of both the photovoltaic device to be tested and the photovoltaic reference cell.

6.2.4 The spectroradiometer must be able to scan the required wavelength range in a time period short enough such that the spectral irradiance at any wavelength does not vary more than ±5 % during the entire scan.

6.2.5 Test Methods E948, E1036, and E1125 provide additional guidance for spectral irradiance measurements.

6.3 *Temperature Measurement Equipment*—As required by Test Method E948 or Test Methods E1036.

7. Procedure

7.1 Obtain the reference spectral irradiance distribution, $E_0(\lambda)$, to which the photovoltaic reference cell is calibrated, such as Tables E490 or G173.

7.2 Obtain the quantum efficiency of the photovoltaic reference cell at its calibration temperature, $Q_R(\lambda,T_{R0})$.

7.2.1 An expression that converts spectral responsivity to quantum efficiency is provided in Test Methods E1021.

NOTE 1—Test Methods E1125 and E1362 require the spectral responsivity to be provided as part of the reference cell calibration certificate.

7.3 Obtain the partial derivative of quantum efficiency with respect to temperature, $\Theta_R(\lambda)$, for the photovoltaic reference cell (see 8.1).

7.3.1 If $\Theta_R(\lambda)$ is not provided with the calibration certificate of the photovoltaic reference cell, the derivatiave function must be calculated from a series of quantum efficiency measurements at several temperatures. An acceptable procedure is given in Annex A1.

7.4 Measure the quantum efficiency of the photovoltaic device to be tested at the temperature to which its performance will be reported, $Q_D(\lambda,T_{D0})$, and its partial derivative of quantum efficiency with respect to temperature, $\Theta_D(\lambda)$, using the procedure given in Annex A1(see also 8.1).

7.5 Measure the spectral irradiance, $E_S(\lambda)$, of the test light source, using the spectral irradiance measurement equipment (see 6.2.1).

7.6 Measure the temperature of the photovoltaic reference cell, T_R, using the temperature measurement equipment.

7.7 Measure the temperature of the photovoltaic device to be tested, T_D, using the temperature measurement equipment.

8. Calculation of Results

8.1 Calculate the spectral mismatch parameter with:[3]

$$M = \frac{\int_{\lambda 1}^{\lambda 2} \lambda Q_D(\lambda,T_{D0}) E_S(\lambda)d\lambda + \Delta T_D \int_{\lambda 1}^{\lambda 2} \lambda \Theta_D(\lambda)\, E_S(\lambda)d\lambda}{\int_{\lambda 3}^{\lambda 4} \lambda Q_R\,(\lambda,T_{R0}) E_S(\lambda)d\lambda + \Delta T_R \int_{\lambda 3}^{\lambda 4} \lambda \Theta_R(\lambda) E_S(\lambda)d\lambda} \times \frac{\int_{\lambda 3}^{\lambda 4} \lambda Q_R\,(\lambda,T_{R0}) E_0(\lambda)d\lambda}{\int_{\lambda 1}^{\lambda 2} \lambda Q_D\,(\lambda,T_{D0}) E_0(\lambda)d\lambda}, \qquad (1)$$

where $\Delta T_R = T_R - T_{R0}$ and $\Delta T_D = T_D - T_{D0}$. Use an appropriate numerical integration scheme such as that described in Tables G173. Appendix X1 provides the derivation of Eq 1. If $|\Delta T_R| \leq 0.5°C$ and $|\Delta T_D| \leq 0.5°C$, then $\Theta_R(\lambda)$ and $\Theta_D(\lambda)$ may be omitted and Eq 1 simplified to:

$$M = \frac{\int_{\lambda 1}^{\lambda 2} \lambda Q_D(\lambda,T_{D0}) E_S(\lambda)d\lambda}{\int_{\lambda 3}^{\lambda 4} \lambda Q_R(\lambda,T_{R0}) E_S(\lambda)d\lambda} \times \frac{\int_{\lambda 3}^{\lambda 4} \lambda Q_R\,(\lambda,T_{R0}) E_0(\lambda)d\lambda}{\int_{\lambda 1}^{\lambda 2} \lambda Q_D\,(\lambda,T_{D0}) E_0(\lambda)d\lambda}, \qquad (2)$$

8.1.1 The wavelength integration limits λ1 and λ2 shall correspond to the spectral response limits of the photovoltaic device.

8.1.2 The wavelength integration limits λ3 and λ4 shall correspond to the spectral response limits of the photovoltaic reference cell.

8.2 *Optional*—Calculate the measurement error due to spectral mismatch using:

$$\varepsilon = |M - 1| \qquad (3)$$

9. Precision and Bias

9.1 *Precision*—Imprecision in the spectral irradiance and the spectral response measurements will introduce errors in the calculated spectral mismatch parameter.

9.1.1 It is not practicable to specify the precision of the spectral mismatch test method using results of an interlaboratory study, because such a study would require circulating at least six stable test light sources between all participating laboratories.

9.1.2 Monte-Carlo perturbation simulations[4] using precision errors as large as 5 % in the spectral measurements have shown that the imprecision associated with the calculated spectral mismatch parameter is no more than 1 %.

9.1.3 Table 1 lists estimated maximum limits of imprecision that may be associated with spectral measurements at any one wavelength.

9.2 *Bias*—Bias associated with the spectral measurements used in the spectral mismatch calculation can be either independent of wavelength or can vary with wavelength.

9.2.1 Numerical calculations using wavelength-independent bias errors of 2 % added to the spectral quantities show the error introduced in the spectral mismatch parameter to be less than 1 %.

9.2.2 Estimates of maximum bias that may be associated with the spectral measurements are listed in Table 2. These limits are listed for guidance only and in actual practice will depend on the calibration of the spectral measurements.

TABLE 1 Estimated Limits of Imprecision in Spectral Measurements

Source of Imprecision	Estimated Limit, %
Spectral response measurement	2.0
Spectral irradiance measurement	5.0

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[4] Emery, K. A., Osterwald, C. R., and Wells, C. V., "Uncertainty Analysis of Photovoltaic Efficiency Measurements," *Proceedings of the 19th IEEE Photovoltaics Specialists Conference—1987*, pp. 153–159, Institute of Electrical and Electronics Engineers, New York, NY, 1987.

TABLE 2 Estimated Limits of Bias in Spectral Measurements

Source of Bias	Estimated Limit, %
Spectral response measurement	3.0
Spectral irradiance measurement	5.0

10. Keywords

10.1 cell; mismatch; photovoltaic; reference; solar; spectral; testing

ANNEX

(Mandatory Information)

A1. DETERMINATION OF THE TEMPERATURE DEPENDENCE OF PHOTOVOLTAIC DEVICE QUANTUM EFFICIENCY

A1.1 Accurate reporting of photovoltaic device performance over temperature requires knowledge of the thermal behavior of short-circuit current, which is a function of the incident spectral irradiance and the quantum efficiency of the device. The quantum efficiency is the device property that varies with temperature, and its temperature dependence can be mapped with multiple measurements over a range of temperatures.

A1.2 Select a series of temperatures at which the device quantum efficiency will be measured.

A1.2.1 The first must be the temperature at which the device to be tested will be reported, T_{D0}. For Standard Reporting Conditions (SRC), this will typically be 25°C.

A1.2.2 Determine the range of temperatures over which the device will be expected to operate; select the minimum and maximum temperatures from this range.

A1.2.3 Additional temperatures may be added to the series as desired.

A1.3 Mount the device to be tested in the spectral responsivity test fixture (see Test Method E1021).

A1.4 For the device to be tested, at each temperature in the series, T_i:

A1.4.1 Adjust the device temperature to $T_i \pm 1°C$.

A1.4.2 Measure the spectral responsivity according to Test Method E1021.

A1.4.3 Any multiplicative calibration or scaling constants that may be applied to the spectral responsivity data must not be changed when the device temperature is adjusted. This preserves the constant cancelling properties inherent in Eq 1 (see 5.3).

A1.4.4 All spectral responsivity measurements shall be performed with identical wavelength intervals.

A1.5 Convert the resulting tables of spectral responsivity versus wavelength data to quantum efficiency with the following identity (see 10.10 in Test Method E1021):

$$Q(\lambda) = \frac{hc}{q\lambda}R(\lambda) \tag{A1.1}$$

A1.6 At each wavelength of the quantum efficiency data, λ_j:

A1.6.1 Form a table of Q_i versus T_i,

A1.6.2 Perform a straight-line fit and extract the slope of the line, which is equal to $\partial Q_i/\partial T_i(\lambda_j)$,

A1.6.2.1 The calculation in A1.6.2 assumes that the partial derivative function at any wavelength λ is independent of temperature T. This is the typical situation.

A1.7 Assemble the slope data versus wavelength to form the $\Theta(\lambda)$ characteristic of the device.

APPENDIX

(Nonmandatory Information)

X1. DERIVATION OF THE TEMPERATURE-DEPENDENT SPECTRAL MISMATCH CORRECTION

X1.1 The temperature-spectral mismatch correction, $M(T)$, that is, Eq 1, is formulated as a function of four photovoltaic short-circuit current densities, two of the photovoltaic device to be tested, and two of the photovoltaic reference cell used to measure total irradiance.

X1.2 The mismatch function is developed as a general translation of a test device's short-circuit current under the test light source, $E_S(\lambda)$, operating at a temperature equal to T_D, to the short-circuit current under $E_0(\lambda)$ and temperature T_{D0}. It is common for $T_{R0} = T_{D0} = 25°C$ (see Discussion in 3.3.18), but they may be unequal if the quantum efficiency at $T = T_{D0}$ of the device to be tested is known.

X1.3 To begin, the light-generated photocurrent density in a solar cell, J_L, is equal to a convolution of quantum efficiency and spectral irradiance (integration limits of the definite integral are omitted for brevity), and that J_L is assumed to be equal to the short-circuit current, I, divided by the active area, A:

$$J_L = \int \frac{q\lambda}{hc} Q(\lambda\ ,\ T) E(\lambda) d\lambda = I/A \tag{X1.1}$$

X1.4 For the device to be tested, with temperature equal to T_D and under illumination from the test light source, Eq X1.1 can be written as the following:

$$I_D = A_D \int \frac{q\lambda}{hc} Q_D(\lambda,T_D) E_S(\lambda) d\lambda \tag{X1.2}$$

X1.5 For the device to be tested at $T = T_{D0}$ and under the reference spectral irradiance distribution, Eq X1.2 can be written as:

$$I_{D0} = A_D \int \frac{q\lambda}{hc} Q_D(\lambda,T_{D0}) E_0(\lambda) d\lambda \tag{X1.3}$$

X1.6 Similar equations can be written for the reference cell; Eq X1.5 represents the reference cell's calibration condition:

$$I_R = A_R \int \frac{q\lambda}{hc} Q_R(\lambda,T_R) E_S(\lambda) d\lambda, \tag{X1.4}$$

$$I_{R0} = A_R \int \frac{q\lambda}{hc} Q_R(\lambda,T_{R0}) E_0(\lambda) d\lambda. \tag{X1.5}$$

X1.7 Next, Eq X1.2 is divided by Eq X1.3 and Eq X1.4, and multiplied by Eq X1.5.

$$\frac{I_D}{I_{D0}} \cdot \frac{I_{R0}}{I_R} = \frac{A_D \int \frac{q\lambda}{hc} Q_D(\lambda,T_D) E_S(\lambda) d\lambda}{A_D \int \frac{q\lambda}{hc} Q_D(\lambda,T_{D0}) E_0(\lambda) d\lambda} \cdot \frac{A_R \int \frac{q\lambda}{hc} Q_R(\lambda,T_{R0}) E_0(\lambda) d\lambda}{A_R \int \frac{q\lambda}{hc} Q_R(\lambda,T_R) E_S(\lambda) d\lambda} \tag{X1.6}$$

X1.8 The active areas and the constants inside the integrals cancel, so that Eq X1.6 becomes:

$$\frac{I_D}{I_{D0}} \cdot \frac{I_{R0}}{I_R} = \frac{\int \lambda Q_D(\lambda,T_D) E_S(\lambda) d\lambda}{\int \lambda Q_D(\lambda,T_{D0}) E_0(\lambda) d\lambda} \cdot \frac{\int \lambda Q_R(\lambda,T_{R0}) E_0(\lambda) d\lambda}{\int \lambda Q_R(\lambda,T_R) E_S(\lambda) d\lambda} \tag{X1.7}$$

X1.9 Solving for I_{D0} gives:

$$I_{D0} = I_D \frac{I_{R0}}{I_R} \left[\frac{\int \lambda Q_D(\lambda,T_D) E_S(\lambda) d\lambda}{\int \lambda Q_D(\lambda,T_{D0}) E_0(\lambda) d\lambda} \cdot \frac{\int \lambda Q_R(\lambda,T_{R0}) E_0(\lambda) d\lambda}{\int \lambda Q_R(\lambda,T_R) E_S(\lambda) d\lambda} \right]^{-1} \tag{X1.8}$$

X1.10 The expression inside the brackets in Eq X1.8 is the temperature-dependent spectral mismatch correction. Rearranging terms:

$$M(T) = \frac{\int \lambda Q_D(\lambda,T_D) E_S(\lambda) d\lambda}{\int \lambda Q_R(\lambda,T_R) E_S(\lambda) d\lambda} \cdot \frac{\int \lambda Q_R(\lambda,T_{R0}) E_0(\lambda) d\lambda}{\int \lambda Q_D(\lambda,T_{D0}) E_0(\lambda) d\lambda} \tag{X1.9}$$

X1.11 If the four quantum efficiencies at the four temperatures are known, then Eq X1.9 can be used as written. These could be obtained from a series of curves as measured in Annex A1, using linear interpolation if the quantum efficiencies at the exact temperatures are missing. However, if the $\partial Q/\partial T(\lambda) = \Theta(\lambda)$ characteristics are known (see Annex A1), then the interpolations can be expressed as offsets from the quantum efficiencies at the reference temperatures, and Eq X1.9 becomes (using the temperature offsets as defined in 8.1):

$$M(T) = \frac{\int \lambda \left[Q_D\ (\lambda,T_{D0})\ +\ \frac{\partial Q_D}{\partial T}\ (\lambda)\ \Delta T_D \right] E_S(\lambda) d\lambda}{\int \lambda \left[Q_R\ (\lambda,T_{R0})\ +\ \frac{\partial Q_R}{\partial T}\ (\lambda)\ \Delta T_R \right] E_S(\lambda) d\lambda} \times \frac{\int \lambda Q_R(\lambda,T_{R0}) E_0(\lambda) d\lambda}{\int \lambda Q_D(\lambda,T_{D0}) E_0(\lambda) d\lambda} \tag{X1.10}$$

X1.12 The definite integrals with the summed quantum efficiencies can be split into parts, giving Eq 1:

$$M(T) = \frac{\int \lambda Q_D(\Delta T_{D0}) E_S(\lambda) d\lambda + \Delta T_D \int \lambda \Theta_D(\lambda) E_S(\lambda) d\lambda}{\int \lambda Q_R(\Delta T_{R0}) E_S(\lambda) d\lambda + \Delta T_R \int \lambda \Theta_R(\lambda) E_S(\lambda) d\lambda} \times \frac{\int \lambda Q_R(\Delta T_{R0}) E_0(\lambda) d\lambda}{\int \lambda Q_D(\Delta T_{D0}) E_0(\lambda) d\lambda} \tag{X1.11}$$