HOT-SPOT QUALIFICATION TESTING OF CONCENTRATOR MODULES*

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ABSTRACT

Results of a study to determine the hot-spot susceptibility of concentrator cells, to provide a hot-spot qualification test for concentrator modules, and to provide guidelines for reducing hot-spot susceptibility are presented. Hot-spot heating occurs in a photovoltaic module when the short-circuit current of a cell is lower than the string operating current forcing the cell into reverse bias with a concurrent power dissipation.

Although the basis for the concentrator-module hot-spot qualification test is the test developed for flat-plate modules, issues, such as providing cell illumination, introduce additional complexities into the testing procedure.

The same general guidelines apply for protecting concentrator modules from hot-spot stressing as apply to flat-plate modules. Therefore, recommendations are made on the number of bypass diodes required per given number of series cells per module or source circuit. In addition, a new method for determining the cell temperature in the laboratory or in the field is discussed.

INTRODUCTION

In support of Sandia National Laboratories photovoltaic concentrator development activities, and under contract to them, a study was carried out with the objective to develop an understanding of the hot-spot susceptibility levels of concentrator modules, to define a qualification test for quantifying the hot-spot endurance of concentrator modules, and to provide guidelines for improving their endurance.

The study centered on the exploratory testing of an Intersol second-generation, point-focus module (Serial Number 1069). This module has 14 one-inch-square cells in series, each attached to an aluminum heat sink, and has a geometric concentration of 80, achieved with planar Fresnel lenses. A single bypass diode is externally mounted across the module's terminals.

Meeting the above objectives involved conducting a variety of research activities as described in this paper. These included:

1) Characterizing the reverse-quadrant I-V curves of the Intersol cells.

2) Quantifying the hot-spot heating characteristics of the Intersol cells and module.

3) Generating a draft hot-spot test procedure for concentrator modules.

4) Developing illumination sources to allow operating the modules in the laboratory environment under simulated steady-state field conditions.

5) Developing techniques for accurately measuring cell temperatures including localized hot spots.

HOT-SPOT HEATING FUNDAMENTALS

Hot-spot heating is caused when the module operating current level exceeds the reduced short-circuit current level of an individual cell or group of cells in an array circuit. The reduced short-circuit current fault condition can be the result of a variety of causes including non-uniform illumination (local shadowing or mistracking), or individual cell degradation due to cracking. Under this condition the cell carrying the excess current

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dissipates power equal to the product of the current and the reversed voltage that develops across the cell. It is desirable to ensure that the resulting hot-spot heating due to the reverse biasing does not cause propagation of the fault or electrical safety hazards.

The degree of hot-spot heating within an affected cell is dependent on a variety of conditions including the number of series cells per bypass diode, the amount of illumination, the amount of over-current in the affected cell, and the reverse-voltage I-V characteristics of the affected cell. Because the reverse-voltage I-V characteristics vary considerably from cell to cell within a given module, it is necessary to determine the dark reverse-voltage I-V curve for a representative sample of cells.

Based on the shape of their reverse-quadrant I-V curves, cells are divided into two classifications. One class, Type A, is composed of those cells whose reverse-breakdown voltage is higher than the maximum available reverse voltage (V_L) under field hot-spot conditions. The maximum field voltage (V_L) is determined by either the maximum system voltage (if no bypass diodes are used) or by the number of series cells per bypass diode (if bypass diodes are used). Type A cells suffer the greatest amount of back-bias power dissipation under conditions of partial illumination; this is because the back-bias current increases with illumination up to a maximum at a particular partial illumination level (see Fig. 1).

The second class of cells, Type B, is those whose breakdown voltage is less than the reverse voltage that may be applied by the field array. These cells operate at the full string current and at a reverse voltage determined by the voltage drop across the cell. These cells suffer the greatest amount of power dissipation under full shadow; under these conditions they have the greatest back-bias voltage across them (see Fig. 2).

CHARACTERIZATION OF INTERSOL CELLS

Initial characterization of the Intersol cells was performed on cell assemblies consisting of only the heat sinks and the attached cells (see Fig. 3).

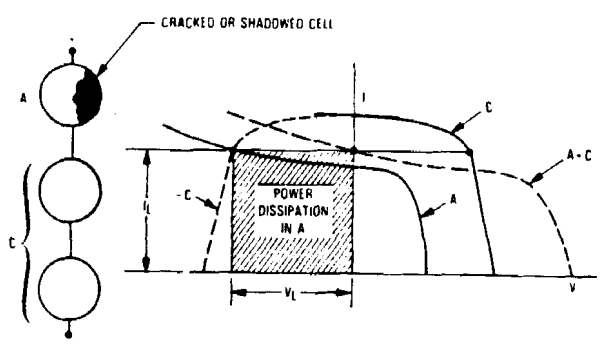

Figure 1. Visualization of Hot-Spot Cell Heating for High-Shunt-Resistance Cell

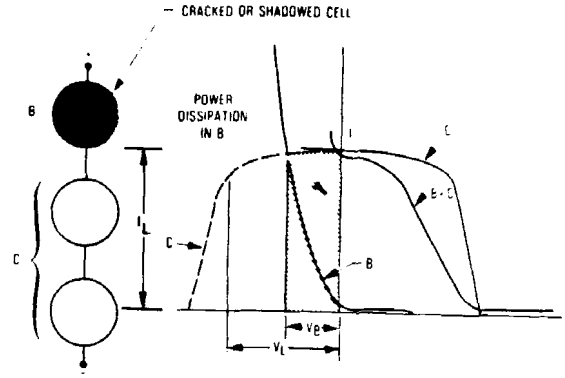

Figure 2. Visualization of Hot-Spot Cell Heating for Low-Shunt-Resistance Cell

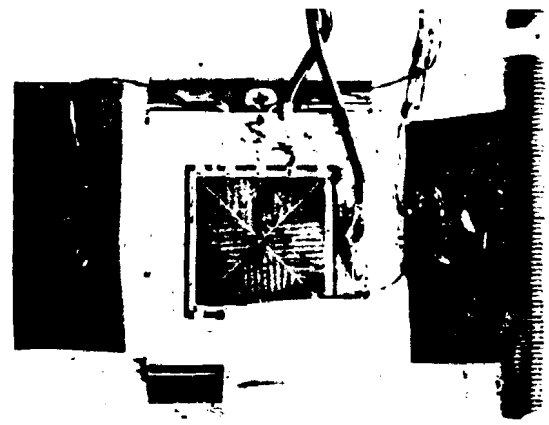

Figure 3. Intersol Module Receiver Assembly

A number of units was isolated electrically with separate electrical leads to allow the individual reverse quadrant I-V curves to be measured. Fig. 4 displays the typical reverse-quadrant I-V response of these cells, both in the dark and at working irradiance levels.

The measured cells exhibit a high shunt resistance with reverse voltage breakdown at 10-12 volts. Because this breakdown voltage exceeds the module voltage, the cell is voltage limited by the module bypass diode under back-bias conditions, i.e., the cells are classified as type A cells. When thermal runaway was allowed to occur, the cells generally break down and exhibit significant reductions in shunt resistance (partial shunting); this behavior is also noted in Fig. 4.

HOT-SPOT TESTING

This phase of the activity was addressed to quantifying the hot-spot heating levels of the Intersol modules. The laboratory tests developed at JPL to determine the hot-spot susceptibility of flat-plate modules (Refs. 1 and 2), served as a

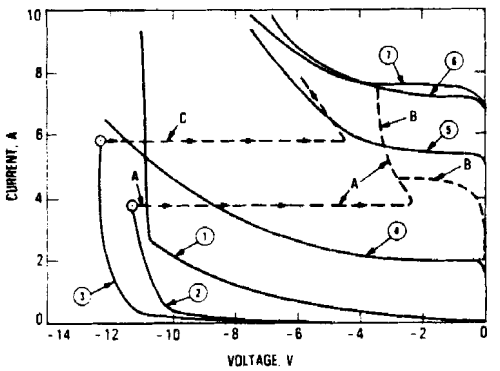

Figure 4. Typical Concentrator Cell Reverse-Quadrant I-V Curves for Various Illumination Levels

starting point for the development of the test procedures used here for concentrator modules.

Module hot-spot heating levels and endurance are normally quoted for representative worse-case field thermal conditions and peak irradiance levels. Building on the test procedures for flat-plate modules, the conditions for concentrator modules were chosen to be 80 mW/cm^2 direct-normal irradiance, 40°C ambient air temperature, and still air conditions (no wind).

Initial attempts at testing modules in the outdoor environment led to extreme data scatter because of transient wind cooling and variable irradiance levels. It quickly became clear that accurate characterization would require a stable laboratory test setup. Accurately measuring cell temperature was also a significant problem.

The ideal laboratory test set-up involves first using an external radiant heater to raise the module heat sink and cell assembly to a background (unilluminated) temperature simulating the 40°C ambient condition plus the influence of adjacent illuminated cells. Next, the cell is electrically reverse-biased to achieve the worst-case hot-spot electrical operating point. For high-shunt-resistance (type A) cells such as these, the cells must also be partially illuminated to achieve worst-case current levels. Lastly, the maximum hot-spot temperature must be measured.

Achieving illumination of the cells and measuring cell temperatures both required development of new techniques and experimental apparatus.

Solar Simulator Development

Hot-spot testing of high-shunt-resistance cells typically requires illuminating cells to levels approaching 80% of the outdoor peak illumination level, i.e., to levels near 60 mW/cm^2. This must be done under steady-state conditions and must also simulate the natural heating of the cell/heat sink assembly that would normally occur from the concentrated sunlight. Particular concerns include:

1) Excessive infrared (IR) content in the indoor illumination source leading to excessive heating.

2) Optical incompatibility with the concentrator leading to insufficient illumination of the cell and/or excessive illumination and heating of the region surrounding the cell.

To meet the above concerns a Spectrolab Model XT-10 steady-state Xenon solar simulator was modified extensively to provide an optical beam simulating the sun's disk at infinity (see Fig. 5). The size of the sun's disk was established via a carefully selected aperture located internal to the simulator at the focal point of the lamp's condensing optics. The aperture is imaged to infinity by an objective lens on the exit of the simulator. When shown on the Intersol module (including its Fresnel lens) the simulator achieves the desired irradiance levels and causes minimal illumination outside of the cell itself.

Cell Temperature Instrumentation

Determining maximum cell temperature during hot-spot heating is difficult with flat-plate cells and especially challenging with concentrator cells. With flat-plate cells the usual technique involves using an IR video camera to image the hot-spot and quantify the differential temperature between the maximum heating point and a reference thermocouple attached directly to the rear surface of the cell.

With a concentrator, it is difficult to view the cell because of its position behind the concentrating optics, and its IR signature is partially masked by reflected IR from the solar simulator; it is also very difficult to accurately instrument the cell with thermocouples.

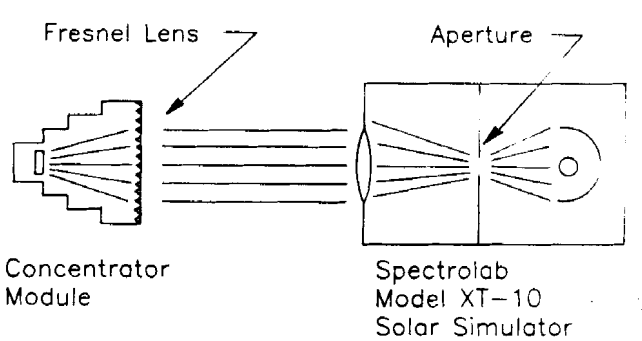

Figure 5. Modified Spectrolab XT-10 Steady-State Solar Simulator

To achieve a best-effort temperature determination, the Intersol module was cut away to allow video IR imaging of the cell at an angle (see Fig. 6). In addition, a thermocouple was attached directly to the cell periphery, outside of the illuminated region and shielded from stray light; a second thermocouple was attached to the heat sink assembly. For a closeup of the thermocouples see Fig. 3.

In addition to the thermocouples and IR imaging, a new technique of sensing cell temperature was developed based on the known relationship between the voltage drop across a diode p-n junction (at a particular current level) and the junction temperature. With this technique, the cell's temperature is determined by measuring the voltage drop across the cell's p-n junction in the dark using a fixed, reverse-current level. The measuring current is supplied rapidly after disconnecting the hot-spot-inducing back-bias current and removing any illumination from the cell. The method builds on the technique previously developed for measuring the junction temperature of bypass diodes in situ (Ref. 3).

Several of the concentrator cells were calibrated to provide cell temperature versus the voltage drop across the cell for given measuring currents. The cells were placed in a constant-temperature oven where the junction temperature equilibrated at the measured oven temperature. Fig. 7 shows a sample of the voltage-versus-temperature plots.

The new junction-temperature measurement technique was used to obtain the cell temperature in a variety of trial operating situations; in one, the cell was illuminated while mounted in one of the partial-module assemblies, and radiant heating was provided to the heat-sink. The cell temperature and heat-sink temperature were measured with thermocouples and the highest and lowest cell temperatures were measured with the IR camera. The measured values of temperature generally fell in the range of temperatures between the thermocouple cell and the heat-sink measurements.

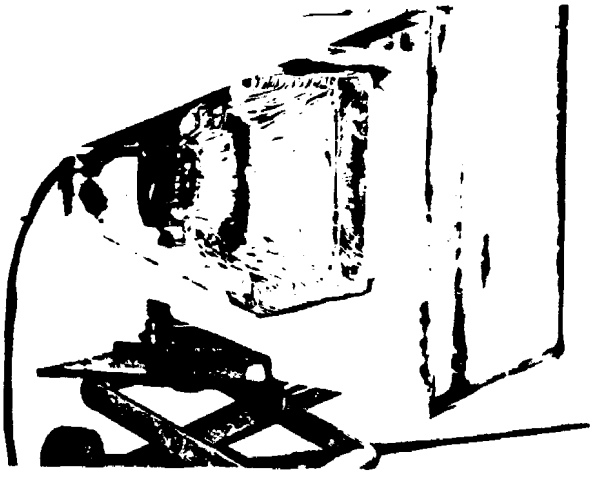

Figure 6. Fresnel Lens and Receiver Assembly

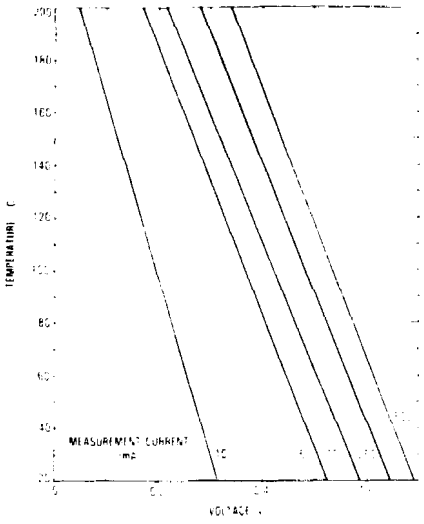

Figure 7. Cell Temperature Versus Junction Voltage and Current

The preliminary tests indicate that the new procedure is a promising technique for measuring cell temperature, but that the readings are sensitive to the choice of measuring current when the cell has substantial temperature gradients. An analysis of the technique predicts that the readings at the lowest measuring currents should be indicative of the hottest localized regions of the cell, whereas readings at higher measuring currents should be indicative of larger cooler areas of the cell. A definitive assessment of the feasibility of using the junction temperature measurement technique will have to await further study.

Overall Test Set-up

Based on the issues described above two test setups were developed: one for initial hot-spot characterization in the dark (see Fig. 8), and one for complete module hot-spot testing with partial illumination (see Fig. 9).

The equipment comprising the test set-ups included: (1) a power supply for providing the back-bias voltage and current to the test cell,

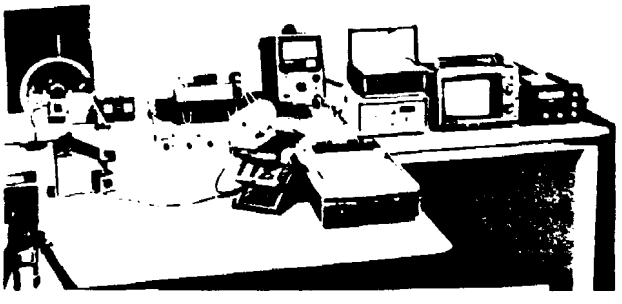

Figure 8. Test Setup for Hot-Spot Testing of Receiver Assembly

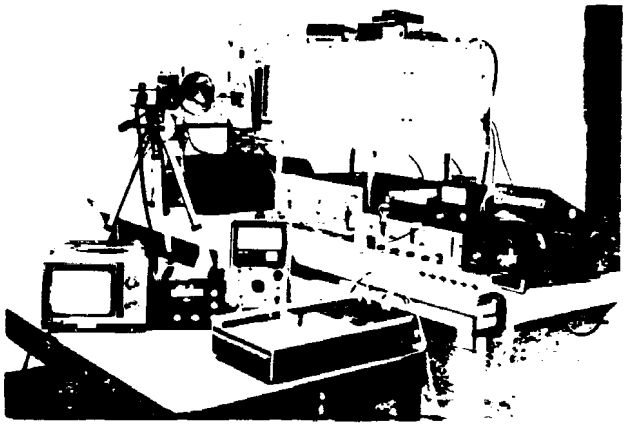

Figure 9. Test Setup for Hot-Spot Testing of Concentrator Modules

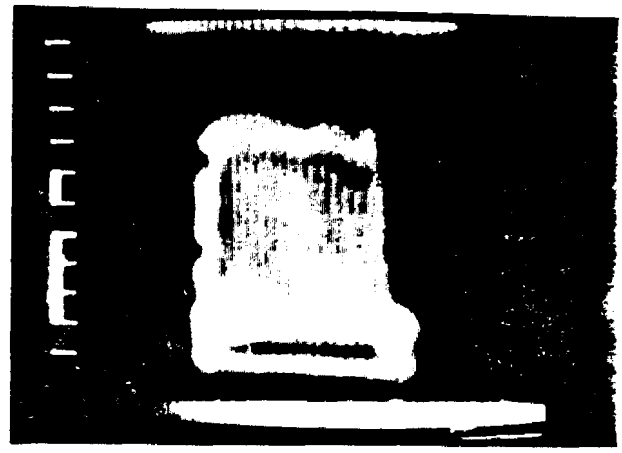

Figure 10. IR Camera Video Image of Cell Hot Spot

(2) meters and an x-y plotter for measuring the test parameters, (3) temperature recording devices including thermocouples and the IR camera, (4) radiant heating source to bring the cell to the desired temperature prior to back-biasing (heat source maintained during entire test), and (5) the light source described above.

Additional equipment for measuring the junction temperature included: (1) a constant-current power supply for providing the measuring current, (2) an ammeter for measuring the current and a sample-and-hold voltmeter for measuring the resultant voltage drop across the cell, (3) a switching circuit for switching between the back-bias power supply and the one providing the measuring current, and (4) a solenoid-activated shutter for quenching the illumination on the cell during the cell junction temperature measurement.

Test Results

The results of cell back-bias testing can be presented in several ways. The key parameters that are measured are cell temperature and power dissipated. The cell temperatures were measured both with thermocouples and with the IR camera. The thermocouple readings are average cell values unless the thermocouple is fortuitously placed on or near a hot-spot. Fig. 10 shows the video image of a hot spot on the cell as produced by the IR camera. The hot spot is the bright spot visible in the lower corner of the cell.

One method of data presentation, shown in Fig. 11, is to plot the cell hot-spot temperature as a function of power dissipated. Although this method gives an unambiguous indication of the cell's susceptibility to hot-spot heating in terms of power dissipated, it does not provide the module and array designer with a useful tool for optimizing the circuitry to minimize hot-spot problems. For the tested concentrator cells the controllable parameter is voltage, which can be limited by the use of bypass diodes. Therefore, Fig. 12 gives the cell temperature as a function of the number of cells per bypass diode; the latter parameter

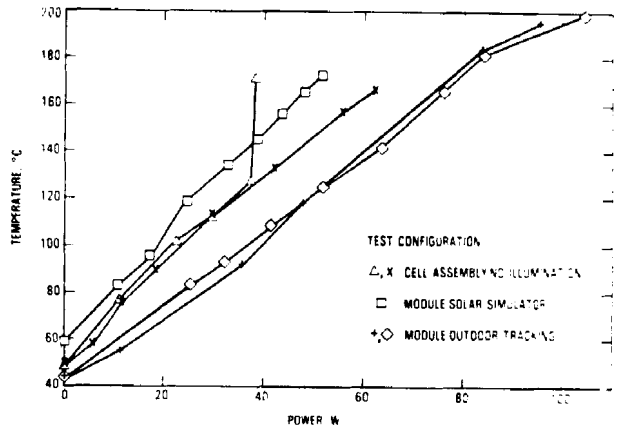

Figure 11. Cell Temperature Versus Power Dissipated for Various Test Configurations

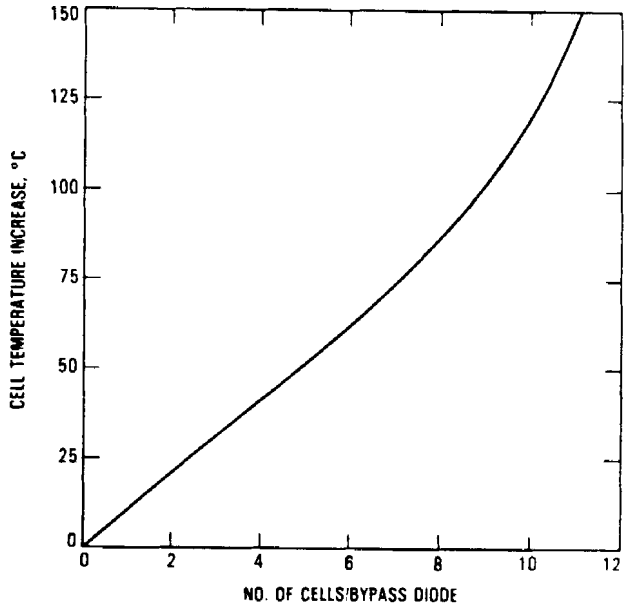

Figure 12. Cell Hot-Spot Temperature Increase Above Operating Temperature Versus Number of Cells per Bypass Diode

directly determines the back-bias voltage. The module designer must, of course, choose a maximum allowable temperature based on the construction materials and endurance of his cell assembly. Some of the concerns are solder melting, increase of thermal resistance between the cell and heat sink due to cell delamination, degradation of the cell front surface coating, and cell shorting. Generally a maximum temperature between 100°C and 120°C is appropriate.

HOT-SPOT QUALIFICATION TEST DEVELOPMENT

As the hot-spot test procedure was refined during the above described investigation, it was used as a model to specify a hot-spot endurance qualification test for concentrator modules. This draft qualification test procedure is included as Appendix A. The procedure draws heavily upon the comparable procedure for flat-plate arrays and uses the same 40°C, still-wind ambient conditions as that procedure (Ref. 1,2). Specific differences include: 1) reference to 80 mW/cm^2 direct normal irradiance (as opposed to 100 mW/cm^2 global), 2) the requirement for a specialized illumination source, and 3) reference to a fixed 50°C background module temperature (as opposed to NOCT for flat-plate modules). This last 50°C figure was selected based on the absence of a design-specific reference temperature similar to NOCT, and the great variability in heat transfer between adjacent cells in different types of concentrators.

In concept, the 50°C figure is intended to represent the operating temperature of a single fully-shadowed concentrator cell when the remainder of the module is fully illuminated with 80 mW/cm^2 direct irradiance, and the ambient air is 40°C and still. Under these conditions it is likely that thermally isolated cells in point-focus concentrators (such as the Intersol) will run at temperatures somewhat closer to the 40°C ambient than those in thermally integrated receivers (such as the Entech). The 50°C figure was believed to be a good compromise.

CONCLUSIONS AND RECOMMENDATIONS

Since the cells in concentrator modules are already designed for maximum cooling using large heat-sinks, the only practical means for improving hot-spot heating endurance of marginal modules is limiting the maximum reverse voltage via bypass diodes. The Intersol modules tested in this activity demonstrated excellent endurance against full-shadow fault conditions, but exhibited very high heating levels under the partial illumination conditions that are more probable in field applications; foreseeable causes of the highly stressful, partial illumination conditions include spotty soiling, localized shadowing from narrow objects, and partial cell area loss from cell cracking.

Fig. 12 provides the data on the frequency of bypass diodes required to limit hot-spot heating of the Intersol module to safe temperature levels. Similar data can be developed for other module designs using the procedures defined herein. It is recommended that additional hot-spot testing be carried out to further refine these trial procedures and provide additional manufacturers with specific recommendations for their designs.

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APPENDIX A

TEST PROCEDURE FOR CONCENTRATOR-MODULE HOT-SPOT TEST

Purpose

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

Commentary

Field experience indicates that periodic circuit faults such as partial shadowing and cracking of cells must be expected to occur even in highly reliable arrays. Under these fault conditions it is desirable to ensure that possible hot-spot heating due to reverse biasing does not cause propagation of the fault or electrical safety hazards.

Hot-spot heating is caused when module operating current levels exceed the reduced short-circuit current level of an individual cell or group of cells in an array circuit. The reduced short-circuit current fault condition can be the result of a variety of causes including non-uniform illumination (local shadowing or mistracking), or

individual cell degradation due to cracking. Under this condition the cell(s) carrying the excess current dissipate power equal to the product of the current and the reversed voltage that develops across the cell(s), which can heat the cell(s) to elevated temperatures.

Test Procedure

The preferred procedure for conducting this test includes a series of steps, first to select and instrument appropriate cells for testing, then to determine the hot-spot test levels, and last to conduct the hot-spot endurance test.

Cell Selection and Instrumentation. The degree of hot-spot heating within an affected cell is dependent on a variety of conditions, including the number of series cells per bypass diode, the amount of illumination, the amount of over current in the affected cell, and the reverse-voltage I-V characteristics of the affected cell(s). Because the reverse-voltage I-V characteristics vary considerably from cell to cell within a given module, it is necessary first to determine the dark reverse-voltage I-V curve for a representative sample of cells (at least 10). This may require a specially built module. Each cell's dark characteristics should be determined for reverse voltages from 0 to V_L or currents from 0 to I_L, whichever limit is reached first, where:

I_L = I_{SC} of an average cell at 80 mW/cm^2, at standard test conditions (STC)
V_L = N x V_{mp} of an average cell at 80 mW/cm^2, STC
N = Number of series cells per bypass diode or number of series cells per module, whichever is less.

When the family of reverse-voltage I-V curves is plotted for the representative sample of cells, a graph similar to Fig. A-1 should be obtained.

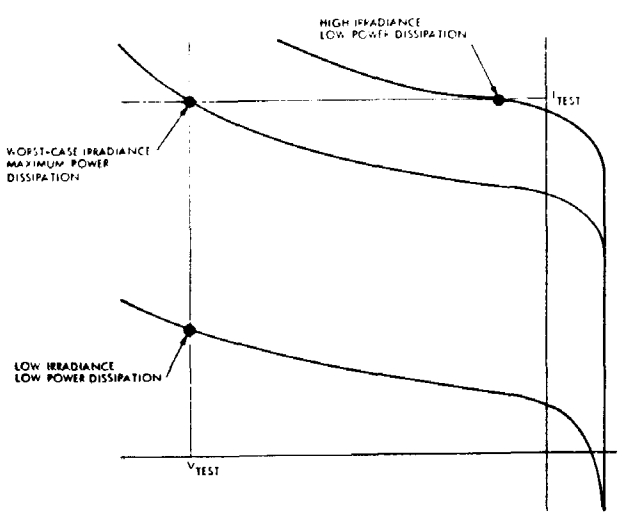

Figure A1. Typical Reverse-Voltage I-V Plot for a Sample of Cells

The individual curves may be either all voltage limited, Type A, current limited, Type B, or a combination of both (as shown). Whether a cell is a Type A or Type B cell is a function of the number of series cells, N, as defined above. A cell that is a Type A cell in one circuit configuration may switch to a Type B cell as N is increased. In general, the cells associated with the highest hot-spot heating levels are those with the highest shunt resistance, although low shunt resistance may be associated with highly localized heating.

For testing, select three individual cells (non-adjacent if not thermally isolated) within the test module from the measured sample: one representative of the highest shunt resistance obtained; one representative of the average shunt resistance; and one representative of the lowest shunt resistance. Provide the test cells with positive and negative electrical leads to allow them to be connected individually to separate power supplies. Any parallel current paths around the selected test cells must be eliminated. The lead attachment should minimize disruption of the cell's heat-transfer characteristics or the hot-spot endurance of the encapsulation/interconnect system.

Selection of Hot-Spot Test Level. The objective of this portion of the test procedure is to select the level of heating corresponding to test conditions that will stress the module in a manner similar to a severe field hot-spot condition. The severity of the field condition will depend on the array circuit configuration, the array I-V operating point, the ambient thermal conditions, the overall irradiance level, and the previously described shunt-resistance characteristics of the affected cells. In particular, whether cells are Type A or Type B is important.

For Type A Cells. The maximum cell reverse voltage (V_L), the ambient thermal environment, and the cell illumination level are the key parameters. When a module is incorporated into an array source circuit without bypass diodes the maximum reverse voltage imposed on an individual cell can approach the maximum array operating voltage. In this procedure it is assumed that the array designer has used bypass diodes or other means to limit the reverse voltage. The test voltage (V_{test}) is thus set to the maximum reverse voltage than can develop across an affected cell as determined by the number of series cells per bypass diode. For type A cells, V_{test} shall be set equal to N times the average Vmp of an individual cell, where N is the number of series cells per bypass diode or the number of series cells per module, whichever is less.

The second test condition is the cell background thermal environment, which is selected to simulate a high temperature (40°C) ambient air temperature with minimal wind, together with heating from adjacent illuminated cell assemblies and heat sinks. For the test, the background thermal environment shall be implemented by uniformly irradiating the heat sink assembly with a steady-state infrared (IR) flux sufficient to achieve an equilibrium cell temperature of 50°C $\pm$

2°C prior to the application of hot-spot power and cell illumination. The IR flux shall remain at this level during the test.

The third key test condition for Type A cells is the illumination level; it directly controls the hot-spot current level, and therefore the power dissipation level. As shown in Fig. A-2, there is a unique illumination level that corresponds to worst-case power dissipation for any particular Type A solar cell. In the test, the irradiance level on the test cell shall be adjusted to achieve this worst-case condition with I_{test} set equal to the average cell maximum power current at 80 mW/cm^2, STC. The incremental cell heating resulting from the illumination source should cause an incremental cell temperature increase approximately equal to that associated with an equivalent exposure to natural direct normal sunlight.

Type B Cells. Type B cells have a cell shunt resistance so low that the maximum reverse voltage is set by the voltage drop across the cell associated with the available current level. In these cells, worst-case heating occurs when the cell is totally shadowed and the current level is at a maximum. Test conditions for Type B cells shall therefore maintain a cell illumination level of less than 5 mW/cm^2 (to allow for room lighting) and a current test level (I_{test}) equal to the short-circuit current of an average cell at 80 mW/cm^2, STC.

As with Type A cells, the background thermal environment shall be implemented using IR heaters to achieve an equilibrium cell temperature of 50°C ± 2°C prior to the application of the hot-spot test current. The air surrounding the heat sink assembly shall be still.

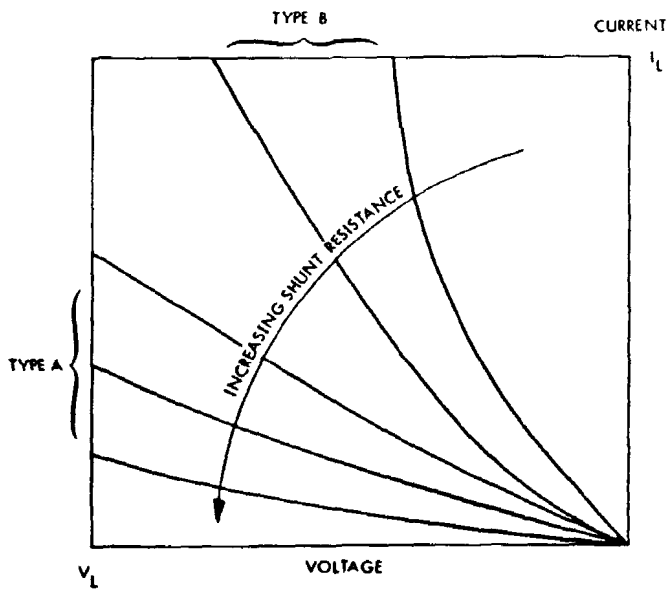

Figure A2. Effect of Test-Cell Illumination Level on Hot-Spot Power Dissipation

Test Execution. Detailed steps for execution of the test involves subjecting the three selected test cells to cyclic hot-spot heating, at the le2vels determined above, for a period of 100-h total on-time, as follows:

(1) Apply an IR radiant-heating source to the cell heat-sink assembly and adjust the heating level to achieve a uniform cell temperature equal to 50°C ± 2°C. The ambient air shall be still.

(2) Connect a separate dual-limiting constant-current, constant-voltage power supply to each test cell with polarity arranged to drive the cells with reverse voltage. Adjust the voltage and current limits to V_{test} and I_{test} values determined in the section, Selection of Hot-Spot Test Level above.

(3) For Type A cells only, arrange a solar simulator to illuminate each test cell to the unique level determined in the section, Selection of Hot-Spot Test Level above (Fig. A-2). This must be done after the power supply and IR source are turned on and adjusted. Adjust the illumination level to achieve, simultaneously, both current and voltage limiting at I_{test} and V_{test} after equilibrium test conditions stabilize. The illumination source should not contain excessive IR or ultraviolet (UV) irradiance that would lead to abnormal heating or accelerated UV aging. The source should also avoid illuminating portions of the concentrator interior or cell assembly that are not normally illuminated (heated) during operation in natural sunlight.

(4) Connect the power supplies, IR source, and light sources to an appropriate timer to obtain a cyclic on-off operation with an on-time equal to 1-h, and an off-time sufficient to allow the test cells to cool to within 10°C of the ambient air temperature.

(5) Conduct the test until a total of 100-h of on-time has been accumulated.

(6) Visually inspect the module and test cell at approximately 24-h intervals during the test, and upon completion of the 100-h sequence. Identify any evidence of degradation, including cell cracking, and delamination, outgassing or blistering of encapsulants, solder melting, or other defects resulting from the test. Measure the post-test electrical performance of the module for comparison with baseline electrical performance. Perform a post-test electrical isolation test.