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.

Designation: E816 – 15 (Reapproved 2023)

Standard Test Method for Calibration of Pyrheliometers by Comparison to Reference Pyrheliometers[1]

This standard is issued under the fixed designation E816; 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.

INTRODUCTION

Accurate and precise measurement of the direct (beam) radiation component of sunlight are required in *(1)* the calibration of reference pyranometers by the shading disk or optical occluding methods, *(2)* determination of the energy collected by concentrating solar collectors, including exposure levels achieved in use of Practice G90 dealing with Fresnel-reflecting concentrator test machines, and *(3)* the assessment of the direct beam for energy budget analyses, geographic mapping of solar energy, and as an aid in the determination of the concentration of aerosol and particulate pollution, and water vapor effects.

This test method requires calibration to the World Radiometric Reference (WRR), maintained by the World Meteorological Organization (WMO), Geneva. The Intercomparison of Absolute Cavity Pyrheliometers, also called Absolute Cavity Radiometers, on which the WRR depends, is covered by procedures adopted by WMO and by various U.S. Organizations who occasionally convene such intercomparisons for the purpose of transferring the WRR to the United States, and to maintaining the WRR in the United States. These procedures are not covered by this test method.

1. Scope

1.1 This test method has been harmonized with, and is technically equivalent to, ISO 9059.

1.2 Two types of calibrations are covered by this test method. One is the calibration of a secondary reference pyrheliometer using an absolute cavity pyrheliometer as the primary standard pyrheliometer, and the other is the transfer of calibration from a secondary reference to one or more field pyrheliometers. This test method prescribes the calibration procedures and the calibration hierarchy, or traceability, for transfer of the calibrations.

NOTE 1—It is not uncommon, and is indeed desirable, for both the reference and field pyrheliometers to be of the same manufacturer and model designation.

1.3 This test method is relevant primarily for the calibration of reference pyrheliometers with field angles of 5° to 6°, using as the primary reference instrument a self-calibrating absolute cavity pyrheliometer having field angles of about 5°. Pyrheliometers with field angles greater than 6.5° shall not be designated as reference pyrheliometers.

1.4 When this test method is used to transfer calibration to field pyrheliometers having field angles both less than 5° or greater than 6.5°, it will be necessary to employ the procedure defined by Angstrom and Rodhe.[2]

1.5 This test method requires that the spectral response of the absolute cavity chosen as the primary standard pyrheliometer be nonselective over the range from 0.3 µm to 10 µm wavelength. Both reference and field pyrheliometers covered by this test method shall be nonselective over a range from 0.3 µm to 4 µm wavelength.

1.6 The primary and secondary reference pyrheliometers shall not be field instruments and their exposure to sunlight shall be limited to calibration or intercomparisons. These reference instruments shall be stored in an isolated cabinet or room equipped with standard laboratory temperature and humidity control.

NOTE 2—At a laboratory where calibrations are performed regularly, it is advisable to maintain a group of two or three secondary reference pyrheliometers that are included in every calibration. These serve as controls to detect any instability or irregularity in the standard reference pyrheliometer.

1.7 This test method is applicable to calibration procedures using natural sunshine only.

[1] This test method is under the jurisdiction of ASTM Committee G03 on Weathering and Durabilityand is the direct responsibility of Subcommittee G03.09 on Radiometry.

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[2] Angstrom, A., and Rodhe, B., "Pyrheliometric Measurements with Special Regard to the Circumsolar Sky Radiation," *Tellus*, Vol 18, 1966, pp. 25–33.

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1.8 *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.*

1.9 *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:*[3]

E772 Terminology of Solar Energy Conversion

E824 Test Method for Transfer of Calibration From Reference to Field Radiometers

G90 Practice for Performing Accelerated Outdoor Weathering of Materials Using Concentrated Natural Sunlight

G167 Test Method for Calibration of a Pyranometer Using a Pyrheliometer

2.2 *ISO Standards:*[4]

ISO 9059 Calibration of Field Pyrheliometers by Comparison to a Reference Pyrheliometer

ISO 9060 Specification and Classification of Instruments for Measuring Hemispherical Solar and Direct Solar Radiation

ISO TR 9673 The Instrumental Measurement of Sunlight for Determining Exposure Levels

ISO 9846 Calibration of a Pyranometer Using a Pyrheliometer

2.3 *WMO Standard:*

Guide to Meteorological Instruments and Methods of Observation, Seventh ed., WMO-No. 8[5]

3. Terminology

3.1 *Definitions:*

3.1.1 The relevant definitions of Terminology E772 apply to the calibration method described in this test method.

3.1.2 *absolute cavity pyrheliometer, n*—see *self-calibrating absolute cavity pyrheliometer*.

3.1.3 *direct radiation, direct solar radiation, and direct (beam) radiation, n*—radiation received from a small solid angle centered on the sun's disk, on a given plane whose normal (perpendicular to the plane) points to the center of the sun's disk (see ISO 9060). That component of sunlight is the beam between an observer, or instrument, and the sun within a solid conical angle centered on the sun's disk and having a total included planar field angle of, for the purposes of this test method, 5° to 6°.

3.1.4 *field pyrheliometer, n*—pyrheliometers that are designed and used for long-term field measurements of direct solar radiation. These pyrheliometers are weatherproof and therefore possess windows, usually quartz, at the field aperture that pass all solar radiation in the range from 0.3 µm to 4 µm wavelength.

3.1.5 *opening angle, n*—with radius of field aperture denoted by R and the distance between the field and receiver apertures denoted by l, the opening angle is defined for right circular cones by the equation:

$$Z_o = \tan^{-1} R/l \quad (1)$$

The field angle is double the opening angle.

3.1.6 *primary standard pyrheliometers, n*—pyrheliometers, selected from the group of absolute pyrheliometers (see *self-calibrating absolute cavity pyrheliometer*).

3.1.7 *reference pyrheliometer, n*—pyrheliometers of any category serving as a reference in calibration transfer procedures. They are selected and well-tested instruments (see Table 2 of ISO 9060), that have a low rate of yearly change in responsivity. The reference pyrheliometer may be of the same type, class, and manufacturer as the field radiometers in which case it is specially chosen for calibration transfer purposes and is termed a secondary standard pyrheliometer (see ISO 9060), or it may be of the self-calibrating cavity type (see *self-calibrating absolute cavity pyrheliometer*).

3.1.8 *secondary standard pyrheliometer, n*—pyrheliometers of high precision and stability whose calibration factors are derived from primary standard pyrheliometers. This group comprises absolute cavity pyrheliometers that do not fulfill the requirements of a primary standard pyrheliometer as described in 3.1.6.

3.1.9 *self-calibrating absolute cavity pyrheliometer, n*—a radiometer consisting of either a single- or dual-conical heated cavity that, during the self-calibration mode, displays the power required to produce a thermopile reference signal that is identical to the sampling signal obtained when viewing the sun with an open aperture. The reference signal is produced by the thermopile in response to the cavity irradiance resulting from heat supplied by a cavity heater with the aperture closed.

3.1.10 *slope angle, n*—with radius of the sensor denoted by r, the radius of the limiting aperture is denoted by R, and the distance between aperture and sensor denoted by l, the slope angle equation is defined as:

$$S = \mathrm{arcTan}\,(R - r)/l \quad (2)$$

3.2 *Acronyms:*

3.2.1 *ACR*—Absolute Cavity Radiometer

3.2.2 *ANSI*—American National Standards Institute

3.2.3 *ARM*—Atmospheric RadiationMeasurement Program

3.2.4 *DOE*—Department of Energy

3.2.5 *GUM*—(ISO) Guide to Uncertainty in Measurements

3.2.6 *IPC*—International Pyrheliometer comparison

3.2.7 *ISO*—International Standards Organization

3.2.8 *NCSL*—National Council of Standards Laboratories

3.2.9 *NIST*—National Institute of Standards and Technology

3.2.10 *NREL*—National Renewable Energy Laboratory

[3] 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.

[4] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, http://www.iso.org.

[5] Available from World Meterological Organization, 7bis, avenue de la Paix, CP. 2300, CH-1211 Geneva 2, Switzerland, www.wmo.int.

3.2.11 *PMOD*—Physical Meteorological Observatory Davos

3.2.12 *SAC*—Singapore Accreditation Council

3.2.13 *SINGLAS*—Singapore Laboratory Accreditation Service

3.2.14 *UKAS*—United Kingdom Accrediation Service

3.2.15 *WRC*—World Radiation Center

3.2.16 *WRR*—World Radiometric Reference

3.2.17 *WMO*—World Meteorological Organization

4. Significance and Use

4.1 Though the sun trackers employed, the number of instantaneous readings, and the data acquisition equipment used will vary from instrument to instrument and from laboratory to laboratory, this test method provides for the minimum acceptable conditions, procedures, and techniques required.

4.2 While the greatest accuracy will be obtained when calibrating pyrheliometers with a self-calibrating absolute cavity pyrheliometer that has been demonstrated by intercomparison to be within ±0.5 % of the mean irradiance of a family of similar absolute instruments, acceptable accuracy can be achieved by careful attention to the requirements of this test method when transferring calibration from a secondary reference to a field pyrheliometer.

4.3 By meeting the requirements of this test method, traceability of calibration to the World Radiometric Reference (WRR) can be achieved through one or more of the following recognized intercomparisons:

4.3.1 International Pyrheliometric Comparison (IPC) VII, Davos, Switzerland, held in 1990, and every five years thereafter, and the PMO-2 absolute cavity pyrheliometer that is the primary reference instrument of WMO.[6]

4.3.2 Any WMO-sanctioned intercomparison of self-calibrating absolute cavity pyrheliometers held in WMO Region IV (North and Central America).

4.3.3 Any sanctioned or non-sanctioned intercomparison held in the United States the purpose of which is to transfer the WRR from the primary reference absolute cavity pyrheliometer maintained as the primary reference standard of the United States by the National Oceanic and Atmospheric Administration's Solar Radiation Facility in Boulder, CO.[7]

4.3.4 Any future intercomparisons of comparable reference quality in which at least one self-calibrating absolute cavity pyrheliometer is present that participated in IPC VII or a subsequent IPC, and in which that pyrheliometer is treated as the intercomparison's reference instrument.

4.3.5 Any of the absolute radiometers participating in the above intercomparisons and being within ±0.5 % of the mean of all similar instruments compared in any of those intercomparisons.

4.4 The calibration transfer method employed assumes that the accuracy of the values obtained are independent of time of year and, within the constraints imposed, time of day of measurements. With respect to time of year, the requirement for normal incidence dictates a tile angle from the horizontal that is dependent on the sun's zenith angle and, thus, the air mass limits for that time of year and time of day.

5. Interferences

5.1 *Radiation Source*—Transfer of calibration from reference to secondary standard or field pyrheliometers is accomplished by exposing the two instruments to the same radiation field and comparing their corresponding measurands. The direct irradiance should not be less than 300 $W \cdot m^{-2}$, but irradiance values exceeding 700 $W \cdot m^{-2}$ is preferred.

5.2 *Sky Conditions*—The measurements made in determining the instrument constant shall be performed only under conditions when the sun is unobstructed by clouds for an incremental data-taking period. The most acceptable sky conditions should be such that the direct irradiance is not less than 80 % of the hemispherical irradiance measured with a pyranometer aligned with its axis vertical and calibrated in accordance with Test Method G167. Also, no cloud formation may be within 15° of the sun during the period data are taken for record when either transferring calibration to a secondary standard pyrheliometer (to be used as a reference pyrheliometer) from an absolute cavity pyrheliometer, or when transferring calibration from a secondary reference pyrheliometer to field pyrheliometers. Generally, good calibration conditions exist when the cloud cover is less than 12.5 %.

NOTE 3—Contrails of airplanes that are within 15° of the sun can be tolerated providing the ratio of so affected measurements to unaffected measurements is small in any series.

NOTE 4—Atmospheric water vapor in the pre-condensation phase occasionally causes variable atmospheric transmission. Generally, the scattering of measuring data that is produced by these clusters is acceptable.

5.2.1 The atmospheric turbidity during transfer of calibration should be close to values typical for the field measuring conditions. Generally, the turbidity should be confined to conditions with Linke turbidity factors lower than six (see ISO 9059 and ISO 9060).

5.2.2 The circumsolar radiation (aureole) originates from forward scattering of direct solar radiation. It decreases from the limb of the sun to an angular distance of about 15° by several orders of magnitude, depending on the type and concentration of the aerosol.[2,8,9] The typical amount of circumsolar radiation within an angular distance of 5° of the sun represents only a few percent of the direct solar radiation. If standard and field pyrheliometers have different field-of-view angles, the aerosol may strongly influence the accuracy of the transfer of calibration. Calculated percentages of circumsolar contained in direct solar radiation, for different aerosol types and solar elevation angles, are given for information in Appendix X1.

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[6] WRCD, "Results, Seventh International Pyrheliometer Comparisons," *Working Report No. XX*, Swiss Meteorological Institute, Zurich, Switzerland, Month, 1991.

[7] Currently (2005) the TMI/Kendall Absolute Cavity Radiometer, SN 67502 and Eppley Laboratory Model AHF SN 28553.

[8] Eiden, R., " Calculations and Measurements of the Spectral Radiance of the Solar Aureole," *Tellus* , Vol 20, No. 3, 1968, pp. 380–399.

[9] Thomalla, E., Köpke, P., Müller, H., and Quenzel, H., "Circumsolar Radiation Calculated for Various Atmospheric Conditions," *Solar Energy*, Vol 30, No. 6, 1983, pp. 575–587.