PROPOSED ACCEPTANCE, QUALIFICATION, AND CHARACTERIZATION TESTS FOR THIN-FILM PV MODULES

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ABSTRACT

The Solar Energy Research Institute is actively engaged in the study and evaluation of module reliability. The Department of Energy has directed SERI to prepare an evaluation test document for PV thin-film modules as a part of this effort. The tests are being written in cooperation with the Jet Propulsion Laboratory, Sandia National Laboratories, and the major thin-film manufacturers. The objective of these tests is to establish a common approach to testing modules that will be acceptable to both users and manufacturers. The tests include acceptance, qualification, and characterization tests. Acceptance tests verify that randomly selected modules have similar characteristics and establish a baseline to which further testing is referenced. Qualification tests are based on accelerated test methods designed to simulate conditions known to promote field failures or impact system safety. Tests include weather related effects of temperature, humidity, rain, hail, wind loading, corrosion, and shadowing. Characterization tests provide data on performance in a predefined environment to establish a basis for future system design. They include module operating temperature, electrical stability under solar exposure, and performance at different temperatures after stability. Details of the proposed test program are presented in Part I of the paper; Part II presents the results of one of the characterization tests that SERI has performed.

PART I: PROPOSED TESTS

Test Guidelines

The purpose of the proposed acceptance, qualification, and characterization tests for thin-film modules is to provide a standard approach to testing so that the comparison of results may easily be made. The detailed test requirements are written in a logical sequence so that testing, in which the result of one test may affect the outcome of the next, can be minimized. Tests are also written so that a manufacturer or a procuring agency may perform, or require performance, of any or all of the specific tests as desired. Acceptable results from these tests should provide reasonable assurance that the modules representative of those that pass these tests will perform reliably.

As the state of the art of thin-film module development progresses, and as deployed systems provide long-term field data, tests will be revised to meet changing requirements. Tests proposed in this document are preliminary and will be continually updated and revised. At the time of this publication, the only thin-film modules considered in detail are amorphous silicon. As other material types come into production, tests will be modified to reflect necessary changes.

A minimum of nine modules, randomly selected from a production lot representative of the type to be deployed in the field, is required to perform all of the tests defined in this paper. If only acceptance and qualification tests are to be performed, the quantity may be reduced to six. Any change in manufacturing processes or materials that is made after testing may require a retest.

An electrical performance test, which is the measurement of an I-V curve, is the prime test for determining initial module performance and also for determining any change brought about by the environmental or mechanical stresses of the tests. All electrical performance tests are required to be performed under standard test conditions, which include: A light source defined in ASTM E892 (1) as AM 1.5 Global Spectrum, at an intensity of 1000 W/m^2, and a module temperature of 25°C, per ASTM E948 (2).

ACCEPTANCE TESTS

Purpose

The purpose of acceptance tests or prequalification tests is to verify that received modules are acceptable for qualification and/or characterization tests. Nine modules are to be randomly selected from the production lot planned for field deployment. The test sequence is shown in Figure 1.

The tests and criteria for acceptance are:

Visual Inspection

No shipping damage or mechanical defects such as cracked glass, delamination, broken connections or bent frames shall be observable to the naked

Proceedings of the 20th IEEE PV Specialists Conference
Las Vegas, NV, September 26-30, 1988, IEEE, New York, pp. 1236-1241..

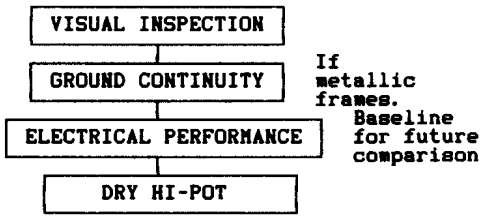

Figure 1. ACCEPTANCE TEST SEQUENCE

eye. Color changes throughout the module are not a factor for rejection.

Ground Continuity

If the module has metal frames, the electrical bonding between frame members is checked by the method of UL 1703 No. 24 (3) in which a current of twice the rated short-circuit current of the module is conducted through each joint and the voltage drop from points within 12.7 mm on each side of the joint is measured. Computed resistance of each joint must be less than 0.1 ohm.

Electrical Performance Test

The electrical performance test is the measurement of an I-V curve defining the loaded performance of an illuminated module. The test is based on the procedures of ASTM E948 (2) and E1036 (4) and requires a light source of 1000 W/m^2 conforming to the spectral definition of AM1.5 Global as required in ASTM E892 (1). The module is maintained at a temperature of 25+/-1°C for the test. Sufficient data points must be taken between open-circuit voltage and short-circuit current to determine the maximum power point. The measured I-V curve for each module establishes a baseline for that module to which all subsequent performance tests will be referenced.

Dry Hi-Pot

This is a safety test to verify that there is no hazardous continuity between electrical circuitry of the module and insulated parts. The test is based on UL 1703 No. 25 (3). A voltage equal to twice the planned system voltage plus 1000 V is impressed between the shorted module leads and the frame, grounding point, or a sheet of aluminum foil pressed against the face or back of the module and wrapped around the edge. The current is measured and must be less than 50 μA.

Allocation

One module is stored in the dark at room temperature to serve as a control module during the test program. It may be tested at any time to verify that no change has occurred in the performance due to aging.

Four modules are specified for the combined thermal and mechanical qualification tests.

One module is required for the diode and hot-spot qualification tests.

Three additional modules will be needed for the characterization tests, if they are to be run.

QUALIFICATION TESTS

Purpose

The purpose of the qualification tests is to subject the modules to environmental and mechanical stresses typical of those to which they will be subjected in the field. Some of the tests, although typical in type, exceed normal stress so that accelerated testing may be accomplished. The intent is to verify that the modules that survive these tests have a good probability of long-term operation under field conditions. The proposed tests and their sequence are shown in Figure 2.

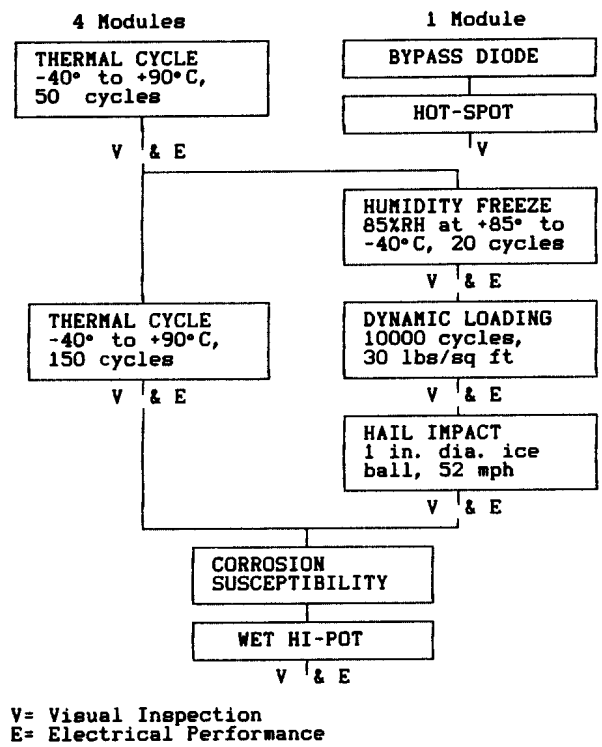

Figure 2. QUALIFICATION TEST SEQUENCE

Pass-Fail

Requirements for passing the qualification tests are: no visible damage, wet-leakage current ≤50 μA, and electrical performance ≥90% of the original electrical performance measured in the acceptance tests.

Thermal Cycle Test

The thermal cycling test is based on UL 1703 No. 32 (3). The limits are -40° to +90°C with a cycle length not to exceed 6 hours and a rate of change of temperature not more than 100°C/hr. Figure 3 shows a time-temperature graph of the recommended test. The intent is to run the test dry,

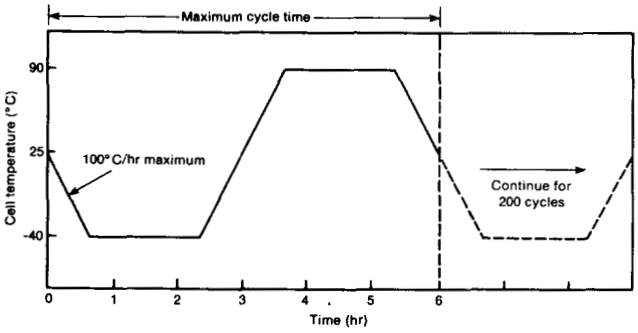

Figure 3. THERMAL CYCLE

i.e., with a minimum of condensable moisture. This can be accomplished by providing an air bleed to the chamber through a tube of silica gel. After 50 cycles have been performed, the test is stopped and a visual inspection and an electrical performance test are run. If all modules pass, two of the modules are transferred to the humidity freeze test while the remaining two modules continue for another 150 thermal cycles.

Visual Inspection

Any warping, cracked glass, or delamination visible to the naked eye is a basis for rejection.

Electrical Performance Test

Data to plot an I-V curve are taken using a procedure identical to that used in the acceptance test. The maximum power of the module shall be equal to or greater than 90% of the maximum power measured and recorded for the baseline for the specific module in the acceptance test.

Humidity-Freeze Test

This test is based on UL 1703 No. 33 (3). It requires cycling from -40° to +85°C with a relative humidity of 85% present at the 85°C temperature. During the cooling part of the cycle, condensation will occur and eventually freezing. Twenty cycles are recommended based on some of the comments received from the manufacturers. Figure 4 shows a time-temperature profile of one cycle.

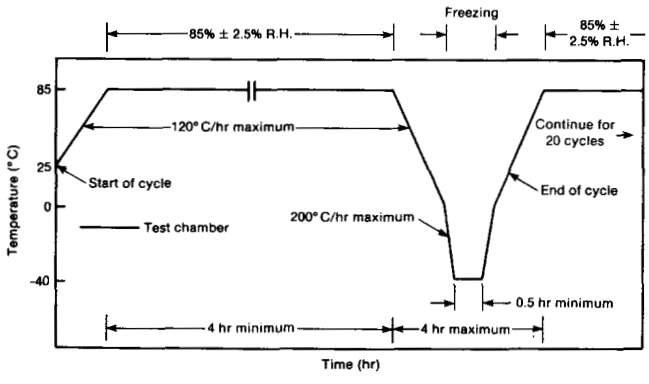

Figure 4. HUMIDITY-FREEZE TEST CYCLE

Dynamic Loading Test

This test is designed to stress the module in a manner similar to wind gust loading. It requires 10,000 cycles of alternate loading on the face and back of the module based on the similar test defined in Block V No. V.C. (5), but uses the load of 30 lbs/ft^2 defined in UL 1703 No. 38 (3). The criteria for passing are no visible damage and power output within limits (≥90% of baseline) as determined by the electrical performance tests.

Hail Impact Test

This test is the same as the Block V No. V.E. (4) and requires the normal impact of one-inch-diameter ice balls at a velocity of 52 miles per hour. The criteria for passing are no damage as determined by subsequent visual inspection and an electrical performance test with power output ≥90% of the original baseline.

Corrosion Susceptibility Test

The purpose of this test is to verify that moisture due to rain, fog, dew, or melted snow that may wet the module during normal deployment will not enter the active portions of the module circuitry where it may cause corrosion, or could lead to conductive paths that might be hazardous to personnel.

Modules mounted outside and exposed to moisture have exhibited corrosion. It is believed that water ingress caused the corrosion and was due to poor sealing of the module. Tests at JPL indicate that the corrosion was due to electrochemical action created by the potential difference between wetted cells and the frame element holding the water against the module edge. JPL has suggested a total of one coulomb as the total charge that might be transferred to create a failure in 30-years' life. The following proposed test procedure is designed to provide data on potential corrosion.

The edge or end of the module is immersed in a water-wetting agent solution. The immersion depth covers the ends or edges of the cells but does not wet the connection box, if any. A megger or a source of 500 V is connected between the leads of the module and the frame or a plate in the bottom of the water container. A one-megohm series resistor will limit current to 500 μA if a power supply is used, but will enable a high-impedance DVM to measure currents down to the nA range. After two minutes' immersion in the liquid, to provide time for the liquid to enter and advance through any capillary openings that may be present, the current, if any, is measured while the module surface is sprayed with the liquid. JPL personnel have suggested that currents of the order of 0.04 μA (40 nA) per linear foot of wetted module edge would be a reasonable criterion for limiting the total charge transfer during a 30-year life. Since there is little experience with this test, the limit is presently set at not more than a total of 5 μA, or the equivalent of 100 megohms for any size of module to pass the test.

Wet Hi-Pot Test

This test is proposed as a means of determining electrical safety for modules or arrays of modules immediately after a rainstorm or after they have been washed. It is based on a combination of UL 1703 25 and 30 (3). The requirement is to completely wet the module by spraying it with water containing a wetting agent. A regular hi-pot test would then be made in which a voltage equal to twice the proposed system voltage plus 1000 V would be impressed between the shorted leads and the frame, if metallic. In the case of a plastic frame, the return would be made to an aluminum foil on the face or back of the module and wetted with the same spray. An alternative proposal is to perform the test for each edge of the module while dipping the edge in the liquid. The dipping approach would not submerge the connector block. If the module did not have a metal frame, the return would be to a metal plate in the liquid. The current limit is 50 μA, which is probably adequate for safety, but may be excessive from the corrosion standpoint.

Bypass Diode Test

If one or more bypass diodes are incorporated in the module, it is essential that they be tested to insure that they are providing the module with the protection for which they were installed. The face of the module is covered to exclude light, but to permit air circulation and cooling. The module is instrumented with a thermocouple or other means to measure its temperature. The diode(s) are provided with leads so that the voltage drop across the diode can be measured. Initially, the module is heated with a heat lamp or in an oven to two different temperatures above room temperature. The voltage drop across the diode is measured with an externally supplied current of 100 mA at room temperature and at each of the two elevated temperatures to establish a temperature-voltage curve. The module is then heated to a stable temperature of 50°C, representative of the operating temperature in full sunlight. The module short-circuit current (I_{sc}), provided by a separate power supply, is run through the diode in the heated module for a period of two hours. The diode voltage drop is measured at 100 mA immediately, i.e., within 0.5 sec., after turning off the I_{sc}. The diode junction temperature is determined by the temperature-voltage curve. The temperature must not exceed the diode handbook temperature rating, but 50°C below the manufacturer's limit is recommended.

Hot-Spot Test

If a cell in a module should become shaded, the other cells and modules that are connected in series with it will attempt to force current through it in the forward direction. When no bypass diode is present, the current going forward through the shaded cell will cause a voltage drop depending on the resistance of the shaded cell. This voltage drop times the current, which is probably the maximum power current and could approach short-circuit current, represents a power dissipation in the shaded cell and can cause enough heat to destroy the cell, crack the glass, or even cause a plastic backing to burn.

Two different methods of hot-spot testing are proposed. One is a proposed IEC standard which can be performed on a standard production module. The second is the method that was developed by JPL and documented in Block V appendix C (5) which requires the construction of a special module with leads brought out for each cell.

The procedure for hot-spot testing based on the proposed IEC standard for "Non-Intrusive Hot-Spot Test of Modules" (6) requires illuminating the module with full sunlight or with a simulator and connecting a power supply in series additive to it. The test is performed with the module at 50°C, simulating the module operating temperature. The cell to be tested is shaded by covering it with an opaque material such as electrical insulating tape. If there are no parallel cells, this may drop the current to zero. The power supply voltage is then increased until either of two limits is reached but neither exceeded. The limits are: short-circuit current of the module or system operating voltage as limited by existing diodes, if any, across the module, whichever occurs first. If the voltage limit is reached first, the cell is called a type A cell. If short-circuit current is reached first, the shaded cell is called a type B cell. For a type A cell, the power dissipation in the shaded cell is the product of the short-circuit current and the voltage across the module. The power dissipation in the type B cell is equal to the product of the current and the impressed voltage less the voltage contribution of the unshaded cells in the series string between diodes at that current level. The present recommendation is to run the test five times with the current and the light on for an hour and both off for half an hour. The test should be repeated for one quarter of the cells in the module, randomly selected. If the module is built of series-connected groups of parallel cells, the test should be performed at least once with a complete parallel group shaded.

The JPL method involves a pre-test in which the dark I-V characteristics of each cell are plotted to determine if the cell is a type A or a type B cell. If both types are present, a number of non-adjacent cells of each type are selected for the heating test. Type A cells have the maximum system voltage that installed or planned diodes will allow impressed upon them. The cells are heated to 50°C with a heat lamp. They are then illuminated with an artificial light source at an intensity that will make the current equal to the maximum power current of the module at the module operating temperature. Type B cells are tested in the dark by forcing module short-circuit current through them while maintaining the temperature at 50°C. Both Type A and B tests are continued for 100 hours.

For each test method, there should be no visible damage. If damage has occurred, it indicates that a diode or more diodes per series string are required.

CHARACTERIZATION TESTS

Purpose

The purpose of the characterization tests is to provide data that will predict the module performance after light stabilization under the environmental operating conditions at the planned deployment location. Characterization tests are not a part of the qualification test and may eventually appear as an appendix to the qualification test document or even in a separate test document. A block diagram of the proposed tests and their sequence is shown in Figure 5.

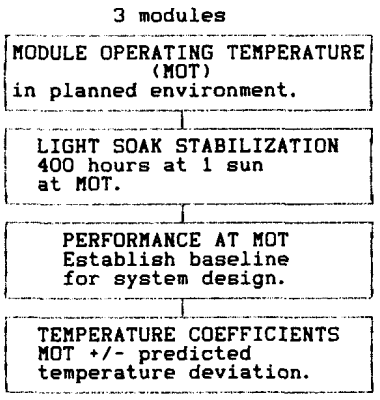

Figure 5. CHARACTERIZATION TEST SEQUENCE

Module Operating Temperature Test

The purpose of this test is to determine the average operating temperature of the module in the location and environment in which it is planned to be used. Ideally this would mean measuring the temperature over a one-year period; since this is impractical, a simplified approach is presented. The proposed method also provides data on the expected temperature ranges of module operation to be expected throughout a year's operation.

A module of the type under consideration is mounted in a manner similar to that planned, and instrumented to measure temperature by installing a thermocouple or RTD on the back side. A means of measuring the ambient temperature in the shadow of the module is provided. If the location is usually windy, a sunny day is chosen with average wind speed and direction. If there is seldom wind, a day with no wind is chosen. The ambient temperature and module temperature are recorded hourly during the sunlit portion of the day. The mean temperature difference between the ambient temperature and the module temperature is then determined for the measurement period. Weather data, as available, are used to determine the ambient temperature swing throughout the year on sunny days. The MOT is the sum of the mean annual ambient temperature with sunlight for the area and the mean difference between the measured ambient and module temperature.

The predicted operating temperature range of the module over a year's exposure is from the lowest ambient with sunlight plus the lowest difference measured between ambient and module temperature to the highest ambient with sunlight plus the highest measured difference between the ambient and module temperature.

Light Soak Stabilization Test

Thin-film modules, specifically amorphous silicon, are known to degrade during the first few months of exposure to sunlight (the Staebler-Wronski Effect). The purpose of this test is to provide an artificial and accelerated light exposure so that the modules may reach a stabilized condition. The modules are illuminated at approximately one sun for a continuous period of 400 hours while being maintained at the module operating temperature determined above. A sodium vapor street lamp, or lamps, is recommended, although metal halide lamps may also be used. (Tests of this type that have been performed at SERI are discussed in Part II of this paper.)

Performance at MOT

Electrical performance tests are made in order to provide the characteristics of operation of the stabilized modules. These are basically the same type of tests to provide I-V data as were performed in the acceptance and qualification tests except that the temperature is controlled to the module operating temperature. It is recommended that the light intensity be held at one sun, but if the planned location has a known average intensity that is greater or smaller, this value may be used. The end result of the test is to provide the operating characteristics of the light-stabilized module at the intensity and temperature in which it is to be used. These data are the baseline for system design in the planned location.

Temperature Coefficients

In order to provide further design data, the temperature coefficients of a stabilized module can now be determined by tests to measure I-V data at the maximum and minimum operating temperatures determined in the MOT test. These data will provide performance limits for the planned location.

PART II: TESTS PERFORMED AT SERI

Light Soak Stabilization Test

The purpose of this test was to evaluate methods to stabilize amorphous silicon modules. It is desirable to have a standard method of testing to provide performance data that will permit system design based upon stabilized performance.

It is known that amorphous silicon modules degrade when exposed to sunlight and that some or all of this degradation can be recovered by annealing at an elevated temperature. To evaluate approaches, two different spectra of lamps were used at two different temperatures as well as reverse current in the dark at two different temperatures.

Two 1500 W multi-vapor metal halide arc lamps and two 1000 W high-pressure sodium arc lamps were

obtained. These were mounted in reflector housings and equipped with Teflon diffusers to promote uniformity on the test plane. Provision was made so that test specimens could be maintained at nominal temperatures of 25° and 75°C ±5°C under each light source.

Test samples were obtained from a number of manufacturers and each sample was given a baseline performance test. This test was an I-V curve run under a SPIRE simulator at 1000 W/m^2 and a temperature of 25°C. One sample from each manufacturer was then placed under each light source at each temperature regime and illuminated at approximately one sun in an open-circuit condition. After illumination for discrete periods of time, each sample was again tested under the simulator and an I-V curve obtained under the standard test condition.

A second test setup was made in which reverse current of 1 I_{sc} was forced through samples that were maintained in the dark at nominal temperatures of 25° and 75°C. Samples were again periodically tested by running I-V curves at standard test conditions.

Figure 6 shows the power degradation caused by the light sources and the times at which performance tests were run. There was little change in short-circuit current or open-circuit voltage, with the majority of change evidenced by fill factor, as shown in Figure 7. It was noted that if a light-soaked sample was stored in near darkness for one week at a room temperature of a nominal 20°C, there was a noted improvement in performance. When the sample was again light soaked, the degradation was as rapid as when first light soaked but ended up with a little more degradation. As can be seen by studying the curves, the difference in stabilization between the two light sources was negligible, but the difference between the two temperatures was significant. For simplicity, the metal halide, which was predominantly a mercury vapor, was called mercury (Hg) and the sodium vapor called sodium (Na). The samples from each manufacturer behaved in a similar manner although the stabilization levels were different.

The dark I_{sc} tests showed similar-shaped curves to the light soaking, but the degradation did not nearly equate to that caused by light soaking. If modules can carry greater reverse current, this might be an easier and less expensive means of promoting stabilization, but 1 I_{sc} does not appear to be adequate.

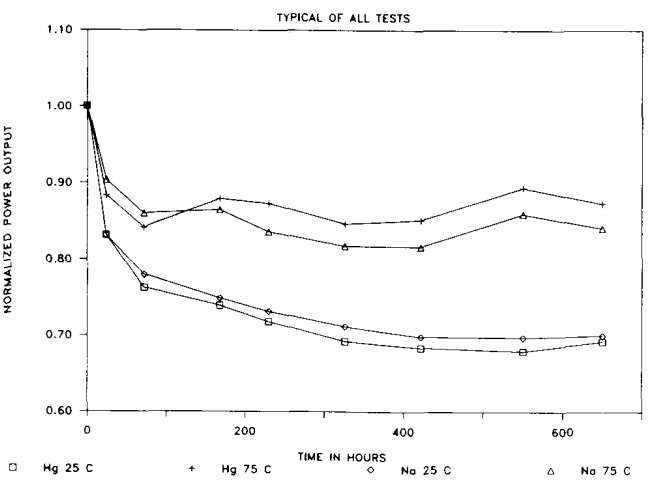

Figure 6. RELATIVE POWER DECREASE AS A RESULT OF LIGHT SOAKING

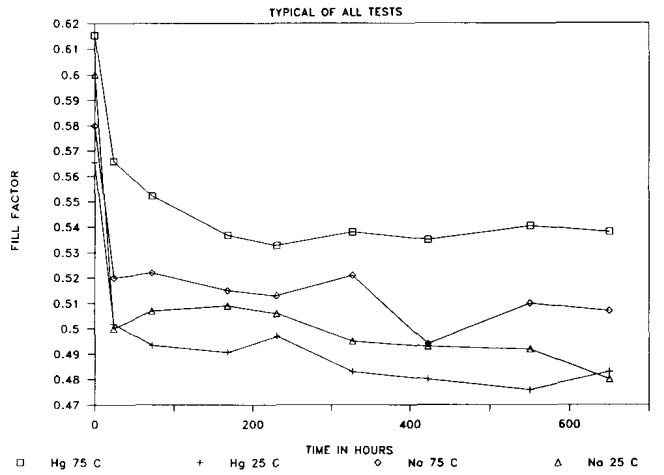

Figure 7. CHANGE IN FILL FACTOR AS A RESULT OF LIGHT SOAKING

CONCLUSIONS

A proposed draft of a test document has been prepared and reviewed by some of the manufacturers, JPL, and Sandia. A revised draft is being prepared.

Additions and modifications will have to be made to the test requirements and procedures as new materials and fabrication methods of thin-film modules develop.

The proposed characterization tests have not yet been incorporated into either an appendix to the qualification document or into a separate publication.

A method of light stabilizing amorphous silicon modules, proposed as a part of the characterization tests, has been verified by SERI.

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