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Evaluation Tests for Photovoltaic Concentrator Receiver Sections and Modules

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Prepared by
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Albuquerque, New Mexico 87185 and Livermore, California 94550
for the United States Department of Energy
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Sandia National Laboratories

Albuquerque, New Mexico 87185

June 15, 1992

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Dear Colleague:

Thank you for taking the time to comment on the new set of concentrator test specifications. Your input was invaluable in improving the document.

Attached is the finished document "Evaluation Tests for Photovoltaic Concentrator Receiver Sections and Modules," SAND92-0958. This supersedes "Qualification Tests for Photovoltaic Concentrator Cell Assemblies and Modules," SAND86-2743. Changes in the specifications are summarized below:

General Changes

Revised and verified the recommended technique for monitoring hardware for open-circuit conditions and ground faults during testing. We have attempted to quantify absolute tolerances for test procedures where possible.

Changes to Receiver Section Tests

	<u>Old</u>	<u>New</u>
Specific tests for control hardware	No	Yes
Number of receiver sections required	4	6
Minimum time for testing	3 weeks	8 weeks
Number of humidity/freezing cycles	10	20
Number of temperature cycles	250	250
Allowable solder-bond contact-area loss	5%	10%
Wet Insulation-Resistance Test required (100 MΩ pass/fail criterion)	No	Yes
One intermediate electrical test required (5% electrical degradation allowed after individual tests)	No	Yes
Overall allowable electrical degradation	8%	8%
One month of outdoor exposure required	No	Yes
Specific UV exposure requirements	1000 hrs.	160 hrs.*

*Outdoor exposure replaces receiver UV test.

MASTER

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June 15, 1992

Changes to Module Tests

	<u>Old</u>	<u>New</u>
Specific tests for control hardware	No	Yes
Number of modules required	3	6
Minimum time for testing	12 weeks	16 weeks
Revised grounding tests	No	Yes
Number of humidity/freezing cycles	10	20
Number of temperature cycles	120	200
Wet Insulation-Resistance Test required (50 MΩ pass/fail criterion)	No	Yes
Two intermediate electrical tests required (5% electrical degradation allowed after individual tests)	No	Yes
Overall allowable electrical degradation	8%	8%
Cable Strain-Relief Test required	No	Yes
Twisted Mounting Surface Test required	No	Yes

You may call Joe Woodworth at 844-7247 or me at 844-3154 if you have comments about the new document. Please continue to provide feedback about the document so we can continue to improve it. In particular, specific data on field failures will help us assess the validity of the evaluation tests we have specified.

Joe Woodworth will be presenting a summary of the new specifications at the Crystalline Photovoltaic Technology Project Review Meeting (PRM) in Albuquerque on July 15. We will be available during the PRM to address any issues you would like to discuss. If there is sufficient interest, we can arrange for a group discussion of the document, possibly during a lunch break. Please call us if you are interested.

Sincerely,

Marjorie L. Whipple
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**EVALUATION TESTS FOR PHOTOVOLTAIC CONCENTRATOR
RECEIVER SECTIONS AND MODULES**

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U. S. Department of Energy**

ABSTRACT

Sandia has developed a third-generation set of specifications for performance and reliability testing of photovoltaic concentrator modules. Several new requirements have been defined. The primary purpose of the tests is to screen new concentrator designs and new production runs for susceptibility to known failure mechanisms. Ultraviolet radiation testing of materials precedes receiver section and module performance and environmental tests. The specifications include the purpose, procedure, and requirements for each test. Recommendations for future improvements are presented.

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The authors thank Elizabeth Richards and Jay Chamberlin for their valuable input concerning this document. Jack Cannon's experience in testing was very valuable for addressing safety concerns and testing methods. Review and comment by David King has improved several sections of the document, particularly the electrical performance test descriptions. We also thank the following people for their help in updating these specifications: Alex Maish, Tom Hund and Charles Stillwell.

SECTION 1

INTRODUCTION

1.1 Purpose of the Evaluation Tests

This document provides specifications for performance and reliability evaluation of photovoltaic (PV) concentrator receiver sections and modules. The purpose of the tests is to evaluate new designs and new production processes for susceptibility to known failure mechanisms. Accordingly, the tests are designed to promote the types of failure mechanisms that have been identified in previous generations of photovoltaic concentrator hardware operating in the field. These tests involve electrical performance characterization, checks to assure safety and structural integrity of modules, and accelerated environmental aging or cycling.

These tests were created for use at Sandia National Laboratories to evaluate PV concentrator hardware developed through our in-house program, as well as by our contractors. It is important to note that the specification in its present form is not intended to serve as a uniform standard for the concentrating photovoltaic industry. However, since this document may be used by concentrator system specifiers, it is intended to describe the tests in enough detail that agencies other than Sandia could perform them. The tests are described as evaluation tests because hardware which passes the tests will have been exposed to many of the mechanisms which have caused failures in concentrator modules in the field, without experiencing significant electrical degradation. Successful completion of these tests is not intended to guarantee that modules will survive for 20 to 30 years in field operation, the goal for PV systems. Our current understanding of failure mechanisms and the relationships between accelerated tests and field reliability is not sufficient to allow accurate estimation of life expectancy, thus the cycling tests prescribed in this document are not intended to be equivalent to a full 20- or 30-year field exposure. Rather, these tests are intended to help assure that developmental hardware will be sufficiently durable to operate without significant reliability problems for many years, allowing thorough, long-term, electrical performance characterization.

1.2 Background

In developing these evaluation tests, we have drawn from a number of sources of information or experience:

- The Jet Propulsion Laboratory (JPL) Block V specification for one-sun modules.¹
- Recommended test methods compiled by the National Renewable Energy Laboratory (NREL) for photovoltaic energy systems.^{2,3}
- Previous qualification specifications used at Sandia.⁴
- The European Solar Test Installation (ESTI) qualification test procedures for crystalline silicon modules.⁵
- The Underwriters Laboratories (UL) standard for one-sun modules.⁶
- Data on concentrator module reliability and failure mechanisms from field surveys and failure analyses of components.^{7,8,9,10}
- Data from solder fatigue experiments on representative components.¹¹

In the years since the JPL Block V specification was implemented, one-sun module designs that passed the Block V tests have demonstrated low failure rates in field installations. The UL specification, which includes most of the Block V tests, was developed to serve as a standard for the one-sun industry and has been widely accepted. The typical operating environment and service requirements for concentrators are in many ways similar to those for one-sun modules. Accordingly, there are many similarities between the present evaluation tests and the Block V specifications. Some tests, such as the humidity-freeze test for receiver sections, have been adapted directly from the JPL and UL documents. Other tests in this document are modeled after tests for one-sun modules, but specifications have been modified to account for the particular operating characteristics of concentrators. For example, cells in typical flat-plate modules operate at 20 to 40°C above ambient temperature and cells in well-designed concentrator modules operate at 30 to 50°C above ambient. Therefore, the thermal cycling test for concentrator receiver sections is more severe than that for one-sun modules. A few tests, such as the off-axis beam damage test, are relevant only to concentrators.

1.3 Significant Changes in the Specifications

This third revision to the previous concentrator qualification document⁴ represents the latest information on failure mechanisms in concentrator modules. Significant changes include the following: incorporation of a wet insulation-resistance test, increased number of environmental cycles for both receiver sections and modules, a cable strain relief test, a twisted mounting surface test, increased number of test samples required, and combination of the ground continuity check and the grounding bond-path resistance test. Intermediate electrical performance tests have been added to identify the effects of individual tests in the sequence.

Revisions to the document are based on information on failure mechanisms acquired from both field experience and laboratory experiments. Also, recommendations from test operators have been incorporated to improve the ease and safety of several of the existing test specifications.

The definitions below describe categories of PV concentrator hardware that are referred to throughout the document.

Cell Assemblies; (Appendix A) are defined as a PV cell with its grid metallization, its solder or adhesive connection to a heat spreader, and its interconnects. Inclusion of the secondary optical element (if any) and the cell encapsulation is optional.

Receiver Sections; (Section 3) are defined as hardware assemblies including at least two PV cells, an interconnect, secondary optical elements (if used), encapsulants, adhesives, and representative components of the heat sink or housing. Receivers must be constructed using the same materials and techniques as the complete module.

Modules; (Section 4) are defined as a complete receiver, permanently mounted in the correct orientation relative to the primary lens or mirror, with A) all appropriate lens/housing seals and breather vents in place, B) all the hardware to mount the module on its tracking frame and C) all appropriate electrical components to allow the module to produce power when aligned with the sun.

1.4 Overview of the Test Sequence

This section describes categories of tests, hardware and time requirements for the complete sequence of tests used to evaluate receiver sections and PV modules. The document

describes each test by addressing the purpose, background (when appropriate), procedure, and requirements of the test.

Categories of Tests:

1) Recommended tests on cell assemblies are described in Appendix A. These tests should be carried out early in the design phase to evaluate the durability of any solder bonds. While these tests are not mandatory, it is our experience that performing these tests on cell assemblies before receiver sections are constructed will save the module manufacturer time and money.

2) Ultraviolet (UV) exposure tests on materials and individual components are described in Section 2. These tests should be carried out as early as possible in the design phase to ensure that proposed materials are not UV sensitive.

3) Performance and environmental tests on receiver sections are specified in Section 3.

4) Performance and environmental tests on complete modules are given in Section 4.

This document will be revised periodically to incorporate the latest information on failure mechanisms and the relationships between accelerated tests and field reliability. Accordingly, Section 5 provides recommendations for continued evolution of the tests.

Hardware Requirements:

Two flat (planar) samples of lens material and two housing samples (if non-metallic) are required for the ultraviolet exposure tests described in Section 2. Components encapsulated with materials that may be sensitive to UV exposure must also be tested, and two samples of each are required.

Six receiver sections are required for the performance and environmental tests described in Section 3. Larger numbers are preferred when practical.

Six complete modules are required for environmental tests shown in Figure 4-1. The hot-spot endurance test may require alteration or penetration of one module to allow appropriate instrumentation.

Time Requirements:

Time requirements for evaluation testing must be taken into account in scheduling any module development activity. The minimum time to complete the test sequence for receiver sections is eight weeks. The test sequence for modules could take as long as four months.

1.5 Requirements for Re-Test

Any change in the design, materials, or construction method of the hardware is considered an alteration of the module and should be evaluated by undergoing the complete test sequence. The hardware manufacturer, the evaluator, and the agency or individual requiring the tests (the test requestor) should discuss this issue before testing begins.

1.6 Pass/Fail Criteria

Modules and receiver sections which meet or exceed the requirements of all of the tests described in Sections 2, 3, and 4 are judged to have "passed" the evaluation tests. Hardware designs which have been modified, after failing a specific test, should be subjected to the same test to verify the problem has been corrected before reinitiating the entire test sequence.

SECTION 2

ULTRAVIOLET (UV) EXPOSURE TESTS ON MATERIALS AND COMPONENTS

Purpose: To assure that materials and components which will be subjected to light containing a UV component in the field have the ability to withstand UV exposure without significant degradation.

Background: This section describes UV exposure tests for individual materials and components. Lens material samples, non-metallic housing samples, painted metal housing samples, receiver samples, and any other relevant materials (such as sealants) will be exposed to accelerated UV aging to assure resistance to UV degradation. The exposure for housing samples is less severe than the lens exposure for two reasons: 1) Most lens materials contain UV inhibitors which serve to protect the inside of the housing, and 2) as long as the module is tracking properly, the outside of the housing will receive very little UV exposure. Candidate materials should be tested as early as possible in the design process, so that UV resistance is established before the construction of prototype receivers or modules.

Samples are normally maintained at a controlled temperature and exposed to concentrated UV radiation. The UV-region of the ASTM Standard Spectral Irradiance ¹² is shown in Fig 2-1. In Figure 2-1, the integrated solar irradiance for wavelengths shorter than 400 nm is 46.2 W/m². The spectrum is essentially zero for wavelengths shorter than 300 nm. This spectrum may be approximated using a 1-kW xenon arc-lamp and two 0.32-cm-thick borosilicate (Pyrex^R) glass filters. The filters are essential to suppress the significant amount of light that the Xenon arc-lamp radiates at wavelengths shorter than 300 nm.

2.1 UV Exposure for Lens Material Samples

Procedure: Two flat (planar) samples (roughly 5 x 5 cm) of the material used in the lens will be tested for direct spectral transmittance over the wavelength range of 300 to 1100 nm. One sample will then be exposed to a 30-sun UV spectrum for 1000 hours, corresponding to a total UV radiant-exposure of 1385 kWh/m². (A different concentration may be used, as long as the total radiant-exposure in the UV is 1385 kWh/m² and the UV intensity never exceeds the 30-sun level.) Ideally, the transmittance of the sample should be remeasured periodically during the UV testing (ie. after 1,000, 3,000, 7,000, 15,000 and 30,000 one-sun hours).

The temperature of the lens sample during this test will be maintained at $30^{\circ} \pm 3^{\circ}\text{C}$. The second sample will be stored in the dark at room temperature as a control. After this test, the direct spectral transmittance of both samples will be recharacterized.

Requirements: The solar-averaged transmittance of the exposed sample must not degrade by more than 5%. The solar-averaged transmittance is computed by integrating the product of the ASTM spectral irradiance and the direct spectral transmittance of the sample over the region from 300 to 1100 nm.

2.2 UV Exposure for Non-Metallic Housing Samples

Procedure: Two samples (roughly 5 x 5 cm) are required. Using the xenon arc-lamp and borosilicate glass filters, one sample will be exposed to 77 kWh/m² of UV radiation (200 hours at 30 suns, or the equivalent) at a temperature of $30^{\circ} \pm 3^{\circ}\text{C}$. The second sample will be stored in the dark at room temperature to act as a control.

Requirements: The exposed sample must exhibit no observable damage.

Figure 2-1. UV Region of ASTM AM1.5 Standard Spectral Irradiance.

SECTION 3

TEST SPECIFICATIONS FOR RECEIVER SECTIONS

This section describes the evaluation test sequence for receiver sections. Receiver sections, or receivers, are tested separately from complete modules for two reasons. First, receivers are exposed to higher temperatures in operation than the lens and most components of the housing. It would be inappropriate to cycle the lens and housing to the same high temperature used in the thermal cycle for receivers. Second, receivers have traditionally presented difficult design and reliability problems because of the simultaneous requirements of electrical isolation and good thermal contact between the cell and the heat sink. Thus, in a developmental program, it is advisable to test the receiver thoroughly before constructing complete modules.

The complete evaluation sequence requires six receiver sections and ordinarily requires about ten weeks of testing time. When not undergoing testing, the receiver used as a control shall be stored in a dry environment, out of direct sunlight, preferably indoors.

Test specifications for receivers are diagrammed in Figure 3-1. Visual inspections (not shown in Figure 3-1) shall be performed after each test. Any changes shall be photographed and documented. All receivers must pass all tests. Descriptions of each test follow.

3.1 Initial Inspection

Purpose: To reject damaged hardware and to establish a baseline against which receiver sections can be compared as they pass through the environmental tests.

Procedure: All hardware will be thoroughly inspected and photographed 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, will be documented with appropriate sketches or photographs to show the locations of the defects. When appropriate, X-ray and ultrasound imaging will be used as part of the inspection process to characterize the quality of the solder bonds under the cells. Ultrasound imaging can be used to detect relatively large void areas but is most useful for detecting changes in solder bond quality. Components, such as secondary optical elements, heat spreaders and encapsulants, shall be inspected for defects.

Requirements: Major defects, such as cracked cells, unsoldered interconnects, or severe damage due to handling, constitute cause for rejection of the hardware without further testing. Using the average contact area of all samples as the standard, samples with contact areas less than 90% of the average (as determined by the number of colored pixels on the ultrasound image) will be rejected. Obvious debonding between components will also cause the samples to be rejected.

Figure 3-1. Test Sequence for Receiver Sections. Vertical lines show how many receiver sections undergo each test. Numbers preceding the titles refer to the section of text describing each test. Numbers in parenthesis refer to the approximate number of days needed to perform the test. Visual inspections are performed after each test.

3.2 High-Voltage Standoff (Hipot)

Purpose: To insure that electrical isolation between the PV circuit and any externally exposed conductive part is good enough to protect personnel from electrical shock hazards.

Background: Photovoltaic concentrator systems are now available in array sizes ranging from less than 1 kW to more than 100 kW. In some cases, the same modules are used on the largest and smallest arrays. Because of the difficulty of setting a current limit without knowing the details of the array in which the module will be fielded, a relatively conservative current limit of 50 μA per receiver section or per module has been adopted.

Procedure: The output terminations of the receiver section shall be electrically joined (shorted) and connected to the high-potential lead from a suitable dc power supply. The ground of the power supply will be connected to the heat sink or to the exposed conductive part closest to the PV circuit. The cut-off threshold on the leakage current detector will be set at 50 μA . Voltage will be increased at a rate not to exceed 200 V/s to a test voltage equal to twice the system open-circuit voltage (at 1000 W/m² irradiance and 20°C ambient temperature) plus 1000 V. If the system voltage is not specified, a test voltage of 2200 V will be used. The test voltage will be maintained for one minute with the receiver at room temperature. If the 50 μA limit is reached, the corresponding voltage will be recorded. The total uncertainty at the 95% confidence level for measured leakage current must not exceed $\pm 5\mu\text{A}$.

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.

Receiver sections will also be hipot tested within one hour after completion of environmental cycling tests as shown in Figure 3-1.

Requirements: Leakage of dc current will be monitored and recorded and must not exceed 50 μA . The hardware will be observed during the test and there must be no sign of arcing or flashover.

3.3 Baseline Electrical Performance Characterization

Purpose: To verify that a receiver section produces power and to establish a baseline against which performance subsequent to reliability tests will be gauged.

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

If the use of a solar simulator is not feasible, receiver sections should be mounted on a two-axis solar tracker and tested outdoors as described in Section 4.4, Baseline Electrical Performance Characterization of Modules.

Requirements: A receiver section must be operated reliably enough that Pmp, Isc, and Voc can be accurately and repeatably measured before and after reliability tests.

3.4 Wet-Insulation Resistance

Purpose: To verify that moisture will not penetrate to the electrically active portion of the receiver section 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.

Since electrochemical corrosion is driven by the integrated current over the life of the hardware, the maximum allowable leakage current is much less than that which ensures personnel safety¹³.

Procedure: With the receiver section at $22^{\circ} \pm 5^{\circ}\text{C}$, the output terminations of the receiver shall be tied together (shorted) and connected to the high potential lead of a megohmmeter that is capable of producing a 500-V output. The ground of the megohmmeter shall be connected to the receiver's ground point. A 0.3% solution of Liquinox¹⁴ in deionized water shall then be sprayed or poured over the cell string until the solution forms a continuous film, covering the PV cell string and extending to the nearest ground point on the receiver section.

The megohmmeter shall then be used to measure the resistance between the cell string and ground with a 500-V potential applied between the two points. After waiting two minutes to allow capacitive charging currents to dissipate, read and record the resistance.

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: The resistance measured from the cell string to the receiver ground must be above 100 megohms under these wet insulation conditions to pass the test. Reference 13 presents the arguments used in developing these criteria.

3.5 Thermal Cycling

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

Background: The criteria for this test are based on solder fatigue studies of point focus concentrator cells (1 cm^2) soldered to copper heat spreaders¹¹. The data reveal solder fatigue crack propagation under the cell measured by ultrasound inspection. 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.

Thermal finite element analysis calculations have shown that for point-focus concentrator cell assemblies with a uniformly-soldered back surface, no significant increase in cell operating temperature occurs until the loss in solder contact area exceeds 50%. As a conservative estimate which accounts for the great variety in concentrator cells, we therefore assume that a cell assembly will "fail" in the field (ie.

its performance will become unacceptably degraded) after 50% of the solder contact area is lost.

In order to test cell assemblies in a reasonable amount of time, the thermal cycling tests must be accelerated. Theoretical models of solder bond fatigue and limited data suggest that a 70-minute-long thermal cycle from 0° to 80° C is roughly equivalent to a diurnal cycle containing a ~30° C temperature variation over 24 hours.

Results of experiments by T. Hund indicate that cycling from -40° to +110° C provides a factor of three acceleration over cycling from 0° to 80° C. The data on solder bond fatigue for cycling between -40° and +110° C show an average contact area loss of $6\% \pm 3\%$ (1σ) after 250 cycles and $42\% \pm 22\%$ (1σ) after 1000 cycles.

Based on this cycling data, we have adopted a 10% contact area loss after 250 cycles from -40° to +110° C as the point at which a cell assembly will fail the thermal cycling tests. We would expect a cell assembly which passes the thermal cycling tests to operate without noticeable degradation in the field for at least 3000 diurnal cycles.

It should be noted that optimum cell assembly designs with a low expansion copper-molybdenum-copper insert between the cell and copper heat spreader have survived in excess of 2,250 cycles between -40 and 110°C. At the end of the 2,250 cycles, the cell contact area loss with this improved design was about 31%, with a standard deviation of 8%. These data indicate that optimum cell assembly designs can survive in excess of 6,700 diurnal cycles (18 years). To achieve the required cell assembly life expectancy, solder joint quality must be high, solder joint geometry must be optimized, and the differential thermal expansion between the cell and heat spreader must be minimized.

In the ultrasound tests, areas with good contact between the cell and the heat sink will transmit the ultrasound energy and will normally be represented as colored pixels. Areas where contact has been lost (voids) will not transmit ultrasound and are normally represented as black pixels. Contact area loss is calculated by using the pixel count from the ultrasonic scan using the following equation:

$$\% \text{ Contact Area Lost} = [(P_s - P_f) \cdot 100] / P_s$$

P_s = Number of colored pixels in as-soldered sample before thermal cycling.
 P_f = Number of colored pixels in sample after thermal cycling.

Procedure: Receiver sections will be subjected to thermal cycling between -40°C. and 110°C. Cycling may be carried out in air in a single-chamber system or 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 as illustrated in Figure 3-2. The cycling frequency must not be greater than 24 cycles per day nor less than 4 cycles per day. The recommended frequency is 18 cycles per day. Receiver circuitry should be instrumented and monitored for ground faults and open-circuit conditions. Appendix B describes a monitoring technique. Four samples will be thermally cycled for 100 cycles then be subjected to visual inspection, hipot testing, and electrical performance testing (see Sections 3.1, 3.2, and 3.3). Two samples will then be returned to thermal cycling until they have accumulated a total of 250 cycles. (The other two samples will be subjected to the humidity-freeze test described in Section 3.6.)

Requirements: All samples will be inspected after the tests for any signs of cracking, separation of bonds, peeling of metallization from cells, or other degradation. In particular, a decrease in electrical contact area of 10% on either the positive or negative side of the cell will be cause of failure. Also, a 10% increase in the void ratio under the cell will be considered a failure. Any decrease in Pmp, Voc, and Isc from their initial values must be less than 5%. The receiver sections must not have exhibited ground faults or open circuits during cycling.

Figure 3-2. Thermal Cycle for Receiver Sections.

3.6 Humidity-Freeze

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 removed from the thermal cycling test after 100 cycles will be subjected to 20 humidity-freeze cycles in accordance with the profile shown in Figure 3-3. Receiver circuitry should be instrumented and monitored using a method similar to that described in Appendix B to verify that no open circuits or ground faults occur during the test.

Requirements: The receiver sections; a) must not have exhibited ground faults or open circuits during cycling, b) must pass a hipot test (Section 3.2) within one hour of being removed from the environmental chamber and c) must meet the requirements of section 3.5.

Figure 3-3. Humidity-Freeze Cycle for Receiver Sections.

3.7 Outdoor Exposure for Receiver Samples

Purpose: To determine the effect of concentrated solar radiation on the electrical performance and structural integrity of the receiver section.

Procedure: The sample will be mounted behind a lens on a two-axis tracker and exposed to 160 hours of solar radiation at design geometric concentration. The receiver shall be mounted on a heat sink or radiator fins similar to those which will be used in the module, so that the cell temperature in these tests will be comparable to the cell temperature in the complete module.

Requirements: After exposure, the test receiver sections and the control will be recharacterized using the procedure in section 3.3. Any decrease in P_{mp} , V_{oc} , I_{sc} must be less than 5% of its initial value, and there must be no visible evidence of damage.

3.8 Final Hipot

After the receiver sections have completed environmental cycling and outdoor exposure, all the receivers, including the controls, will again be subjected to a hipot test according to the requirements in Section 3.2.

3.9 Final Wet-Insulation Resistance

After completing the final hipot test, all receivers, including the controls, shall again be subjected to a wet-insulation resistance test according to the requirements in Section 3.4.

3.10 Final Electrical Performance Characterization

Purpose: To determine the effect of reliability tests on the electrical performance of receiver sections.

Procedure: After reliability tests have been completed, the electrical performance of receiver sections, including the "control," will again be characterized using the procedure defined in Section 3.3, Baseline Electrical Performance Characterization.

The change in performance parameters, percent change in Pmp for example, is defined at follows:

$$\Delta Pmp = 100 \cdot (Pmp_f - Pmp_i) / Pmp_i$$

Where:

Pmp_f = Final maximum power measurement
Pmp_i = Initial maximum power measurement

When a solar simulator is used, the average performance values from at least three replicate measurements shall be used to calculate performance changes due to reliability tests. If outdoor test results are used, then regression analyses should be used as described in Section 4.17.

The uncertainties (95% confidence limits) associated with measured performance values must be included with the results in order to clearly define whether a test item meets the pass/fail criterion. See Section 4.17 and Figure 4.9 for a clarification of how test results are interpreted relative to the pass/fail criterion.

Requirements: The decrease in the measured values for Pmp, Isc, and Voc from their initial (baseline) values must be less than 8% subsequent to the complete series of reliability tests to which the receiver section is exposed. If performance is characterized before and after an individual reliability test, the decrease in Pmp, Isc, and Voc must be less than 5%.

3.11 Final Inspection

Purpose: To document any damage, degradation, or abnormalities resulting from environmental tests that might affect long-term reliability.

Procedure: Same as in section 3.1. In addition, appropriate failure analyses will be carried out to identify causes of performance degradation or failures.

Requirements: Some inspection criteria are contained in this section. However, detailed acceptance criteria are not included in this document because this procedure will be applied to prototype receiver sections with widely varying designs. With prototype or experimental receivers, generally applicable inspection criteria are difficult to define.

Therefore, the final inspection and evaluation of prototype hardware must be somewhat subjective and must rely in part, on the expertise and engineering judgment of the inspectors. Detailed inspection/acceptance criteria should be developed in cooperation with manufacturers as a given design moves toward commercial production. The following types of degradation are particularly important:

1. Separation of cell solder joints.
2. Separation of interconnects.
3. Cell metallization failures.
4. Cracked cells.
5. Fatigue cracks in solder joints.
6. Cracking or delamination of bonding materials.
7. Cracking, debonding or discoloration of encapsulants, especially any cracking or debonding which exposes electrically live parts.
8. Evidence of corrosion.

Separation of solder joints and interconnects is evaluated in terms of the fraction of electrical contact area that is lost due to the separation, cracking, or void growth. The electrical contact area between any cell and the interconnect for either polarity must not be reduced by more than 10% due to environmental cycling. Thus, if more than 10% of the positive or negative interconnect fingers become detached or if the cell contact area loss, as determined by ultrasound scanning, is greater than 10%, the receiver section fails evaluation.

If items 1 through 8 are identified, the degree of degradation will determine whether the part passes or fails evaluation. Specific acceptance criteria for these items are not included here. Therefore, if acceptance criteria have not been established separately for the hardware in question, the decision to pass or fail the part will be at the discretion of the testing agency.

SECTION 4

TEST SPECIFICATIONS FOR MODULES

This section describes the qualification test sequence for complete modules. Ideally, receiver sections of the type used in the modules should be evaluated through the test sequence in Section 3 before testing complete modules. However, concurrent testing is allowed. In either case, the receiver design must pass the receiver evaluation tests of Section 3 for the design to pass all aspects of evaluation testing.

The evaluation sequence requires six modules and may require four months to complete.

Modules which are being used as controls shall be stored in a dry environment out of direct sunlight, preferably indoors except when being used for electrical performance characterizations.

Test specifications for modules are diagrammed in Figure 4-1. All modules submitted must pass all tests. Descriptions of each test follow.

4.1 Initial Inspection

Purpose: To establish a baseline against which modules can be compared as they pass through the environmental tests and to assure modules meet requirements for further testing.

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

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

1. Damage incurred during shipping and handling, such as cracked lenses, cracked or bent housings, and bent terminals or mounting brackets.
2. Integrity of the seal around the lens and housing joints. Any cracks or gaps in sealant materials will be noted.
3. Adequacy or function of module vent hole or breather. (The breather must not be plugged.)
4. Provision for grounding all accessible conductive parts. The grounding procedure must comply with the provisions of the UL standards⁶, Sections 9 and 10.
5. Clear and indelible markings of manufacturer's identification number, terminal polarity and grounding point.
6. The following ratings shall be permanently marked on the module (based on 1000 W/m² DNI, Air Mass 1.5, 25 °C cell temperature):

- Open-circuit voltage
- Short-circuit current

Figure 4-1. Test Sequence for Complete Modules. Vertical lines indicate how many modules undergo each test. Numbers preceding the titles refer to the section of text describing each test. Numbers in parenthesis refer to the approximate number of days needed to perform the test. Visual inspections are performed after each test.

- Nominal voltage and current at the maximum power operating point.
- Maximum permissible system voltage
- Maximum current which can be passed through any of the module's overcurrent protection devices.

Requirements: Serious damage, defects, or lack of compliance with Requirements 4, 5, and 6 above will cause the module to be rejected without further testing.

4.2 High Voltage Standoff (Hipot)

Purpose: To insure that electrical isolation between the PV circuit and any externally exposed conductive part is good enough to protect personnel from electrical shock hazards.

Background: Photovoltaic concentrator systems are now available in array sizes ranging from less than 1 kW to more than 100 kW. In some cases, the same modules are used on the largest and smallest arrays. Because of the difficulty of setting a leakage-current limit without knowing the details of the array in which the module will be fielded, a relatively conservative current limit of 50 μ A per receiver section or per module has been adopted.

In determining the safety of a PV array, designers cannot rely on the 50- μ A leakage-current limit per module and must consider a variety of factors. Photovoltaic modules may become shock hazards if the isolation between the cell string and the module frame is inadequate, and the ground connection to the module frame fails. When these conditions occur, dc currents above the 30 to 60 mA "let go" current range will prevent personnel from releasing the electrically live part¹⁵. Direct currents of only a few mA will cause an involuntary muscular reaction. While ground-fault interrupters are often used between the array and the inverter to protect personnel working on the inverter or the load, these interrupters provide no protection to individuals working directly on the PV array. A discussion of grounding and lightning-protection issues for PV modules is given in Reference 16.

Procedure: The voltage for the hipot testing shall be 2 times the array voltage plus 1000 V. If the array voltage is not known, the test voltage shall be 2200 V. After determining the test voltage, the output terminations of the module shall be tied together and connected to the high-potential lead from a suitable dc power supply. The ground of the power supply shall be connected to the module's grounding point. The cut-off threshold on the power supply's leakage current detector will be set at 50 μ A. Voltage will be increased at a rate not to exceed 200 V/s to the test voltage determined above. The test will be conducted at room temperature ($20^{\circ} \pm 5^{\circ}$ C) and the test voltage will be applied for one minute. If the current limit is reached, the corresponding voltage will be recorded. The uncertainty in the process at the 95% confidence for the measured leakage current must not exceed ± 5 μ A.

Modules will also be hipot tested within one hour after humidity-freeze cycling and water spray exposure and prior to final electrical characterization, as shown in Figure 4-1.

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 sample with a clamp.

Requirements: Leakage of dc current will be monitored and recorded and must not exceed the 50- μ A limit. The hardware will be observed during the test, and there must be no sign of arcing or flashover.

4.3 Grounding-Path Continuity

Purpose: To verify electrical continuity between all exposed conductive parts and the grounding point of the module. This test is primarily concerned with determining that individual modules are safe enough to test. Safety, under high-current situations, is addressed in Section 4.6, High-Current, Grounding-Path Resistance Test.

Procedure: A continuity tester (ohmmeter) shall be used to test electrical continuity between the part in question and the module ground point.

Requirements: Resistance must be less than 0.2 Ohms between all points tested and the module ground point. The uncertainty in the process at 95% confidence should be ± 0.05 ohm or less.

4.4 Baseline Electrical Performance Characterization

Purpose: To verify that a module produces power and to establish its baseline characteristics prior to the reliability tests.

Procedure: Modules shall be mounted on a two-axis solar tracker, spray-washed with deionized water if necessary, and aligned for maximum short-circuit current using the alignment procedure summarized in this section. All modules, including the "control," must be characterized. Performance data shall be recorded, analyzed, and have confidence limits determined for specific parameters. Depending on the test equipment and procedures used at the evaluation laboratory, it may be necessary to record performance data on more than one day in order to reduce the uncertainty in measured results. If multiple days are required, the data sets from each day should be examined for internal consistency, analyzed separately, then averaged.

During this performance characterization, values of direct normal insolation should span at least 150 W/m^2 within the range 700 to 1000 W/m^2 . Values of cell or heat sink temperature should span a range of at least 15°C . These ranges are specified to ensure sufficient overlap of test conditions before and after reliability tests so that changes in electrical performance can be accurately determined.

Tracking error monitors¹⁷, or equivalent, shall be used on both axes of the tracker to assure that the relative orientation of the tracker to the sun does not change after the alignment procedure has been completed. For many concentrator modules, a tracking accuracy of ± 0.1 degrees is necessary to make accurate performance measurements.

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

Perform an initial alignment of the module on the tracker by mechanically adjusting the mounting fixtures while monitoring the short-circuit current (I_{sc}) from the module using a portable current meter. This is an iterative procedure and should result in module alignment within 0.5° to 1° in both azimuth and elevation.

Note: The module 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} from the module 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.

After thermal equilibrium has been achieved (typically 15 to 30 minutes) a final alignment must 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 value of I_{sc} does not change much. The module should be adjusted to the center of this "plateau", which should also correspond to a value within 0.2% of the maximum observed value of I_{sc} . For a point-focus module, this alignment procedure should yield a module which is positioned within 0.1° of 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 since using tracker control biases to align one module may misalign other modules.

Analysis of I-V Measurements: Once the module has been aligned, current-voltage (I-V) scans shall be taken and recorded at successive intervals along with associated measurements of cell and/or heat sink temperature, direct normal irradiance (DNI), ambient temperature, wind speed, and wind direction. Values for the maximum power point (Pmp), the short-circuit current (Isc), and the open-circuit voltage (Voc) are determined from the I-V scans. Typically, over 100 scans are recorded during a full day test period. Linear regression analysis should be used to determine an empirical relationship between each of these three performance parameters and both DNI and cell (or heat sink) temperature (T). The model typically used is a linear model with two independent variables (DNI and T). For example, the empirical relationship for Pmp resulting from regression analysis can be described as follows:

$$Pmp = a_0 + a_1(DNI) + a_2(T) \pm \epsilon$$

where a_0 , a_1 , and a_2 are coefficients determined from the regression analysis. The ϵ term in this equation is an error term related to the quality of the fit of the model to the measured data.

This is a relatively limited model in that it; 1) is linear, 2) has no dependence on wind velocity or direction and 3) uses a calculated cell temperature and has no explicit dependence on ambient temperature. For these reasons, the analyst should be careful to compare baseline and final electrical data at points of overlapping DNI and T if possible and should look for systematic effects of the three factors stated above before assigning numerical values to changes in the performance parameters. As an example, changes in slope between baseline and final electrical performance plots of Pmp versus DNI at a fixed cell temperature are evidence that there are "hidden" factors biasing the data.

In order to assign 95% confidence limits to the results obtained from the regression analysis, it is necessary to consider both random and bias (systematic) errors. If bias errors are known to be constant for performance tests performed before and after reliability tests, then they can be ignored since pass/fail criteria are based on the relative change in performance. Random error sources can be combined into an overall uncertainty using the procedures defined in References 18 and 19. For example, the uncertainty in Pmp (δPmp) at 95% confidence associated with random error sources is given by the following expression:

$$\delta P_{mp} = \pm [(a_1 \cdot \delta DNI)^2 + (a_2 \cdot \delta T)^2 + (\delta \epsilon)^2]^{1/2}$$

In this expression for δP_{mp} , the uncertainties associated with DNI and T measurements (δDNI and δT), as well as the uncertainty in the regression fit ($\delta \epsilon$), should also be at the 95% confidence level. Typically, the value used for $\delta \epsilon$ is two times the "standard error of the estimate" associated with the regression fit.

Requirements: A PV module must operate reliably enough that P_{mp} , I_{sc} , and V_{oc} can be accurately and repeatably measured before and after reliability tests.

4.5 Wet-Insulation Resistance

Purpose: To verify that moisture will not penetrate to the electrically active portion of the module 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.

Since electrochemical corrosion is driven by the integrated current over the life of the hardware, the maximum allowable leakage current is much less than that which ensures personnel safety¹³. The minimum resistance specified here for modules is a factor of two lower than the resistance for receiver sections since there may be more independent leakage paths in a complete module than in a small receiver section.

Procedure: With the module at $22^\circ \pm 5^\circ\text{C}$, the output terminations of the module shall be tied together (shorted) and connected to the high potential lead of a megohmmeter that is capable of producing a 500-V output. The ground of the megohmmeter shall be connected to the module's ground point. A 0.3% solution of Liquinox¹⁴ in deionized water shall then be sprayed or poured over the cell string until the solution forms a continuous film, covering the PV cell string and extending to the nearest ground point on the module.

The megohmmeter shall then be used to measure the resistance between the cell string and ground with a 500-V potential applied between the two points. After waiting two minutes to allow capacitive charging currents to dissipate, read and record the resistance.

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: The resistance measured from the cell string to the module ground must be above 50 megohms under these wet insulation conditions to pass the test. Reference 13 presents the arguments used in developing these criteria.

4.6 High-Current, Grounding-Path Resistance

Purpose: To verify adequate electrical continuity between all exposed conductive parts and the grounding point of the module under high-current conditions.

Procedure: This test is adapted from the UL specification for flat-plate modules (Reference 6, Section 24). The resistance between the grounding terminal or lead and any accessible conductive part shall be measured when a current of 2 times the rated short-circuit current of the module at standard test conditions (1000 W/m² DNI, air mass 1.5, 25°C cell temperature) is passed through the module, between the grounding terminal and conductive part in question. If the module manufacturer has not provided contact points for this test on the modules, a small area of the module will be scraped clear of any anodization or coatings in order to make good contact.

The resistance shall 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 shall be applied for one minute. 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. All such paths must have been previously tested by the procedure defined in Section 4.3. In order to minimize danger to personnel, a current and voltage limited power supply which is not capable of producing more than 10 V dc between its output terminals shall be used for this test.

At the end of this test, the module will be subjected to a hipot test according to the procedure in Section 4.2.

Requirements: Resistance must be less than 0.1 Ohms between all points tested and the module ground point. Also no damage must be produced at joints between different exposed conducting parts during the test.

4.7 Off-Axis Beam Damage

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 900 W/m². 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 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 900 W/m².

At the end of this test, the module will be subjected to a hipot test according to the procedure in Section 4.2.

Requirements: There must be no evidence of melting, smoking, charring, deformation, or burning of any material. Any evidence of damage will be documented.

4.8 Thermal Cycling

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.

Background: The thermal cycling tests are designed as accelerated tests which will expose in a short period of time, failure mechanisms which 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 most modules.

Procedure: Three modules will be subjected to 200 thermal cycles between -40°C and 60°C in accordance with the profile shown in Figure 4-2. The relative humidity need not be controlled. The rate of temperature change must not exceed 100°C/h. The module shall be instrumented to test for ground faults or open circuits during the cycling. Appendix B describes a monitoring technique. Hipot testing and electrical performance characterization, as given in Sections 4.2 and 4.4, will be performed following this test.

Requirements: Modules will be inspected after cycling and any visible damage or degradation documented. Modules must not show any cracking and there must be no delamination of sealing materials. Any warping of the modules must be small enough that it does not affect the mechanical integrity of the module or decrease its electrical performance beyond the limits specified below. The module must not have exhibited any ground faults or open circuits during the thermal cycling. Any decrease in Pmp, Voc, or Isc from their initial values must be less than 5%.

Figure 4-2. Thermal Cycle for Concentrator Modules.

Figure 4-3. Humidity-Freeze Cycle for Concentrator Modules.

4.9 Humidity-Freeze Cycling

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

Procedure: Three modules will be subjected to 20 humidity-freeze cycles in accordance with the profile shown in Figure 4-3. Note that the maximum temperature of 60°C is

lower than that used in the humidity-freeze test for receiver sections. Modules should be monitored for electrical continuity and short circuits to ground per the procedure given in Appendix B. A complete hipot test (Section 4.2) will be conducted within 1 hour after cycling is completed. Following the hipot test an electrical performance test, as described in Section 4.4, will be performed.

Requirements: The module will be inspected after testing, and any observable damage or degradation will be documented. The module must show no cracking or severe corrosion. There must not be any delamination of sealing materials. Any warping of the module must be small enough that it does not affect the mechanical integrity of the module or decrease its electrical performance beyond the limits specified below. The module must pass the hipot test, as described in Section 4.2. Any decrease in Pmp, Voc, or Isc from their values measured after thermal cycling (Section 4.8) must be less than 5%.

4.10 Hot-Spot Endurance

Purpose: To evaluate the capacity of a module to endure the long-term effects of periodic hot-spot heating associated with common fault conditions, such as cracked or mismatched cells or partial shadowing of the module.

Procedure: Procedures for hot-spot testing of concentrators continue to be developed at the Jet Propulsion Laboratory (JPL) and Sandia National Laboratories. When completed, these procedures will be published as an addendum to this document.

4.11 Hail Impact

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

Procedure: The module will be subjected to normal impact loading with 25.4-mm (1-in.) diameter ice balls traveling at a terminal velocity of 23.0 m/s (52 mph)²⁰. At least 10 representative locations on the module lens and housing should be tested. These should include the lens locations diagrammed in Figures 4-4 and 4.5. 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 test.

After being formed in an appropriate mold, the ice balls should be stored at $-8^{\circ} \pm 2^{\circ}\text{C}$ for at least 8 hours but not longer than 32 hours. The ice balls should be spherical with a maximum deviation in diameter of ± 3 mm and should have a mass of 7.9 ± 0.4 grams. The velocity of the ice balls at impact must be within $\pm 5\%$ of the specified terminal velocity. These tests should be performed with the module at a temperature of $20^{\circ} \pm 10^{\circ}\text{C}$.

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.

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 4-4. Representative Impact Locations for Hail Test on Point-Focus Lens.

Locations:

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

Figure 4-5. Representative Impact Locations for Hail Test on Line-Focus Lens.

4.12 Water-Spray

Purpose: To determine whether rain water can enter the module under field conditions and to determine whether rain water that does enter the module can cause any electrical shorting problems.

Procedure: The module being tested will be placed in the rain test fixture shown schematically in Figure 4.6. The fixture has 10 spray nozzles angled down at 45° to spray on the module. Each nozzle sprays one gallon per minute of tap water (nominal 2 kΩ-cm resistivity) when the water pressure at the input to the nozzle is set to 8 - 10 psig. The nozzles on each side are 26" apart. Nozzles on opposite sides of the module are separated by 72". In order to achieve a uniform spray of water on the surface of the module, the module is centered in the fixture, approximately 48" below the nozzles. The test fixture is tilted 35° from the horizontal so that the module surface is approximately normal to the sun's rays at local solar noon.

The module will be tested in four orientations:

1. With the module approximately "on track" with its surface normal to the solar radiation.
2. With the module upside down.
3. With the module in its "stow" position.
4. With the module at the normal limit of its allowed travel.

For some module designs, these orientations may be redundant.

Before the first spray exposure, the module should be aligned with the sun and allowed to come up to operating temperature over a period of at least 15 minutes. When the water spray is initiated, the cooling effect will draw air into the module, increasing the likelihood that water will be drawn into the module and simulating the conditions of an isolated rain shower during field operation. The module will be exposed to the water spray for 1 hour in each orientation with at least 15 minutes between tests in different orientations. After each exposure, the module will be examined for evidence of water penetration or collection of water in any area containing electrically active parts. If water is present in such an area, there must be adequate means, such as drain holes, to ensure that the water level will not reach uninsulated, electrically active parts.

A hipot test should be conducted within 1 hour after the last spray exposure. If the stand-off voltage is found to be below that specified in Section 4.2, the hipot test should be repeated after the module has dried to determine if the condition was caused by moisture inside the module.

Requirements: The module must pass the hipot test and no significant amounts of water (< 100 ml) should remain inside the module after the test.

- ↘ = Spray Nozzle
 ○ = Pressure Gauge
 X = Pressure Regulator

Figure 4.6. Schematic of Apparatus used for Water-Spray Tests

4.13 Twisted Mounting Surface

Purpose: To determine whether the module will develop ground faults or open circuits when twisted slightly in its mounting.

Procedure: Test A: All modules which are supported at more than three points shall be subjected to a twist test by deflection of the structure or surface to which they are mounted as shown in Figure 4.7. The deviation of the test mount from a true flat surface during the test shall be 20 mm/m (0.25 in/ft) measured along either mounting surface in the direction of the module's shortest dimension.

Test B: All modules which are supported on both ends shall be subjected to a twist test as shown in Figure 4.8. For Test B, the deviation of the mounting surface shall be 1.2° or 20 mm/m along the long dimension of the module.

The module circuits shall be instrumented to verify that no open circuits or ground faults occur during the deflection test. Appendix B describes a monitoring technique. For these tests, the modules shall be mounted as specified by the manufacturer.

Requirements: No ground faults or open circuits must occur during the tests. No permanent warping or breakage of the modules must occur and there must be no delamination of lens seals.

Figure 4.7. Schematic of Apparatus for Twisted Surface Mounting (Test A)

Figure 4.8. Schematic of Apparatus used in Twisted Mounting Surface (Test B)

4.14 Cable Strain-Relief:

Purpose: To assure that the leads and connectors bringing current out of each module are sufficiently robust that they will survive normal handling procedures.

Procedure: Perform this test indoors or with the module shaded to minimize any electrical hazard which may develop as a result of the test.

A 20-lb. (9-kg) weight shall be suspended from the end of the module power leads for one minute with the module in each of four positions:

1. With the module in the on-track position.
2. With the module upside down.
3. With the module in its stow position.
4. With the module at the normal limit of its travel.

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

4.15 Final Hipot

After the modules have completed the hot spot endurance (4.10), hail impact (4.11), water spray (4.12), and cable strain-relief (4.14) tests, the modules will again be subjected to hipot testing according to the procedure in Section 4.2

4.16 Final Wet-Insulation Resistance

After the final hipot test, the modules will again be subjected to a wet insulation resistance test according to the procedure in Section 4.5.

4.17 Final Electrical Characterization

Purpose: To determine the effect of reliability tests on the electrical performance of modules by quantifying the change in performance parameters relative to their initial values.

Procedure: After reliability tests have been completed, the electrical performance of PV modules will again be characterized using the procedure defined in Section 4.4, Baseline Electrical Performance Characterization. The "control" module should also be characterized every time another module's performance is evaluated subsequent to reliability testing.

As an example of the change in performance parameters, percent change in Pmp is defined as follows:

$$\Delta Pmp = 100 \cdot (Pmp_f - Pmp_i) / Pmp_i$$

Where:

Pmp_f = Final maximum power measurement

Pmp_i = Initial maximum power measurement

Using the results from the regression analyses, the change in performance should be calculated using regression values calculated at a single DNI and T (cell or heat sink temperature) combination common to data sets taken before and after reliability tests. A DNI, T combination that is frequently used is DNI = 850 W/m² and T = 50°C. If temperature ranges do not overlap due to seasonal constraints or mechanical changes, then the calculated results from regression analyses will be extrapolated to a temperature value midway between temperature ranges. If more than one data set is taken before or after reliability tests, then calculated performance values for each day should be averaged before calculating the change in performance. Prior to performing the regression analysis, it is also advisable to screen separate data sets to obtain consistent ranges for wind speed and wind direction.

The uncertainties (95% confidence limits) associated with measured performance changes must be included with the results in order to clearly define whether a test item meets the pass/fail criterion. Procedures for calculating uncertainty limits are documented in References 18 and 19. For example, the uncertainty in ΔPmp (δΔPmp) at 95% confidence level expressed as a percentage of Pmp, is given by the following:

$$\delta \Delta Pmp = \pm 100 / Pmp_f \cdot [\delta Pmp_i^2 + (\delta Pmp_f \cdot Pmp_i / Pmp_f)^2]^{1/2}$$

In this expression for δΔPmp, the uncertainties associated with Pmp_i and Pmp_f (δPmp_i and δPmp_f) should both be at the 95% confidence level.

Figure 4.9 illustrates five possible cases that might occur subsequent to reliability testing. Case 1 shows a performance change that is near zero with associated 95% confidence limits quantifying the uncertainty in the value. For Case 1 it is clear that there is greater than 95% confidence that the test item has met the pass/fail criterion, and it can be stated with similar confidence that there has been no detectable change in performance. In Case 2 there is 95% confidence that the item has degraded, but it still passes with greater than 95% confidence. In Case 3 there is greater than 95% confidence that the item failed the test. In Case 4 the item is judged to have passed the test, but there is only about 50% confidence in this assessment. In Case 5 the item is judged to have failed the test but with only about 50% confidence in the assessment. As is evident from Figure 4.9, the ability to confidently state that a test item has passed or failed the test criterion is strongly dependent on the magnitude of the 95% confidence limits.

Each time that the "control" module is characterized, the change in its performance relative to its initial (baseline) characterization should also be calculated. Ideally, the calculated changes in the control module's performance will be similar to Case 1 shown in Figure 4.9, indicating that the control module has not changed within measurement uncertainty during the time necessary for all testing to be completed. If not, then performance changes attributed to reliability tests on other modules may need to be reinterpreted based on degradation seen in the "control" module.

Requirements: The decrease in the measured values for Pmp, Isc, and Voc from their initial (baseline) values must be less than 8% subsequent to the complete series of reliability tests to which the PV module is exposed. If performance is characterized before and after an individual reliability test, the decrease in Pmp, Isc, and Voc must be less than 5%.

Figure 4.9 Illustration of Typical Cases of Measured Performance Change Subsequent to Reliability Testing. Ninety-five percent confidence limits and a typical pass/fail criterion are shown.

4.18 Final Inspection

Purpose: To make a detailed assessment of any mechanical or electrical problems with the modules resulting from the environmental tests that could affect module performance or reliability in the field.

Procedure: Modules will be thoroughly inspected and photographed after testing. Any damage, degradation, or abnormalities that might affect long-term reliability will be documented. Observations regarding damage or degradation observed during inspections after individual tests will be included with the documentation for the final inspection. This inspection process will be carried out in two steps. First, modules will be inspected as thoroughly as possible from the outside. Then, the modules will be dismantled to allow direct inspection of the receiver and internal circuitry. (Dismantling may be inappropriate for some designs).

Inspection of the receiver will follow the procedure and evaluation criteria outlined in Section 3.11 except that ultrasound images before testing may not be available.

As part of the final inspection, appropriate failure analysis should be carried out to identify the causes of performance degradation or failures.

Requirements: Due to the considerable variety in module design, it is not possible to list all possible causes of failure here. The tester reserves the right to report unanticipated problems that are felt to jeopardize the module's likelihood of performing reliably for many years in the field.

The following types of damage or degradation are particularly important and will cause a module to fail:

Module Exterior:

1. Cracks in the lens or housing.
2. Cracking or debonding of sealants.
3. Severe corrosion of housing materials.
4. Degradation of the lens, including delamination, discoloration, cracking or peeling of coatings, or warpage.
5. Loss of mechanical integrity such that the installation or operation of the module would be impaired.

Module Interior:

6. Off-Axis beam damage.
7. Evidence of water collection near a path connecting electrically active components and ground.
8. Corrosion of components.
9. Separation of solder joints or separation of interconnects which reduce the area of any joint by more than 10%
10. Cell metallization failures which reduce the contact area on a cell by more than 10%.
11. Cracking, debonding or discoloration of encapsulants, especially any cracking or debonding which exposes electrically live parts.

SECTION 5

CONTINUED EVOLUTION OF EVALUATION TESTS

These evaluation tests will be updated on a regular basis to incorporate the latest information on failure mechanisms and the relationship between accelerated testing and field reliability. Existing concentrator designs are evolving, and new concepts for concentrators continue to appear. This requires that evaluation tests be versatile enough to allow a fair assessment of new designs, yet complete enough to identify weaknesses that would lead to problems in the field. Ideally, modules that would experience early failures in field operation should fail the evaluation tests, and modules that pass the evaluation should have good field reliability for many years. This is essentially the same philosophy used in JPL's development of the Block V specifications.

The wet insulation-resistance, twisted mounting surface, and cable strain-relief tests are new in their application to concentrators. Therefore, it is important that the performance and field reliability of concentrator designs that have passed these evaluation tests be monitored over an extended period, say five years. If performance degrades or a significant number of failures occur, the cause(s) of the problems will have to be identified, and the evaluation tests will have to be modified appropriately.

For concentrator systems evaluated using this series of tests, we recommend that extra modules from the same production run be retained in storage by Sandia. These extra modules will be useful in developing revised evaluation procedures if early failures occur in the installed modules. They will also be useful in evaluating the general applicability of new tests developed in conjunction with other module designs.

Detailed inspection/acceptance criteria should be developed in cooperation with manufacturers for each module design as it matures to the point of commercial production. These criteria should be published as separate documents.

The present specification does not include dynamic mechanical loading tests which would simulate wind loading conditions. Mechanical loading tests should be developed if field experience shows that module failures are being caused by actual wind loads experienced during operation.

The humidity-freeze cycle specified in Sections 3.6 and 4.9 was developed for evaluating one-sun modules. The test attempts to accelerate failures due to corrosion and was developed based on the use of materials found in one-sun modules. Since the materials used in concentrator modules are typically different from those used in one-sun modules, this cycle may not be appropriate for concentrators. Sandia and JPL are investigating the use of a more appropriate cycle. Also, Sandia and JPL are developing a non-intrusive hot-spot endurance test for concentrator modules.

SECTION 6

REFERENCES

1. Block V Solar Cell Module Design and Test Specifications for Intermediate Load Applications - 1981, JPL Report #5101-161, February 20, 1981.
2. Performance Criteria for Photovoltaic Energy Systems, Vol. II, SERI/TR-214-1567, July 1982.
3. R. DeBlasio, L. Mrig, D. Waddington, "Interim Qualification Tests and Procedures for Terrestrial Photovoltaic Thin-Film Flat-Plate Modules," SERI/TR-213-3624, January 1990.
4. R. S. Barlow and E. H. Richards, "Qualification Tests for Photovoltaic Concentrator Cell Assemblies and Modules," SAND86-2743. Albuquerque: Sandia National Laboratories, January 1988.
5. H. Ossenbrink and E. Rossi, "Qualification Test Procedures for Crystalline Silicon Photovoltaic Modules," Specification No. 503, Version 2.2, European Solar Test Installation, Ispra, Italy, March 1991.
6. Standard for Flat-Plate Photovoltaic Modules and Panels, Underwriters Laboratories, UL 1703, August 1986 (reprinted May 1987).
7. E. H. Richards, "Photovoltaic Concentrator Module Reliability: Failure Modes and Qualification", Photovoltaic Module Reliability Workshop, Denver, Colorado, Oct. 25, 1990.
8. E. H. Richards and C. J. Chiang, "Reliability of Photovoltaic Concentrator Modules," Proceedings of the 21st IEEE Photovoltaic Specialists Conference, Orlando, Florida, May 1990.
9. A. A. Salim, F. S. Huraib, N. N. Eugenio and T. C. Lepley, "Performance Comparison of Two Similar Concentrating PV Systems Operating in the U. S. and Saudi Arabia" Proceedings of the 19th IEEE Photovoltaic Specialists Conference, New Orleans, Louisiana, 1987.
10. M. J. O'Neil, "Measured Performance for the First Three Years of Operation of the DFW Airport 27-kW (Electric)/120-kW (Thermal) Photovoltaic and Thermal (PVT) Concentrator System", Proceedings of the 18th IEEE Photovoltaic Specialists Conference, Las Vegas, Nevada, 1985.
11. T. D. Hund and S. N. Burchett, "Solder Fatigue Reduction in Point Focus Photovoltaic Concentrator Modules", Proceedings of the 22nd IEEE Photovoltaic Specialists Conference, Las Vegas Nevada, October 1991.
12. "Standard Tables for Terrestrial Solar Spectral Irradiance at Air Mass 1.5 for a 37° Tilted Surface," ASTM Publication E892-87, 1987.
13. R. S. Sugimura and R. G. Ross, Jr. "Trial Wet Insulation-Resistance Test Procedure for Photovoltaic Concentrator Modules", JPL Report JPL D-7892, March 1991.
14. Liquinox is produced by Alconox, Inc. 217 Park Ave. South, NY, NY, 10003, (212) 473-1301. The resistivity of the 0.3% solution of liquinox in deionized water will

be 3,500 +1,000 Ohm-cm, making the solution a conducting liquid for the purposes of this test. Also, the liquinox solution will have a surface tension between 30 and 35 dynes/cm - about half the surface tension of pure water.

15. U.S. Department of Energy. "Development of Photovoltaic Array and Module Safety Requirements," Publication No. DOE/JPL/955392-1, prepared for JPL by Underwriters Laboratories, Inc., June 1982.
16. Schalles, F. T. Handbook for Grounding and Lightning Protection of Photovoltaic Arrays and Power Systems, prepared by EG&G-Special Projects Division for the Design Assistance Center, PV Systems Research Division 6223. Albuquerque: Sandia National Laboratories, 1992.
17. Galbraith, G. "Development and Evaluation of Tracking Error Monitors for Solar Trackers," Publication No. SAND88-7075. Albuquerque: Sandia National Laboratories, 1988.
18. Abernethy, R. B., and R. P. Benedict. "Measurement Uncertainty: A Standard Methodology," ISA Transactions. Vol. 24, No. 1 (1985), pp. 75-79.
19. U.S. Standards Office, International Standard. "Measurement of Fluid Flow: Estimation of Uncertainty of a Flow-Rate Measurement," Publication No. ISO 5168, 1978.
20. D. Moore and A. Wilson, "Photovoltaic Solar Panel Resistance to Simulated Hail", Low-Cost Solar Array Project report 5101-62, Jet Propulsion Laboratory, Pasadena, CA, 1978.

APPENDIX A

RECOMMENDED TESTS FOR CELL ASSEMBLIES

Experience at Sandia indicates that the processes of developing appropriate PV-cell grid metallization, soldering interconnects to the cell and fixing the cell to a heat spreader are difficult enough that it is worth evaluating these processes as a group before proceeding with the construction of receiver sections. Therefore, Sandia is willing to perform tests on the adequacy of these processes on cell assemblies. These tests are not mandatory, but it is our experience that performing these extra tests may save the module manufacturer time and money in the long run.

For these tests, a cell assembly is defined as a PV cell with its grid metallization, its solder or adhesive connection to a heat spreader and cell interconnects. Encapsulation of the cell is optional, but may serve to protect the assembly from stress cracking during the humidity-freeze tests.

The tests for cell assemblies, some of which are identical to some of the tests for receiver sections in Section 3, are listed below:

A.1 Cell Metallization Test

Purpose: To determine the adhesion of the cell's metallization before cells are mounted in cell assemblies^{A-1}.

Procedure: Prepare several samples by soldering a cell to a copper substrate and soldering copper tabs to each of the cell's busbars. After the samples have cooled, clamp the substrate in a vise, bend a tab to an angle of 45°, clamp a hemostat and spring scale to the tab, and pull until the sample breaks. Repeat for all tabs.

Requirements: The metallization should withstand a force of 2 pounds (4.4×10^3 dynes).

A.2 Initial Inspection

Purpose: To reject damaged hardware and to establish a baseline against which cell assemblies can be compared as they pass through the environmental tests.

Procedure: All hardware will be thoroughly inspected and photographed 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, will be documented with appropriate sketches or photographs to show the locations of defects. Ultrasound imaging will be used as part of the inspection process to characterize the quality of the solder bonds under the cells.

Requirements: Same as Section 3.1.

A.3 Hipot Test

If the cell assembly is attached to a grounded surface, a hipot test, as described in Section 3.2, will be performed.

A.4 Baseline Electrical Performance

Purpose: To verify that a cell assembly produces power and to allow determination of the effects of the environmental tests on the cell's electrical performance.

Procedure: Obtain I-V curves for the cell assembly at design concentration and 25° C using a calibrated solar simulator. Values of P_{mp} , I_{sc} , V_{oc} and actual irradiance used for the tests shall be recorded.

Requirements: A cell assembly must operate reliably enough that P_{mp} , I_{sc} , and V_{oc} can be accurately and repeatably measured before and after the reliability tests.

A.5 Thermal Cycling

The cell assembly shall be subjected to thermal cycling as described in Section 3.5.

A.6 Humidity-Freeze Cycling

The cell assembly shall be subjected to the humidity-freeze cycling described in Section 3.6.

A.7 Final Electrical Characterization

Purpose: To determine the effect of the environmental tests on the electrical performance of the cell assembly.

Procedure: After the tests have been completed, cell assemblies will again be electrically characterized following the same procedure used in Section A.4.

Requirements: Any decrease in P_{mp} , I_{sc} and V_{oc} from the initial performance tests must be less than or equal to 8% of the original values.

A.8 Final Inspection

Purpose: To document any damage, degradation, or abnormalities that might affect long-term reliability.

Procedure: Same as in Section A.2. In addition, appropriate failure analysis will be carried out to identify causes of performance degradation or failures.

Requirements: Same as in Section 3.11.

REFERENCES

- A-1 Chiang, C. "Silicon Concentrator Solar Cell Development," a letter to Martin Green, UNSW, reprinted in Publication No. SAND89-7043, Silicon Concentrator Solar Cell Development. Albuquerque: Sandia National Laboratories, May 1990.

APPENDIX B

TECHNIQUE FOR MONITORING FOR OPEN CIRCUITS AND GROUND FAULTS DURING CYCLING TESTS

This appendix describes an interim technique developed to monitor modules for open circuits and ground faults during environmental cycling tests. For safety reasons this test is run at low voltage (typically 2 to 10 V) instead of at field voltage, so it is not a substitute for the hipot test. A schematic of the circuit used for monitoring is shown in Figure B-1. As described here, this technique can reliably detect ground faults if they have a resistance of 10 M Ω or less but cannot detect an open circuit until the circuit resistance rises above 10 k Ω .

In this circuit, a low voltage power supply is used to provide a 5-to-10 Volt bias between the cell string and the grounded module frame or heat sink. A 10 M Ω resistor is used to limit power supply current in the event of a ground fault. The PV module is illuminated at a high enough level (typically 50 to 100 foot-candles of diffuse illumination) to produce an easily measurable V_{oc} (typically 0.1 V or more) across the 10 k Ω resistor. The PV module can be tested for ground faults and open circuits by measuring the voltage on one side of the 10 k Ω resistor (V_1) and the voltage across the 10 k Ω resistor (ΔV). A monitor of the lamp output is included to assure that changes in V_1 or ΔV are not due to lamp problems.

Expected values of the voltages across the 10 k Ω resistor for the circuit shown in Figure B-1 are as follows:

module condition	V_1	ΔV ($V_2 - V_1$)
normal operation	$\sim 10 \text{ V} - V_{oc}$	V_{oc}
open circuit	$\sim 10 \text{ V}$	0
ground fault at A:	$-V_{oc}$	V_{oc}
ground fault at B:	0	V_{oc}

These voltages are for complete open circuit and hard ground fault conditions.

Notes:

1. The input impedances of the voltmeters used to measure V_1 and ΔV should be high compared to 10 M Ω .
2. V_{oc} will typically be a small fraction of the value it would normally be when the module is tracking the sun.
3. Voltages and resistances shown in this circuit are nominal and may need to be varied depending on the illumination level and the output impedance of the cell string in the PV module.
4. The value of V_{oc} can be expected to change by about a factor of two as the module responds to thermal cycling.

5. The module will not give a constant output if the lamp is powered by an AC power source (i.e. standard fluorescent or incandescent lights) because the lamp output itself will fluctuate at 60 Hz. In this case it will be necessary to take a number of readings over a 1 minute interval and average the readings.
6. The module will fail the test if V_1 and ΔV change by a factor of two beyond the normal oscillation caused by the changing cell temperature. This pass/fail criterion corresponds to a ground fault having a resistance of less than 10 M Ω or an open circuit having a resistance greater than 10 k Ω .

Figure B-1. Circuit for Ground-Fault and Open-Circuit Monitoring.

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