IEEE Recommended Practice for Qualification of Concentrator Photovoltaic (PV) Receiver Sections and Modules

Sponsor

IEEE Standards Coordinating Committee 21 on Photovoltaics

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Abstract: The minimum tests and inspections required to evaluate photovoltaic concentrating modules, and a common approach (e.g., between producer and purchaser) in conducting qualification tests are provided.
Keywords: concentrators, modules, photovoltaic (PV), qualification tests, receivers, recommended practices

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

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Introduction

[This introduction is not part of IEEE Std 1513-2001, IEEE Recommended Practice for Qualification of Concentrator Photovoltaic (PV) Receiver Sections and Modules.]

This recommended practice provides qualification tests and procedures to evaluate terrestrial photovoltaic concentrating modules intended for power generation applications. It builds on a Sandia publication (SAND92-0958, "Evaluation Tests for Photovoltaic Concentrator Receiver Sections and Modules," 1992), and follows the format of the recently completed IEEE Std 1262-1995 for flat plate PV modules.

The intent of this recommended practice is to provide the minimum tests and inspections required to evaluate photovoltaic concentrating modules and to provide a common approach (e.g., between producer and purchaser) in conducting qualification tests. The tests and procedures provided in this recommended practice may be supplemented by additional tests and procedures established between the producer and purchaser.

Concentrator module designs are under development, and new concepts continue to appear. This situation requires that qualification tests be flexible enough to allow a reasonable assessment of new designs, yet complete enough to identify weaknesses that would lead to problems in the field. Ideally, modules that experience early failures in field operation should fail qualification tests. Therefore, it is important to note that the design of this recommended practice and the tests specified were developed to eventually serve as a uniform standard for the photovoltaic concentrator industry.

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IEEE Recommended Practice for Qualification of Concentrator Photovoltaic (PV) Receiver Sections and Modules

1. Overview

1.1 Scope

This recommended practice establishes recommended procedures and specifications for qualification tests that are structured to evaluate concentrator photovoltaic receiver sections and modules intended for power generation applications.

1.2 Purpose

The qualification tests provided in this document should assist in evaluating the design performance, reliability, safety, and susceptibility to known failure mechanisms of concentrator photovoltaic (PV) receiver sections and modules.

Emphasis is placed on testing for potential degradation of receiver sections and module performance resulting from environmental weathering, mechanical loading, shadowing, or corrosion.

The procedures given in this recommended practice provide a common approach for conducting module qualification tests. Although acceptable results from these tests should provide reasonable assurance that the modules produced by the same processes as those that pass these tests will perform reliably in the field after installation, this recommended practice does not address design, safety, or performance of PV systems.

1.3 Limitations

These qualification tests are applicable to concentrator photovoltaic receivers and modules.

This document will be revised as required to incorporate the latest information on failure mechanisms and the relationships between accelerated tests and field reliability.

2. References

This recommended practice should be used in conjunction with the following publications. If the following publications are superseded by an approved revision, the revision shall apply.

ASTM E892-87 (1992), Standard Tables for Terrestrial Solar Spectral Irradiance at Air Mass 1.5 for a 37° Tilted Surface.[1]

ASTM E927-97, Standard Specification for Solar Simulation for Terrestrial Photovoltaic Testing.[2]

ASTM E973M-96, Standard Test Method for Determination of the Spectral Mismatch Parameter Between a Photovoltaic Device and a Photovoltaic Reference Cell.

ASTM E1036-96, Standard Test Methods for Electrical Performance of Nonconcentrator Terrestrial Photovoltaic Modules and Arrays Using Reference Cells.

ASTM E1038-98, Standard Test Method for Determining Resistance of Photovoltaic Modules to Hail by Impact with Propelled Ice Balls.

ASTM E1171-99, Standard Test Method for Photovoltaic Modules in Cyclic Temperature and Humidity Environments.

ASTM E1462-00, Standard Test Methods for Insulation Integrity and Ground Path Continuity of Photovoltaic Modules.

ASTM E1802-96, Standard Test Methods for Wet Insulation Integrity Testing of Photovoltaic Modules.

ASTM E1830M-96, Standard Test Methods for Determining Mechanical Integrity of Photovoltaic Modules.

IEC 61215 (1993-04), Crystalline silicon terrestrial photovoltaic (PV) module—Design qualification and type approval.[3]

IECQ PQC 12, Provisional blank detail specification: Crystalline silicon terrestrial Photovoltaic (PV) modules.

IEEE Std 928-1986 (Reaff 1991), IEEE Recommended Criteria for Terrestrial Photovoltaic Power Systems.[4]

IEEE Std 1262-1995, IEEE Recommended Practice for Qualification of Photovoltaic (PV) Modules.

UL 1703-2000, Standard for Safety for Flat-Plate Photovoltaic Modules and Panels.[5]

[1]This standard was discontinued in 1999 and replaced by ASTM G159-98, Tables for References Solar Spectral Irradiance at Air Mass 1.5: Direct Normal and Hemispherical for a 37° Tilted Surface.

[2]ASTM publications are available from the American Society for Testing and Materials, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959, USA (http://www.astm.org/).

[3]IEC publications are available from the Sales Department of the International Electrotechnical Commission, Case Postale 131, 3, rue de Varembé, CH-1211, Genève 20, Switzerland/Suisse (http://www.iec.ch/). IEC publications are also available in the United States from the Sales Department, American National Standards Institute, 11 West 42nd Street, 13th Floor, New York, NY 10036, USA.

[4]IEEE publications are available from the Institute of Electrical and Electronics Engineers, 445 Hoes Lane, P.O. Box 1331, Piscataway, NJ 08855-1331, USA (http://standards.ieee.org/).

[5]UL standards are available from Global Engineering Documents, 15 Inverness Way East, Englewood, Colorado 80112, USA (http://global.ihs.com/).

3. Background and overview of qualification test program

3.1 Background

In developing this qualification test document, several sources of information were referenced and used in designing and formulating the majority of the tests given. Primary sources included: SAND92-0958 [B5][6] document for evaluation tests for PV concentrator receiver sections and modules; IEEE Std 1262-1995 for flat plate modules;[7] IEC 61215 (1993-04) for crystalline silicon modules; UL 1703-2000 for flat plate modules; and Technical Specifications for the Photovoltaics for Utility Scale Applications (PVUSA) Project, as referred to in Hester, et al [B6].

Since the publication of these documents, photovoltaic materials technology and concentrator module development have advanced. Efforts in module reliability research have produced a better understanding of known and potential failure mechanisms associated with photovoltaic concentrator modules, especially with regard to the effects of moisture ingress. The results of these efforts and experience gained have been used in formulating new tests and modifying earlier tests for inclusion in this recommended practice.

3.2 Overview of qualification test program

The qualification test sequence is illustrated in Figure 1. Module qualification test program requirements, which provide detailed guidance and minimum requirements for the overall qualification test, are given in Clause 4. Requirements and evaluation of test results necessary for passing the qualification test are provided in 4.4, and they include the following:

a) Initial tests and inspections.
b) Sequence "A," "B," "C," "D," and "E" tests, which subject the modules to a specified sequence of environments and stresses. All intermediate electrical performance tests are optional and they may help identify which test caused a failure, but they are not required.
c) Final tests and inspections.

Descriptions of the required test and inspection procedures are provided in Clause 5.

Initial tests and inspections (see 4.2) establish selection and acceptance of as received modules as test module specimens. They also establish "baseline" visual inspection information and electrical performance measurement data for comparison and determination of the effects on module physical characteristics and electrical performance following all subsequent tests.

A minimum of five test modules and seven receiver sections are required to complete all the specified tests. If the intrusive bypass diode thermal test (sequence E) is to be performed, an additional specially fabricated receiver is required. A module is the smallest, complete, environmentally protected assembly of receivers and optics, and related components such as interconnects and mounting, that accepts unconcentrated sunlight. A receiver is an assembly of one or more PV cells that accepts concentrated sunlight and incorporates the means for thermal and electric energy removal. Figure 2 is a schematic of cells, receivers, and modules. In the case of a large PV concentrator module and receiver, a receiver section is a portion suitable for specific tests.

Test sequences A through E subject the receivers or modules to a specified sequence of environments and typical or accelerated stresses similar to those which final, deployed modules should survive. The final tests and inspections (see 4.3) provide data for comparison with initial test and inspection results. The criteria for passing the qualification tests are provided in 4.4.

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[6] The numbers in brackets correspond to those of the bibliography in Annex A.

[7] Information on references can be found in Clause 2.

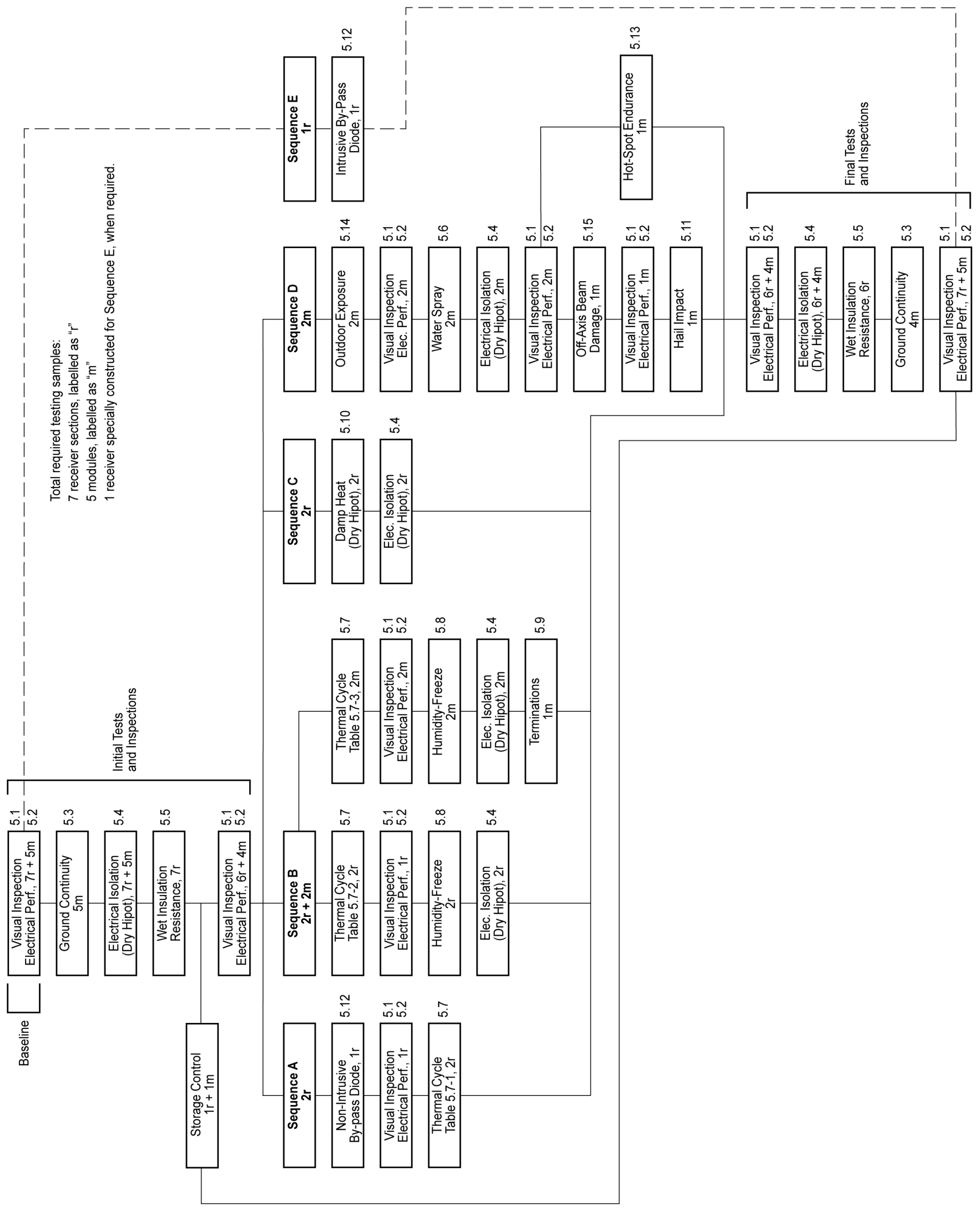


Figure 1—Concentrator PV receiver sections and modules qualification test program

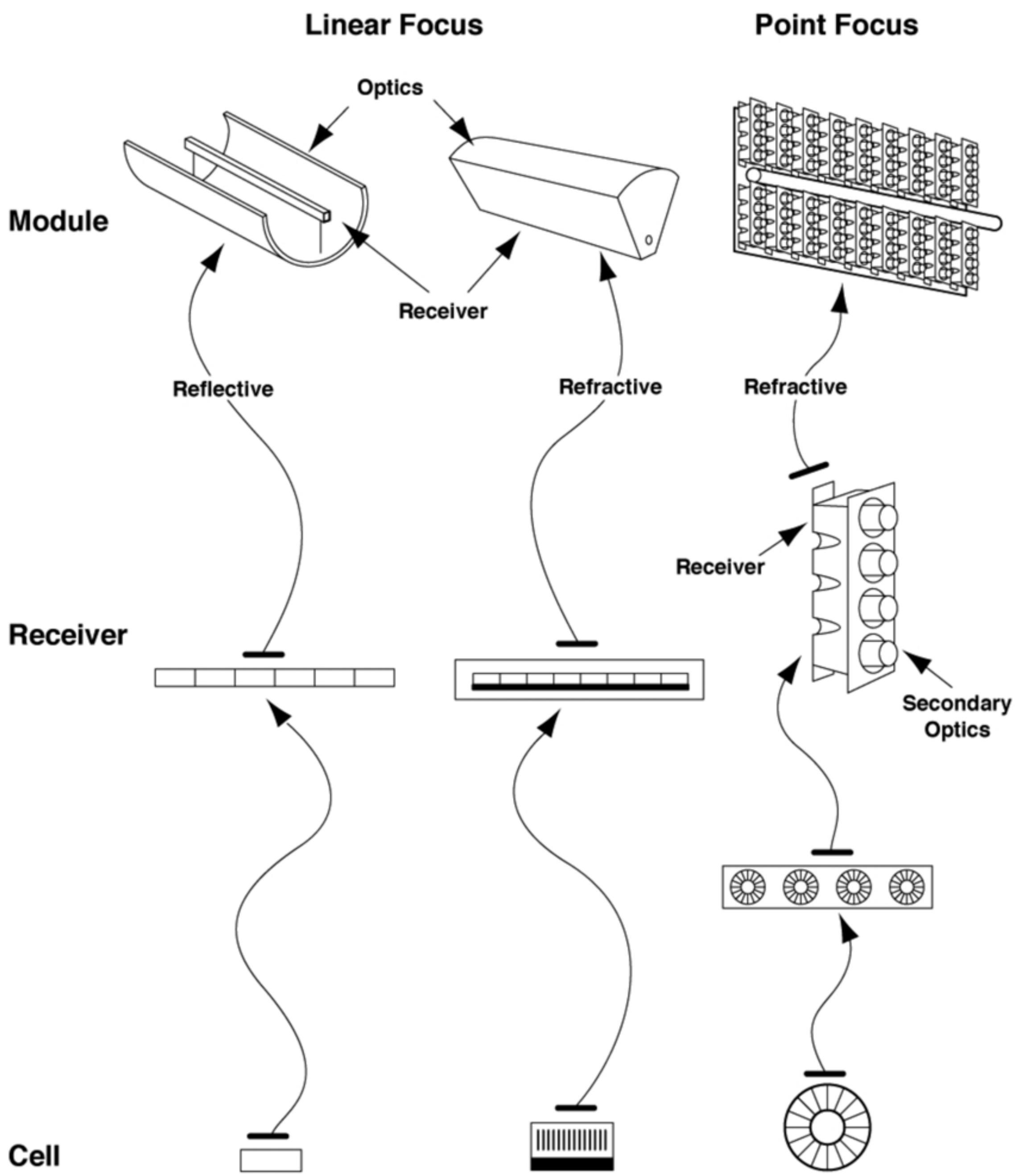


Figure 2—Schematic of module, receiver, and cell for (from left to right) line focus reflecting, line focus Fresnel lens, and point focus Fresnel lens concentrators

4. Module qualification test requirements

This clause specifies the recommended tests and inspections to be performed and the required test sequence to be followed to evaluate photovoltaic concentrator modules. The required test sequence is illustrated in the flow diagram provided in Figure 1, along with designated inspection and test identification numbers corresponding to inspections and test procedures specified in Clause 5.

4.1 Test specimens

A minimum of five concentrator modules and seven receiver test specimens, of each module type representative of the modules to be deployed in the field, are required to conduct all the tests specified in this recommended practice if the non-intrusive bypass diode thermal test is performed. When the intrusive bypass diode thermal test is to be conducted, an additional test receiver section should be constructed with thermocouples brought out for accessing individual diodes. The intrusive bypass diode thermal test requires performance of test sequence E. Use of the non-intrusive bypass diode thermal test eliminates test sequence E. Use of the intrusive bypass diode thermal test eliminates the non-intrusive bypass diode test. If the test described in 5.2.2.3 is used, the control module/receiver may be used as the reference module/receiver described in 5.2.2.3.

The modules should be randomly selected from production manufactured to the standard procedures and drawings, be approved by the manufacturer's quality control, and conform to the manufacturer's acceptance procedures. When the modules to be tested are prototypes of a new design and not from production, this fact should be noted in the test report. Modules should not be preconditioned, e.g., light soaked or subjected to other special procedures that are not part of standard production.

4.1.1 Representative module or receiver test specimens

If the size of a complete module or receiver is too large to fit into the available environmental chambers, representative module or receiver test specimens can be substituted for full-size modules or receivers. These test specimens should be specially fabricated from sub-receivers that include a string of cells connected as in the full-size receiver. The cell string should be long enough to include at least two bypass diodes, but in no case less than three cells.

The encapsulation interconnects and terminations on the sub-receiver should be the same as in the full module. The sub-receiver should include other representative module components, including lens/housing joints, receiver/housing joints, endplate/lens, and housing and receiver joints, to be tested in sequences A, B, and C.

Two full-size modules should be used for the outdoor exposure test in sequence D.

4.1.2 Label and marking requirements

Those articles submitted for test that require labels to meet various code or listing requirements should carry the required labels during the testing. Such labels generally require at least the manufacturer's name, the model number of the article, the maximum system voltage for which the article is designed, the power rating, and a serial number. Additional information may be required. Other labels may be required to indicate terminal polarity and grounding point. If representative test specimens are submitted for test, all labels used for full-size modules should be included. The labels should be capable of surviving the test sequences.

Those articles submitted for test that do not require a label should be marked at appropriate locations with clear and indelible markings of manufacturer's identification number, terminal polarity, and grounding point.

4.1.3 Analytical analysis

A full-size module and its interfaces should be analyzed by an independent registered professional engineer to determine whether it is designed to withstand the following:

a) Survival of a 510 Pa load in the worst case position.
b) Survival of a 1420 Pa load in a stowed position.
c) Survival of other potential hazards, such as those resulting from thermal expansion of components and condensation, which are affected by the total air volume inside the module.

4.2 Initial tests and inspections

Initial tests and inspections should be performed in the order illustrated in Figure 1. Selection and acceptance of received receivers and modules as test specimens should be based on passing the initial inspections and tests. Rejected samples could be substituted before beginning the test sequence.

Following the wet insulation resistance test (see 5.5), one module and one receiver section should be removed from the test sequence, as shown in Figure 1, and be kept in dark storage at room temperature as a control.

Data from these initial tests and inspections are critical for establishing the baseline condition and performance of each module/receiver, to which subsequent test data will be compared. If a receiver is tested in sequence E, this receiver should also complete the initial test and inspection.

After all modules/receivers have passed the initial tests and inspections, modules/receivers should be assigned to test sequences as listed in Table 1.

Table 1—Test sequence allocation

Test sequence	Number of modules	Number of receivers
(Control)	1	1
A		2
B	2	2
C		2
D	2	
E (as required)		1 (specially constructed for intrusive bypass diode thermal test)

4.3 Final tests and inspections

At the completion of all the test sequences A, B, C, and D, the final tests and inspections should be conducted in the order indicated in Figure 1. Note that the control module/receiver, and the receiver from test sequence E, if applicable, shall also undergo the final visual inspection and electrical performance test.

4.4 Evaluation of qualification test results

The criteria for passing the qualification tests are that each test specimen, as allocated, should pass all of the tests and inspections. If any one of the test specimens fail a test, another two specimens should be retested and should pass the whole relevant test sequence. If a module or receiver fails one of initial tests and inspections, it should not be accepted as a test specimen, and therefore should not be subjected to this two-to-one retest.

Receiver area is the encapsulated active area including cells and interconnections, which is somewhat larger than the area of the cells.

A summary of the requirements is listed in 4.4.1 through 4.4.5.

4.4.1 Initial tests and inspections

a) Each visual inspection should show no major visual defects, as defined in 5.1.
b) The baseline power output determined in accordance with the electrical performance test (see 5.2) for each of the test modules and receivers should be within ±10% of the manufacturer's specifications. The only purpose of this check is to confirm that the sample is an acceptable test specimen.
c) None of the ground continuity resistance measurements should exceed 0.1 Ω (see 5.3).
d) The dry hi-pot test (see 5.4) should show no arcing or flashover. Dry insulation resistance times receiver area should exceed 40 MΩ-m^2. If the receiver area is less than 0.1 m^2, the insulation resistance should exceed 400 MΩ.
e) Wet insulation resistance (see 5.5) times receiver area should exceed 40 MΩ-m^2. If the receiver area is less than 0.1 m^2, the insulation resistance should exceed 400 MΩ.

4.4.2 Requirements, sequence A through sequence E

a) All intermediate visual inspections should show no major visual defects, as defined in 5.1.
b) All intermediate electrical performance tests are optional and any of four methods described in 5.2.2.1, 5.2.2.2, 5.2.2.3, and 5.2.3 can be used at the request of the manufacturer for diagnostic purposes. These tests are recommended at key points in the test sequence, but additional tests may be conducted at the discretion of the manufacturer or the testing organization. When completed, each electrical performance test should show a power of 90% or greater of the original baseline electrical performance (see 5.2).
c) No specific failure (as described in Clause 5) should have occurred, and any additional requirements specified in Clause 5 should be satisfied.
d) Dry hi-pot tests (see 5.4) should show no arcing or flashover. Dry insulation resistance times receiver area should exceed 40 MΩ-m^2. If the receiver area is less than 0.1 m^2, the insulation resistance should exceed 400 MΩ.
e) After the water spray test (see 5.6), the insulation resistance times receiver area should exceed 40 MΩ-m^2. If the receiver area is less than 0.1 m^2, the insulation resistance should exceed 400 MΩ.

4.4.3 Requirements, final tests, and inspections

a) Each visual inspection should show no major visual defects, as defined in 5.1.
b) The final electrical performance test should show a power of 90% or greater of the original baseline electrical performance (see 5.2).
c) None of the ground continuity resistance measurements should exceed 0.1 Ω (see 5.3).

d) The dry hi-pot test (see 5.4) should show no arcing or flashover. Dry insulation resistance times receiver area should exceed 40 MΩ-m^2. If the receiver area is less than 0.1 m^2, the insulation resistance should exceed 400 MΩ.

e) Wet insulation resistance (see 5.5) times receiver area should exceed 40 MΩ-m^2. If the receiver area is less than 0.1 m^2, the insulation resistance should exceed 400 MΩ.

4.4.4 Reporting requirements

For each test specimen, relevant test data, along with appropriate comments, should be documented and provided as part of the qualification test report. Note that only selected tests are conducted for each module, depending on the test sequence for that particular module.

4.4.5 Retesting requirements for modifications

Modifications on module design or fabrication (e.g., materials, manufacturing process, or assembly) of a module type previously tested and qualified requires reevaluation and may or may not require retesting. Use IECQ PQC 12 as a guideline.

5. Module test and inspection procedures

The following module test and inspection procedures provide the detailed steps and specifications required to conduct and meet the overall qualification test requirements given in Clause 4. Each of the following procedures provides a purpose for the test or inspection, detailed procedural steps and specifications for conducting the test or inspection, and recommended requirements for passing each test or inspection when requirements are not specified in Clause 4.

5.1 Visual inspection procedure

This procedure provides guidelines for performing the baseline, intermediate, and final visual inspections required to identify and determine any physical changes or defects in module construction at the beginning and after the completion of each required test.

Receiver

Purpose: To establish the current visual status so receiver sections can be compared as they pass through each test and to assure they meet requirements for further testing.

Procedure: All components, such as cells, secondary optical elements, heat spreaders, and encapsulants, should be thoroughly inspected, with particular attention paid to the quality of solder joints. Any defects or abnormalities—such as inadequate or excessive solder, solder balls, surface contamination or dirt, bent interconnects, or misalignment of parts—should be documented with appropriate sketches or photographs to show the status and locations of the defects.

Requirements: The receivers should show no major defects, which are defined as follows:

a) Broken, cracked, bent, misaligned or torn external surfaces.

b) Cracked cells and unsoldered interconnects, which could remove more than 10% of that cell's area from the electrical circuit of the module.

c) Bubbles or delamination forming a continuous path between any part of the electrical circuit and the enclosure of the module.

d) Loss of mechanical integrity, to the extent that the installation and/or operation of the module would be impaired.

Module

Purpose: To establish the current visual status so modules can be compared as they pass through each test and to assure modules meet requirements for further testing.

Procedure: Modules should be thoroughly inspected before testing. Any defects or abnormalities that might adversely affect module performance or reliability should be documented with appropriate sketches or photographs to show the status and locations of the defects.

During the inspection, particular attention will be given to the following:

a) Cracked lenses, cracked or bent housings, and bent terminals or mounting brackets.
b) Integrity of the seal around the lens and housing joints.
c) Provision for grounding all accessible conductive parts. The grounding procedure should comply with the provisions of the UL 1703-2000, Section 11.

Requirements: The modules should show no major defects, which are defined as follows:

a) Any major defects defined for receivers section.
b) Cracked or bent lenses and housings to the extent that the alignment (see 5.2.1) becomes impossible.
c) Loss of insulation integrity, to the extent that the active parts are accessible (UL1703-2000, Section 15).

5.2 Electrical performance test

Purpose: To characterize the electrical performance of test modules and receivers and to determine their peak output power.

Procedure: Detailed procedures are given in the following subclauses:

a) Before each outdoor light I-V test, samples should be accurately aligned to the sunlight. The alignment procedure is given in 5.2.1.
b) Three different outdoor light I-V test methods are described in 5.2.2.
c) Dark I-V test as an alternative method for outdoor light I-V is described in 5.2.3.
d) In addition to the above common procedures for receivers and modules, procedures specific to receivers or modules are as follows:

Receiver

All receiver sections, including the “control,” should be tested at concentration levels that produce current levels representative of intended operating conditions. The preferred test method is to obtain current voltage (I-V) curves at concentration using a multi-sun solar simulator, with cell temperature controlled to a reference value (e.g., 25 °C). Use of a solar simulator minimizes uncertainties due to uncontrolled factors—such as wind speed, wind direction, and variable insolation—that occur during outdoor testing.

If the use of a solar simulator is not feasible, receiver sections should be mounted with optics on a two-axis solar tracker and tested outdoors as described below for modules. If the optics cannot be temporarily mounted on the receivers, modules may be substituted for the receiver tests or dark I-V measurements may be obtained as a baseline.

Module

Modules should be mounted on a two-axis solar tracker or appropriately adjustable tracker supplied by the manufacturer, spray washed and water spots wiped off if necessary, and aligned for maximum short-circuit current using the alignment procedure summarized in this subclause, or according to manufacturer's specification. All modules, including the "control," should be characterized. Performance data should be recorded, analyzed, and have confidence limits determined for specific parameters according to 5.2.2. The performance data should be corrected to a convenient set of reporting conditions. The reporting conditions may be chosen for convenience, but once the conditions are chosen, the same conditions should be used throughout, e.g., 850 W/m^2 for direct normal irradiance (DNI), and 1000 W/m^2 global spectral irradiance in the plane of array (POA), ambient temperature of 20 °C, and air mass (AM) 1.5. The light source should be natural sunlight.

During this performance characterization, values of direct normal irradiance and values of cell or heat-sink temperature should span a range sufficient to obtain a rich data set, as described in 5.2.2. If the module has a significant response to diffuse light, the data set should allow separation of the effects of diffuse and direct irradiance.

Requirements: Initial test data should be recorded to establish a baseline electrical output power that will serve as the comparison value for determining the effects of qualification testing on electrical performance.

For intermediate and final performance tests, the maximum power measured for each module or receiver tested should not be less than 90% of the initial measured baseline power.

5.2.1 Alignment

a) Securely mount the module on the tracker using adjustable mounting fixtures and then start the solar tracking function.

b) Perform an initial alignment of the module on the tracker by mechanically adjusting the mounting fixtures while monitoring the short-circuit current from the module. This is an iterative procedure and should result in module alignment within 1° in both azimuth and elevation.

   NOTE—The module short-circuit current (I_{sc}) is weakly sensitive to cell temperature; as the light is concentrated onto the cells during the alignment process, the cells will heat up and increase the I_{sc} until thermal equilibrium is achieved. For instance, a 40 °C rise in the temperature of typical crystalline silicon cells will result in an I_{sc} increase of about 3%. For the initial alignment, this magnitude of temperature influence is not a concern.

c) After thermal equilibrium has been achieved (typically in 5 to 30 minutes), a final alignment should be conducted. The I_{sc} of the module should, again, be used to obtain the final alignment, either by refining the adjustment of the module mounting fixtures or by adjusting the control biases in the tracker control system. Typically, the operator will find a "plateau" around the maximum I_{sc} over which the changes of I_{sc} versus angle become less sensitive. For a point focus module, this alignment procedure should yield a module that is positioned within the manufacturer's specifications for its optimum alignment in both axes.

   NOTE—If more than one module is being tested simultaneously on the same tracker, final alignment should be achieved by adjusting module alignment rather than tracker control biases, because using tracker control biases to align one module may misalign other modules.

d) The alignment should meet the manufacturer's specifications. If the specifications are not available, the relative orientation of the tracker to the sun should not change the I_{sc} more than 1%.

5.2.2 Outdoor-light I-V test methods

Any one of three outdoor-light I-V test methods (see 5.2.2.1, 5.2.2.2, and 5.2.2.3) can be used for the initial and final electrical performance tests. Outdoor-light I-V test method A is generally applicable for higher concentration modules (20X and above), but does not account for any diffuse radiation or spectral distribution. Outdoor light test method B is applicable for all concentrations, does account for diffuse radiation, and partially accounts for spectral distribution (using AM), but is analytically more complex. Outdoor-light test method B or C should be used when manufacturers wish to include the effects of diffuse radiation or spectral distribution changes between the initial and final test.

5.2.2.1 Outdoor-light I-V test method A

Procedure: Refer to Draft ASTM 131 [B1]. The limitation is that the procedure given in ASTM 131 [B1] can only be used for concentration ratios of 10X or more.

5.2.2.2 Outdoor-light I-V test method B

Procedure: This procedure should be used for initial and final performance tests. Intermediate measurements are done using a single data point for each module, which is corrected to reference conditions using the results of the analysis below.

Once the module has been aligned, using the short-circuit current, I-V scans should be taken and recorded at successive intervals. Additionally, measurements should be taken of cell and/or heat-sink temperature, direct normal irradiance (E_{DNI}), plane of array global irradiance (E_{POA}) (if diffuse insolation contributes to the output of a low concentration module), ambient temperature, wind speed. Values for the maximum power point current (I_{mp}) and maximum power point voltage (V_{mp}), short-circuit current (I_{sc}), and open-circuit voltage (V_{oc}) are determined from the I-V scans. Typically, more than 100 scans are recorded during a full day test period. Typically as few as 20 scans are acceptable, as they must cover the following ranges of irradiance, air mass, and cell temperature. The irradiance range needs to span 150 W/m^2, with a minimum of 600 W/m^2. Extrapolations of V_{mp} and V_{oc} to irradiance values that are lower than the lower limit measured are not valid. Cell temperature needs to span 15 °C. Absolute air mass needs to span 1.5 units, with the lowest value under 2.

Module performance is modeled using the approach described below. This approach requires a value for the cell temperature. If cell temperature is not measured, it can be computed using V_{oc} and I_{sc}, using Equation (8), or it can be computed using heat-sink temperature, using Equation (9). To extend this model for predicting module performance based on ambient environmental conditions, one can compute the coefficients in Equation (11), which relates heat sink (or cell) temperature to ambient temperature, insolation, and wind speed. Changes made to the original flat plate modeling approach are included to account for the different irradiance to which concentrators respond versus flat plates. Concentrators respond to the direct normal irradiance (E_{DNI}), rather than to global irradiance. Some low concentration modules may also respond to a fraction of the diffuse irradiance (E_{DIF}), which is the plane of array global irradiance minus direct normal irradiance.

The approach is based on the premise that module I_{mp}, V_{mp}, and V_{oc} are functions of I_{sc} and cell temperature (T_c) only. This implies that the I-V curve is the same for any solar spectrum and angle of incidence for a given I_{sc} and T_c. Performance characterization of a module is then a two-part process. In the first part, the parameters and functions used in computing I_{sc} [Equation (1)] are determined, and an "effective irradiance," E_e, is computed [Equation (2)]. The effective irradiance gives the response of the module short-circuit current relative to the reference conditions. At reference conditions, effective irradiance has the value 1. The parameters and functions used in computing I_{sc} are the absolute air mass function, $f_1(AM_a)$; the angle of incidence function, $f_2(AOI)$; the short-circuit current at a reference operating condition, I_{sc_o}; the response fraction to diffuse irradiance, C_6; and the I_{sc} temperature coefficient, α_{isc}. In the second part of the analysis, I_{mp}, V_{mp}, and V_{oc} are related to E_e using Equation (3) through Equation (5). The default reference operating condition is 50 °C cell temperature, 850 W/m^2 direct irradiance, 150 W/m^2 diffuse irradiance, 1.5 absolute air mass, and 0° angle of incidence. Alternatively, a reference condition may be selected to be within or near the range of test conditions that are used as a common operating condition for comparing pre- and post-test module performance. For the purposes of the module qualification procedure, all measurements should be made at an angle of incidence of 0°, with $f_2(AOI) = 1$ to maximize output.

$$I_{sc}(T_c, E_{DNI}, E_{DIF}, AM_a, AOI) = [(E_{DNI}/850) * f_1(AM_a) * f_2(AOI) + C_6 E_{DIF}/150] * \{[I_{sc_o}/(1 + C_6)] + \alpha_{isc}(T_c - 50\ °C)\} \quad (1)$$

where

$$I_{sc_o} = I_{sc}(50\ °C, 850\ W/m^2, 150\ W/m^2, 1.5, 0°)$$

$$E_e(E_{DNI}, E_{DIF}, AM_a, AOI) \equiv I_{sc}(T_c = 50\ °C, E_{DNI}, E_{DIF}, AM_a, AOI)/I_{sc_o} \quad (2)$$

$$I_{mp}(E_e, T_c) = C_1 + E_e * [C_2 + \alpha_{imp}\ (T_c - 50\ °C)] \quad (3)$$

$$V_{oc}(E_e, T_c) = V_{oc_o} + C_3 \ln(E_e) + \beta_{voc}(T_c - 50\ °C) \quad (4)$$

$$V_{mp}(E_e, T_c) = V_{mp_o} + C_4 \ln(E_e) + C_5[\ln(E_e)]^2 + \beta_{vmp}(T_c - 50\ °C) \quad (5)$$

The sequence of analysis should be as follows:

a) Obtain or estimate a module level temperature coefficient for $\beta_{voc} = \Delta V_{oc}/\Delta T$ for modules or cells. This can be done using the procedure presented in ASTM E1036-96 Annex A2, which describes measuring V_{oc} at different temperatures under a solar simulator and computing the change in V_{oc} divided by the change in temperature at a reference temperature and illumination. Because β_{voc} varies with insolation and temperature, cell β_{voc} values need to be determined at the operational concentration levels, not at one sun. As part of the analysis, a refined estimate of β_{voc} will be obtained, but an initial estimate is required to develop I_{sc_o} and to compute T_c from scan measurements. Because of the non-linear nature of Equation (1), values for α_{isc} cannot be assumed. The coefficients α_{isc}, α_{imp}, and β_{vmp} will be obtained as part of the analysis procedure.

b) Compute air mass (AM) and absolute air mass (AM_a) using:

$$AM(Z_s) = \{\cos(Z_s) + 0.50572\ [96.07995 - Z_s(\text{degr})]^{-1.634}\}^{-1} \quad (6)$$

$$AM_a(Z_s, P/P_o) = (AM) * P/P_o \quad (7)$$

where

$$P/P_o = e^{-0.0001184*h} \text{ (with } h \text{ in meters)}$$

Air mass is the relative path length that the sun's rays traverse through the atmosphere before reaching the ground. Z_s is the zenith angle of the sun, which can be calculated given the site location, the day of the year, and the time of day. Absolute air mass is "pressure corrected" to compensate for altitudes, h, other than sea level.

c) Determine the cell temperature. If cell temperature is not measured, it can be computed using one of two methods. Equation (8) provides a method to compute cell temperature directly from the V_{oc} and I_{sc} measured in each I-V scan. It uses β_{voc} determined in step a) and the corresponding values V_{oc_r}, I_{sc_r}, and T_r taken at an arbitrary reference condition when the module is in thermal equilibrium. It is useful to pick T_r as the reference cell temperature used for standard conditions. T_r shall be in Kelvin.

$$T_c = \{[(1/N)(V_{oc} - V_{oc_r})] + \beta_{voc} T_r\} / \{[(\mathrm{nk/q})\ \ln(I_{sc}/I_{sc_r})] + \beta_{voc}\} \quad (8)$$

where

N = Total number of cells connected in series in the array
I_{sc} = Measured array short-circuit current, A
V_{oc} = Measured array open-circuit voltage, V
I_{sc_r} = Array short-circuit current at the reference temperature, A
V_{oc_r} = Array open-circuit voltage at the reference temperature, V
T_c = Temperature of cells inside module, K
T_r = Arbitrary reference temperature for cells, K
β_{voc} = Temperature coefficient for V_{oc} for individual cell, V/°C
n = Cell diode factor (n = 1 can be assumed for typical silicon cells)
k = Boltzmann's constant, 1.38066×10^{-23} J/K
q = Elementary charge, 1.60218×10^{-19} C

Because β_{voc} varies over wide temperature ranges, this method is probably not as accurate for wide ranges of T_c as a second method. This alternate method, given by Equation (9), computes cell temperature from a measured heat-sink temperature, T_{hs}. The differential temperature constant, C_7, is computed using Equation (10) with measured values of T_{hs}, E_{DNI}, and E_{DIF}, and a value of T_c computed using Equation (8). This is done using data measured with conditions near the reference condition that was used to compute β_{voc}. Constant C_7 represents the temperature difference between the cell and heat sink per unit of insolation at 850 W/m^2 direct insolation and 150 W/m^2 diffuse insolation. For flat plates, C_7 is generally about 3 °C per 1000 W/m^2 total insolation. For concentrators, C_7 can range from 3 to 10 °C per 1000 W/m^2 insolation, depending on the module design.

Estimate the initial value of $C_6 = 1 / X$.

$$T_c = T_{hs} + C_7 * (E_{DNI} + C_6 E_{DIF}) \quad (9)$$

$$C_7 = (T_c - T_{hs}) / (E_{DNI} + C_6 E_{DIF}) \quad (10)$$

Equation (11) provides a relationship between heat-sink temperature and ambient temperature, insolation, and wind speed. (Cell temperature can be substituted for heat-sink temperature in this relationship.)

$$T_{hs} = T_{amb} + (E_{DNI} + C_6 E_{DIF})[C_8 + C_9 * \exp(-C_{10} * V)] \quad (11)$$

Constants C_8, C_9, and C_{10} are computed by performing a regression analysis of Equation (11), where V is wind speed in m/s.

d) The influences of the parameter C_6 and the air mass function $f_1(AM_a)$ cause Equation (1) to be nonlinear. A non-linear regression method is required to properly estimate these effects. For the functions employed in this model, the iterative non-linear regression techniques found in Bevington

[B3] readily allow rapid estimation of the parameters. An estimate of goodness of fit and of the parameter uncertainties can also be made. The air mass function, $f_1(AM_a)$, can be expanded as a one- or two-term power series as follows:

Compute $amz = [AM(Z_s)\ 1.5]$ for each data point. Assume the expansion of $f_1(AM_a)$ as follows:

$$f_1(AM_a) = 1 + C_{11} * amz + C_{12} * amz^2 \tag{12}$$

The air mass function is analogous to the spectral mismatch parameter. It is the ratio of the module short-circuit current to the output of the solar irradiance sensor (Eppley thermopile, broadband, normal incidence pyrheliometer, normal incidence pyranometer) as a function of air mass.

Perform a non-linear curve fit of the following function to determine the parameters C_6, C_{11}, C_{12}, I_{sc_o}, and $\propto_{isc}$ as follows:

$$I_{sc}(T_c, E_{DNI}, E_{DIF}, AM_a, 0°) = [(E_{DNI}/850) * (1 + C_{11} * amz + C_{12} * amz^2) + C_6(E_{DIF}/150)] * [I_{sc_o}/(1 + C_6) + \alpha_{isc}(T_c - 50\ °C)] \tag{13}$$

e) Compute I_{sc} (T_c = 50 °C, E_{DNI}, E_{DIF} , AM_a, AOI) using Equation (14):

$$I_{sc}(T_c = 50\ °C, E_{DNI}, E_{DIF}, AM_a, AOI) = I_{sc}(\text{measured}) - \alpha_{isc}(T_c - 50\ °C) \tag{14}$$

then compute E_e, the effective irradiance, for each data point using Equation (2).

f) Perform a regression on Equation (15) to identify C_1, C_2, and $\propto_{imp}$ for Equation (3):

$$I_{mp}(\text{meas}) = C_1 + E_e * [C_2 + \alpha_{imp}\ (T_c - 50\ °C)] \tag{15}$$

then compute $I_{mp_o} = C_1 + C_2$.

g) Perform a regression on Equation (16) to identify V_{oc_o}, C_3, and β_{voc} for Equation (4):

$$V_{oc}(\text{meas}) = V_{oc_o} + C_3\ln(E_e) + \beta_{voc}(T_c - 50\ °C) \tag{16}$$

h) Perform a regression on Equation (17) to identify V_{mp_o}, C_4, C_5, and β_{vmp} for Equation (5):

$$V_{mp}(\text{meas}) = V_{mp_o} + C_4\ln(E_e) + C_5[\ln(E_e)]^2 + \beta_{vmp}(T_c - 50\ °C) \tag{17}$$

i) Finally, compute P_{max_o} using Equation (18):

$$P_{max_o} = V_{mp_o} * I_{mp_o} \tag{18}$$

Record the values of parameters obtained, along with estimated standard deviations, for use in comparative analysis.

Check the values obtained for $\propto_{isc}$, $\propto_{imp}$, β_{voc}, and β_{vmp} for consistency with expected results from cell data. The value for β_{voc} used to compute T_c in Equation (8) should be compared with the value found in step h) with Equation (16). Reasonable agreement should be found.

Once all the functions and coefficients are obtained, Equations (1), (3), (4), and (5) are used to compute I_{sc}, V_{mp}, I_{mp}, and V_{oc} for the measured data. These can then be used to compute the maximum power by multiplying I_{mp} by V_{mp}.

5.2.2.3 Outdoor-light I-V test method C

This is an alternative method to I-V test methods A and B to identify degradation of a module by comparing its post-stress test relative power to its initial one. The relative power is defined as the maximum power output of a test module divided by the maximum power output of the control module, measured under similar test conditions. It is based on the assumption that the change of the control module's electrical performance is negligible during the whole qualification test period. By using this method, all environmental variables are self-corrected, and the translation procedures are eliminated. The same method is applicable to receivers as well.

Procedure:

a) Measure the initial relative power of a module before any stress test has been applied by using step b) through step e).
b) On a sunny day, mount the test module and the control module side-by-side on a two-axis tracker. Adjust the alignment according to 5.2.1. Both modules are open-circuit. For a receiver, refer to 5.2, Receiver.
c) Wait until the temperature changes of both modules are less than 2 °C in any 30-second period.
d) Make I-V measurements on both modules to get their maximum power output. This procedure should be completed in a quick manner so that the changes of solar irradiance, ambient temperature, and wind speed cause a variation in power output of less than 2% during this step.
e) Calculate the module's initial relative power Pr_i as follows:

$$Pr_i = \frac{Pm_i}{Pmc_i} * 100\%$$

where

Pr_i is the module's initial relative power, in %
Pm_i is the module's initial maximum power, W
Pmc_i is the control module's maximum power measured at the same condition of Pm_i, W

f) Measure the module's post-stress test relative power after each stress test has applied to the module by repeating step b) through step d);
g) Calculate the module's post-stress test relative power Pr_p as follows:

$$Pr_p = \frac{Pm_p}{Pmc_p} * 100\%$$

where

Pr_p is the module's post-stress relative power, in %
Pm_p is the module's post-stress maximum power, W
Pmc_p is the control module's maximum power measured at the same condition of Pm_p, W

When Pr_p is 1% less than Pr_i, it represents a 1% power decrease.

5.2.3 Dark I-V test

In addition to all three of the outdoor light I-V test methods for the initial and final electrical performances, the dark I-V test may be used to monitor the electrical performance of the module after each required test by quantifying an increase in series resistance. The dark I-V test is not intended to be used as the criterion as to whether the module passes the series of qualification tests, but as a cost effective method for identifying degradation of the module's electrical performance. If degradation is identified by a dark I-V test, the tester and manufacturer should discuss whether to proceed with the rest of the test sequence or to terminate testing while the module construction is improved.

Procedure:

a) Use a power source[8] to forward bias the module with a current equivalent to the rated current for the module (the current generated by the module under 850 W/m^2 direct normal irradiance). Record the exact current and voltage. Complete this procedure as quickly as possible to avoid significant heating of the cells. If the temperature drift is too fast to give a reproducible reading, allow the current to flow while the module heats to its equilibrium temperature, then record the steady state values.
b) Repeat step a) using a forward bias current 1.2 to 1.6 times larger.
c) Repeat step a) with the original current to see if it is reproducible.
d) Calculate the effective increase in resistance, ΔR, as follows:

$$\Delta R = \frac{(V_{bp} - V_{ap}) - (V_{bi} - V_{ai})}{I_b - I_a}$$

where

V_{ai} is the voltage measured in step a) initially,
V_{ap} is the voltage measured in step a) for post-stress test,
V_{bi} is the voltage measured in step b) initially,
V_{bp} is the voltage measured in step b) for post-stress test,
I_a is the current used in step a) (approximately I_{sc} or I_{mp}), and
I_b is the current used in step b).

When $I_a \Delta R$ is 1% greater than V_{ai}, it represents a 1% power decrease.

5.3 Ground continuity test

Module

Purpose: To verify electrical continuity between all exposed conductive parts and the grounding point of the module.

Procedure: A continuity tester (ohmmeter) should be used to test electrical continuity between the part in question and the module ground point (ASTM E1462-00, Section 7.3). This test is adapted from the UL specification for flat plate modules (UL 1703-2000, Section 25). The resistance between the grounding terminal or lead and any accessible conductive part should be measured when a current of two times the rated short-circuit current of the module is passed through the grounding terminal and conductive part in question.

[8]The power source could be a conventional DC power supply or a charged-up capacitor, whatever is most convenient, as long as it will generate currents in the ranges specified above.

If the module manufacturer has not provided contact points for this test on the modules, a small area of the module at a worst case location will be scraped clear of any anodization or coatings to make good contact.

The resistance should be calculated from the applied current and the measured voltage between the grounding terminal and a point within 1.3 cm (0.5 in) of the point of current injection. For each test, the test current is applied for less than one minute to avoid overheating. If more than one test is needed to evaluate all paths of conduction, there is to be a cooling time of at least 15 minutes between tests. To minimize danger to personnel, a current and voltage limited power supply that is not capable of producing more than 48 V dc between its output terminals should be used for this test.

Requirements: Resistance should be less than 0.1 Ω between each point tested and the module ground point. All exposed surfaces shall be tested.

5.4 Electrical isolation test (dry hi-pot)

Purpose: To ensure that electrical isolation between the module circuit and any externally exposed conductive part is adequate to prevent corrosion and to provide safety for personnel.

Procedure: Each receiver or module should be subjected to direct current (DC) hi-pot testing conducted at room temperature with the output terminations short circuited, as specified in ASTM E1462-00, Section 7.1. To determine the dry insulation resistance, apply DC voltage not less than 500V.

Cautions—Capacitive effects of the hardware may cause lethal conditions to occur during this test. Do not contact the test probes while voltage is applied; secure them to the receiver section with clamps.

Requirements: The sample should show no arcing or flash-over. Dry insulation resistance times receiver area should exceed 40 MΩ-m^2. If the receiver area is less than 0.1 m^2, the insulation resistance should exceed 400 MΩ.

5.5 Wet insulation resistance test

Purpose: To verify that moisture will not penetrate to the electrically active portion of the receiver, where it could cause corrosion, ground faults, or present a personnel safety hazard.

Background: Field experience has shown that due to the volume of air that concentrators contain, it is virtually impossible to seal them against moisture intrusion. As an example, during an afternoon thunderstorm, the rapid cooling of a module can draw large amounts of moist air into the module through small openings or vent holes. The seals on the module housing typically function only to keep gross amounts of water or dust out of the module. Condensation inside the module will almost certainly result in occasional episodes of water on the receiver section.

Because the integrated current drives electrochemical corrosion over the life of the hardware, the maximum allowable leakage current is much less than that which ensures personnel safety.

Procedure:

a) Prepare the test solution with the resistivity 3500 Ω-cm or less, surface tension 0.03 N/m (30 dynes/cm) or less.
b) Receivers should be wetted by either spraying, or immersing into the solution for 5 to 30 minutes.
c) Connect a DC source not less than 500 V to the receiver with the high potential to shorted sample output leads and low potential to the ground point.
d) Take readings after two minutes of energizing to allow capacitive charging currents to dissipate.

Caution—As a safety precaution, the operator should not touch the test item, cabling, or test equipment (other than the controls) while the test is in progress.

Requirements: Wet insulation resistance times receiver area should exceed 40 MΩ-m^2. If the receiver area is less than 0.1 m^2, the insulation resistance should exceed 400 MΩ.

5.6 Water spray test

Purpose: The field wet resistance test (FWRT) evaluates the PV module's electrical insulation under wet operating conditions. This test simulates rain or dew on the array and its wiring and verifies that moisture will not enter active portions of the array's electrical circuitry where it may enhance corrosion, cause ground faults, or pose an electrical safety hazard to personnel or equipment.

Procedure:

a) Mount the module and spray water for one hour following the procedure in UL 1703-2000, Section 31.
b) Immediately after step a), measure insulation resistance by connecting a DC source not less than 500 V to the module with the high potential to shorted output leads and low potential to the ground point.

Requirements: Insulation resistance times receiver area should exceed 40 MΩ-m^2. If the receiver area is less than 0.1 m^2, the insulation resistance should exceed 400 MΩ.

5.7 Thermal cycle test

Receiver

Purpose: To determine whether receiver sections have adequate resistance to failures due to differential thermal expansion of component parts and bonding materials. Solder bonds and encapsulation quality are of particular concern.

Background: Thermal cycle tests for concentrator cells soldered to copper heat spreaders reveal solder fatigue crack propagation under the cell measured by thorough transmission ultrasonic inspection (SAND92-0958 [B5]). The crack propagation is a function of the number of thermal cycles, the initial integrity of the solder joint, solder joint geometry, the thermal expansion mismatch between the cell and heat spreader, and the temperature cycle parameters. The thermal cycle test also tests the quality of encapsulation and insulation materials used in receiver construction.

There are two sequences in the test program for test receivers as shown in Figure 1: sequence A and sequence B. Sequence A tests receivers for resistance to thermal stresses caused by differential thermal expansion. Sequence B employs thermal cycling to precondition receivers for the humidity freeze cycle testing. This preconditioning pre-stresses the materials in the receiver to initiate defects that are caused by humidity freeze stresses in the field. To accommodate different concentrator receiver designs, several options are available for conducting the thermal cycle tests for sequences A and B, as shown in Table 2 and Table 3.

Those receivers that employ a design where the solar cell is directly bonded to a copper heat spreader are required to use the conditions in the first row of Table 2. This will ensure that potential failure mechanisms, which may result from defects in the design implementation, are detected. Those designs that employ different methods to bond the cell to heat sinks may use the alternative conditions shown in the table.

Table 3 shows the alternative options for conducting the sequence B thermal cycle preconditioning of the receiver sections. Because sequence B primarily tests the other materials in the receiver, the alternatives are available for all designs.

Table 2—Receiver thermal cycle sequence test conditions Sequence A – thermal cycling

Option	Maximum temperature	Total cycles	Applied current	Required for designs
TCR-A	110 °C	250	None	Cells soldered directly to Cu heat spreaders
TCR-B	90 °C	500	None	Alternate for other designs
TCR-C	90 °C	250	I(applied) = I_{sc}	Alternate for other designs

Table 3—Receiver thermal cycle sequence test conditions Sequence B – thermal cycling for humidity freeze test preconditioning

Option	Maximum temperature	Total cycles	Applied current	Required for designs
HFR-A	110 °C	100	None	Alternate for all designs
HFR-B	90 °C	200	None	Alternate for all designs
HFR-C	90 °C	100	I(applied) = I_{sc}	Alternate for all designs

Procedure: Receiver sections will be subjected to thermal cycling between –40 °C and T_{max} derived from Table 2 and Table 3, depending on the test sequence. Cycling may be carried out in air in a single chamber system or in a dual chamber, shock cycling system. Liquid-to-liquid shock cycling should not be used. A dwell time of at least 10 minutes within ±5 °C of the high and low temperatures is required. The cycling frequency should not be greater than 24 cycles per day nor less than 4 cycles per day. The recommended frequency is 18 cycles per day. Two samples will be thermally cycled for the required number of cycles and T_{max} from Table 3 (sequence B in Figure 1), then will be subjected to visual inspection and electrical performance testing (see 5.1 and 5.2). The samples will be subjected to the humidity freeze test, described in 5.8. In the case of large receivers, see 4.1.1. (This procedure is illustrated in Figure 3.)

Requirements: All samples should be inspected after the tests for any signs of cracking, separation of bonds, peeling of metallization from cells, encapsulation delamination or bubbling, or other degradation. If an optional electrical performance test is applied, the output power should be 90% or greater of the original baseline performance for the same reference condition.

Module

Purpose: To determine whether module components that have not already been cycled as part of a receiver section have adequate resistance to failures due to differential thermal expansion.

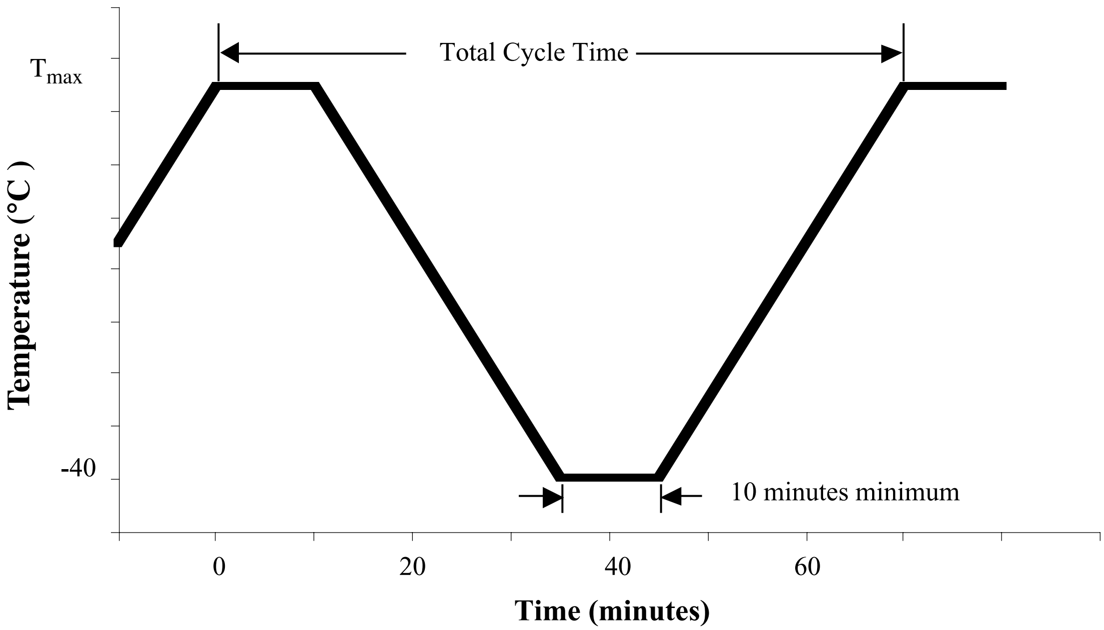


Figure 3—Thermal cycle for receiver sections

Background: The thermal cycling tests are designed as accelerated tests that will expose, in a short period of time, failure mechanisms that have been previously identified in PV concentrator hardware in the field. As such, the tests include a higher temperature differential than modules are likely to see in the field. The upper limit to the thermal cycling of 60 °C is set primarily by softening temperatures of the acrylic lenses used in many modules. For all other designs, the upper limit to thermal cycling is 90 °C (see Table 4).

Table 4—Module thermal cycle sequence test conditions
Sequence B – thermal cycling for humidity freeze test preconditioning

Option	Maximum temperature	Total cycles	Applied current	Required for designs
TCM-A	90 °C	50	None	Alternate for all designs
TEM-B	60 °C	200	None	May be required for plastic lens module designs

Procedure: Two modules will be subjected to 200 thermal cycles between –40° and 60 °C or to 50 cycles between –40° and 90 ºC, in accordance with the profile described and shown in ASTM E1171-99. The relative humidity does not need to be controlled. The rate of temperature change should not exceed 100 °C/h. A dwell time of at least 10 minutes within ±5 °C of the high and low temperatures is required.

Requirements: Modules will be inspected after cycling and any visible damage or degradation documented. Modules should not show any cracking or warping, and there must be no delamination of sealing materials. If an optional electrical performance test is applied, the output power should be 90% or greater of the original baseline performance for the same reference condition.

5.8 Humidity freeze cycle test

Receiver

Purpose: To determine whether receiver sections have adequate resistance to the detrimental effects of corrosion and/or humidity expansion of polymeric materials. Also, to determine resistance to failures caused by freezing moisture.

Procedure: Samples after the thermal cycling test on Table 3 will be subjected to 20 cycles of 85% relative humidity, 85 °C and –40 °C freeze test, in accordance with the profile shown in ASTM E1171-99. In the case of large receivers, see 4.1.1.

Requirements: The receiver sections should meet the requirements listed in 5.7. Within 2 to 4 hours of removal from the environmental chamber, receiver sections should meet the requirements of the hi-pot test (see 5.4).

Module

Purpose: To determine whether modules have adequate resistance to the detrimental effects of corrosion and/or differential expansion at material interfaces.

Procedure: Two modules will be subjected to 20 humidity freeze cycles, in accordance with the profile shown in Figure 4 or to 10 cycles to 85 ºC as in ASTM E1171-99. Note that the maximum temperature of 60 °C is lower than that used in the humidity freeze test for receiver sections. A complete hi-pot test (see 5.4) will be conducted within two to four hours after cycling is completed. Following the hi-pot test, an electrical performance test, as described in 5.2, may be performed. In the case of large modules, see 4.1.1.

Requirements: The module will be inspected after testing, and any observable damage or degradation will be documented. The module should show no cracking, warping, or severe corrosion. There should not be any delamination of sealing materials. The module should pass the hi-pot test, as described in 5.4. If an optional electrical performance test is applied, the output power should be 90% or greater of the original baseline performance for the same reference condition.

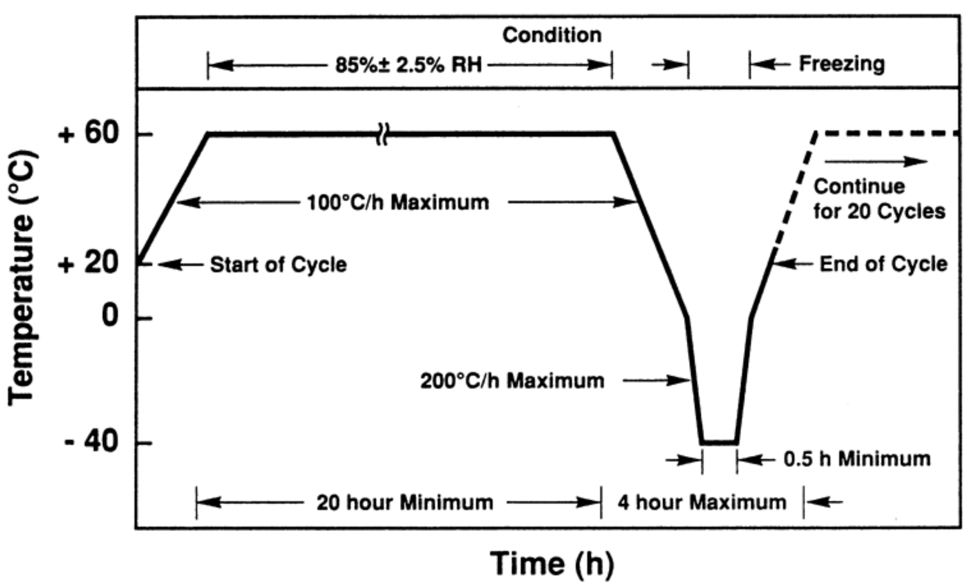


Figure 4—Humidity freeze cycle for module sections

5.9 Robustness of terminations test

Module

Purpose: To ensure that the leads and connectors that bring power out of each module are sufficiently robust to survive normal handling procedures.

Procedure: A 9-kg (20-lb) weight should be suspended from each module lead/termination for one minute with the module in each of the following four positions:

a) In the on-track position
b) Upside down if this position is appropriate
c) In its stow position
d) At the normal limit of its travel

(Terminations should be tested in accordance with UL 1703-2000, Section 28, for terminal-type connectors and with UL 1703-2000, Section 22, for pigtails or other external wire terminations.)

Caution—Perform this test indoors or with the module shaded to minimize any electrical hazard that may develop as a result of the test.

Requirements: There should be no damage to the power lead or connectors.

5.10 Damp heat test

Purpose: To determine the ability of the receiver to withstand the effects of long-term penetration of humidity.

Procedure: The test receivers should be subjected to a test in an environmental chamber in which the relative humidity should be controlled to 85% ± 5%, when the temperature is 85 °C ± 2 °C, as described in ASTM E1171-99. The test should be performed for 1000 hours, but may be continued for up to an additional 60 hours to permit the following dry hi-pot test to be performed. Receiver subsections may be used for this test.

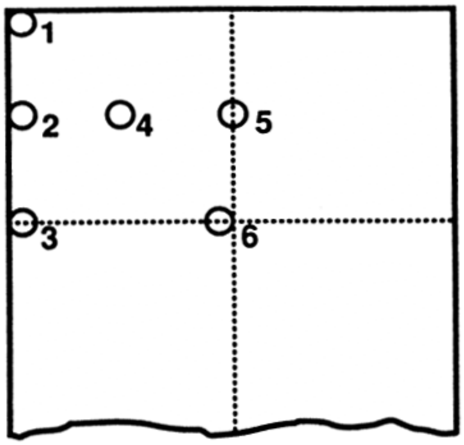
Requirements: The receiver should pass the dry hi-pot test (see 5.4) between 2 and 4 hours of removal from the damp heat chamber. The receiver should pass the visual inspection (see 5.1). If an optional electrical performance test is applied, the output power should be 90% or greater of the original baseline performance for the same reference condition.

5.11 Hail impact test

Purpose: To determine whether the module, particularly the concentrator lens, can survive a hailstorm.

Procedure: This test should be performed in accordance with ASTM E1038-98. The module will be subjected to normal impact loading with 7.9 g ± 5%, 25.4 mm ± 5% (1 in) diameter spherical ice balls traveling at a terminal velocity of 23.1 m/s ± 2% (52 mph). At least 10 representative locations on the module lens and housing sides (if deemed appropriate) should be tested. These should include the lens locations diagrammed in Figure 5 and Figure 6. For concentrator systems based on reflecting mirrors, the mirror will be subjected to the hail impact test. If the receiver in the reflecting system is exposed to the elements, it too will be subjected to the hail impact test.

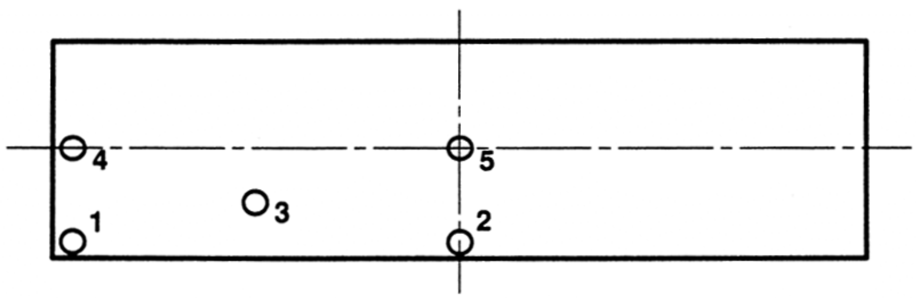
After being formed in an appropriate mold, the ice balls should be stored at –8 °C ± 2 °C for at least 8 hours. These tests should be performed with the module at a temperature of 20 °C ± 10 °C.



Locations:

1) 2 to 4 cm from lens/housing bond at corner.
2) 2 to 4 cm from lens/housing bond at lens midpoint.
3) 2 to 4 cm from lens/housing bond between lens elements.
4) Center of lens element.
5) Center of line between lens elements.
6) 2 to 4 cm from lens support point.

Figure 5—Representative impact locations for hail test on point focus lens



Locations:

1) 2 to 4 cm from lens/housing bond at corner.
2) 2 to 4 cm from lens/housing bond at lens midpoint.
3) Half way from corner to lens midpoint.
4) 2 to 4 cm from lens/housing bond at lens midpoint.
5) Lens midpoint.

Figure 6—Representative impact locations for hail test on line focus lens

Requirements: The module will be inspected after each impact to determine if any obvious damage has occurred. Any damage will be documented. Any cracks or holes in the module that are visible to the unaided eye will cause the module to fail this test.

5.12 Bypass diode thermal test

Purpose: To assess the adequacy of thermal design and relative long-term reliability of bypass diodes used to limit the detrimental effects of module hot-spot susceptibility.

5.12.1 Non-intrusive bypass diode thermal test

Procedure: Follow the procedure as described in Test 5.15.1 in IEEE Std 1262-1995, with applied current equal to 1.25 times rated short-circuit current corresponding to rated DNI and ambient temperature of 25 °C.

Requirements: Each diode case temperature should be such that the diode manufacturer's maximum junction temperature rating on the diode is not exceeded during step c) in Test 5.15.1 in IEEE Std 1262-1995. No physical damage should occur during step d). The diode should conduct the required current for the duration of the test. The module should pass the visual inspection (see 5.1). If an optional electrical performance test is applied, the output power should be 90% or greater of the original baseline performance for the same reference condition.

5.12.2 Intrusive bypass diode thermal test

Procedure: This test is required only if bypass diodes are part of the receiver construction and only if access to bypass diodes is not possible without compromising the integrity of the receiver. The intrusive bypass diode thermal test requires the fabrication of a special test receiver. This receiver should be manufactured with accessible 30-gauge thermocouple wire attached to the cases of the bypass diodes to measure the case temperatures. The thermocouple wires should be attached in a way to ensure a minimum of disturbance to the diode and its thermal environment. In all other respects, this receiver should be manufactured as close as possible to the standard receiver module.

The remainder of this test follows the procedure in 5.12.1, except for the mounting of the thermocouple.

Requirements: Same as 5.12.1.

5.13 Hot-spot endurance test

Purpose: To evaluate the ability of a module to endure the long-term effects of periodic hot-spot heating associated with common fault conditions such as severely cracked or mismatched cells, single point open circuit failures, or non-uniform shadowing (partial shadowing).

Procedure: Follow the procedure as described in IEEE Std 1262-1995, Test 5.16.1, with direct normal irradiance of not less than 600 W/m^2 for Test 5.16.1, procedure b), and a DNI of 800W/m^2 for a minimum ambient of 20 ºC in procedure f).

A module is exempt from this test if it has one bypass diode for each cell.

Requirements: The module should pass the visual inspection (see 5.1). If an optional electrical performance test is applied, the output power should be 90% or greater of the original baseline performance for the same reference condition.

5.14 Outdoor exposure test

Purpose: To make a preliminary assessment of the ability of the module to withstand exposure to outdoor conditions (including ultraviolet exposure) and to reveal any synergistic degradation effects that may not be detected by laboratory tests.

Procedure: The modules should be short circuited and mounted outdoors, as recommended by the manufacturer. Any hot-spot protective devices recommended by the manufacturer should be installed before the modules are mounted. The modules should be exposed outdoors for accumulated exposure of 15 kWh/m^2, for wavelengths below 400 nm, or 90 days, whichever is longer.

Requirements: After the completion of this test, the modules should pass the dry hi-pot test (see 5.4) and the visual inspection (see 5.1). If an optional electrical performance test is applied, the output power should be 90% or greater of the original baseline performance for the same reference condition.

5.15 Off-axis beam damage test

Purpose: To ensure that no part of the module could be damaged by concentrated solar radiation during conditions of module misalignment.

Procedure: The module design and the module itself will first be examined to determine whether any materials are present that might be damaged by high temperatures or intense solar radiation, and whether these materials are sufficiently protected from exposure. If such insufficiently protected materials are identified, the module alignment will be offset, so that light is focused on the suspect location. The module will then track the sun in this position for at least 15 minutes, with DNI greater than 850 W/m^2. This will be repeated for each suspect location, and the module observed during each exposure and inspected for evidence of damage after each exposure. If no specific locations are identified, a simple “walk-off” test will be performed. The module will be aligned toward the sun, then tracking will be stopped, allowing the sun to “walk off” to an angle of 45° relative to the module (3 hours). Throughout this test, DNI should be at least 850 W/m^2.

Requirements: There should be no evidence of melting, smoking, charring, deformation, or burning of any material.

Annex A

(informative)

Bibliography

[B1] ASTM 131 (draft)—Revision 10, dated 10/20/98—Standard Test Methods for Electrical Performance of Concentrator Terrestrial Photovoltaic Modules and Arrays under Natural Sunlight.

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[B3] Bevington, P. R. and Robinson, D.K., Data Reduction and Error Analysis for the Physical Sciences, 2nd ed., McGraw Hill, Boston, MA, 1992.

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[B5] Evaluation Tests for Photovoltaic Concentrator Receiver Sections and Modules, 1992, SAND92-0958, Albuquerque, NM: Sandia National Laboratories.

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