# Standard Method for Calibration of Reference Pyranometers With Axis Vertical by the Shading Method[1]

This standard is issued under the fixed designation E 913; 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 measurements of the total global (hemispherical) irradiance of sunlight are required in (*1*) the determination of the energy available to flat plate solar collectors, ( *2*) the assessment of irradiance and radiant exposure in the testing of solar and nonsolar-related materials technologies, and ( *3*) the assessment of the direct solar versus diffuse sky components for energy budget analysis, 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 method describes required calibration to the World Radiation Reference Scale (also known as the Absolute Radiometric Scale); traceability to the International Pyrheliometric Scale of 1956 shall not be permitted.

The intercomparison of absolute radiometers, on which the Absolute Radiation Scale depends, is covered by procedures adopted by the World Meteorological Organization (Geneva) and by various U.S. intercomparisons, chief among which are the New River intercomparisons of absolute cavity solar pyrheliometers commencing on Nov. 1 to 3, 1978. These intercomparison procedures are not covered by this method.

## 1. Scope

1.1 This method covers the calibration of reference pyranometers with field angles of 180° (2π steradians) utilizing self-calibrating absolute cavity pyrheliometers having field angles of 5.0° and slope angles of 0.75 to 0.8° as the primary reference instrument.

1.2 This method is applicable to reference pyranometers regardless of the radiation receptor employed.

1.3 Two types of calibrations are covered: (1) Type I employs a self-calibrating absolute cavity pyrheliometer, and (2) Type II calibrations employ a secondary reference pyrheliometer as the standard instrument.

1.4 This standard calibration of reference pyranometers covers the sensitive element in the horizontal plane only, that is, with the axis vertical. The calibration of reference pyranometers at various tilt angles is covered in another ASTM standard (see Section 2.).

1.5 This method is only applicable to calibration procedures using light from the sun.

## 2. Referenced Documents

2.1 *ASTM Standards:*

E 772 Terminology Relating to Solar Energy Conversion[2]

E 816 Method for Calibration of Secondary Reference Pyrheliometers and Pyrheliometers for Field Use[3]

E 824 Method for Transfer of Calibration from Reference to Field Pyranometers[3]

E 941 Test Method for Calibration of Reference Pyranometers with Axis Tilted by the Shading Method[3]

## 3. Terminology

3.1 *Definitions:*

3.1.1 *altazimuthal mount*—a tracking mount capable of rotation about orthogonal altitude and azimuth axes; tracking may be manual or by a follow-the-sun servomechanism. (see also Terminology E 772.)

3.1.2 *direct beam radiation*—that component of solar irradiance within the solid angle subtended by the sun at the observer. (See solar irradiance, direct Terminology E 772.)

3.1.3 *equatorial mount*—see Definitions E 772.

3.1.4 *solar irradiance, global*—see Definitions E 772. Also often termed hemispherical solar irradiance when applied to surfaces tilted from the horizontal.

3.1.5 *pyranometer*—see Terminology E 772.

3.1.6 *pyranometer, field*—a pyranometer essentially meeting WMO Class II specifications or better (that is, Class I),

[1] This method is under the jurisdiction of ASTM Committee G-3 on Durability of Nonmetallic Materialsand is the direct responsibility of Subcommittee G03.09.

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[2] *Annual Book of ASTM Standards*, Vol 12.02.

[3] *Annual Book of ASTM Standards*, Vol 14.04

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appropriate to field use and typically exposed continuously.

NOTE 1—The WMO Classification of Pyranometers and Pyrheliometers is currently under study and may be eliminated altogether by WMO.

3.1.7 *pyranometer, reference*—a pyranometer essentially meeting WMO Class I specifications and used principally to calibrate other instruments.

3.1.8 *pyrheliometer*—a radiometer used to measure the direct irradiance incident on a surface normal to the sun's rays. (See Terminology E 772.)

3.1.9 *pyrheliometer, absolute (self-calibrating)*— a radiation sensor for determining the direct solar irradiance having a field of view of 5° and a slope angle of 0.75 to 0.8° and having a blackened cavity receiver for absorption of the incident radiation; the measured electrical power in a heater affixed to the cavity receiver constitutes the method of self calibration and traceability to Absolute SI units; the sensing of the temperature rise of the receiving cavity is employed to either relate the radiation quantity to the SI electrical quantity (passive) or to control the heater to stabilize cavity temperature at a desired set-point (active).

3.1.10 *pyrheliometer, secondary reference*—a pyrheliometer essentially meeting WMO Class I specifications but not having self-calibrating capability.

## 4. Summary of Method

4.1 The reference pyrheliometer is mounted on a sun tracker designed to maintain the instrument axis pointing directly toward the sun. The pyranometer being calibrated, that is, the test instrument, is mounted with its axis vertical. An adjustable and removable opaque disk is provided which, when suitably disposed, can be made to shade the pyranometer dome and sensor assembly from the direct solar radiation. A second pyranometer, of the same type as the test instrument, is mounted nearby to monitor the global solar irradiance during the experiment. The second pyranometer will have its axis vertical but will not be shaded. Readings from the second pyranometer will be used to resolve any inconsistencies in the test data, by providing a record of sky variability.

4.2 The direct solar irradiance on a surface normal to the sun is measured and recorded. Knowing the solar zenith angle, the corresponding irradiance on a horizontal surface is computed using the cosine of the zenith angle as a multiplier.

4.3 The output signal from the test pyranometer, unshaded ($V_u$) and shaded ($V_s$), provides, by difference, the signal corresponding to the direct solar irradiance on a horizontal surface.

4.4 The calibration procedure determines the scaling factor, $kC$, in the equation connecting the source measurement with the pyranometer response, as follows:

$$kC_\theta = (V_u - V_s)/(I_d \cos z)\ V \cdot w^{-1} \cdot \mathrm{m}^2 \quad (1)$$

where:

$C_\theta$ = the cosine correction at angle θ which makes $k$ largely independent of θ .

If $C_\theta$ is not known, it is taken as unity. The determination of incident angle effects is the subject of another ASTM standard currently under development.

$I_d$ = direct irradiance normal to the pyranometer
θ = incident angle of the direct radiation on the pyranometer
$z$ = zenith angle of sun
$V_u$ = output signal of pyranometer when unshaded
$V_s$ = output signal of pyranometer when shaded
$k$ = instrument response, independent of cosine (and other) corrections. (See Section 7.)

## 5. Significance and Use

5.1 The pyranometer is an instrument designed to measure the sum of direct solar radiation and sky radiation in such proportions as solar altitude and cloud cover may produce.

5.2 The method described represents the preferred means for calibration of a pyranometer and employs a standard reference pyrheliometer. While the sun-trackers employed, the shading disk, the number of instantaneous readings and the electronic display equipment used will vary from instrument to instrument and from laboratory to laboratory, the method provides for the minimum acceptable conditions, procedures and techniques required.

5.3 While the greatest accuracy normally will be obtained when calibrating pyranometers with a self-calibrating absolute cavity pyrheliometer that has been demonstrated by direct intercomparison to be within ±0.5 % of the mean of a family of similar absolute instruments, suitable accuracy of calibration can be achieved by careful attention to the requirements of this method when performing a shading device calibration with a secondary reference pyrheliometer as the reference instrument.

5.4 Traceability of calibration to the reference pyrheliometer represented by one or more of the following is accomplished when employing the method and when meeting the requirements associated therewith:

5.4.1 International Pyrheliometric Comparisons IV and V, Davos, held in 1975 and 1980, respectively, with PACRAD III and PMO2 being primary reference instruments of WMO **(1)**[4].

5.4.2 One of the New River Intercomparisons of Absolute Cavity Solar Pyrheliometers (two of which were International) with TMI/Kendall 67502 being the primary reference standard of the NOAA Solar Radiation Facility/Boulder **(2)**.

5.4.3 Any future intercomparison of comparable reference quality.

5.4.4 Any of the absolute radiometers participating in the Intercomparisons in 5.4.2 and 5.4.3 and being within ±0.5 % of the mean of all similar instruments compared in any of those intercomparisons.

5.4.5 A documented intercomparison with an absolute radiometer participating in the intercomparisons in 5.4.1-5.4.3 and having a response within ±0.5 % of the mean of all similar instruments compared in said comparisons.

5.5 The calibration method employed assumes that the accuracy of the values obtained are independent of time of year, within the constraints imposed by the test instrument's temperature compensation (neglecting cosine errors).

[4] The boldface numbers in parentheses refer to references at the end of this method.

5.6 The reference pyranometer tested as described herein has a calibration limited to the axis vertical orientation and may not give true readings if tilted. Without further characterization, it cannot be used to transfer calibration to tilted field pyranometers.

## 6. Apparatus

6.1 *Digital Electronic Readout*—Any digital microvoltmeter capable of repeatability to 0.1 % of average reading, and an accuracy of ±0.2 %, may be employed. Data loggers having print-out must be capable of a measurement frequency of at least two per min. A data logger having at least 3 channel capacity may be useful.

6.2 *Pyranometer*—A pyranometer meeting the WMO Class I specification **(3)** for such instruments shall be employed as the test instrument (which then may be employed as a primary reference pyranometer in Method E 824 to transfer calibration to field pyrheliometers).

6.3 *Pyranometer, Monitoring*—A pyranometer nominally meeting WMO Class I specifications employed to monitor the sky variability during calibration.

6.4 *Self-Calibrating Absolute Cavity Pyrheliometer*[5]—A self-calibrating absolute cavity pyrheliometer identified as a primary reference shall be an instrument that has either participated in one of the Intercomparisons listed in 5.4, or that has been intercompared with any one of the absolute cavity radiometers that participated in those Intercomparisons. If the primary reference carried indirect traceability to one or more of the Intercomparisons, it shall have been determined or corrected to read within ±0.5 % of the mean of the Intercomparison to which it is traceable.

NOTE 2—The absolute cavity pyrheliometer has an unobstructed aperture. Hence, no question arises concerning the spectral transmission of window materials.

6.5 *Secondary Reference Pyrheliometer*[6]—The secondary reference pyrheliometer when employed for a Type II calibration shall be of suitable quality in terms of linearity of response, sensitivity, and temperature compensation that it meets or exceeds the specifications of a WMO Class I pyrheliometer **(3)**. The principal additional requirement is that it shall have been calibrated within 6 months by the procedures presented in Method E 816 to calibrate secondary reference pyrheliometers utilizing a self-calibrating absolute cavity pyrheliometer as described in Sections 5 and 6.4.

6.6 *Shading Disk*—A blackened circular disk with a diameter of 88 mm to 100 mm shall be mounted at the end of a slender, rigid blackened support rod such that the distance between the disk and the test pyranometer specified in 6.2 is 1 m (±5 mm). The disk and rigid support must be so positioned that the disk will just shade the entire receiver and outer transparent hemispherical enclosure from the direct radiation. The mounting fixture shall be designed to permit easy and rapid positioning of the shading disk perpendicular to the direct radiation. A suggested configuration is shown in Fig. 1. The purpose of these dimensions and adjustments is to create a geometry such that the opening angle of the shaded pyranometer is essentially the same as that of the reference pyrheliometer employed. For example, when calibrating against the self-calibrating pyrheliometer described in 6.4, the appropriate disk diameter is 88 mm.

6.7 *Sun Tracker(s)*[7]— Sun tracker(s), whether power driven or manually operated shall be employed to maintain the

[5] Suitable self-calibrating absolute cavity pyrheliometers are the Mark VI manufactured by Technical Measurements, Inc., La Canada, Calif. 91011 **(4)**, and the Eppley Model HF manufactured by Eppley Laboratories, Inc., 12 Sheffield Ave., Newport, R.I. 02840 **(5)**. Active cavity radiometers (ACR's) are also suitable **(6)**.

[6] A suitable secondary reference pyrheliometer is an Eppley Model NIP pyrheliometer manufactured by Eppley Laboratories, Inc.

[7] Suitable trackers are available from Eppley Laboratories, Inc. and Technical Measurements, Inc.

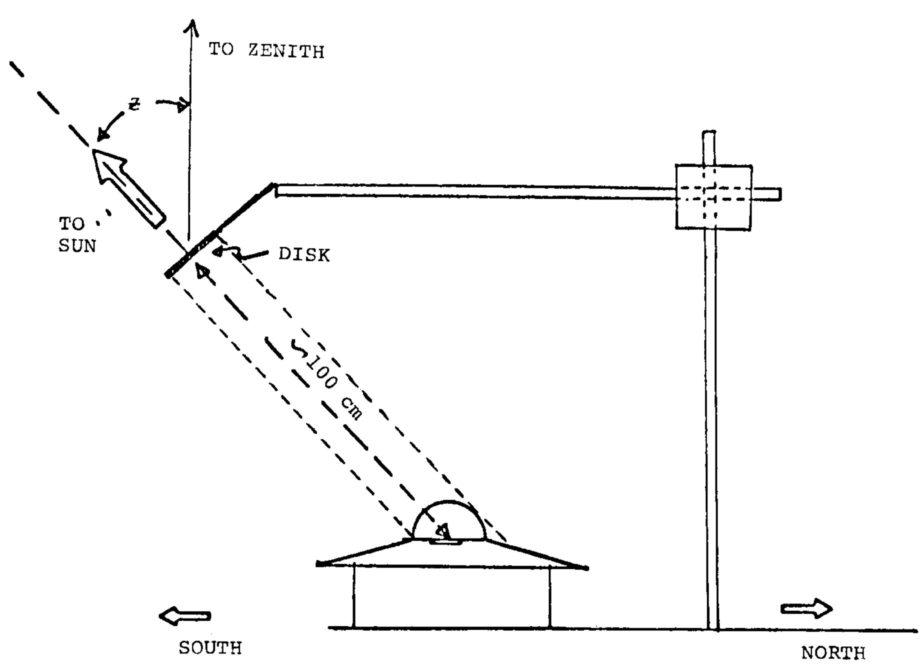



**FIG. 1 Schematic Arrangement for Shading Disk Geometry**

reference pyrheliometer normal to the sun for the entire test period. The tracking precision shall be such that the pyrheliometer is properly aimed at the sun for all data taking periods as demonstrated by an optical alignment system on the pyrheliometer or the tracker.

## 7. Interferences and Precautions

7.1 *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 minimum acceptable direct solar irradiance on the horizontal surface, given by the product of the measurement and the cosine of the incident angle, shall be 80 % of the global solar irradiance, given by the pyranometer measurement. Also, no cloud formation shall be within 30° of the sun during the period data is taken for record.

7.2 *Instrument Orientation Corrections*— Generally the irradiance calibration of the pyranometer is influenced by the tilt and azimuthal orientation of the case; however, since the method is limited to the axis vertical orientation, tilt is not a consideration. Since the calibration is performed with the sun in a range of azimuths, the azimuthal angle between the sun and the direction of the cable connector or other reference mark may be significant.

7.3 *Cosine Corrections*—Because this method requires the pyranometer to be tested with axis vertical, the zenith and incident angles are the same and never smaller than the following:

$$z = L - \delta \tag{2}$$

where:

$z$ = the zenith (or incident) angle,
$L$ = the latitude of the site, and
$\delta$ = the solar declination for the day. The range of minimum incident angles available for test due to the range of latitudes available in the continental U.S. is shown below:

| Place | Season | Minimum $z$,° |
|---|---|---|
| Miami, FL | Summer | 2.4 |
| Miami, FL | Winter | 49.2 |
| Seattle, WA | Summer | 24.6 |
| Seattle, WA | Winter | 71.4 |

The flux calibration is derived from flux measurements made at incident angles of convenience but referred to the value the calibration would have if the measured flux were incident along the pyranometer axis. Therefore, since each calibration involves the cosine and azimuth correction of the pyranometer at each incident angle, the accuracy of the calibration is limited by the cosine and azimuth correction uncertainty. The calibration uncertainty will be minimized if the correction is known; otherwise, the correction is taken as unity.

7.4 *Environmental Conditions*—Under general conditions of both calibration and use the pyranometer output is a function of many parameters which may affect calibration factors or data derived from use to a significant degree. Many of these parameters are beyond the scope of this document or the control of the practitioner. This topic is discussed in more detail in Appendix X1.

7.5 *Time Measurement*[8]—Some measurements will be taken at low solar altitudes. Under these conditions accurate time-keeping to 0.2 s and the difference between local time and zone time are important.

7.6 *Deviations of the Reference Pyranometer from a Perfect Pyranometer*—A perfect pyranometer is one which evaluates the irradiance correctly and reports a correct single number representing the total irradiance integrated over the instrument's field of view regardless of the spatial distribution of the irradiance and the orientation of the pyranometer in azimuth and tilt. This perfection may stem from instrument design and construction, experimentally determined correction factors or a combination thereof.

7.7 Because of possible drift or degradation with time, the primary reference pyrheliometer shall not be used as a field instrument and its exposure to sunlight shall be limited to calibration or intercomparisons.

7.7.1 At a laboratory where calibrations are performed regularly, it is advisable to maintain a group of two or three reference pyranometers which are included in every calibration. These serve as controls to detect any instability or irregularity in the reference pyranometer being calibrated.

7.8 Reference standard instruments shall be stored in such a manner as to not degrade their calibration. Exposure to excessive temperature or humidity can cause instrumental drift.

7.9 Precautions shall be taken to ensure that the horizon is substantially free of natural or manmade objects that obscure more than 5 % of the sky at the horizon. Special emphasis shall be given to ensure that any objects that do exist above the horizon do not reflect sunlight onto the calibration facility.

## 8. Procedure

8.1 *Mounting*:

8.1.1 Mount the self-calibrating absolute cavity pyrheliometer (hereinafter designated the primary reference pyrheliometer) or a secondary reference pyrheliometer (if a Class II shading calibration is desired) on either an altazimuth or equatorial sun tracker. Align the sun tracker with a solar-noon south reference (and level the tracker with the "bubble level" provided if an equatorial mount is employed). Set the latitude angle adjustment of the equatorial tracker to the exact local latitude. Align the reference pyrheliometer with the sight mechanism provided.

8.1.2 Mount the test and monitoring pyranometers on a horizontal plate. Rotate each until the instrument cable connector or other reference mark faces north. Level each pyranometer with leveling screws and bubble level provided.

8.1.3 Connect the reference, monitoring, and test instruments to their respective, or common, digital voltmeter, utilizing proper shielding. Check out the instruments for electrical continuity, polarity of the signal, and the nominal signal strength and stability. (An analog strip chart or x-y recorder for the monitoring unit signal is suggested).

8.1.4 If a Class I calibration is desired, calibrate the self-calibrating absolute cavity pyrheliometer in accordance with

[8] Accurate time is provided by the National Institute of Standards and Technology through WWV, Boulder, Colo. Electronic stores sell completely adequate time cube radios for this purpose.

the procedure required for that particular absolute radiometer and record the irradiance for each instantaneous reading. If a Class II calibration is desired, compute the irradiance for each instantaneous reading by dividing the signal from the secondary reference pyrheliometer with the instrument constant for that pyrheliometer.

8.2 *Shading Disk Alignment*—Mount the shading disk apparatus such that all posts and mounts are north of the test pyranometer. Ensure that no mounting brackets or obstructions subtend more than a very small portion of the north sky. Adjust the shading disk to be 1 m distant from the test pyranometer's receiver in such a manner that the shadow just completely covers the outermost hemispherical transparent enclosure. Provide means for rapidly and accurately moving the disk in and out of the shading condition.

8.3 *Determination of Thermopile Time Constant*—Illuminate the pyranometer for 10 min (unshaded) and record the signal $V_u$. Then shade the pyranometer for 60 s and record the signal $V_s$. Unshade the pyranometer and, taking continuous voltage readings, determine the time required for the response signal to reach 1/e (63 %) of the final steady state value $V_u$. Record the time "$t_c$" as the instrument constant.

NOTE 3—Eppley Model PSPs have time constants of 1 s.

8.4 *Data-Taking Sequence*:

8.4.1 Allow a 30-min warm-up of all instruments before taking data. Precondition the test pyranometer by exposing in the unshaded mode during this 30-min period as shown in segment "A" of Fig. 2. Ensure that the data-taking sequence takes place during cloud-free conditions.

8.4.2 Adjust shading disk and prepare to take the readings prescribed in 8.4.3.

8.4.3 At the completion of the unshaded (illuminated) preconditioning soak period "A" (Fig. 2), shade the pyranometer for 20 to 30 time constants, "B." This completes the first preconditioning cycle.

NOTE 4—The preconditioning cycle is required to stabilize the temperature of the case and dome prior to taking data.

8.4.4 Take data in accordance with the sequence of unshaded and shaded conditions shown in Fig. 2. Repeat the shaded-unshaded sequence for a total of five cycles. Each cycle represents first 60 time constants" C" of full illumination (unshaded) followed by 30 s of data taking" M" during which not less than 3 instantaneous readings of the pyranometer response $V_u$ are recorded, then 20 time constants of "B" with the direct component shaded, followed by 30 s of data taking "M" during which not less than 3 instantaneous readings of the pyranometer response $V_s$ are recorded. Take not less than 3 instantaneous readings of the direct irradiance during each data-taking segment, "M" employing the reference pyrheliometer chosen.

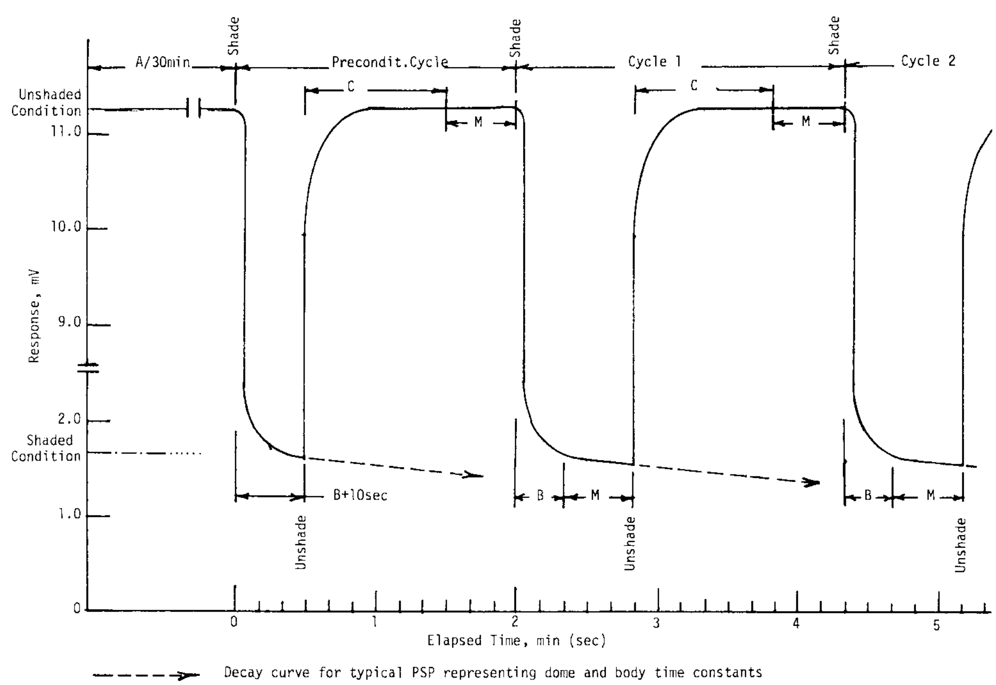
8.4.5 Perform the sequence of 5 cycles shown in Fig. 2 over a sufficient number of days such that at least one sequence is obtained for each hour from 0800 to 1600 h apparent solar time (or to limits defined by the requirement to take data at zenith angles of at least 60°).

NOTE 5—At certain times of the year and under certain conditions it may be possible to complete the sequence in one day. Also, by distributing the data throughout a day, incident angle effects (cosine and azimuth) can be obtained.

8.4.6 Take not less than three instantaneous readings of $V_u$ with an unshaded monitoring pyranometer for each period of data taking "M". Record as $V_o$ .

8.5 *Data Recording and Calculation*:

8.5.1 From the mean time of each scan, determine the zenith angle from the following equation:




NOTE 1—Actual numbers shown are for a typical Eppley PSP with a first time constant of 1 s.

**FIG. 2 Shade/Unshade Timing Sequence for Shading Disk Calibration of Pyranometers**

PYRAMETER WITH AXIS VERTICAL

TEST WORK SHEET

DATE ______ RUN NO. ______ AVG.θ ______ Cθ ______

R.H. ______ % TEMPERATURE ______ °C

| Time Limit | Zenith Angle z | Cos(z) | $I_d$ | $V_u$ | $V_s$ | $V_o$ | $C_\theta$ |
|---|---|---|---|---|---|---|---|
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| MEAN | | | | | | | |
| S. D. | | | | | | | |

$$K = \frac{(V_u - V_s)}{C_\theta I_d \cos z}$$

K = ______________

**FIG. 3 Pyranometer Test Worksheet**

$$\cos z = \sin L \cdot \sin \delta + \cos L \cdot \cos \delta \cdot \cos H \tag{3}$$

where, expressing all angles in degrees:

$z$ = the sun's zenith angle,
$L$ = the station latitude, and
$\delta$ = the solar declination, = 23.45 sin (0.9863 ( $n$ + 283.4))

where:
$n$ = the day of the year, and
$H$ = the hour angle from solar noon, with solar noon being zero, and each hour equaling 15° of longitude with mornings negative and afternoons positive (for example, $H = -15$ for 11:00, and $H = +37.5$ for 14:30).

NOTE 6—In this standard method the solar zenith angle, $z$, is identically equal to the instrument incident angle, θ. In the text, $z$ and θ will identify the same value, but will refer to the sun and to the pyranometer, respectively.

8.5.2 Using the form of work sheet shown in Fig. 3 and the recorded alternate and consecutive values of $V_u$, the test instrument signal in the unshaded condition, $V_s$, the test instrument signal in the shaded condition, $V_o$, the signal from the unshaded pyranometer, and the direct irradiance, compute the mean and standard deviation of $\Delta V$ ($\Delta V = V_u - V_s$) versus observation time for each data sequence.

8.5.3 From the mean value of the zenith angles for each cycle (in 8.4.4), compute $I_d$ cosine $z$, the solar irradiance projected on a horizontal surface. List appropriate values of $C_\theta$, the instrumental cosine correction factor, if available; otherwise enter the value 1.000.

8.5.4 From the following equation:

$$k = (V_u - V_s)/(C_\theta I_d \cos z) \; V \cdot W^{-1} \cdot m^2 \tag{4}$$

compute $k$, the calibration constant, for each run and each incident angle. Assemble all $k$ values. Plot the $k$ values as a function of angle of incidence (that is, zenith angles) as shown in Fig. 4. Select as the instrument constant the $k$ value representative of the end use application of the instrument. For meteorological and resource assessment purposes, the $k$ value at 30° angle of incidence may be the best weighted value for the continental U.S. on an annual basis.

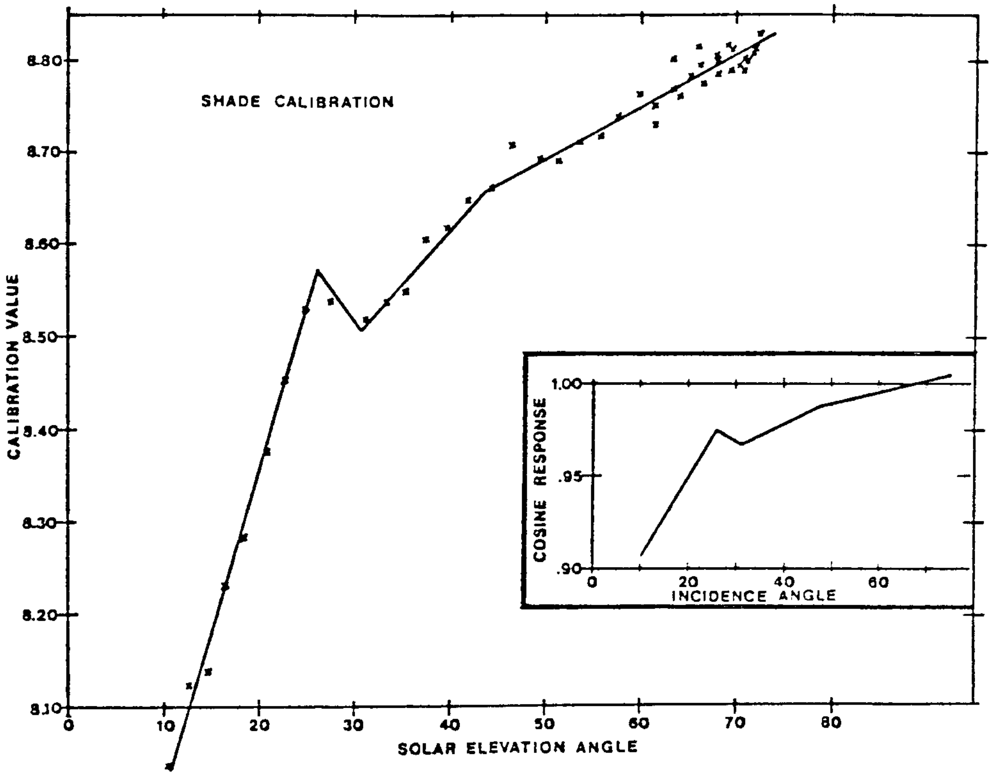


**FIG. 4 Example of Shading Disk Calibration Values for an Eppley PSP Pyranometer with Axis Vertical as a Function of Solar Elevation Angle**

## 9. Report

9.1 The report shall state as a minimum the following information:

9.1.1 Instrument type,

9.1.2 Manufacture and model number,

9.1.3 Date of calibration(s),

9.1.4 Range of zenith angles,

9.1.5 $C_\theta$ values (10° increments),

9.1.6 Scale: Absolute,

9.1.7 Latitude, longitude, and altitude (in m),

9.1.8 Calibration class,

9.1.9 Mean value of instrument constant, for *k* (see 8.5.4) and *S.D.* (solar declination), and

9.1.10 *Traceability*—A concise statement of the hierarchy of traceability including SN of secondary and primary reference instruments.

## 10. Precision and Bias

10.1 The precision achievable in determining the instrument constant of a reference pyranometer tested with axis vertical is influenced by sky conditions, and particularly by variations in cosine response when performing measurements at low solar elevations. Repeatability within any test sequence performed at or near solar noon should be such that the standard deviation is less than ±0.4 % of the mean of the shaded and unshaded voltages tabulated on the work sheet, Fig. 3. Substantially larger standard deviation may be observed under certain meteorological conditions. For example, high thin cirrus clouds nearly invisible to the naked eye may cause rapid variation in the diffuse irradiance. Superior calibrations are obtained when the meteorological conditions are stable as evidenced by small standard deviation in the measurements.

10.2 The uncertainty of the absolute value to be expected when calibrating pyranometers with axis vertical by the shading disk method depends on (*a*) the accuracy of the reference pyrheliometer calibration, (*b*) the bias of the transfer to the pyranometer, (*c*) the bias of the time and angle *z* determinations, and (*d*) the bias of the pyranometer's cosine correction. Of these, the cosine correction is dominant. Under best conditions, the cosine corrections can be measured to ±1 % and the instrument variability may be but little more. Therefore, the 1.5 % to 3.0 % level of uncertainty is achievable, with good timing and a knowledge of the cosine corrections. Good temperature compensation is assumed. If the cosine and other corrections are unknown, or if there is a strong azimuthal dependence to cosine correction (see 7.2), and the instrument calibration is based on large *z*-angles, then experience shows that the variability in the calibration may reach twice this uncertainty, or more—5.0 % to 10.0 %.

10.3 The standard deviation assigned to the calibration constant reported in Section 9 indicates a lower bound on variability. The actual value may be higher because of biases which this standard deviation does not disclose.

# APPENDIX

**(Nonmandatory Information)**

## X1. DISCUSSION OF ENVIRONMENTAL CONDITIONS

X1.1 In addition to the direct and diffuse solar irradiances to which a pyranometer responds, it is also sensitive to many conditions which can be discussed as environmental parameters. For the direct application of this discussion to this Standard, see 7.2-7.4.

X1.2 The functional dependence on some of the better understood parameters may be written as:

$$S = f[\lambda, \theta, \phi, \psi, T, G, T, P, \Delta T_n] \quad (X1.1)$$

where:

$S$ = output,
$\lambda$ = wavelength of incident radiation (spectral flatness),
$\theta$ = angle of source with respect to receiver normal (cosine response, 0 to 90°),
$\phi$ = angle to source about axis of receiver (azimuthal dependence),
$\psi$ = angle between normal of instrument and local normal (tilt dependence, including convective effects),
$T$ = thermal transients, change of temperature (of heat sink, etc.) with respect to time,
$P$ = pressure; (pressure dependence of thermal conductivity of air),
$G$ = irradiance level at receiver (linearity of response), and
$\Delta T_n$ = gradients and temperature differences within the instrument case, or heat sink

X1.3 Many experiments are needed to characterize the functional dependence of those factors which are orthogonal, such as tilt, cosine, and azimuth dependence, and allow one to write:

$$f[\lambda, \theta, \phi, \psi, T, G, T, \Delta T_n] = h[\theta] \times g[\phi] \times k[\psi] \times f[\lambda ...] \quad (X1.2)$$

where:

$h$, $g$, and k = functions which may be determined or found by experiment and used to make appropriate corrections to data. The remaining parameters can make significant contributions to instrument error if they are not understood, or their existence is ignored.

X1.4 Particular attention needs to be paid to those terms which are dependent on the same parameter as the basic principle of the instrument, namely on temperature $T$, difference in temperature $\Delta T$, and temperature gradients $\Delta T_n$ . For example, calibrating and using a pyranometer at a tilt with improper mounting may lead to temperature effects which override and mask out effects due to tilt alone, which one feels he may have "calibrated out" using a tilt correction factor technique.

## REFERENCES


(**1**) WRCD, Results, Fourth International Pyrheliometer Comparisons, Working Report No. 58, Swiss Meteorological Institute, Zurich, Switzerland, September 1976, 196 pp.

(**2**) Flowers, E. C., Zerlaut, G. A., Huss, R., Stoffel, T., Wells, C. V., and Meyers, D., *The New River Intercomparisons of Absolute Cavity Radiometers*, (in final preparation), 1979.

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