Designation: E2848 – 13

Standard Test Method for Reporting Photovoltaic Non-Concentrator System Performance[1]

1. Scope

1.1 This test method provides measurement and analysis procedures for determining the capacity of a specific photovoltaic system built in a particular place and in operation under natural sunlight.

1.2 This test method is used for the following purposes:

1.2.1 acceptance testing of newly installed photovoltaic systems,

1.2.2 reporting of dc or ac system performance, and

1.2.3 monitoring of photovoltaic system performance.

1.3 This test method should not be used for:

1.3.1 testing of individual photovoltaic modules for comparison to nameplate power ratings,

1.3.2 testing of individual photovoltaic modules or systems for comparison to other photovoltaic modules or systems,

1.3.3 testing of photovoltaic systems for the purpose of comparing the performance of photovoltaic systems located in different places.

1.4 In this test method, photovoltaic system power is reported with respect to a set of reporting conditions (RC) including: solar irradiance in the plane of the modules, ambient temperature, and wind speed (see Section 6). Measurements under a variety of reporting conditions are allowed to facilitate testing and comparison of results.

1.5 This test method assumes that the solar cell temperature is directly influenced by ambient temperature and wind speed; if not the regression results may be less meaningful.

1.6 The capacity measured according to this test method should not be used to make representations about the energy generation capabilities of the system.

1.7 This test method is not applicable to concentrator photovoltaic systems; as an alternative, Test Method E2527 should be considered for such systems.

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 *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]

D6176 Practice for Measuring Surface Atmospheric Temperature with Electrical Resistance Temperature Sensors
E772 Terminology of Solar Energy Conversion
E824 Test Method for Transfer of Calibration From Reference to Field Radiometers
E927 Specification for Solar Simulation for Photovoltaic Testing
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
E1040 Specification for Physical Characteristics of Nonconcentrator Terrestrial Photovoltaic Reference Cells
E1125 Test Method for Calibration of Primary Non-Concentrator Terrestrial Photovoltaic Reference Cells Using a Tabular Spectrum
E1362 Test Method for Calibration of Non-Concentrator Photovoltaic Secondary Reference Cells
E2527 Test Method for Electrical Performance of Concentrator Terrestrial Photovoltaic Modules and Systems Under Natural Sunlight

---

[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 Sept. 1, 2013. Published September 2013. Originally approved in 2011. Last previous edition approved in 2011 as E2848-11$^{\varepsilon 1}$. DOI: 10.1520/E2848-13.

[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.

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

G167 Test Method for Calibration of a Pyranometer Using a Pyrheliometer

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

G183 Practice for Field Use of Pyranometers, Pyrheliometers and UV Radiometers

2.2 *IEEE Standards:*

IEEE 1526-2003 Recommended Practice for Testing the Performance of Stand-Alone Photovoltaic Systems

IEEE 1547-2003 Standard for Interconnecting Distributed Resources with Electric Power Systems

2.3 *International Standards Organization Standards:*

ISO/IEC Guide 98-1:2009 Uncertainty of measurement—Part 1: Introduction to the expression of uncertainty in measurement

ISO/IEC Guide 98-3:2008 Uncertainty of measurement—Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)

2.4 *World Meteorological Organization (WMO) Standard:*

WMO-No. 8 Guide to Meteorological Instruments and Methods of Observation, Seventh Ed., 2008

3. Terminology

3.1 *Definitions*—Definitions of terms used in this test method may be found in Terminology E772, IEEE 1547-2003, and ISO/IEC Guide 98-1:2009 and ISO/IEC Guide 98-3:2008.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *averaging interval, n*—the time interval over which data are averaged to obtain one data point. The performance test uses these averaged data.

3.2.2 *data collection period, n*—the period of time defined by the user of this test method during which system output power, irradiance, ambient temperature, and wind speed are measured and recorded for the purposes of a single regression analysis.

3.2.3 *plane-of-array irradiance, POA, n*—see *solar irradiance, hemispherical* in Tables G173.

3.2.4 *reporting conditions, RC, n*—an agreed-upon set of conditions including the plane-of-array irradiance, ambient temperature, and wind speed conditions to which photovoltaic system performance are reported. The reporting conditions must also state the type of radiometer used to measure the plane-of-array irradiance. In the case where this test method is to be used for acceptance testing of a photovoltaic system or reporting of photovoltaic system performance for contractual purposes, RC, or the method that will be used to derive the RC, shall be stated in the contract or agreed upon in writing by the parties to the acceptance testing and reporting prior to the start of the test.

3.2.5 *sampling interval, n*—the elapsed time between scans of the sensors used to measure power, irradiance, ambient temperature and wind speed. Individual data points used for the performance test are averages of the values recorded in these scans. There are multiple sampling intervals in each averaging interval.

3.2.6 *utility grid, n*—see **electric power system** in IEEE 1547-2003.

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

3.3.1 α—reference cell I_{SC} temperature coefficient, °C^{-1}

3.3.2 a_1, a_2, a_3, a_4—linear regression coefficients, arbitrary

3.3.3 a, b, c, d—spectral mismatch factor calibration constants, arbitrary

3.3.4 C—reference cell calibration constant, Am^2W^{-1}

3.3.5 C_o—reference cell calibration constant at SRC, Am^2W^{-1}

3.3.6 E—plane-of-array irradiance, W/m^2

3.3.7 E_o—irradiance at SRC, plane-of-array, W/m^2

3.3.8 $E_o(\lambda)$—reference spectral irradiance distribution, Wm^{-2} nm^{-1}

3.3.9 E_{RC}—RC rating irradiance, plane-of-array, W/m^2

3.3.10 $E_{RC}(\lambda)$—spectral irradiance distribution at RC, Wm^{-2} nm^{-1}

3.3.11 $E_T(\lambda)$—spectral irradiance distribution, test light source, Wm^{-2} nm^{-1}

3.3.12 F—fractional error in short-circuit current, dimensionless

3.3.13 I_{SC}—short-circuit current, A

3.3.14 M—spectral mismatch factor, dimensionless

3.3.15 p—p-value, dimensionless quantity used to determine the significance of an individual regression coefficient to the overall rating result

3.3.16 P—photovoltaic system power, ac or dc, W

3.3.17 P_{RC}—photovoltaic system power at RC, ac or dc, W

3.3.18 RC—reporting conditions

3.3.19 $R_R(\lambda)$—reference cell spectral responsivity, A/W

3.3.20 $R_T(\lambda)$—test device spectral responsivity, A/W

3.3.21 SRC—standard reporting conditions

3.3.22 SE—standard error, W

3.3.23 T_a—ambient temperature, °C

3.3.24 T_{RC}—RC rating temperature, °C

3.3.25 U_{95}—expanded uncertainty with a 95 % coverage probability of photovoltaic system power at RC, W

3.3.26 λ—wavelength, nm

3.3.27 v—wind speed, m/s

3.3.28 v_{RC}—RC rating wind speed, m/s

4. Summary of Test Method

4.1 Photovoltaic system power, solar irradiance, ambient temperature, and wind speed data are collected over a defined period of time using a data acquisition system.

4.2 Multiple linear regression is then used to fit the collected data to the performance equation (Eq 1) and thereby calculate the regression coefficients a_1, a_2, a_3, and a_4.

$$P = E(a_1 + a_2 \cdot E + a_3 \cdot T_a + a_4 \cdot v) \tag{1}$$

4.3 Substitution of the RC values E_o, T_o, and v_o into Eq 1 then gives the ac or dc power at the reporting conditions.

$$P_{RC} = E_{RC}(a_1 + a_2 \cdot E_{RC} + a_3 \cdot T_{RC} + a_4 \cdot v_{RC}) \quad (2)$$

4.4 The collected input data and the performance at the reporting conditions are then reported.

5. Significance and Use

5.1 Because there are a number of choices in this test method that depend on different applications and system configurations, it is the responsibility of the user of this test method to specify the details and protocol of an individual system power measurement prior to the beginning of a measurement.

5.2 Unlike device-level measurements that report performance at a fixed device temperature of 25°C, such as Test Methods E1036, this test method uses regression to a reference ambient air temperature.

5.2.1 System power values calculated using this test method are therefore much more indicative of the power a system actually produces compared with reporting performance at a relatively cold device temperature such as 25°C.

5.2.2 Using ambient temperature reduces the complexity of the data acquisition and analysis by avoiding the issues associated with defining and measuring the device temperature of an entire photovoltaic system.

5.2.3 The user of this test method must select the time period over which system data are collected, and the averaging interval for the data collection within the constraints of 8.3.

5.2.4 It is assumed that the system performance does not degrade or change during the data collection time period. This assumption influences the selection of the data collection period because system performance can have seasonal variations.

5.3 The irradiance shall be measured in the plane of the modules under test. If multiple planes exist (particularly in the case of rolling terrain), then the plane or planes in which irradiance measurement will occur must be reported with the test results. In the case where this test method is to be used for acceptance testing of a photovoltaic system or reporting of photovoltaic system performance for contractual purposes, the plane or planes in which irradiance measurement will occur must be agreed upon by the parties to the test prior to the start of the test.

NOTE 1—In general, the irradiance measurement should occur in the plane in which the majority of modules are oriented. Placing the measurement device in a plane with a larger tilt than the majority will cause apparent under-performance in the winter and over-performance in the summer.

5.3.1 The linear regression results will be most reliable when the measured irradiance, ambient temperature, and wind speed data during the data collection period are distributed around the reporting conditions. When this is not the case, the reported power will be an extrapolation to the reporting conditions.

5.4 Accumulation of dirt (soiling) on the photovoltaic modules can have a significant impact on the system rating. The user of this test may want to eliminate or quantify the level of soiling on the modules prior to conducting the test.

5.5 Repeated regression calculations on the same system to the same RC and using the same type of irradiance measurement device over successive data collection periods can be used to monitor performance changes as a function of time.

5.6 Capacity determinations are power measurements and are adequate to demonstrate system completeness. However, a single capacity measurement does not provide sufficient information to project the energy generation potential of the system over time. Factors that may affect energy generation over time include: module power degradation, inverter clipping and overloading, shading, backtracking, extreme orientations, and filtering criteria.

6. Reporting Conditions

6.1 The user of this test method shall select appropriate RC. In the case where this test method is to be used for acceptance testing of a photovoltaic system or reporting of photovoltaic system performance for contractual purposes, the RC, or the method that will be used to derive the RC, must be agreed upon by the parties to the test.

6.1.1 Reporting conditions may be selected either on the basis of expected conditions or actual conditions during the data collection period. Choose RC irradiance and ambient air temperature values that are representative of the POA irradiance and ambient air temperature for the system location for a clear day in the data collection period. When the selection is based on expected conditions, irradiance can be evaluated from a year-long hourly dataset of projected POA values calculated from historical data measured directly on the system site or at a nearby site. Ambient temperatures can be evaluated by a review of historical data from the site or a nearby location. Reporting conditions should be chosen such that the system is not subject to frequent shading, inverter clipping or other non-linear operation at or around the RC. For instance, in larger photovoltaic systems, the ratio of installed DC capacity to AC inverter capacity may be such that the inverter limits the production of the modules under certain conditions. If this is the case, care should be taken to choose a reference within the normal operating range of the inverters.

NOTE 2—There are many publicly-available irradiance modeling tools that can be used to develop an hourly year-long dataset for POA irradiance at a project site based on historical global horizontal irradiance data or, if available, from data measured directly at the project site.

NOTE 3—Historically, a specific case of RC known as "Performance Test Conditions", or "PTC", have been used commonly. PTC conditions use plane-of-array irradiance equal to 1000 W/m^2, ambient temperature equal to 20°C, and wind speed equal to 1 m/s. The PTC parameters were based on the Nominal Terrestrial Environment (NTE) conditions that define the Nominal Operating Cell Temperature (NOCT) of an individual solar cell inside a module (see Annex A1 in Test Methods E1036). However, NTE differs from PTC in that it specifies a lower irradiance of 800 W/m^2.

7. Apparatus

7.1 *Ambient Air Temperature Measurement Equipment*—The instrument or instruments used to measure the ambient air temperature shall have a resolution of at least 0.1°C, and shall have a total error of less than ±1°C of reading. The sensor should be mounted in the immediate vicinity of the photovoltaic system under test, but should not be so close to the modules as to be in the thermal boundary layer of the array. The sensor shall be mounted with an aspirated radiation shield as defined in 3.2.3 of Practice D6176. Practice D6176 contains additional guidance for ambient air temperature measurements.

7.2 *Irradiance Measurement Equipment*—The irradiance measurement equipment shall be mounted coplanar (to within 1 degree) with the photovoltaic system under test and shall be connected to a data acquisition system. The equipment should be mounted in a location that minimizes, and ideally eliminates, shading of and reflections on the instrument.

7.2.1 A calibrated hemispherical pyranometer (instruments with fields-of-view approaching 180°, see Terminology E772) is the most common choice for measurement of the incident solar irradiance. Pyranometers used in this test shall be calibrated using Test Method E824 or Test Method G167. Test Method E E824 is a transfer calibration from a reference to a field pyranometer, while Test Method G167 involves calibration against either of two types of narrow field-of-view pyrheliometers. The uncertainty of the pyranometer calibration is a function of the calibration method, with the Type I calibration in Test Method G167 giving the lowest uncertainty.

7.2.2 Pyranometers are sensitive to both temperature and the angle of incidence of irradiance, so may require measurement of device temperature and angle of incidence during the data collection period. It is recommended that pyranometer responsivity be characterized to the extent practicable. Sections 5.5, 5.5.1, 5.5.2, and 5.5.3 in Practice G183, describes pyranometer characteristics which influence the level of uncertainty in solar radiation data and should be considered.

7.2.3 *Optional*—A calibrated photovoltaic reference device may be used in place of a pyranometer if it is mutually agreed by the parties to the test prior to the start of the test.

7.2.3.1 Annex A1 and Annex A2 present information and procedures related to the use of photovoltaic reference devices as radiometers. It is strongly recommended that these procedures be used if a photovoltaic reference device is chosen. Use of photovoltaic reference devices can significantly reduce uncertainty in the overall test result when they are calibrated with respect to the RC. This type of calibration introduces complexity (and therefore cost) to the test. The additional complexity and cost is justified for large-scale commercial and utility-scale photovoltaic plants, but will not be economically feasible for small commercial or residential installations. While the test may be carried out with a photovoltaic reference device without executing the corrections described in Annex A1 and Annex A2, it is critical that the user understand the information presented in them. If a photovoltaic reference device is used without applying the procedures for spectral correction, the test report must clearly state that the test result includes uncertainty of an unknown magnitude due to spectral mismatch in addition to the reported uncertainty.

7.2.3.2 Reference devices used in this test shall be primary or secondary reference devices as defined in Terminology E772. If the in-situ calibration procedure outlined in Annex A2 is not employed, the reference device must be calibrated according to Test Method E1362 using the hemispherical spectral irradiance distribution in Tables G173.

7.2.3.3 Recommended physical characteristics of photovoltaic reference devices are available in Specification E1040.

7.2.3.4 Note that the calibration values of photovoltaic reference devices are temperature-sensitive and require measurement of the reference device's temperature during the data collection period. Reference devices that adhere to Specification E1040 must have a temperature sensor.

7.3 *Wind Speed Measurement Equipment*—The instrument used to measure the wind speed shall have an uncertainty of less than 0.5 m/s, and should be mounted in the immediate vicinity of the system under test. Because of the many possible system configurations, care should be taken to minimize effects on the instrument readings from the system or nearby obstacles. Averaging readings from multiple instruments for large systems may be required.

7.3.1 Ultrasonic wind speed instruments are preferred because they do not have the dead band between 0 and 0.5 m/s in which mechanical cup-based wind speed instruments are unable to rotate.

7.4 *Power Measurement Equipment, ac*—System ac power is typically measured at the point of interconnection, however, the measurement point can be any point specified by the users of this test. The measurement point shall be specified and agreed to prior to the start of the test. AC power shall be measured with a total uncertainty of ±1.5 % or less of the expected power value at RC.

7.5 *Power Measurement Equipment, dc*—System dc power is typically measured at the input of the inverter or other power conditioning units using calibrated shunt resistors and voltage dividers. IEEE 1526-2003 and Test Method E1036 shall be used to specify dc current and voltage measurements on photovoltaic systems.

8. Procedure

8.1 Connect the required instrumentation for the photovoltaic system under test to the data acquisition system.

8.2 For each averaging interval, measure and record the average system power, solar irradiance, ambient temperature, and wind speed over the interval.

8.3 Continue data acquisition until the end of the data collection period. This will constitute one complete data set. The data collection period shall be at least three (3) days and at most four (4) weeks. The default data averaging interval is 15 min. Data is collected until a minimum of 50 data points (averaging intervals, post filtering) are available for the regression. The data set shall include data from at least three separate days. If sufficient data is not collected in 4 weeks, then begin using a 4-week "moving window". For example, if the original test start date is January 1 and data collection begins on January 1, and by January 28, there are not 50 data points available for the regression, then adjust the start of the data collection period to January 2 and continue collecting data through January 29, and so on.

NOTE 4—50 data points using 15-min averaging intervals represents approximately 12.5 h of system operating time. If smaller averaging intervals are used, the minimum data point requirement may be increased. For example, if 5-min averaging intervals are used, then 150 data points would be needed to represent the same number of system operating hours.

8.3.1 The data collection period shall be chosen to ensure that all criteria described in 8.3 are met after excluding data per the data selection guidelines outlined in 9.1.

9. Calculation of Results

9.1 *Selection of Data:*

9.1.1 The following filter criteria (described further in 9.1.2 through 9.1.10) should be applied to the data set in the following order:

9.1.1.1 Visual examination (9.1.2)

9.1.1.2 Preliminary regression (9.1.3)

9.1.1.3 Missing data (9.1.4)

9.1.1.4 DAS equipment malfunction (see 9.1.5)

9.1.1.5 Irradiance outside of range (9.1.6)

9.1.1.6 Unstable conditions (optional, see 9.1.7)

9.1.1.7 Inverter not peak power point tracking (see 9.1.8)

9.1.1.8 Obscuration of the system or radiometer by shading (see 9.1.9)

9.1.1.9 Radiometer not co-planar with system under test (see 9.1.10)

9.1.2 *Visual Examination*—Most data that will be filtered out based on the filter criteria above can be quickly recognized using a simple visualization. Make a graphical plot of the output power versus irradiance for the entire data set. For systems that have power conditioning units that perform maximum power point tracking, such as inverters, this plot should have a linear relation between power and irradiance. Points that appear as outliers on this plot should be investigated and excluded if they are found to not meet the filter criteria. Additionally, nonlinear power-irradiance characteristics should be investigated; a common cause is an inverter that begins to malfunction at some time during the data collection period. Plots with two or more distinct lines can be the result of power losses. Irradiance measurement instruments that are not mounted coplanar with the system under test will split the power-irradiance relationship into double concave and convex curves between morning and afternoon data. Suspect data shall be investigated to find the root cause, and shall be excluded if they do not meet the filter criteria.

9.1.3 *Preliminary Regression*—Another method to quickly identify data that may be excluded is to perform a preliminary regression and search for statistical outliers. After computing the regression coefficients per 9.2, evaluate Eq 1 for each averaging interval and calculate the residual between the measured power and the power computed using the regression coefficients in Eq 1. Averaging intervals for which the residual exceeds two standard deviations of the mean residual should be investigated and may be excluded if they do not meet the filter criteria.

9.1.4 *Missing Data*—If any of the four regression parameters (power, plane-of-array irradiance, ambient temperature, or wind speed) are missing for an averaging interval, all data for this averaging interval shall be excluded.

9.1.5 *DAS Equipment Malfunction*—If any of the four regression parameters (power, plane-of-array irradiance, ambient temperature, or wind speed) is affected by a DAS recording error or sensor equipment malfunction, all data for this averaging interval shall be excluded. If more than a few averaging intervals in a data collection period are affected by DAS errors or equipment malfunctions, it is recommended that the sensing apparatus be investigated prior to proceeding with the test.

9.1.6 *Irradiance Outside of Range*—Select a range of irradiance values over which the regression will be performed, and exclude data outside of this range. Ranges of E_{RC} ± 20 % have been shown to give reliable results. Larger ranges may be selected if the test is performed during a season in which the range E_{RC} ± 20 % will yield an insufficient number of data points or will eliminate too many days from the data set. In general, a range that allows for a data set with 100 or more data points is preferred. Larger ranges (up to E_{RC} ± 50 %) may also be selected if data are limited to periods with stable sky conditions (see 9.1.7).

9.1.7 *Unstable Conditions (optional)*—When climate and season allow, limiting the selection of data to periods of clear, stable sky conditions is recommended. Selecting data exclusively from clear-sky periods will reduce the scatter in the regression significantly, reducing the statistical uncertainty in the regression result.[3] As with selection of an irradiance range, excluding data during unstable conditions can reduce the data set to too few data points or too few days. Stability criteria may be relaxed if they prove too stringent for the data collection period or climate. Limiting data to clear, stable sky conditions can be accomplished using one of the following techniques:

9.1.7.1 *Statistical Technique*—Calculate the mean and standard deviation of sampling intervals for each averaging interval

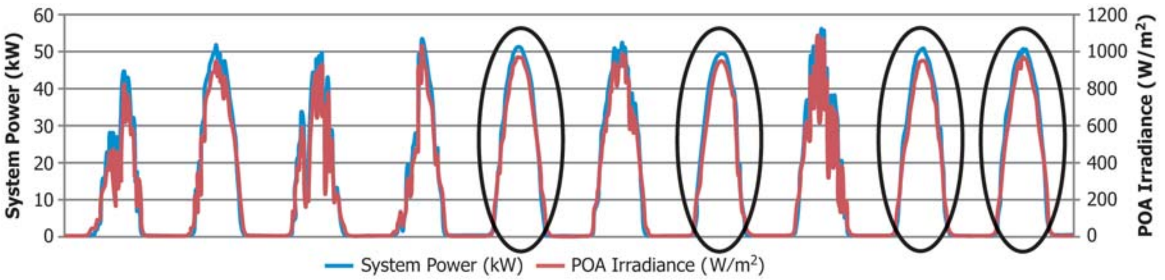

FIG. 1 Example Plot of Irradiance and System Power as a Function of Time, with Preferable Days Circled

---

[3] Kimber, et al, Improved Test Method to Verify the Power Rating of a Phtovoltaic (photovoltaic) Project, Proceedings of the 34th IEEE Photovoltaic Specialists Conference, Philadelphia, PA, USA, June 7-12, 2009.

(data point) in the data collection period. Next, compute the standard deviation as a percentage of the mean. For instance, if the data sampling interval is 5 s and the averaging interval is 5 min, compute the standard deviation of each of the 60 sampled points and compare it to the mean of those 60 points. This percent standard deviation for each period can then be used to assess operating stability and formulate data exclusion criteria. Typical maximum allowable values are on the order of 2 to 4 %.

9.1.7.2 *Visual Technique*—Alternately, make a graphical plot of the output power and irradiance versus time for the entire data set. Visually inspect the plot to identify days with little to no cloud cover, where irradiance changes relatively slowly throughout the day. Fig. 1 shows an example of a 10-day period in which the clear days are indicated by circles around the data. Exclude data from periods in which irradiance changes too quickly.

9.1.8 *Inverter not Peak Power Point Tracking*—Averaging intervals in which the inverter is off shall be excluded. Averaging intervals in which the inverter limits the production of the photovoltaic array because the photovoltaic array could produce more power than the inverter is rated to convert (for example, the inverter is operating in a "clipping" mode) shall be excluded. Averaging intervals in which the inverter is not peak power point tracking for other reasons should be investigated and data should be excluded.

9.1.9 *Obscuration and Shading*—Averaging intervals in which either the irradiance measurement device or the system is shaded or obscured by snow, frost or other environmental debris shall be excluded.

9.1.10 *Radiometer not Coplanar with System Under Test*—Averaging intervals in which the radiometer is not coplanar (within 1 degree) with the modules will appear on a plot of power versus irradiance as outliers or non-linear "off-shoots" of the primary curve. For arrays in which all modules are mounted coplanar, averaging intervals in which the radiometer is not coplanar shall be excluded. For arrays with multiple planes, averaging intervals in which the radiometer is not coplanar may be excluded.

9.2 Compute the regression coefficients $a1$, a_2, a_3, and a_4 by performing a multiple linear regression[4] of P as a function of E, v, and T_a against Eq 1. Review the regression statistics from the regression and look for p values that exceed 0.05. p values in excess of 0.05 indicate that the data collected for the given predictor variable is insufficient for system rating.

NOTE 5—In most Analysis of Variance (ANOVA) tabular results for regression coefficient results, either a t-statistic or p-value, and perhaps upper and lower confidence limits for the coefficients are reported. Upper and lower confidence intervals that include zero between those limits imply that "zero" is a possible value for the coefficient, and it may not be significant. The t-statistic is the value of the coefficient divided by the standard error in the coefficient. "Small" values of a t-statistic indicate the coefficient is probably not significant. Conversely, "small" p-values indicate the coefficients probably are significant [with probability 1-(p-value)].

9.3 Calculate the power rating at RC, P_{RC}, using Eq 2.

9.4 Calculate the expanded uncertainty of the power rating at RC, U_{95}, according to ISO/IEC Guide 98-3:2008. The Type A evaluation of uncertainty should use the standard error of estimate, *SE*, and the Type B evaluation of uncertainty should include the expanded uncertainties of the individual sensor measurements.

NOTE 6—The Standard Error (of the estimate) is the square root of the mean square error between the regression and the experimental data. It represents one standard deviation of the distribution of experimental values about the regression line.

10. Report

10.1 The user ultimately determines the amount of information to be reported. At a minimum, the user shall report the following:

10.2 *Selected Reporting Conditions:*
10.2.1 Chosen E_{RC}, T_{RC}, and v_{RC} and radiometer type (pyranometer or photovoltaic reference device),
10.2.2 Description of conditions under which test was performed (clear, diffuse sky, etc.),
10.2.3 Range of irradiance values used,
10.2.4 Beginning and ending dates and times for data collection period, and
10.2.5 Data sampling and averaging interval lengths.

10.3 *System Tested:*
10.3.1 Identification,
10.3.2 Location,
10.3.3 Physical description,
10.3.4 Description of module cleaning or any other maintenance conducted in preparation for the test,
10.3.5 $P_{RC} \pm U_{95}$,
10.3.5.1 The coefficients of the regression equation, namely a_1, a_2, a_3, and a_4 from Eq. 1, and
10.3.5.2 The mean and standard deviation of the residuals for the data used to derive the regression shall be reported as an indicator of the quality of the regression.

10.4 *Irradiance Measurement Equipment:*
10.4.1 Each irradiance sensor will be identified by:
10.4.2 Model and serial number,
10.4.3 Physical description,
10.4.4 Calibration laboratory,
10.4.5 Calibration test method,
10.4.6 Date of calibration,
10.4.7 Calibration constant,
10.4.8 Uncertainty of calibration, and
10.4.9 Location within array, tilt and azimuth of mounting.
10.4.10 When a photovoltaic reference device is used, description of the spectral irradiance determination and reference cell calibration to RC per Annex A2 or, if procedure in Annex A2 is not used, statement that spectral irradiance was not considered and that additional uncertainty of an unknown magnitude is included in the test result.

10.5 Description of power measurement equipment, including calibration information, uncertainty of calibration, model and serial number, location and physical description.

10.6 Description of ambient temperature and wind speed measurement equipment, including placement of instruments

---

[4] Burden, R. L., and Faires, J. D., Numerical Analysis, 3rd Ed., Prindler, Weber & Schmidt, Boston, MA, 1985, p. 42 ff.

and physical description, calibration information, uncertainty of calibration, model and serial number.

10.7 Description of temperature corrections applied to photovoltaic reference device measurements, if used.

10.8 Description of applications of temperature, spectral and angle-of-incidence corrections to pyranometer measurements.

10.9 When multiple or redundant sensors are used, a description of the method(s) used to average or select data from the redundant sensors must be provided.

10.10 Statement of data selection criteria employed, including summary of excluded data.

10.11 Expanded uncertainty of the power rating at RC per 9.4.

11. Precision and Bias

11.1 *Precision*—It is not practicable to specify the precision of the performance rating using results of an interlaboratory study because the results are location and time specific, and because it is impractical to circulate large photovoltaic systems between measurement laboratories.

11.2 Factors that contribute to the expanded uncertainty of the RC power rating include:

11.2.1 Mismatch in spectral response and angle-of-incidence response between the irradiance sensor and test array will contribute to scatter in the regression analysis. As noted in Annex A1 and Annex A2, use of a photovoltaic reference device can minimize scatter in the data due to these effects.

11.2.2 Misalignment of the irradiance measurement equipment to the plane of the array will contribute to scatter in the measured power versus irradiance. Similar effects will occur if different photovoltaic array segments are misaligned with respect to each other.

11.2.3 Uncertainty associated with the instrumentation used to measure the array power will introduce error.

11.2.4 The location of the anemometer used to measure v with respect to the test array can contribute to scatter in the measured power versus irradiance.

11.2.5 Inverter performance characteristics such as maximum power point tracking accuracy and conversion efficiency with respect to changing input voltages and operating temperatures can increase the amount of scatter in the measured power versus irradiance. Such effects may or may not be considered as errors, however, because the inverter may or may not be considered as part of the system under test.

11.2.6 The location of the temperature sensor used to measure T_a with respect to the test array may introduce an error if the ambient temperature around the test array differs from that of the temperature sensor.

11.2.7 The amount of soiling (dirt accumulation) on the test array and the irradiance measurement equipment will appear as a bias error in the results.

11.2.8 The degree of scatter in the data about the regression line will contribute to the overall uncertainty in the result.

11.3 Overall uncertainty in the regression result is influenced most strongly by the following: solar irradiance measurement uncertainty, AC power measurement uncertainty, and model uncertainty. The overall uncertainty of power rating using this test method is estimated to be on the order of 3.5 – 7.5 %.[3]

12. Keywords

12.1 performance; photovoltaics; reporting; systems

ANNEXES

(Mandatory Information)

A1. USE OF CALIBRATED PHOTOVOLTAIC REFERENCE CELLS AS IRRADIANCE MEASUREMENT EQUIPMENT

A1.1 Because of limitations imposed by the characteristics of hemispherical pyranometers (see A1.2), it is desirable to instead use reference cells for irradiance measurements. The most important implication of this is that the total uncertainty in the irradiance measurement can be reduced (see A1.2.2 and A1.3.3). To be valid, however, a reference cell must measure the same irradiance that a pyranometer would measure.

A1.1.1 An easy first approach might be to use a device calibrated against the hemispherical spectral irradiance distribution in Tables G173, and which has a spectral response similar to that of the system under test; such reference cells are readily available. However, consideration of the mathematical basis in which photovoltaic cells are calibrated shows that in many cases this choice is not appropriate.

A1.1.2 To achieve a reduction of uncertainty of irradiance, the reference cell must instead be calibrated with respect to a spectral irradiance that is representative of the local reporting conditions (RC, see 3.2.4). Recalibration to a different reference spectral irradiance is a numerical calculation that introduces negligible error.

A1.1.3 In this Annex, quantities with respect to reporting conditions have the subscript *RC*, while quantities with respect to a reference spectral irradiance distribution have the subscript *O*.

A1.2 *Pyranometer Characteristics*:

A1.2.1 WMO-No. 8, chap. 7, classifies pyranometers into three categories, corresponding to "state-of-the-art" for "stations with special facilities and staff" (high quality), "[a]cceptable for network operations" (good quality), and "[s]uitable for low-cost networks where moderate to low performance is acceptable" (moderate quality). It is assumed that good quality is the appropriate class for the regression procedure.

A1.2.2 Hemispherical pyranometers typically have two concentric quartz domes over the thermal sensor. Although pyranometers are usually assumed to have equal spectral response at all wavelengths, the domes limit the passband to a range of about 290 to 2800 nm. Solar irradiance under clear skies beyond 2800 nm can be as much as 1 % of the total, which a pyranometer cannot detect.

A1.2.3 In Table 7.5, WMO-No. 8 quantifies a number of characteristics of pyranometers, and estimates based on these characteristics of the total uncertainty of irradiance measured with good quality pyranometers are usually in the range of 3 to 5 %, with 3 % likely being optimistic. For moderate quality instruments, total uncertainty should probably be estimated as 6 to 10 %.

A1.3 *Reference Cell Characteristics*:

A1.3.1 Experience has shown that using a reference cell for the regression analysis reduces scatter in the measured power versus irradiance characteristic, thereby improving the precision of the results. These observations are believed to be the result of two properties.

A1.3.1.1 *Response Time Difference*—Photovoltaic response times are essentially instantaneous, while pyranometer response times are of the order of tens of seconds (WMO-No. 8, Table 7.5).

A1.3.1.2 *Spectral Bandwidth Difference*—Pyranometers respond to infrared wavelengths between 1100 and 2800 nm that are beyond the long wavelength bandgap edge of most photovoltaic devices, especially those of silicon. This wavelength range includes four water vapor absorption bands centered at 1120, 1370, 1850, and 2550 nm. Only the smaller 730, 820, and 940 nm bands are common to both photovoltaic devices and pyranometers. Absorption of light in the water vapor bands is non-linear with respect to water vapor content in the atmosphere and will saturate when the content is greater than a certain level; the limits differ for each band. During the data collection period (see 3.2.2) if the water vapor content varies significantly, the pyranometer response can therefore differ from that of the photovoltaic reference device, causing scatter in the power versus irradiance characteristic.

A1.3.2 Uncertainties in irradiance caused by non-equilibrium operation can be minimized by using a detector with a thermal mass that is similar to that of the system under test, and the best way to achieve this is with a calibrated reference module identical to the modules in the system.

A1.3.3 *Calibration Uncertainties:*

A1.3.3.1 Primary crystalline-Si reference cells calibrated according to Test Method E1125 have demonstrated uncertainties of less than 1%.

A1.3.3.2 Secondary Crystalline-Si reference cells calibrated according to Test Method E1362 have demonstrated uncertainties of less than 1.5%.

A1.3.3.3 For reference module calibrations calibrated according to Test Method E1036, the uncertainty has been shown to be proportional to the spatial uniformity of the light source (see Specification E927). With a spatial uniformity of ±1 %, the uncertainty of short-circuit current measured according to Test Method E1036 has been calculated to be less than 2 %.

A1.3.3.4 Thus, the total uncertainty of the irradiance measurement, and by extension the system power regression as well, can be considerably lower with a reference cell.

A1.3.4 Reference cells are calibrated by the ratio of short-circuit current to total irradiance, E (Eq A1.1). Because of the strong spectral sensitivity, $R_R(\lambda)$, the calibration constant C_O is defined as being with respect to the reference spectral irradiance $E_O(\lambda)$, with units of $\mathrm{Am^2W^{-1}}$.

$$C_O = \frac{I_{SC}}{E} = \frac{\int E_O(\lambda)\, R_R(\lambda) d\lambda}{\int E_O(\lambda)\, d\lambda} \tag{A1.1}$$

A1.4 *The Reference Cell Method*:

A1.4.1 Test Methods E1036 are used to measure photovoltaic module performance corrected to a fixed set of Standard Reporting Conditions (SRC), typically 25°C cell temperature, 1000 $\mathrm{Wm^{-2}}$ total irradiance, and the G173 hemispherical spectral irradiance distribution. Even though photovoltaic devices rarely or never operate at this relatively cold temperature when the total irradiance is this high, these conditions define what is commonly called a "peak power rating" which is used to compare the performance of different devices against each other.

A1.4.2 Test Methods E1036 require a calibrated reference cell to measure total irradiance via procedures that are known as the "reference cell method." The spectral responses of the reference cell and the device under test are used to correct measurements from the test light source to the reference spectral irradiance. Such corrections are necessary because the reference spectral irradiance cannot be realized, either indoors in solar simulators or outdoors in natural sunlight.

A1.4.3 Under the illumination of a test light source $E_T(\lambda)$, the current produced in a device under test will differ from that produced by the same device under the reference spectral irradiance by the fractional amount F in Eq A1.2:

$$F = \frac{\int E_T(\lambda) R_T(\lambda) d\lambda}{\int E_O(\lambda) R_T(\lambda) d\lambda} \tag{A1.2}$$

A1.4.4 When a calibrated reference cell is used to measure irradiance, spectral response differences between the test and the reference cells also introduce error. Eq A1.2 can be extended to account for both errors with an expression called the spectral mismatch parameter M shown in Eq A1.3, where the R subscripts refer to the reference cell. In Test Methods E1036, spectral errors are corrected by dividing measured currents by M, as calculated by Test Method E973.

$$M = \frac{\int aE_T(\lambda) \times cR_T(\lambda)d\lambda}{\int bE_O(\lambda) \times cR_T(\lambda)d\lambda} \frac{\int bE_O(\lambda) \times dR_R(\lambda)d\lambda}{\int aE_T(\lambda) \times dR_R(\lambda)d\lambda} \quad \text{(A1.3)}$$

A1.4.5 Because all four spectral quantities appear in both the numerator and the denominator of Eq A1.3, any multiplicative calibration or error constants cancel (shown as *a*, *b*, *c*, *d* in Eq A1.3). As a result, only relative spectral quantities are needed to quantify the spectral error in the measurement.

A1.4.6 *Matched Reference Cell*—Another important property of Eq A1.3 is that if the test and reference cell spectral responses are identical, M is mathematically equal to one. Thus, regardless of the spectral irradiance during the test, the spectral error is zero and the measured current will be that produced by the reference spectral irradiance distribution. This condition is referred to as using a “matched” reference cell.

A1.4.7 *Matched Light Source*—Conversely to the matched reference cell case in A1.4.6, the spectral error will also be zero if the test light source has the same spectral distribution as that of the reference. This condition is normally overlooked because solar spectra such as the G173 hemispherical spectral irradiance distribution are unattainable, as noted in A1.4.2. However, if such a light source existed, reference cells could be calibrated with a single measurement without spectral corrections.

A1.4.8 Note that if a spectral mismatch parameter is calculated with a spectral irradiance that does not match the actual spectral irradiance of the test light source at the time of the performance measurement, the spectral error correction is invalid. The same is true for the spectral responses of the test and reference devices.

A1.5 *In-situ Regression Procedure*—In contrast to single-value SRC power measurements, the on-site regression procedure in this test method was designed to obtain a result that is indicative of the power levels produced by a system in operation, using the following scheme:

A1.5.1 Individual system dc current and voltage data points are not corrected to an artificial SRC condition.

A1.5.2 Irradiance is measured with a flat-spectral response thermal detector, i.e. a hemispherical pyranometer, without corrections to a reference spectral irradiance distribution.

A1.5.3 Ambient temperature is used instead of device temperature, which eliminates the difficulties and uncertainties with defining a single device temperature.

A1.5.4 System power data are collected over a range of irradiance levels, the data are regressed using the procedure outlined in Section 4, and the power calculated by substitution of the irradiance, temperature, and wind speed at the reporting conditions, RC (see 3.2.4).

A1.5.5 When total irradiance is measured with a pyranometer, the power regression is essentially a calibration without spectral corrections (A1.4.7), and the reference spectral irradiance is that of sunlight at or near the RC, $E_{RC}(\lambda)$.

A1.6 *Reference Cell Irradiance Measurement Error Analysis*:

A1.6.1 To measure total irradiance with a reference cell instead of a pyranometer, the short-circuit current is divided by the calibration constant. Using the reference spectral irradiance to which it is calibrated, the measured irradiance value can be expressed by solving Eq A1.1 for *E*, which results in Eq A1.4.

$$E = \frac{I_{SC}}{C_O} = \int E_O(\lambda)d\lambda \frac{\int E_{RC}(\lambda)R_R(\lambda)d\lambda}{\int E_O(\lambda)R_R(\lambda)d\lambda} \quad \text{(A1.4)}$$

A1.6.2 The fractional error in the measured irradiance can then be expressed as the ratio of E_{RC} to *E*, which yields Eq A1.5; note the similarity with the expression for the spectral mismatch parameter *M*, Eq A1.3, with the exception that the spectral response of the system under test does not appear.

$$\frac{E_{RC}}{E} = \frac{\int E_{RC}(\lambda)d\lambda}{\int E_O(\lambda)d\lambda} \frac{\int E_O(\lambda)R_R(\lambda)d\lambda}{\int E_{RC}(\lambda)R_R(\lambda)d\lambda} = \frac{C_O}{C_{RC}} \quad \text{(A1.5)}$$

A1.6.3 Thus, error in total irradiance measured with a reference cell is independent of any differences between the photovoltaic spectral responses, and requiring a matched reference cell (see A1.1.1 and A1.4.6) has no effect on the magnitude of spectral error. Instead, spectral error is reduced only if the reference cell is calibrated with respect to the RC.

A1.6.4 If the spectral irradiance at the reporting conditions, $E_{RC}(\lambda)$, is known, the reference cell calibration C_{RC} can be translated using Eq A1.5 by solving for C_{RC}. The procedure for spectral mismatch in Test Method E973 provides guidance for performing numerical integrations of the spectral quantities.

A1.6.5 Conversely, if $E_{RC}(\lambda)$ is unknown and thus assumed to be $E_O(\lambda)$, the error is unknown. For Si devices, the magnitude can range anywhere from negligible to as high as 8-10 %. The magnitude will depend on atmospheric transmittance factors, especially clouds, water vapor absorption, aerosol scattering, and solar zenith angle. Because a worst-case magnitude should be assumed in a formal uncertainty analysis, the uncertainty with an uncalibrated reference cell is therefore as high or even greater than that of a pyranometer.

A1.7 *Reference Cell Selection*:

A1.7.1 Without the need for a reference cell matched to the spectral response of the system under test (see A1.6.3), other important considerations can be used to select a reference cell. One consideration is stability, which normally precludes thin-film devices because their calibrations generally change with time, irradiance, and temperature. Therefore, it is possible to use crystalline-Si devices to test thin-film systems.

A1.8 *Procedure* :

A1.8.1 Mount the reference cell coplanar with the system under test.

A1.8.2 Establish a maintenance schedule to clean the reference cell.

A1.8.3 Measure its short-circuit current during the data collection period.

A1.8.4 Measure the reference cell temperature and correct the measured short-circuit current using the reference cell’s temperature coefficient, α. Temperature coefficients are required for reference cells calibrated according to Test Method E948 and Test Method E1125.

A1.8.5 Determine $E_{RC}(\lambda)$ using Annex A2. Note that the spectral irradiance determination may be done before, during or after the data collection period.

A1.8.6 Translate the reference cell calibration constant from C_O to C_{RC} using Eq A1.5 (see A1.6.4) and calculate the total irradiance for each short-circuit current measurement using C_{RC}.

A2. DETERMINATION OF SPECTRAL IRRADIANCES FOR REPORTING CONDITIONS

A2.1 A valid translation of a reference cell calibration with Eq A1.5 requires a spectral irradiance distribution that is representative of the reporting conditions selected for regression procedure. As discussed in A1.6, Eq A1.5 differs from the spectral mismatch calculation represented by Eq A1.3 by the absence of the test device spectral response.

A2.2 For spectral mismatch calculations, the integration limits of the spectral irradiances only have to include the ranges over which the spectral responses of the test and reference cells are non-zero, which can simplify the measurement requirements. But without the spectral response weighting, the two integrals in Eq A1.5 represent the total irradiances E_{RC} and E_O and therefore need to cover as many of the wavelengths of terrestrial sunlight as possible.

A2.3 The Tables G173 hemispherical reference spectral irradiance distribution spans 280 to 4000 nm, and integrates to a total irradiance very close to 1000 Wm^{-2}. If an $E_{RC}(\lambda)$ is used that ends at 1500 nm in the infrared and misses 50 Wm^{-2}, for example, the translated reference cell calibration will have an error of 5 %. To prevent this error, $E_{RC}(\lambda)$ should integrate to E_{RC}, and $E_O(\lambda)$ should integrate to E_O.

A2.4 The shape of the spectral irradiance at wavelengths greater than the reference cell's bandgap edge is unimportant.

A2.5 A spectral irradiance at the RC can be determined with atmospheric transmission numerical calculations (i.e. a software model), spectroradiometric measurements, or a combination of the two.

A2.5.1 If only a single test is required (test period less than one month), then a single determination of spectral irradiance corresponding to the RC is sufficient. If multiple tests will be performed (for instance, reporting of monthly performance over a period of years), the determination of a spectral irradiance corresponding to the RC should be performed for each month.

A2.6 *Software Model Calculations*:

A2.6.1 Tables G173 provides details about how the hemispherical spectral irradiance for a 37° tilted surface was generated with the Simple Model of the Atmospheric Radiative Transfer of Sunshine (SMARTS), which can calculate spectral irradiance from a set of input parameters such as water vapor absorber amounts, solar zenith angle, and aerosol optical depth. The model code and documentation is available as an adjunct (ADJG173)[5] to Tables G173. Other software models may be used if available.

A2.6.2 If the RC are under predominately cloudy skies, the SMARTS model cannot be used as it is for cloudless skies only. Under such conditions, refer to A2.7 – Spectroradiometric Measurements.

A2.6.3 Input parameters must be selected for the conditions at the system under test, and Appendix X1 of Tables G173 together with the SMARTS documentation should be consulted. Solar radiation databases can be a source for input parameters. A solar zenith angle can be calculated from a time-of-day that is representative of the RC.

A2.6.4 Alternatively, estimates of water vapor absorber amounts and aerosol optical depths needed for model inputs can be obtained from spectroradiometer data, if available, by matching the model output with the measured spectral irradiance (A2.7). After an average spectral irradiance is obtained, adjust the input parameters until the water vapor absorption bands match the spectroradiometer data.

A2.7 *Spectroradiometric Measurements*:

A2.7.1 Measurements of the spectral irradiance can be made at the system location with a solar spectroradiometer calibrated according to Test Method G138, and which meets the requirements in 6.3 of Test Method E1125.

A2.7.2 Commercial spectroradiometers are available that can measure to 2500 nm.

A2.7.3 The field-of-view of the spectroradiometer should match that of the reference cell as closely as possible. A thin quartz cover can be used over integrating sphere receptors to simulate the reference cell.

A2.7.4 *Procedure:*

A2.7.4.1 Mount the spectroradiometer receptor coplanar with the reference cell.

A2.7.4.2 Establish a maintenance schedule to clean the spectroradiometer receptor during the data collection period (see 3.2.2).

A2.7.4.3 Collect spectral irradiance data during the data collection period. The spectral irradiance scans should be

---

[5] Available from ASTM International Headquarters. Order Adjunct No. ADJG173.

synchronized with the averaging interval (see 3.2.1) if possible and as allowed by the time required to perform one scan.

A2.7.4.4 Sort the spectral irradiance data according to the total irradiance, as calculated by the reference cell's short-circuit current divided by its un-translated calibration constant C_O (see A1.6.1).

A2.7.4.5 Discard scans for which the total irradiance measured in A2.7.4.3 differs from E_{RC} by more than 5 %, and those during periods in which the total irradiance changes by more than 5 %.

A2.7.4.6 Plot the remaining scans versus wavelength and examine them for anomalies. Reject any anomalous scans.

A2.7.4.7 Average the remaining scans at each wavelength.

A2.8 If the spectral irradiance generated with A2.7 does not cover 280 to 4000 nm, the missing wavelengths must be obtained with other means. Several options are available.

A2.8.1 Extract the missing wavelengths from the software model output (cloudless skies only).

A2.8.2 Replace the measured spectral irradiance with the software model output (cloudless skies only).

A2.8.3 If the missing wavelengths are outside of the reference cell's spectral response range, copy the missing wavelengths from an existing reference spectral irradiance such as Tables G173 and scale the copied data to match the spectroradiometer data.

A2.9 Scale the spectral irradiance obtained with A2.6 through A2.8 so that the integrated total irradiance is equal to the total irradiance of the RC. This spectral irradiance becomes $E_{RC}(\lambda)$.

ASTM International takes no position respecting the validity of any patent rights asserted in connection with any item mentioned in this standard. Users of this standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, are entirely their own responsibility.

This standard is subject to revision at any time by the responsible technical committee and must be reviewed every five years and if not revised, either reapproved or withdrawn. Your comments are invited either for revision of this standard or for additional standards and should be addressed to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee, which you may attend. If you feel that your comments have not received a fair hearing you should make your views known to the ASTM Committee on Standards, at the address shown below.

This standard is copyrighted by ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA 19428-2959, United States. Individual reprints (single or multiple copies) of this standard may be obtained by contacting ASTM at the above address or at 610-832-9585 (phone), 610-832-9555 (fax), or service@astm.org (e-mail); or through the ASTM website (www.astm.org). Permission rights to photocopy the standard may also be secured from the Copyright Clearance Center, 222 Rosewood Drive, Danvers, MA 01923, Tel: (978) 646-2600; http://www.copyright.com/