Designation: E905 – 87 (Reapproved 2013)

Standard Test Method for Determining Thermal Performance of Tracking Concentrating Solar Collectors[1]

This standard is issued under the fixed designation E905; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This test method covers the determination of thermal performance of tracking concentrating solar collectors that heat fluids for use in thermal systems.

1.2 This test method applies to one- or two-axis tracking reflecting concentrating collectors in which the fluid enters the collector through a single inlet and leaves the collector through a single outlet, and to those collectors where a single inlet and outlet can be effectively provided, such as into parallel inlets and outlets of multiple collector modules.

1.3 This test method is intended for those collectors whose design is such that the effects of diffuse irradiance on performance is negligible and whose performance can be characterized in terms of direct irradiance.

NOTE 1—For purposes of clarification, this method shall apply to collectors with a geometric concentration ratio of seven or greater.

1.4 The collector may be tested either as a thermal collection subsystem where the effects of tracking errors have been essentially removed from the thermal performance, or as a system with the manufacturer-supplied tracking mechanism.

1.4.1 The tests appear as follows:

	Section
Linear Single-Axis Tracking Collectors Tested as Thermal Collection Subsystems	11–13
System Testing of Linear Single-Axis Tracking Collectors	14–16
Linear Two-Axis Tracking and Point Focus Collectors Tested as Thermal Collection Subsystems	17–19
System Testing of Point Focus and Linear Two-Axis Tracking Collectors	20–22

1.5 This test method is not intended for and may not be applicable to phase-change or thermosyphon collectors, to any collector under operating conditions where phase-change occurs, to fixed mirror-tracking receiver collectors, or to central receivers.

1.6 This test method is for outdoor testing only, under clear sky, quasi-steady state conditions.

1.7 Selection and preparation of the collector (sampling method, preconditioning, mounting, alignment, etc.), calculation of efficiency, and manipulation of the data generated through use of this standard for rating purposes are beyond the scope of this test method, and are expected to be covered elsewhere.

1.8 This test method does not provide a means of determining the durability or the reliability of any collector or component.

1.9 The values stated in SI units are to be regarded as the standard. The values given in parentheses are for information only.

1.10 *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]

E772 Terminology of Solar Energy Conversion

2.2 *Other Standard:*

ASHRAE 93-86, Methods of Testing to Determine the Thermal Performance of Solar Collectors[3]

NOTE 2—Where conflicts exist between the content of these references and this test method, this test method takes precedence.

NOTE 3—The definitions and descriptions of terms below supersede any conflicting definitions included in Terminology E772.

3. Terminology

3.1 *Definitions:*

3.1.1 *area, absorber, n*—total uninsulated heat transfer surface area of the absorber, including unilluminated as well as illuminated portions. **(E772)**

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[1] This test method is under the jurisdiction of ASTM Committee E44 on Solar, Geothermal and Other Alternative Energy Sourcesand is the direct responsibility of Subcommittee E44.05 on Solar Heating and Cooling Systems and Materials.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from the American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc., 1791 Tullie Circle, N.E. Atlanta, GA 30329.

3.1.2 *collector, point focus, n*—concentrating collector that concentrates the solar flux to a point. **(E772)**

3.1.3 *collector, tracking, n*—solar collector that moves so as to follow the apparent motion of the sun during the day, rotating about one axis or two orthogonal axes. **(E772)**

3.1.4 *concentration ratio, geometric, n*—ratio of the collector aperture area to the absorber area. **(E772)**

3.1.5 *quasi-steady state, n*—solar collector test conditions when the flow rate, fluid inlet temperature, collector temperature, solar irradiance, and the ambient environment have stabilized to such an extent that these conditions may be considered essentially constant (see Section 8).

3.1.6 *Discussion*—The exit fluid temperature will, under these conditions, also be essentially constant (see ASHRAE 93-86).

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *altazimuthal tracking, n*—continual automatic positioning of the collector normal to the sun's rays in both altitude and azimuth.

3.2.2 *area, aperture (of a concentrating collector), n*—maximum projected area of a solar collector module through which the unconcentrated solar radiant energy is admitted, including any area of the reflector or refractor shaded by the receiver and its supports and including gaps between reflector segments within a module. **(E772)**

3.2.3 *clear-sky conditions, n*—refer to a minimum level of direct normal solar irradiance of 630 $W \cdot m^{-2}$ (200 $Btu \cdot ft^{-2} \cdot h^{-1}$) and a variation in both the direct and total irradiance of less than ±4 % during the specified times before and during each test.

3.2.4 *end effects, n*—in linear single-axis tracking collectors, the loss of collected energy at the ends of the linear absorber when the direct solar rays incident on the collector make a non-zero angle with respect to a plane perpendicular to the axis of the collector.

3.2.5 *fluid loop, n*—assembly of piping, thermal control, pumping equipment and instrumentation used for conditioning the heat transfer fluid and circulating it through the collector during the thermal performance tests.

3.2.6 *module, n*—the smallest unit that would function as a solar energy collection device.

3.2.7 *near-normal incidence, n*—angular range from exact normal incidence within which the deviations in thermal performance measured at ambient temperature do not exceed ±2 %, such that the errors caused by testing at angles other than exact normal incidence cannot be distinguished from errors caused by other inaccuracies (that is, instrumentation errors, etc.).

3.2.8 *rate of heat gain, n*—the rate at which incident solar energy is absorbed by the heat transfer fluid, defined mathematically by:

$$\dot{Q} = \dot{m} C_p \Delta t_a \qquad (1)$$

3.2.9 *response time, n*—time required for Δt_a to decline to 10 % of its initial value after the collector is completely shaded from the sun's rays; or the time required for Δt_a to increase to 90 % of its value under quasi-steady state conditions after the shaded collector at equilibrium is exposed to irradiation.

3.2.10 *quasi-steady state, n*—refers to that state of the collector when the flow rate and inlet fluid temperature are constant but the exit temperature changes "gradually" due to the normal change in solar irradiance that occurs with time for clear sky conditions.

3.2.10.1 *Discussion*—It is defined by a set of test conditions described in 10.1.

3.2.11 *solar irradiance, direct, in the aperture plane, n*—direct solar irradiance incident on a surface parallel to the collector aperture plane.

3.2.12 *solar irradiance, total, n*—total solar radiant energy incident upon a unit surface area (in this standard, the aperture of the collector) per unit time, including the direct solar irradiance, diffuse sky irradiance, and the solar radiant energy reflected from the foreground.

3.2.13 *thermal performance, n*—rate of heat flow into the absorber fluid relative to the incident solar power on the plane of the aperture for the specified test conditions.

3.3 *Symbols:*

A_a = collector aperture area, m^2 (ft^2).

A_{abs} = absorber area, m^2 (ft^2).

A_1 = ineffective aperture area, m^2 (ft^2).

C = geometric concentration ratio A_a/A_{abs}, dimensionless.

C_p = specific heat of the heat transfer fluid, $J \cdot kg^{-1} \cdot {}^\circ C^{-1}$ ($Btu \cdot lb^{-1} \cdot {}^\circ F^{-1}$).

$E_{s,d}$ = diffuse solar irradiance incident on the collector aperture, $W \cdot m^{-2}$ ($Btu \cdot h^{-1} \cdot ft^{-2}$).

$E_{s,D}$ = direct solar irradiance in the plane of the collector aperture, $W \cdot m^{-2}$ ($Btu \cdot h^{-1} \cdot ft^{-2}$).

$E_{s,DN}$ = direct solar irradiance in the plane normal to the sun, $W \cdot m^{-2}$ ($Btu \cdot h^{-1} \cdot ft^{-2}$).

$E_{s,2\pi}$ = global solar irradiance incident on a horizontal plane, $W \cdot m^2$ ($Btu \cdot h^{-1} \cdot ft^{-2}$).

$E_{s,t}$ = total solar irradiance incident on the collector aperture, $W \cdot m^{-2}$ ($Btu \cdot h^{-1} \cdot ft^{-2}$).

f = focal length, m (ft).

g = spacing between the effective absorbing surfaces of adjacent modules, m (ft).

K = incident angle modifier, dimensionless.

L = length of reflector segment, m (ft).

l_r = length of receiver that is unilluminated, m (ft).

m = mass flow rate of the heat transfer fluid, $kg \cdot s^{-1}$ ($lbm \cdot h^{-1}$).

$\dot{Q}$ = net rate of energy gain in the absorber, W ($Btu \cdot h^{-1}$).

$\dot{Q}_L$ = rate of energy loss, W ($Btu \cdot h^{-1}$).

r = overhang of the receiver past the end of the reflectors, m (ft).

$R(\theta)$ = ratio of the rate of heat gain to the solar power incident on the aperture, dimensionless.

s = angle which the collector aperture is tilted from the horizontal to the equator, and is measured in a vertical N-S plane, degrees.

t_{amb} = ambient air temperature, °C (°F).

$_{\Delta}t_a$ = temperature difference across the absorber, inlet to outlet, °C (°F).

$_{\Delta}t_{a,i}$ = temperature difference across the absorber inlet to outlet at the time of initial quasi-steady state conditions, °C (°F).

$_{\Delta}t_{a,f}$ = temperature difference across the absorber inlet to outlet at the time final quasi-steady state conditions are reached, °C (°F).

$_{\Delta}t_{a,T}$ = temperature difference across the absorber inlet to outlet at time T, °C (°F).

$t_{f,i}$ = temperature of the heat transfer fluid at the inlet to the collector, °C (°F).

w = width of reflector segment, m (ft).

β = solar altitude angle, degrees.

$\Gamma(\theta_{||})$ = end effect factor, dimensionless.

δ = solar declination, degrees.

θ = angle of incidence between the direct solar rays and the normal to the collector aperture, degrees.

$\theta_{||}$, $\theta_{\perp}$ = angles of incidence in planes parallel and perpendicular, respectively, to the longitudinal axis of the collector, degrees.

θ_t = maximum angle of incidence at which all rays incident on the aperture are redirected onto the receiver of the same module, degrees.

θ'_c = minimum angle of incidence at which radiation reflected from one module's aperture is intercepted by the receiver of an adjacent module, degrees.

φ = solar azimuth angle measured from the south, degrees.

4. Summary of Test Method

4.1 Thermal performance is the rate of heat gain of a collector relative to the solar power incident on the plane of the collector aperture. This test method contains procedures to measure the thermal performance of a collector for certain well-defined test conditions. The procedures determine the optical response of the collector for various angles of incidence of solar radiation, and the thermal performance of the collector at various operating temperatures for the condition of maximum optical response. The test method requires quasi-steady state conditions, measurement of environmental parameters, and determination of the fluid mass flow rate-specific heat product and temperature difference, Δt_a, of the heat transfer fluid between the inlet and outlet of the collector. These quantities determine the rate of heat gain, $\dot{m}C_p\Delta t_a$, for the solar irradiance condition encountered. The solar power incident on the collector is determined by the collector area, its angle relative to the sun, and the irradiance measured during the test.

4.2 Two types of optical effects are significant in determining the thermal performance: (*1*) misalignment of the focal zone with respect to the receiver due to tracking errors and errors in the redirection of the irradiance intercepted by the collector, and (*2*) changes in the solar power incident on the collector aperture due to decreased projected area (cosine response) and other optical losses. The first effect is accounted for primarily in terms of the data generated for near-normal incidence thermal performance for a given collector. The cosine response portion of the second effect is accounted for by the determination of the solar power incident on the plane of the aperture. The departure of the optical response of the collector from the cosine response is determined by obtaining the incident angle modifier data. The incident angle modifier is important in predicting such collector characteristics as all-day thermal performance.

5. Significance and Use

5.1 This test method is intended to provide test data essential to the prediction of the thermal performance of a collector in a specific system application in a specific location. In addition to the collector test data, such prediction requires validated collector and system performance simulation models that are not provided by this test method. The results of this test method therefore do not by themselves constitute a rating of the collector under test. Furthermore, it is not the intent of this test method to determine collector efficiency for comparison purposes since efficiency should be determined for particular applications.

5.2 This test method relates collector thermal performance to the direct solar irradiance as measured with a pyrheliometer with an angular field of view between 5 and 6°. The preponderance of existing solar radiation data was collected with instruments of this type, and therefore is directly applicable to prediction of collector and system performance.

5.3 This test method provides experimental procedures and calculation procedures to determine the following clear sky, quasi-steady state values for the solar collector:

5.3.1 Response time,

5.3.2 Incident angle modifiers,

5.3.3 Near-normal incidence angular range, and

5.3.4 Rate of heat gain at near-normal incidence angles.

NOTE 4—Not all of these values are determined for all collectors. Table 1 outlines the tests required for each collector type and tracking arrangement.

5.4 This test method may be used to evaluate the thermal performance of either (*1*) a complete system, including the tracking subsystems and the thermal collection subsystem, or (*2*) the thermal collection subsystem.

5.4.1 When this test method is used to evaluate the complete system, the test shall be performed with the manufacturer's tracker and associated controls, and thus the effects of tracking error on thermal performance will be included in the results. Linear single-axis tracking systems may be supplemented with the test laboratory's tracking equipment to effect a two-axis tracking arrangement.

5.4.2 When evaluating a thermal collection subsystem, the accuracy of the tracking equipment shall be maintained according to the restrictions in 10.3.

5.5 This test method is to be completed at a single appropriate flowrate. For collectors designed to operate at variable flowrates to achieve controlled outlet temperatures, the collector performance shall be characterized by repeating this test method in its entirety for more than one flowrate. These flowrates should be typical of the actual operating conditions of the collectors.

5.6 The response time is determined to establish the time required for quasi-steady state conditions to exist before each

TABLE 1 Required Tests for Each Collector and Tracking Arrangement

Collector Type and Test Configuration	Test Method				
	Response Time	Incident Angle Modifier	Determination of Near-Normal Incidence Angular Range for Rate of Heat Gain at NNI	Determination of Near-Normal Incidence (NNI) for Tracking Accuracy Requirements	Heat Gain at Near-Normal Incidence
Linear Single-Axis Tracking Subsystem:					
One-axis Tracking					
Manufacturer's	×	×	×	×	×
Laboratory's	×	×	×	**	×
Two-Axis Tracking					
Manufacturer's and Laboratory's	×	×		×	×
Laboratory's only	×	×		**	×
Linear Single-Axis Tracking System:					
One-Axis Tracking					
Manufacturer's only	×	×	×		×
Two-Axis Tracking					
Manufacturer's and Laboratory's	×	×			×
Linear Two-Axis Tracking and Point Focus Subsystem:					
Manufacturer's	×			⊗	×
Laboratory's	×				×
Linear Two-Axis Tracking and Point Focus System:					
Manufacturer's only	×				×

× = Required.

⊗ = Required but method may not be practicable for point focus collectors—Safety precautions and technical precautions must be followed because of potential damage to equipment and subsequent damage to personnel due to high levels of solar irradiance on the receiver support structure.

** = Optional test that may provide useful information on the effect of the accuracy of the manufacturer's tracking equipment on thermal performance.

thermal performance test to assure valid test data, and to determine the length of time over which the quasi-steady state performance is averaged. The response time is calculated from transient temperature data resulting from step changes in intercepted solar irradiance with a given flow rate. Initial quasi-steady state conditions are established, the irradiance level is then increased or decreased suddenly, and the final quasi-steady state conditions are established. For most collectors covered by this test method, the difference in the response time determined by each of the two procedures will be small in terms of actual time. It is recognized that for some collectors, particularly those with long fluid residence times, the difference in the two values of response time may be large. However, the difference has not been found to influence the remainder of the test method.

5.7 The incident angle modifier is measured for linear single-axis tracking collectors so that the thermal performance at arbitrary angles of incidence can be predicted from the thermal performance measured at near-normal incidence as required in this test method. This is necessary because, during actual daily operation, linear single-axis tracking collectors will usually be normal to the sun only once or twice.

5.7.1 At non-zero angles of incidence, the thermal performance of a linear single-axis tracking collector may change for several reasons:

5.7.1.1 Increased or decreased reflectance, transmittance, and absorptance at the concentrator and receiver surfaces, or

5.7.1.2 Increased or decreased interception of the reflected or refracted solar radiant energy by the receiver.

5.7.1.3 That part of the decreased interception that is due to loss of collected energy at the ends of the absorber can be calculated analytically from the collector geometry as an end effects factor (see Appendix X1).

5.7.2 The preferred procedure for determining the incident angle modifier minimizes heat loss from the receiver by requiring that the working heat transfer fluid be the same as is used in the rest of the test method, and that it be maintained at an inlet temperature approximately equal to ambient temperature. It is realized, however, that this procedure may not be practical to perform as specified, since some heat transfer oils become too viscous near ambient temperatures to be pumped through the fluid test loop, or the fluid test loop cannot practicably cool the working fluid sufficiently to approximate the ambient temperatures that typically occur in the winter in cold climates. In these cases, either Alternative Procedure A or B may be used at the discretion of the manufacturer or supplier. Alternative Procedure A uses water as the working fluid at an inlet temperature approximately equal to ambient to minimize heat losses, but the procedure requires careful cleaning of the collector fluid passages, possibly use of a separate fluid test loop, and may cause corrosion if the collector fluid passages are incompatible with water. Alternative Procedure B uses the same heat transfer fluid as is used in the rest of the test method, but at an elevated temperature which is as close as practicable to ambient. Alternative Procedure B involves higher heat losses from the receiver which must be calculated and corrected for. An approximate correction for these heat losses is obtained in

Alternative Procedure B by determining the nonirradiated heat loss for the same fluid inlet temperature.

5.8 Determination of the angular range of near-normal incidence is required to establish the test conditions under which the measured thermal performance will adequately represent the thermal performance at true normal incidence.

NOTE 5—Measurement of angular range of the near-normal incidence also provides data that can be used to evaluate the sensitivity of the thermal performance of the tracking accuracy.

5.9 The thermal performance of the solar collector is determined under clear sky conditions and at near-normal incidence because these conditions are reproducible and lead to relatively stable performance.

6. Interferences

6.1 Alignment error, tracker pointing error, and the distorting effects of wind and gravity on the reflector and receiver may contribute to decreased thermal performance by decreasing the fraction of solar radiation incident on the collector aperture that strikes the absorber. The degree to which these errors affect collector thermal performance depends on the incident angle to the collector and the limits of the tracker, collector position and orientation relative to wind direction, wind speed, structural integrity of the collector and its support system, and so forth. Warping and sagging of the reflector due to heat have been observed, particularly in the case of linear trough concentrating collectors, also causing a decrease in the ability of the concentrator to direct the incident solar radiation to the absorber. Thermal expansion of the receiver may also occur under operating conditions of concentrated solar energy, and could cause damage to the receiver or the seals, possibly resulting in increased heat losses.

6.2 Soiling of the collector surfaces (reflector/refractor, absorber cover, etc.) may effectively reduce the solar energy available to the collector, in a way that is neither quantifiable nor reproducible.

6.3 Small variations in the level of solar irradiance during testing may cause considerable difficulties in maintaining quasi-steady state as required in 10.1.

6.4 Variations in the quality of the direct irradiance, comprising solar and circumsolar radiation, may give rise to irreducible fluctuations in the thermal performance because the angular responses of the collector and of the pyrheliometer differ. The wide availability of standard pyrheliometers and the difficulty of making custom instruments make it impractical to test each collector relative to a pyrheliometer with the same angular response as the collector.

6.5 Variations in the level of diffuse irradiance may affect the measured thermal performance, particularly for lower concentration ratio collectors. Therefore total (global) solar irradiance measurements are to be made to indicate the conditions under which the tests are performed, and to allow comparisons to be made with available meteorological data.

7. Apparatus

7.1 *Solar Irradiance Instrumentation*—The direct component of the solar irradiance shall be measured using a pyrheliometer on a separate sun-tracking mount. The opening angle of the instrument's field-of-view shall be between 5° arc and 6° arc. The instrument shall be a secondary reference or field use pyrheliometer whose calibration is directly traceable to a primary reference pyrheliometer. Only the WRR scale is permitted; in no case shall the IPS 1956 or other radiometric scale be used. The instrument shall be recalibrated at no greater than six month intervals. After calibration, the instrument and associated readout electronics shall be accurate to ±1.0 % of the measured value. This accuracy may be met through application of correction factors for temperature and linearity, if appropriate. The pointing error of the associated tracking mount shall not degrade the accuracy of the direct component measurement more than 0.5 %.

7.1.1 The global solar irradiance shall be measured using a pyranometer mounted in a horizontal orientation with the detector surface leveled. The instrument location shall be free from obstruction or enhancement of solar radiation due to nearby structures. The instrument may be a reference or a field use pyranometer, but its calibration shall be directly traceable to a primary reference pyrheliometer. Only the WRR scale is permitted. The instrument shall be recalibrated at no greater than six-month intervals. After calibration, the instrument and its associated readout electronics shall be accurate to ±2.0 % of the measured value. This accuracy may be met through application of correction factors for temperature, linearity, and cosine response, if appropriate.

7.1.2 It is also recommended that total irradiance be measured in the plane of the aperture with a pyranometer mounted to the collector on a suitable part of the tracking mechanism such that the total irradiance measured is indicative of that to which the collector is exposed. The pyranometer and its mount shall not shade or block the collector. The instrument may be a reference or a field use pyranometer, but its calibration shall be directly traceable to a primary reference pyrheliometer. Only the WRR scale is permitted. The instrument shall be recalibrated at no greater than six-month intervals. After calibration, the instrument and its associated readout electronics shall be accurate to ±2.0 % of the measured value. This accuracy may be met through the application of correction factors for temperature, linearity, cosine response, and tilt, if appropriate.

7.2 $(\dot{m}C_p)$, *Product Determination*—The determination of the $(\dot{m}C_p)$-product for the heat transfer fluid shall be accurate to ±2.0 % for each data point. This requirement holds whether the mass flow rate and specific heat are determined separately, or their product is determined using a reference heat source or other technique. The fluid temperature to be used in each determination shall be the average of the fluid temperature at the inlet and outlet of the collector.

7.3 Temperature and temperature difference measurements shall be made in accordance with ASHRAE 93 and meet or exceed its requirements for accuracy and precision.

7.4 All angular measurements except measurement of wind direction shall be accurate to within ±0.1°.

7.5 Any tracking system other than the manufacturer's tracker used by the test lab shall limit the aperture normal tracking error to 0.1° in all principal tracking axes required by the collector.

7.6 Irrespective of the means of collecting data for the determination of thermal performance (see 7.7) irradiance and fluid temperature shall be monitored at not greater than 10-s intervals such that variations in irradiance and fluid temperature stability can be assessed during all periods of quasi-steady state, before and during testing.

7.7 A data point for any variable shall be the average of at least 10 observations taken at intervals (scan rate) of no greater than 30 s. Each data point must meet all the requirements for quasi-steady state conditions, as listed in 10.1, where the allowable variation in any variable refers to the difference between the maximum and minimum observed values.

8. Precautions

8.1 *Safety Precautions*—Potential hazards in operating concentrating solar collectors include high pressures and high temperatures; toxic, flammable, and combustible materials; mechanical and electrical equipment; and concentrated solar radiation.

8.1.1 Pressurized fluids can be released if a rupture occurs or if a relief valve opens. Flashing of the heat transfer fluid may occur. Inspection for leaks and any potential hazards should be conducted frequently.

8.1.2 Caution should be exercised against accidental contact or exposure to components with elevated temperature. Protective gloves should be worn when touching any heated surfaces, including valves which are subject to being heated.

8.1.3 Materials soaked with heat transfer oils are a potential fire hazard and may even undergo spontaneous combustion when exposed to temperatures below the flash point of the fluid (approximately 150°C for some oils). These fluids should be cleaned up immediately should a spill occur, and the materials properly disposed of. Chemicals used for fluid treatment or for solvents have potentially toxic effects. Gloves, eye protection, and aprons should be worn when handling these chemicals.

8.1.4 Moving elements associated with collector tracking may pose entanglement hazards while the collector is under test. If necessary, considerations should be given to shielding these moving elements and providing safety override/controls interlocks. General precautions applicable to the operation of electrical systems should be followed.

8.1.5 High levels of solar radiation that exist during collector testing present a high-temperature hazard to exposed skin and also an intense light hazard to the eyes. Therefore, concentrated solar radiation should be avoided whenever possible. When maintenance is required on the reflector side of the collector, the collector should be positioned so that the reflective surface is shadowed.

8.2 *Technical Precautions:*

8.2.1 Damage to equipment can occur very quickly if for any reason concentrated solar radiation is focused on parts of the collector other than the receiver. This may occur when the collector is not tracking in normal operation, but is not properly stowed so that solar radiation is still incident on the collector aperture and at some point is focused on a part of the receiver support structure, for example.

8.2.2 Damage to the tracker and any piping, wires, etc. attached to the collector may occur in attempting to achieve certain angles of incidence during testing, if precautions have not been taken to stay within the collector's operational limits.

8.2.3 Most concentrating solar collectors require very steady irradiance in order to maintain quasi-steady state conditions. Therefore, a two-axis tracking arrangement is preferred for testing, such that the collector is constantly directed at the sun for near-normal incidence testing, or is maintained at a given angle of incidence, unless such positioning would subject the collector to conditions for which it was not designed. (Such conditions must be specified by the manufacturer.) The testing laboratory's tracking devices may be used to supplement the collector's tracking mechanism to achieve two-axis tracking. If a two-axis tracking arrangement is not used, then the collector shall be allowed to track normally. A two-axis tracking arrangement may be required for testing collectors with long response times in order to maintain quasi-steady state conditions.

9. Preparation of Apparatus

9.1 The collector shall be installed and aligned properly according to a test method approved by the manufacturer.

9.2 Collector surfaces exposed to the environment shall be cleaned at the beginning of each test day according to the manufacturer's recommended procedures. The test method used for cleaning shall be reported in full.

9.3 The geographical location (latitude and longitude) of the collector shall be determined and reported to an accuracy of ±0.1°. Where applicable, the orientation of any fixed collector axis shall be measured to an accuracy of ±0.1 % and reported.

9.4 The pyrheliometer and pyranometer shall be inspected at the beginning of each day at which time the outer glass surface shall be cleaned and dried if dirt or moisture are present. Any evidence of moisture or debris in the interior of the instrument shall be cause to remove it from service.

9.5 The pyrheliometer tracker shall be checked and adjusted for proper alignment periodically throughout the test day.

10. Test Conditions

10.1 Since measurements for determining the rate of heat gain are not made simultaneously at the inlet and outlet of the collector and hence not on the same element of fluid, quasi-steady state conditions are required to ensure valid results. Except where noted, these conditions must exist for a time period equal to two times the response time before each test, and for the duration of each test, which shall be the longer of 5 min or one-half the response time. Quasi-steady state conditions will be said to exist when the requirements in 10.1.1 through 10.1.6 are met.

10.1.1 Inlet temperature to the collector, $t_{f,i}$, shall vary less than ±0.2°C (±0.4°F) or ±1.0 % of the value of $\Delta\ t_a$, whichever is larger, during the specified time before and during each test.

10.1.2 The temperature difference between the inlet and the outlet to the collector, Δt_a, shall vary less than ±0.4°C (±0.8°F) or ±4 % of the value of Δt_a, whichever is larger, during the specified times before and during each test.

10.1.3 The measured value of the ($\dot{m}C_p$)-product shall vary less than ±1.0 % during the specified times before and during each test.

10.1.4 The variation in both the direct and global irradiance shall be less than ±4 % during the specified times before and during each test.

10.1.5 The maximum allowable variation in ambient temperature for quasi-steady state conditions shall be ±2.0°C (3.6°F).

10.1.6 Average wind speed across the collector shall be less than 4.5 $m \cdot s^{-1}$ (10 mph) throughout the quasi-steady state conditions, unless it can be shown that the effects of winds in excess of this requirement are indistinguishable from other measurement inaccuracies.

10.2 Minimum direct normal solar irradiance averaged over each test period shall be 630 $W \cdot m^{-2}$ (200 $Btu \cdot h^{-1} \cdot ft^{-2}$), and the difference between the maximum and minimum irradiance values shall be less than 200 $W \cdot m^{-2}$.

NOTE 6—Since the thermal performance of some concentrating collectors is sensitive to the level of solar irradiance, it may be desirable to repeat the "Rate of Heat Gain at Near-Normal Incidence" test (see 13.5) at more than one range of irradiance values in order to fully characterize the collector. If this is done, the minimum level of irradiance may be lower than 630 $W \cdot m^{-2}$ (200 $Btu \cdot h^{-1} \cdot ft^{-2}$), as long as all other quasi-steady state conditions are met. The difference between the maximum and minimum values of irradiance for testing at each desired level of irradiance may need to be further restricted if testing is done at more than one level.

10.3 When evaluating a thermal collection subsystem using any manufacturer's tracking equipment, the tracking accuracy of such equipment shall be maintained such that the tracking error is shown to be less than the error allowed by the near-normal incidence tracking accuracy requirement. This requires that the procedure in 13.4 be followed, and that the tracking errors of the collector during testing be measured and reported. The device used to measure the tracking error shall be in place throughout the test to verify that the tracking accuracy required by 13.4 is maintained. The device with which this measurement is to be made is not specified in this method. Any test laboratory's equipment used shall meet the requirements of 7.5.

10.4 This test method is to be completed at a single appropriate flow rate unless an exception is specifically noted, as in 13.2.2.

LINEAR SINGLE-AXIS TRACKING COLLECTORS TESTED AS THERMAL COLLECTION SUBSYSTEMS

11. Scope

11.1 This test method covers the determination of the thermal performance of linear, single-axis tracking solar collectors tested as a thermal collection subsystem.

12. Summary of Test Methods

12.1 The response time, the incident angle modifier, and the rate of heat gain at near-normal incidence are determined for the linear single-axis tracking collection subsystem, under clear-sky, quasi-steady state conditions. In addition, determination of the near-normal incidence angular range may be required, depending on the tracking system used (see Table 1).

12.2 Either the test laboratory's tracking system or a tracking system supplied to the test laboratory for the purpose of testing the collector (herein called "manufacturer's tracker") may be used to move the collector about its normal tracking axis, but the tracking accuracy must be maintained according to the requirements in 7.5 and 10.3.

13. Procedure

13.1 *Response Time*—In either of the following alternative procedures for measuring the response time, the heat transfer fluid used shall be the same as that used to measure the rate of heat gain at near-normal incidence (Section 13.5).

13.1.1 *Procedure A*—The response time shall be determined by shading an irradiated collector as follows:

13.1.1.1 Adjust the inlet temperature of the heat transfer fluid, $t_{f,i}$, to within ±10.0°C (±18.0°F) of the ambient temperature, or to the lowest possible operating temperature, whichever is higher, while circulating the transfer fluid through the collector at the flow rate specified and maintaining quasi-steady state conditions as specified in 10.1. While maintaining the mass flow rate and measuring the temperature difference of the heat transfer fluid between the inlet and outlet to the collector, abruptly reduce the incident solar energy to approximately zero by shielding the collector from the sun. This may be accomplished by stowing the collector face down; by turning the collector away from the sun (on a movable mount); shading the collector with a white, opaque cover; intercepting the reflected radiation; or defocusing the collector so that the reflected radiation is no longer incident on the receiver. If a cover is used, it should be suspended off the surface of the collector so that ambient air is allowed to pass over the collector as prior to the beginning of the transient test, and care should be taken to avoid excessive temperature. Turning the collector shall not alter or interrupt the operation of the collector in any manner (such as changing or stopping flow through the collector), nor shall it disturb the instrumentation necessary to perform the test. If the reflected radiation is intercepted, care must be taken to avoid reradiation to the receiver. If the collector is stowed or turned away from the sun, the response time shall be measured relative to the time at which the movement was initiated. Because of possible time delays and relatively slow motion of the collector, the resulting response time measurement will be conservative. Continue to monitor the inlet and outlet temperatures as a function of time (for example, on a strip chart recorder) throughout the test, until final quasi-steady state conditions (Section 10.1 with the exception of 10.1.4) are reached.

13.1.2 *Procedure B*—The response time shall be determined by suddenly irradiating a shaded collector as follows:

13.1.2.1 Shade the collector in the same manner as described in paragraph 13.1.1. Adjust the inlet temperature of the heat transfer fluid, $t_{f,i}$, to within± 10.0°C (±18.0°F) of the ambient temperature, or to the lowest possible operating temperature, whichever is higher, while circulating the fluid through the collector at the flow rate specified until the collector reaches and maintains quasi-steady state conditions as specified in 10.1. Then suddenly turn or uncover the collector so that the collector aperture is fully irradiated. If the collector is stowed or turned away from the sun, the response time shall be measured relative to the time at which the movement was initiated. Because of possible time delays and the relatively slow motion of the collector, the resulting response time measurement will be conservative. Continue to monitor the inlet and outlet temperatures as a function of time (for example, on a strip chart recorder) throughout the test, until final quasi-steady state conditions (see 10.1) are reached.

NOTE 7—Procedure B is the more difficult procedure to complete since it requires stable irradiance, and establishing and maintaining stable tracking conditions throughout the test period.

13.2 *Incident Angle Modifier*—It is the intent of the following procedure to generate sufficient incident angle modifier data, $K(\theta)$, to characterize the collector thermal performance over the full range of actual operating angles that will be encountered. The range of angular data required is influenced by the collector type and orientation (for example, north-south, east-west, polar axis mount). Both the number and range of data points required are in part determined by the manner in which $K(\theta)$ varies. A large, rapid decrease in $K(\theta)$ as θ increases requires a larger number of data points than a gradual decline. Therefore, the procedure provides for this $K(\theta)$ dependence by requiring that the minimum number of data points be a function of the value of $K(\theta)$ at the maximum operating angle of incidence. If the collector is optically asymmetric, the values of $K(\theta)$ are determined on both sides of the normal unless the collector is restricted in actual use to only one operational orientation, in which case the $K(\theta)$ is obtained on the side corresponding to the operational orientation. Preferred and alternate procedures are defined. A two-axis tracking arrangement is preferred for maintaining a given angle of incidence for the duration of each test, and for maintaining the levels of irradiance required for quasi-steady state conditions.

13.2.1 *Preferred Procedure*—Determine the mass flow rate-specific heat product ($\dot{m}C_p$) and the temperature difference, Δt_a, of the design heat transfer fluid between the inlet and outlet of the collector. While maintaining the collector within ±2.5° of the angles of incidence $\theta_{||}$ specified below, the inlet temperature of the heat transfer fluid shall be maintained at $t_{amb} \pm 1.0°C$ ($\pm 1.8°F$) so that the heat loss from the receiver is minimized. The collector shall be made to track about its longitudinal axis such that the angle formed between the sun's ray and the plane formed by the normal to the collector and its longitudinal axis, is within the allowable tracking errors. The angle of incidence $\theta_{| |}$ may be measured or calculated using sun position angles and the equations in Annex A2.

NOTE 8—It may be difficult to achieve the high incident angles at certain times of the year, depending on the location of the test facility.

13.2.1.1 Perform the procedure of 13.2.1 with the collector at normal incidence ($\theta_{||} = 0°$). Repeat the procedure at $\theta_{||} = \theta_{max}$, where θ_{max} shall be 75° unless the collector is specified to operate over a more restricted angular range, in which case θ_{max} shall be the specified smaller limit. Based on the incident angle modifier value obtained at θ_{max}, repeat the procedure at additional, intermediate angles of incidence, the number of which is determined from the following table:

$K(\theta_{max})$	Minimum Number of Additional Angles of Incidence
0.8–1.0	2
0.6–0.8	3
0.4–0.6	4
<0.4	5

13.2.1.2 The intermediate angles of incidence shall be approximately equally spaced between normal incidence and θ_{max}. It is recommended that when incident angle modifier data are obtained on more than one day, the procedure be repeated for normal incidence on each of the test days in order to minimize the effects of meteorological variations on the results.

13.2.2 *Alternative Procedure A*—Follow the procedure of 13.2.1, but use water as the heat transfer fluid through the collector. The mass flow rate must be altered such that the ($\dot{m}C_p$)-product is approximately equal to that used in the rest of this test method. **CAUTION:** If Alternative Procedure A is used, and the heat transfer fluid to be used for the rest of this test method is incompatible with water, then the incident angle modifier must be completed using a separate fluid loop, prior to filling the collector with the usual working fluid.

NOTE 9—If t_{amb} is near or below 0°C (32°F), it may not be possible to hold $t_{f,i} = t_{amb} \pm 1.0°C$ ($\pm 1.8°F$), in which case this alternative procedure may not be used.

13.2.3 *Alternative Procedure B*—Follow the procedure of 13.2.1, using the same heat transfer fluid as used in 13.5 of this test method. The fluid inlet temperature shall be held within ± 0.1°C (± 0.2°F) of the lowest possible fluid inlet temperature. In addition, determine the nonirradiated collector heat loss for this same fluid inlet temperature by shielding the collector in the same manner as prescribed in 13.1.1, and determining that final quasi-steady state conditions (10.1 with the exception of 10.1.4) are reached. Measure the mass flow rate-specific heat product ($\dot{m}C_p$) and the heat transfer fluid temperature difference between the inlet and outlet of the collector (Δt_a).

13.3 *Determination of Near-Normal Incidence Angular Range for Determining the Rate of Heat Gain at Near-Normal Incidence*—"Near-normal incidence" shall be defined as that angular range from true normal within which the thermal performance measured at ambient temperature deviates less than 2.0 % of the thermal performance measured at ambient and at normal incidence. This procedure is required whenever a one-axis tracking arrangement is used to test the collector.

13.3.1 Determine the angle of incidence, measured from normal in a plane containing the normal to the collector and the longitudinal axis, at which the thermal performance at ambient is approximately 95 % of its value measured at normal incidence ($\theta_{||} = 0$). This angle may be the angle for which $K(\theta_{||}) = 0.95$, or it may be determined by trial-and-error testing using one of the procedures in 13.2.

13.3.2 While tracking the collector about its longitudinal axis only such that the sun lies in the plane formed by the normal to the collector aperture and the longitudinal axis, determine the mass flow rate-specific heat product and the temperature difference, Δt_a, of the heat transfer fluid between the inlet and the outlet to the collector. The heat transfer fluid and fluid temperature selected in 13.2 is to be used. Consecutive observations shall be recorded as the sun moves across the collector aperture from the angle determined in 13.3.1 on one side of the collector normal, to the same angle of incidence on the other side of the collector normal. The test conditions described in Section 10, with the exception of 10.1.2, must exist for a time period equal to two times the response time before the observations are begun, and must continue during the observations.

NOTE 10—It may not be possible to achieve the required conditions at times other than near solar noon.

13.4 *Determination of Near-Normal Incidence Angular Range for Tracking Accuracy Requirements*—This procedure is required when a collector is being tested with a tracking arrangement that, in whole or in part, consists of a tracking mechanism supplied to the testing laboratory for the purpose of testing the collector and that has not been documented to have the accuracy (± 0.1°) required of the test laboratory's tracking equipment. This procedure is optional in all other cases, and may be used to obtain data on the effects of tracking errors on the thermal performance of the collector. As required, the procedure will establish the limits of allowable tracking errors, in order to test the collector as a subsystem, that is, its inherent optical and thermal characteristics. Procedure A takes advantage of the sun's apparent motion, and Procedure B uses the tracker motion. It may be difficult to determine the near-normal incidence angular range using Procedure A for fixed east-west linear single-axis tracking collectors, especially near the equinox because the rate of change in solar altitude is significantly less than the rate of increase of solar azimuth and therefore the data will be dominated by incident angle modifier effects.

13.4.1 *Procedure A*—Follow the procedure of 13.3, except that the plane in which the angles of incidence are measured is the plane formed by the normal to the collector and the transverse axis of the collector. The collector shall be fixed such that the sun is normal to both axes of the collector at one instant as the sun moves across the collector. This may cause some incident angle modifier effects to be included, which will result in a more conservative range of angles of incidence. Alternatively, the collector may be made to track such that the sun is in the plane formed by the collector normal and the transverse axis.

13.4.2 *Procedure B*—Determine the angle of incidence, measured from the normal in a plane containing the normal and the transverse axis of the collector, at which the thermal performance measured at ambient is approximately one-half its value measured at normal incidence ($\theta_{||} = 0$). This angle may be approximated using the equations in Annex A2., or it may be determined by trial-and-error testing using one of the procedures of 13.2 (using the transverse axis instead of the longitudinal axis). Determine the mass flow rate-specific heat product ($\dot{m}C_p$) and the temperature difference, $\Delta\, t_a$, of the heat transfer fluid between the inlet and the outlet to the collector, while maintaining the collector at a specific angle of incidence. Repeat this procedure for five angles of incidence on each side of the collector normal (that is, ten angles of incidence total). The angles of incidence used shall be approximately equally spaced between the normal to the collector and the angle of incidence at which the thermal performance at ambient is approximately one-half its value at true normal incidence (determined above).

13.5 *Rate of Heat Gain at Near-Normal Incidence:*

13.5.1 Determine the mass flow rate-specific heat product ($\dot{m}C_p$) and the difference in the temperature of the heat transfer fluid between the inlet and the outlet to the collector (Δt_a), while maintaining the collector aperture normal to the sun within the limits of near-normal incidence and any allowable tracking errors, as applicable.

13.5.2 Repeat this procedure for at least four equally spaced values of inlet fluid temperature, at maximum intervals of 50°C (90°F), covering the entire range of operating temperatures. If a two-axis tracking arrangement is used to test the collector, then at least four data points shall be obtained for each inlet fluid temperature. If the collector is made to track along only one axis, and the angle of incidence measured in the plane containing the collector normal and the longitudinal axis is greater than ±0.1°, then at least four pairs of data points shall be determined for each inlet fluid temperature, where each pair consists of two data points determined symmetrically to the normal to the collector.

SYSTEM TESTING OF LINEAR SINGLE-AXIS TRACKING COLLECTORS

14. Scope

14.1 This test method covers the determination of the thermal performance of linear, single-axis tracking solar collectors, tested as a system consisting of the collector, a tracking mechanism, and the necessary associated controls.

15. Summary of Test Methods

15.1 The response time, the incident angle modifier, and the rate of heat gain at normal incidence are determined for the linear single-axis tracking collector system, under clear sky, quasi-steady state conditions. In addition, determination of near-normal incidence is required if the manufacturer's tracker is not supplemented by the test laboratory's equipment to effect a two-axis tracking arrangement.

16. Procedure

16.1 *Response Time*—Follow 13.1.

16.2 *Incident Angle Modifier*—Follow 13.2.

16.3 *Determination of Near Normal Incidence*—Follow 13.3.

16.4 *Heat Gain at Near-Normal Incidence*—Follow 13.5.

LINEAR TWO-AXIS TRACKING AND POINT FOCUS COLLECTORS TESTED AS THERMAL COLLECTION SUBSYSTEMS

17. Scope

17.1 This test method covers the determination of the thermal performance of point focus and linear two-axis tracking solar collectors, tested as thermal collection subsystem.

18. Summary of Test Methods

18.1 The response time and the heat gain at near-normal incidence are determined for the point-focus or linear two-axis tracking collector subsystem, under clear sky, quasi-steady state conditions. In addition, determination of near-normal incidence angular range for tracking accuracy requirements is necessary whenever the manufacturer's tracking system is used for testing.

19. Procedure

19.1 *Response Time*—Follow 13.1.

19.2 *Determination of Near-Normal Incidence Angular Range for Tracking Accuracy Requirements:*

19.2.1 This procedure is required when a collector is being tested with a tracking arrangement that, in whole or in part, consists of a tracking mechanism supplied to the testing laboratory for the purpose of testing the collector, and that has not been documented to have the accuracy (±0.1°) required of the test laboratory's equipment. This procedure is optional in all other cases, and may be used to obtain data on the effects of tracking errors on the thermal performance of the collector. The following sections assume a symmetrical concentrator, for example, a paraboloidal dish. If the concentrator is assymetrical, or if the collector is a two-axis tracking linear collector, then 13.4.1 and 13.4.2, and 13.3.1 and 13.3.2 shall be followed.

19.2.2 Determine the angle of incidence at which the thermal performance at ambient is approximately 95 % of its value measured at normal incidence ($\theta = 0$). This angle may be determined by trial-and-error testing using one of the procedures of 13.2.

19.2.3 The collector shall be positioned such that the sun will move across the collector normal from a positive to a negative angle of incidence, the value of which was determined in 19.2.2.

19.2.4 Measure the mass flow rate-specific heat product and the temperature difference, Δt_a, of the heat transfer fluid at the inlet and outlet to the collector, recording each observation as the sun moves across the collector. The test conditions described in Section 10, with the exception of 10.1.2, must exist for a time period equal to two times the response time before the observations are begun, and must continue during the observations.

NOTE 11—The user of this procedure is advised that it may not be possible to achieve the required conditions at times other than near solar noon.

19.3 *Heat Gain at Near-Normal Incidence*—Follow 13.5.

SYSTEM TESTING OF POINT FOCUS AND LINEAR TWO-AXIS TRACKING COLLECTORS

20. Scope

20.1 This test method covers the determination of the thermal performance of point focus and linear two-axis tracking solar collectors, tested as a system consisting of the collector, a tracking mechanism, and the necessary associated controls.

21. Summary of Test Methods

21.1 The response time and the rate of heat gain at near-normal incidence are determined for the point focus or linear two-axis tracking collector system, under clear sky, quasi-steady state conditions.

22. Procedure

22.1 *Response Time*—Follow 13.1.

22.2 *Heat Gain at Near-Normal Incidence*—Follow 13.5.

23. Calculations

23.1 *Response Time*—When Procedure A is used, the response time is the time, T, required to reach the condition as follows:

$$(\Delta t_{a,T} - \Delta t_{a,f})/(\Delta t_{a,i} - \Delta t_{a,f}) = 0.10 \qquad (2)$$

Take the initial and final values, $\Delta t_{a,i}$ and $\Delta t_{a,f}$, respectively, from the recorded data, calculate the value of $\Delta t_{a,T}$ required to satisfy Eq 2, and then determine the response time, T, as the time interval from the moment of initiation of shading to the moment $\Delta t_{a,T}$ was reached in the test.

23.1.1 When Procedure B is used, the response time is the time, T, required to reach the condition as follows:

$$(\Delta t_{a,f} - {}_{\Delta}t_{a,T})/(\Delta t_{a,f} - {}_{\Delta}t_{a,i}) = 0.10 \qquad (3)$$

Take the initial and final quasi-steady state values, $\Delta t_{a,i}$ and $\Delta t_{a,f}$, from the recorded data, calculate the value of $\Delta t_{a,T}$ required to satisfy Eq 3, and then determine the response time, T, as the time interval from the moment of initiation of unshading the collector to the moment $\Delta t_{a,T}$ was reached in the test.

23.2 *Angle of Incidence*—If the angle of incidence (θ) of the direct solar radiation on the collector aperture is not measured, then it shall be calculated from the solar azimuth and elevation angles and the collector orientation for each data point using the formulae contained in Annex A. The sun angles may be calculated[4] or taken from tabular sources (for example, an ephemeris.) The angles shall be corrected for atmospheric refraction. The angles shall be accurate to ± 0.1°. The time of day to be used shall be the center of the time interval spanned by the observations that compose the data point.

23.3 *Solar Power Incident on the Collector Aperture*—For each data point, the solar power incident on the collector aperture ($E_{s,D}A_a$) is calculated from the aperture area (A_a), the measured direct normal solar irradiance $E_{s,DN}$ and the measured or calculated angle of incidence (θ), using the relation

$$E_{s,D}A_a = E_{s,DN}A_a\cos\theta \qquad (4)$$

The angle of incidence shall be that for the time of day centered in the time interval over which the observations for the data point are averaged (7.7, 23.2).

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[4] For example, see the following series of discussions:

Wahlraven, R., "Calculating the Position of the Sun,'' *Solar Energy 20,* p. 393, (1978).

Wahlraven, R., "Erratum,'' *Solar Energy 22,* p. 195, (1979).

Archer, C. B., "Comments on 'Calculating the Position of the Sun','' *Solar Energy 25,* p. 91, (1980), and Wilkinson, B. J., "An Improved FORTRAN Program for the Rapid Calculation of the Solar Position,'' *Solar Energy 27,* p. 67, (1981).

23.4 *Rate of Heat Gain*—For each data point, the rate of heat gain ($\dot{Q}$) is calculated from its defining relation

$$\dot{Q} = (\dot{m}C_p)\Delta t_a \quad (5)$$

using the values of mass flow rate-specific heat product ($\dot{m}C_p$) and the difference in heat transfer fluid temperature between the inlet and outlet of the collector (Δt_a) determined for that data point. Where Δt_a is measured directly, the measured value is to be used, otherwise the difference is calculated as

$$\Delta t_a = t_{f,e} - t_{f,i} \quad (6)$$

The values used shall be the averages of the observations for each variable taken over the same time interval (7.7).

23.5 *Incident Angle Modifier*—When the preferred procedure or the alternative procedure A is used, calculate the incident angle modifier values in the following way. For each angle of incidence $\theta_{||}$ at which the procedure is performed, compute the ratio of the rate of heat gain $\dot{Q}$ (23.4) to the solar power incident on the collector aperture $E_{s,D}A_a$ (23.3) calculated using the data measured at the angle of incidence:

$$R(\theta_{||}) = \dot{Q}/E_{s,D}A_a \quad (7)$$

Then, calculate the incident angle modifier for each angle of incidence by normalizing each ratio to the ratio for normal incidence:

$$K(\theta_{||}) = R(\theta_{||})/R(\theta_{||} = 0) \quad (8)$$

It is recommended that the ratio used in this calculation be calculated from data taken on the same day.

23.5.1 When alternative procedure B is used, calculate the nonirradiated collector heat loss $\dot{Q}_L$ from the measured mass flow rate-specific heat product ($\dot{m}C_p$) and the heat transfer fluid temperature difference between the inlet and outlet to the collector (Δt_a) according to Eq 5. ($\dot{Q}_L$ is numerically negative.) For each angle of incidence $\theta_{||}$ at which the procedure is performed, calculate the actual rate of heat gain $\dot{Q}$ (see Eq 5) and the solar power angle incident on the collector aperture $E_{s,D}A_a$ (see Eq 4). Then, for each angle of incidence, calculate the adjusted ratio

$$R(\theta_{||}) = \left(\dot{Q} - \dot{Q}_L\right)/E_{s,D}A_a \quad (9)$$

Finally, calculate the incident angle modifier for each angle of incidence by normalizing each adjusted ratio to the adjusted ratio for normal incidence:

$$K(\theta_{||}) = \left(\dot{Q} - \dot{Q}_L\right)/E_{s,D}A_a \quad (10)$$

23.5.2 It is recommended that the ratios used in this calculation be calculated from data taken on the same day. If this data is to be used for lengths of collectors other than that tested, then the appropriate corrections for end effects must be applied (see Annex A1.).

23.6 *Near-Normal Incidence Angular Range for Determination of the Rate of Heat Gain at Near-Normal Incidence*—Calculate $R(\theta_{||}$) as in 23.5. Plot $R(\theta_{||})$ versus $\theta_{||}$. The curve should be symmetrical about the $R(\theta_{||})$-axis. Any misalignment of the collector during the test will be apparent in a shift of the $R(\theta_{||})$-axis, and the data should then be corrected by shifting the $R(\theta_{||})$-axis until the curve is symmetric. (Asymmetric collectors may produce a curve that cannot be made symmetric, and the $R(\theta_{||})$-axis should then be aligned with the peak of the curve.) Determine the $\theta_{||}$ at which $R(\theta_{||}) = 0.98$. The angular range of near-normal incidence is defined as being between this angle $\theta_{||}$ and $\theta_{||} = 0$.

23.7 *Near-Normal Incidence Angular Range for Tracking Accuracy Requirements*—Follow the procedure of 23.6, substituting $\theta_{\perp}$ for $\theta_{||}$.

24. Report

NOTE 12—The following data are representative of the collector performance under the specific conditions of this test method. The collector should not be rated for these test conditions, but rather for some average of the environmental conditions the collector is likely to encounter in actual use.

24.1 *General Information*—The following information is to be reported:

24.1.1 *Location*—Longitude, latitude, elevation,

24.1.2 Description of the test apparatus and instrumentation, and

24.1.3 Heat transfer fluid used with physical properties in tabular or equation form.

24.2 The following collector information is to be reported:

24.2.1 General collector description,

24.2.2 Manufacturer, model and serial number,

24.2.3 *Dimensions and Area*—Aperture and gross,

24.2.4 *Receiver data*—Shape, dimensions, material, coatings, and turbulence promoters, as applicable,

24.2.5 *Reflector or Refractor*—Shape, dimensions, material,

24.2.6 *Glazings*—Shape, dimensions, materials,

24.2.7 *Design Operating Conditions*—Flow, temperature, pressure,

24.2.8 Tracking and drive mechanism description as applicable,

24.2.9 Collector orientation, mounting, and test facility interface description,

24.2.10 Preconditioning, if any, and

24.2.11 Cleaning procedures used.

24.3 *Test Data:*

24.3.1 The following data (individual observations in the case of response time and near-normal incidence angular range tests, averaged data in the case of thermal performance at near-normal incidence and incident angle modifier tests) are to be reported:

24.3.1.1 Date,

24.3.1.2 Observers,

24.3.1.3 Type of test,

24.3.1.4 T,

24.3.1.5 $\dot{m}$and C_p, or ($\dot{m}C_p$), as applicable,

24.3.1.6 $t_{f,i}$

24.3.1.7 Δt_a, $\Delta t_{a,i}$, $\Delta t_{a,f}$, $\Delta t_{a,T}$, as applicable,

24.3.1.8 t_{amb},

24.3.1.9 $E_{s,DN}$,

24.3.1.10 $E_{s,D}$,

24.3.1.11 $E_{s,2\pi}$,

24.3.1.12 $E_{s,t}$ if measured,

24.3.1.13 Wind direction and speed,

24.3.1.14 θ, $\theta_{||}$, $\theta_{\perp}$, as applicable,

24.3.1.15 Q,

24.3.1.16 $\dot{Q}_L$, as applicable, and

24.3.1.17 $K(\theta_{||})$.

24.3.2 The individual procedures followed will be reported. Any deviations from these procedures will be reported in detail.

24.4 *Test Results*—The following results based on the test data are to be reported (in graphical form if appropriate):

24.4.1 Response Time,

24.4.2 Limits of Near-Normal Incidence, as applicable, and

24.4.3 Incident Angle Modifier.

25. Keywords

25.1 single-axis; thermal performance; tracking concentrating solar collectors; two-axis

ANNEXES

(Mandatory Information)

A1. END EFFECTS

A1.1 Any non-zero angle of incidence $\theta_{||}$ in the plane parallel to the longitudinal axis of line focus collector will result in end effects at the receiver when end reflectors are not used. The end effect factor $\Gamma(\theta_{||})$ accounts for the loss of radiation that is focused beyond the end of the receiver. It is a function of $\theta_{||}$ such that when $\theta_{||} = 0$, $\Gamma(\theta_{||}) = 1$, and for non-zero $\theta_{||}$, $\Gamma(\theta_{||}) < 1$. It is a geometrically determined quantity, defined as one minus the fraction of aperture area that is ineffective in redirecting radiation to the receiver:

$$\Gamma(\theta_{||}) = 1 - (A_{\text{ineffective}}/A_a) = (A_{\text{effective}}/A_a) \tag{A1.1}$$

The dependence on $\theta_{||}$ becomes evident when it is realized that the ineffective area of the aperture increases as $\theta_{||}$ increases.

A1.2 When testing linear collectors that are normally installed end-to-end (effectively extending the axial length of the collector), it is often desirable to remove the end effects from the incident angle modifier, or to correct for the effects of small incident angles in order to normalize all data points to solar noon. The end effect factor has been recognized as an important parameter in the prediction of all-day performance of a series of linear collectors. It is used in the same manner as the incident angle modifiers in determining the performance for modules or arrays of lengths different from that of the test unit.

A1.3 To correct for the end losses, therefore, one simply multiplies the $R(\theta_{||})$ term by Γ^{-1} $\theta_{||}$):

$$\Gamma^{-1} = A_a/A_{\text{effective}} = 1 + (A_{\text{ineffective}}/A_{\text{effective}}) \tag{A1.2}$$

To use this correction factor, the value of $R(\theta_{||})$, calculated Eq 7 for an incidence angle $\theta_{||}$, is multiplied by $\Gamma^{-1}(\theta_{||})$:

$$R(\theta_{||}) = K(\theta_{||})R(\theta_{||} = 0) \tag{A1.3}$$

$$R'(\theta_{||}) = K(\theta_{||})R(\theta_{||} = 0)\Gamma^{-1}(\theta_{||}) \tag{A1.4}$$

A1.3.1 There actually can be two parts to end loss: loss of radiation that is focused beyond the end of the receiver, and the net heat loss from the unilluminated (ineffective) portion of the receiver. When correction for these effects, as encountered in testing at small non-zero angles of incidence $\theta_{||}$, is desired, usually only the loss of radiation need be accounted for. This correction is the $\Gamma(\theta_{||})$ described previously. The second part of the end loss depends upon the difference in heat loss characteristics for that particular collector between the illuminated receiver and the unilluminated receiver, and can be considered negligible in most cases when less than 10 % of the receiver is unilluminated due to $\theta_{||}$. Both effects should be accounted for when predicting all-day efficiency from normal-incidence efficiency data.

A1.3.1.1 It must be noted that special consideration must be given to each collector configuration, taking into account collector geometry, relative lengths of receiver and aperture, the space between units connected in series, and other matters pertinent to the specific application of $\Gamma(\theta_{||})$ as a correction factor or as a predictive tool. The equations for several generic linear collectors follow.

A1.4 The derivation of the end effect factor is straightforward but may be tedious in some cases. The simplest case is a cylindrical array of flat segmented mirrors. (See Fig. A1.1.)

A1.4.1 The area of the aperture that redirects incident solar radiation past the receiver end, and the length of unilluminated receiver are based on the same geometric relationship.

$$A_1 = [(f\tan\theta_{||} - r)w]\xi(\theta_{||}) \tag{A1.5}$$

$$1_r = (f\tan\theta_{||} + r) \tag{A1.6}$$

A1.4.1.1 From Fig. A1.1 it can easily be seen that the largest angle of incidence θ_c at which all rays incident on the aperture still strike the receiver depends on the value of r, that is,

$$\theta_c = \arctan(r/f) \tag{A1.7}$$

A1.4.1.2 When $\theta < \theta_c$ there is no ineffective area of the aperture, and since in most cases the increases in heat losses from the unilluminated portion of the receiver are negligible, there are no end losses. When $\theta > \theta_c$, end losses are present. This is taken into account with the ξ function:
when:

$$\theta < \theta_c, \text{ then } \xi(\theta_{||}) = 0, \tag{A1.8}$$

and when:

$$\theta_{||} > \theta_c, \text{ then } \xi(\theta_{||}) = 1 \tag{A1.9}$$

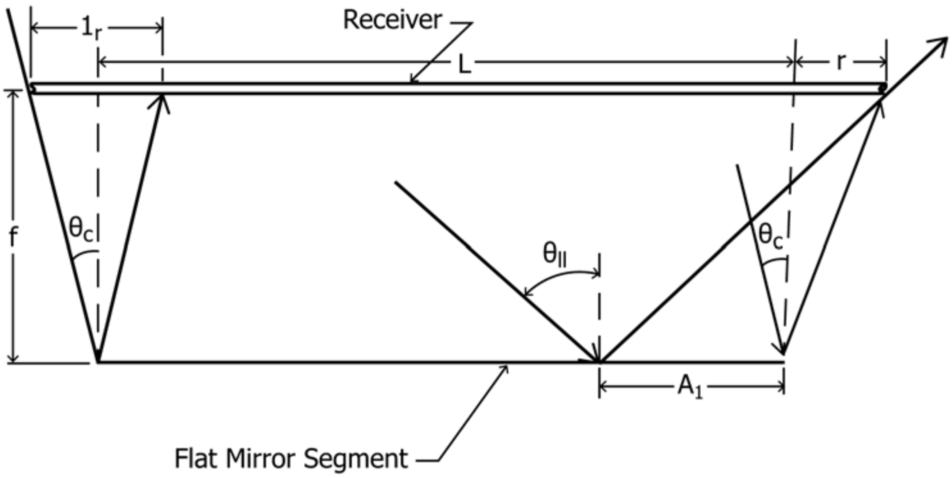

FIG. A1.1 End Effects in Cylindrical Array of Flat Segmented Mirrors

A1.4.2 The conditions previously described apply to all cases where only a single unit is tested at a time, or when test units cannot receive any reflected light from adjacent units, or both. If a unit is tested as part of a row, and can intercept radiation reflected from an adjacent module, then the spacing between the receivers and reflectors of the adjacent units (g) must be taken into account. A second critical angle of incidence

$$\theta'_c = \arctan[(r+g)/f] \tag{A1.10}$$

defines the minimum angle at which light from one unit will be redirected onto its neighbor. Then for $\theta_{||} \leq \theta'_c$, all conditions for determining A_1 and 1_r remain the same as previously defined. For $\theta_{||} > \theta'_c$, however, $\xi\ (\theta_{||}) = 1$ but the value of $\theta_{||}$ used in calculating A_1 and l_r is always θ'_c.

A1.4.3 The end effect factor, as defined to correct for the effects of incident angles $\theta_{||}$, is

$$\Gamma^{-1}\theta_{||} = 1+\frac{A_1}{wL-A_1} \tag{A1.11}$$

$$\Gamma^{-1}\theta_{||} = 1+\frac{\{(f\tan\theta_{||}-r)w\}\xi(\theta_{||})}{wL-\{(f\tan\theta_{||}-r)w\}\xi(\theta_{||})}$$

It may be necessary to average the effects of $\Gamma^{-1}(\theta_{||})$ for all reflector segments in the array.

To apply this correction, the calculated value of $R(\theta_{||})$ at an incident angle $\theta_{||}$ is multiplied by $\Gamma^{-1}(\theta_{||})$ as follows:

$$R'(\theta_{||}) = K(\theta_{||})R(\theta_{||}=0)\Gamma^{-1}(\theta_{||}) \tag{A1.12}$$

A1.4.3.1 For similar collectors that use slightly curved reflector segments instead of flat surfaces, the above is a good approximation, especially if the end effects from each reflector are averaged together. The curvature of the mirror segments essentially only reduce the focal band to a narrower strip.

A1.5 For parabolic troughs, the derivation is more tedious, so only the results will be printed here:

$$A_1 = \{\tan\theta_{||}\ (fw+w^3/48f) - rw\}\xi(\theta) \tag{A1.13}$$

$$\theta_c = \arctan[(r)/(f+w^2/48f)] \tag{A1.14}$$

$$\Gamma^{-1}(\theta_{||}) = 1+A_1/(wL-A_1) \tag{A1.15}$$

$$\{\tan\ \theta_{||}\quad (fw+w^3/48f)$$

$$=1+\frac{-\ rw\}\xi(\theta_{||})}{wL-\{\tan\ \theta_{||}}$$

$$(fw+w/48f)\ -\ rw\}\xi(\theta_{||})$$

$$\theta'_c = \arctan[(r+g)/(f+w^2/48f)] \tag{A1.16}$$

Again, the assumption has been made here that the increase in losses from the unilluminated portion of the receiver are negligible.

A1.6 For use in predicting thermal performance of a solar collector at times other than solar noon, from data collected at $\theta_{||} = 0$, the same basic procedure is followed. A_1 is calculated and is used in the following equation for the end loss factor:

$$\Gamma(\theta_{||}) = 1-(A_1/wL) \tag{A1.17}$$

To use $\Gamma^{-1}\theta_{||}$ as a prediction tool, it is multiplied by the measured value of $R(\theta_{||})$ at $\theta_{||} = 0$.

$$R(\theta_{||}) = \{K(\theta_{||})\,R(\theta_{||}=0)\}\Gamma^{-1}\theta_{||} \tag{A1.18}$$

A2. EQUATIONS FOR ANGLES OF INCIDENCE FOR LINEAR SINGLE-AXIS TRACKING COLLECTORS

A2.1 The angles of incidence for linear single-axis tracking collectors can be found from the equations as follows:

A2.1.1 When a collector whose longitudinal axis is horizontal in the east-west direction tracks by rotating about an axis parallel to the longitudinal axis where the tilt angle, *s*, is a function of sun position:

$$s = \arctan(\cos \Phi / \tan B) \tag{A2.1}$$

$$\theta_{||} = \arctan(\sin \Phi \cos s / \tan B) \tag{A2.2}$$

A2.1.2 When a collector whose longitudinal axis is horizontal in the north-south direction tracks by rotating about an axis parallel to the longitudinal axis:

$$\theta_{||} = \arcsin(\cos B \cos \Phi) \tag{A2.3}$$

A2.1.3 If a linear collector is mounted with its longitudinal axis in a north-south orientation, and tilted a fixed angle *s* from the horizontal to the equator, and the collector tracks about an axis parallel to the longitudinal axis of the collector:

$$\theta_{||} = \arcsin(\cos B \cos \Phi \cos s - \sin s \sin B) \tag{A2.4}$$

Note that if the collector is "polar mounted," the fixed slope *s* will be equal to the latitude.

A2.1.4 If a collector is tilted in any direction other than in the north-south or east-west planes, then the azimuth angle Φ must be adjusted by adding or subtracting the angular difference between due south and the direction the collector faces. The incident angle would then be recalculated with the *adjusted* Φ.

APPENDIX

(Nonmandatory Information)

X1. EQUATIONS THAT MAY BE USED TO ESTIMATE ANGLE OF INCIDENCE WITH VARIOUS KINDS OF RECEIVERS

X1.1 The following equations may be used to estimate angle of incidence at which the measured value of η_o is approximately one-half of the peak ($\theta_{||} = 0$) value of $R(\theta_{||})$.[5]

X1.1.1 For parabolic troughs with cylindrical receiver:

$$\theta_{||} = (\sin \Phi / \pi C) \tag{X1.1}$$

X1.1.2 For parabolic troughs with flat one-sided receiver:

$$\theta_{||} = (\sin \Phi \cos \Phi / C) \tag{X1.2}$$

X1.1.3 For a parabolic dish with spherical receiver:

$$\theta_{||} = \left(\sin \Phi / 2\sqrt{C}\right) \tag{X1.3}$$

where Φ is the rim angle of the collector.

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[5] Bendt, P., Gaul, H., and Rabl, A., "Determining the Optical Quality of Focusing Collectors Without Laser Ray Tracing," *Journal of Solar Energy Engineering*, Vol 102, May 1980, p. 129.