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HOT-SPOT HEATING SUSCEPTIBILITY DUE TO REVERSE BIAS OPERATING CONDITIONS

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HOT-SPOT TEST--TEST PARAMETERS

Because of field experience (indicating that cell and module degradation could occur as a result of hot-spot heating), a laboratory test was developed at JPL to determine hot-spot susceptibility of modules. The initial hot-spot testing work at JPL formed a foundation for the test development.

The test parameters are selected in the following way. For high-shunt resistance cells, as discussed above, the applied back-bias test current is set equal to the test cell current at maximum power. For low-shunt resistance cells, the test current is set equal to the cell short-circuit current. The shadow level is selected to conform to be that which would lead to maximum back-bias voltage under the appropriate test current level as discussed previously. The test voltage is determined by the bypass diode frequency.

The test conditions are meant to simulate the thermal boundary conditions for 100 mW/cm^2, 40 C ambient environment. The test lasts a total of 100 hours.

A key assumption made during the development of the test is that no current imbalance results from the connecting of multiparallel cell strings. Therefore, the test as originally developed was applicable for single-string cases only. Additional work has been done by JPL in conjunction with the personnel involved with the Sacramento Municipal Utility District photovoltaic-central-station array to widen the applicability of the laboratory test to multi-string applications.

KEY LESSONS LEARNED FROM CRYSTALLINE SILICON

Several lessons learned from the testing and field experience associated with crystalline silicon modules are summarized in this section. It cannot be assumed that all of these can be applied directly to amorphous modules:

(1) The maximum allowable temperature for encapsulants before noticeable degradation is 120 C to 140 C. This will apply to amorphous modules if the same types of encapsulants are used.

(2) The hot-spot temperatures reached by different cells varied with the differences in the cell shunt resistance.

(3) The increase in temperature is affected by the ability of the module encapsulant and superstrate and/or substrate to transfer heat laterally from the hot-spot region.

(4) For crystalline cells, a common failure at high heat levels is cell shorting; the preliminary phase of amorphous cell testing does not indicate that this is also true for amorphous cells.

(5) The typical crystalline-silicon module requires bypass diodes around every 12 to 18 cells to limit hot-spot heating to an acceptable level.

(6) Hot-spot heating is a highly nonlinear function of applied current and voltage. First, cells possess nonlinear reverse I-V characteristics. Also, the shunt-resistance and hot-spot area change with temperature, the latter inversely with temperature increase.

AMORPHOUS-CELL HOT-SPOT TESTING

An amorphous-cell hot-spot testing task has been initiated at JPL and is based on the prior crystalline work performed. As the testing has evolved, several issues have surfaced. One of these is the problem of attaching the electrical leads required for testing the cells in an encapsulated module without causing damage. This is a problem for any type of module, especially for glass rear surface modules where attachment is impossible without damage. Hot-spot testing of this type of module requires specially prepared modules with leads attached prior to lamination. The sensitive cell metallization of amorphous cells necessitates the development of techniques different from those used for crystalline cells where leads were simply soldered to the metal backing. The new techniques being considered include use of conductive adhesives, spring-loaded precious-metal-plated contacts and conductive elastomeric gasket material. The latter is good for making distributed current interfaces in applying back-bias current where use of point contacts would lead to burning away of the cell metallization.

Another issue is that of illuminating the long-narrow cells characteristic of amorphous modules. An ELH lamp is used to illuminate crystalline cells. The light pattern produced by the lamp coincides well with round or even square cells, however, it does not conform well to the long cells. Therefore, more lamps will be required to produce the same light intensity per cell active area leading to an added heat load.

Thus far, the testing has been performed on small, unencapsulated test structures. The extrapolation of these results to large cells and encapsulated modules is not straightforward. In fact, the correlation of these types of tests with results obtained or expected from full-size modules requires the ability to accurately simulate module heat transfer characteristics.

AMORPHOUS-CELL HOT-SPOT TESTING OBJECTIVES

The objectives of the JPL amorphous-cell hot-spot testing task are:

(1) To develop the techniques required for performing reverse-bias testing of amorphous cells.

(2) To quantify the response of amorphous cells to reverse biasing.

(3) To develop guidelines for reducing hot-spot susceptibility to amorphous modules.

(4) To develop a qualification test for hot-spot testing of amorphous modules.

To date, the first objective is about 75% complete and a qualitative understanding of cell response has been achieved, but not a quantitative one. Work on the last two objectives has not begun yet.

APPROACH

Amorphous cells are being tested using two techniques. The first is equivalent to that used in the hot-spot testing of crystalline cells; an IR camera is used to monitor hot-spot temperature and a reverse-bias I-V curve is plotted. The testing in the preliminary phase has been performed in the absence of illumination. There are two reasons for this: First, because this phase involved the development of techniques and the identification of relevant cell characteristics, it was decided to limit the number of variables influencing test results. Also, the appropriate illumination level is dependent on the circuit configuration of the test cell and cell area. Because small test structures were used in the initial phase, the required information was not yet available. It should be noted that conclusive results cannot be obtained without performing tests under illumination.

The second technique consists of pulsed reverse-bias voltage ranging in duration from 0.01 to 100 ms. A power-quadrant I-V curve was plotted initially and after each pulse. This test complemented the one discussed above for the following reasons. In some of the cells tested using steady-state back-biasing, the hot-spot reaction proceeded slowly until a voltage breakdown point was reached where the cell began to rapidly heat up, necessitating shutdown before the test structure was destroyed. The pulse testing, on the other hand, produces a controlled and uniform reaction, dependent on pulse duration and voltage test level, with essentially no heating. Therefore, the cell response can be observed in a gradual way before significant damage occurs.

PRELIMINARY OBSERVATIONS

The preliminary observations can be summarized as follows. First, amorphous cells undergo hot-spot heating similar to crystalline silicon cells. Hot-spot heating in amorphous cells does not seem to be any less or any more severe than in the case of crystalline cells. Their shunt resistance levels are similar and their tolerance to hot-spot heating is similar. Second, the same techniques used to reduce the hot-spot susceptibility of crystalline modules are applicable to amorphous cells with the addition of new ones tailored to the unique characteristics of amorphous cells. Foremost, module design must address hot-spot heating. The more heat sinking provided by the module for the cells, the lower the hot-spot temperature. Also, because hot-spot heating is a focused phenomenon being concentrated in a small region of the cell, use of smaller cells will result in a lower maximum current and, consequently, lower hot-spot heating. Finally, the use of bypass diodes is a good technique for reducing the back-bias voltage.

FUTURE WORK

The amorphous-cell hot-spot testing task will continue with work in the following areas:

(1) Refinement of measurement techniques in order to differentiate between effects induced unique to the technique and effects unique to the cell, e.g., some effects at first attributed to the cell response were because of changes in the conductive pad contacting the cell.

(2) Continuation of the testing of cells and modules as they become available from manufacturers.

(3) Correlation of the results of the test cells with module results in terms of:

  (a) The amount of additional heat sinking available.

  (b) The difference in cell size relative to the current output and increased conductance over the front surface.

(4) Performance of tests under an illumination level appropriate to given module series/paralleled configuration, cell size, and bypass diode frequency.

(5) Strive to understand the changes in cell structure after hot-spot heating.

In the last regard, particularly, JPL welcomes the opportunity to work with cell and module manufacturers.

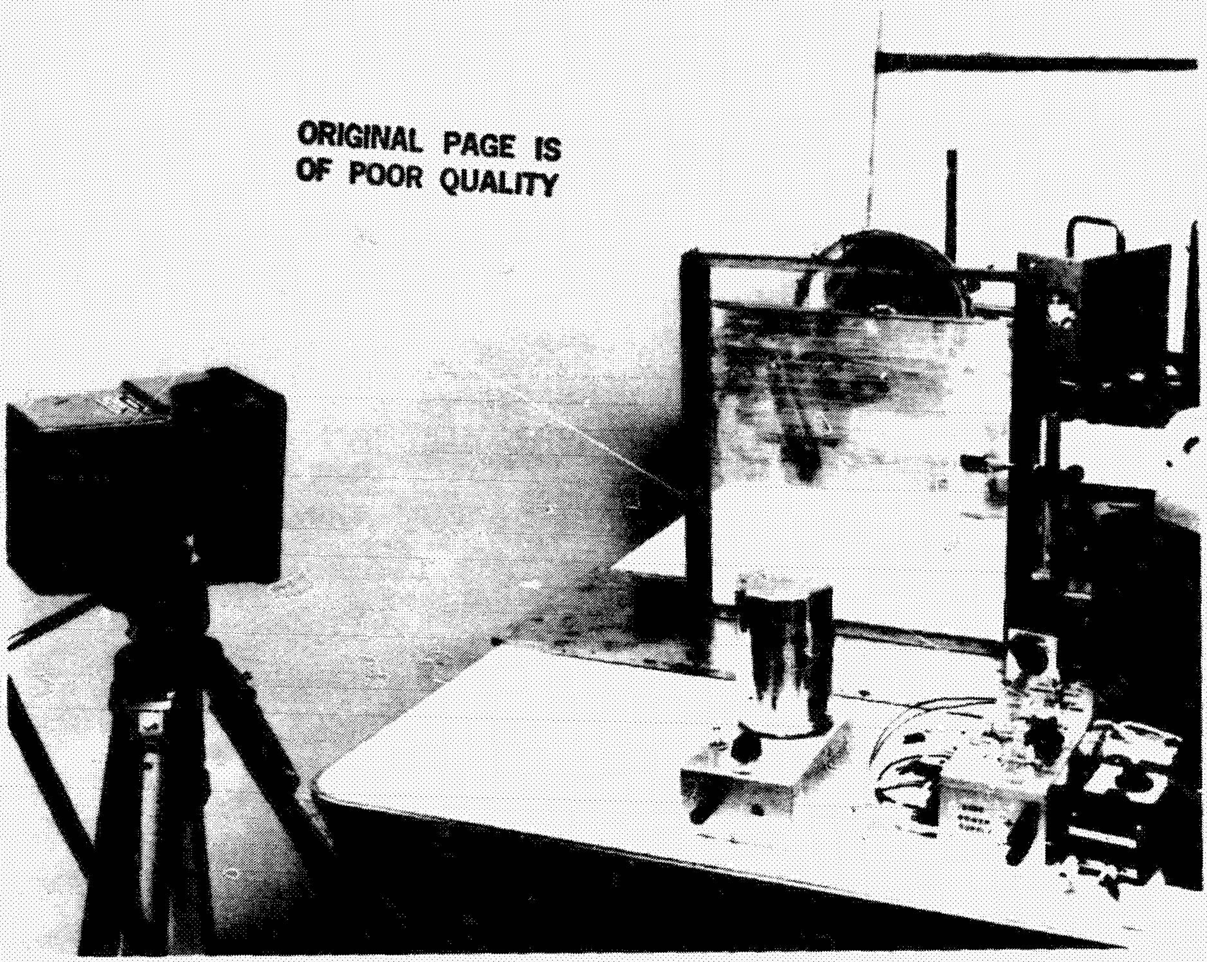

Figure 1. IR Camera and Module Test Setup

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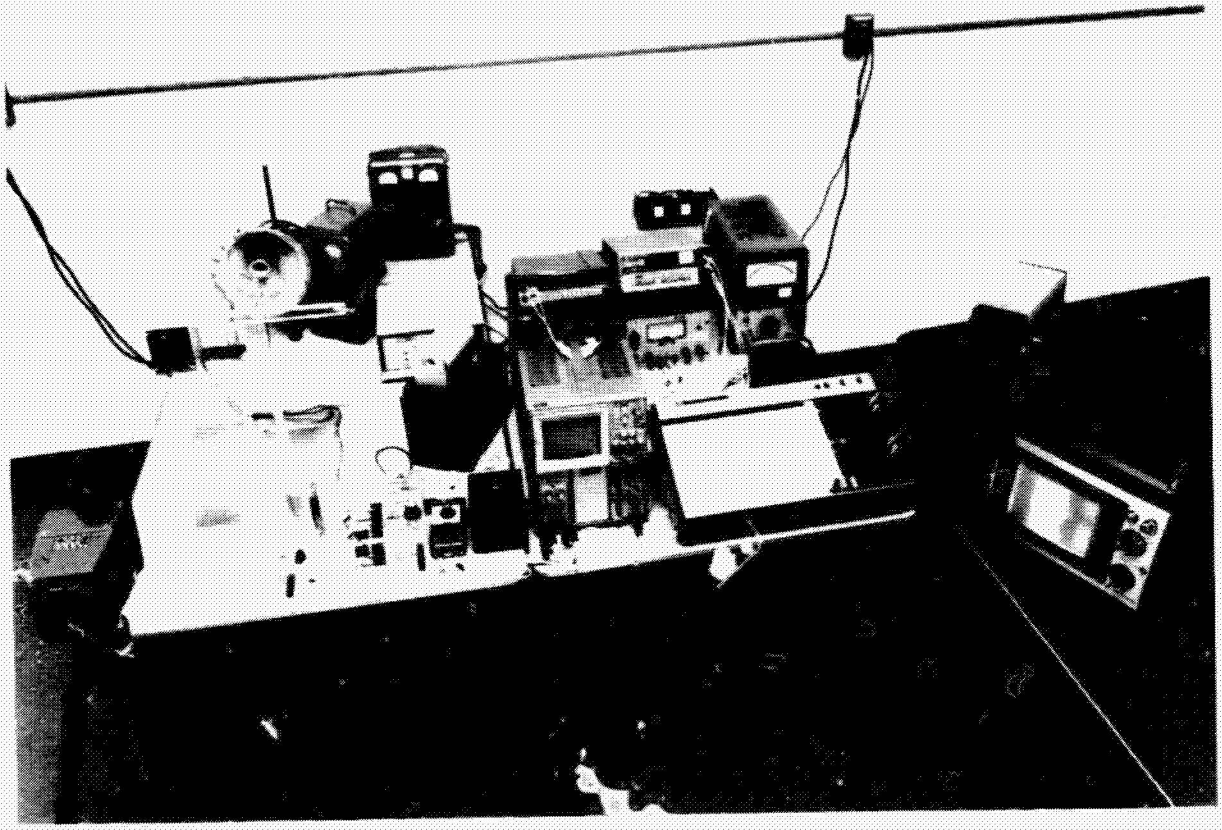

Figure 2. Hot-Spot Test Setup Including All Equipment Used

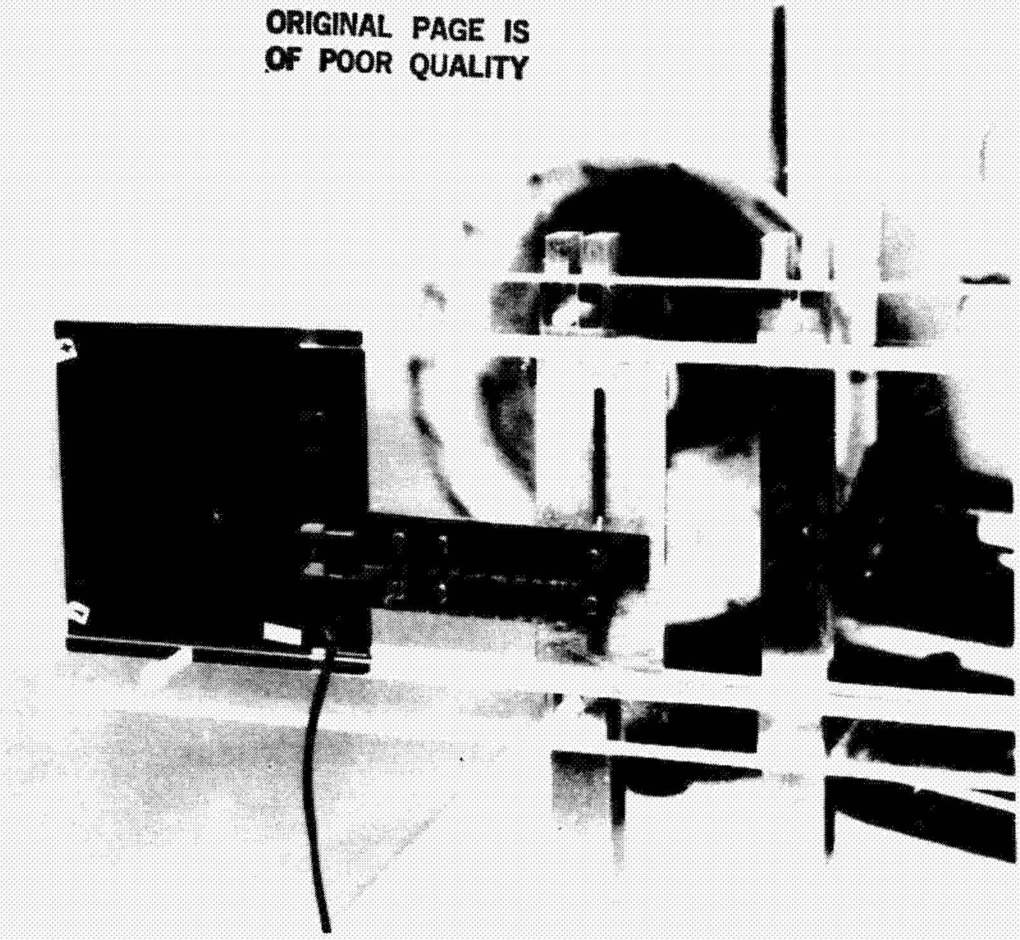

Figure 3. Test Setup Showing Submodule and Contacts Using Conductive Elastomeric Material

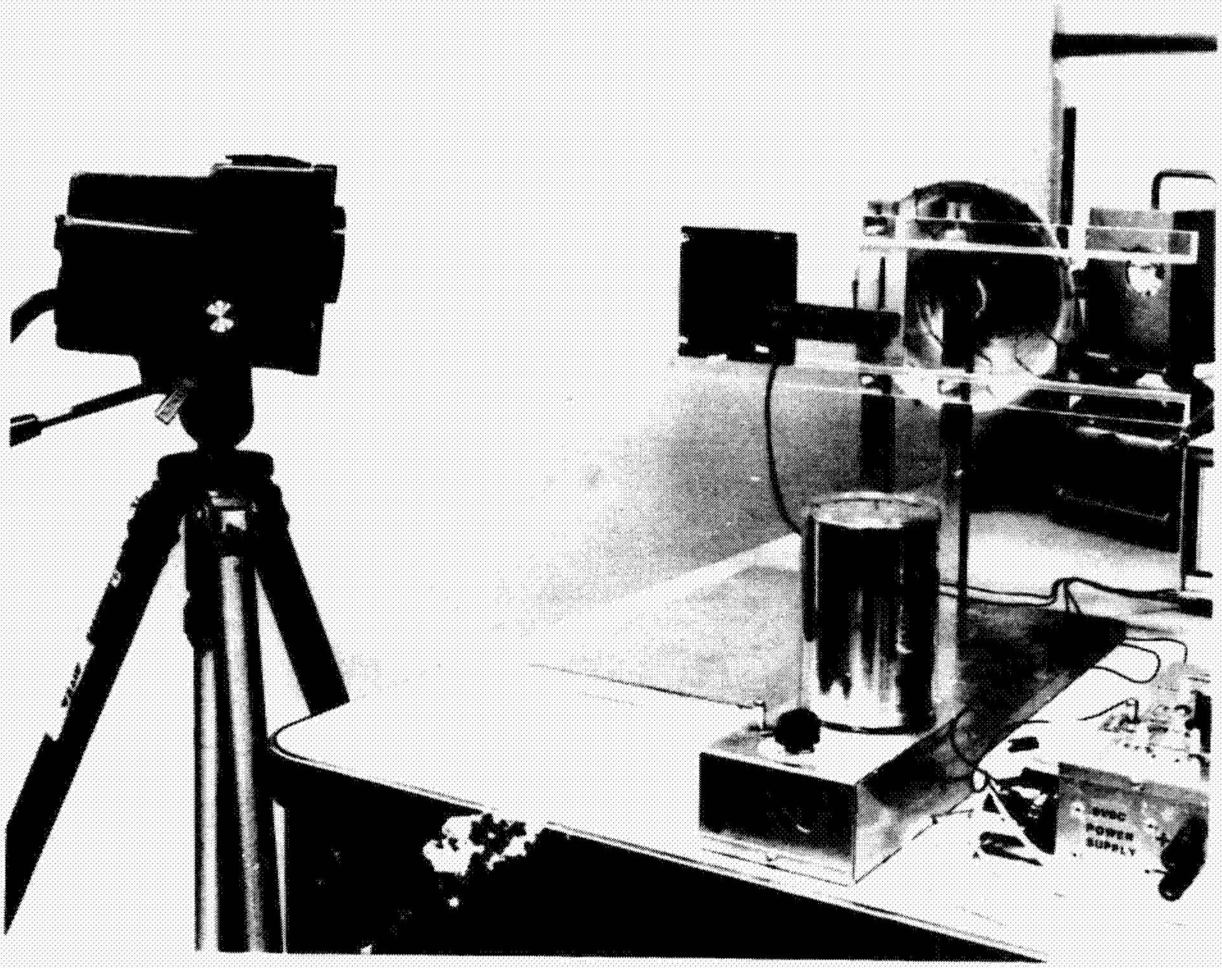

Figure 4. Infrared Camera with Submodule Test Setup

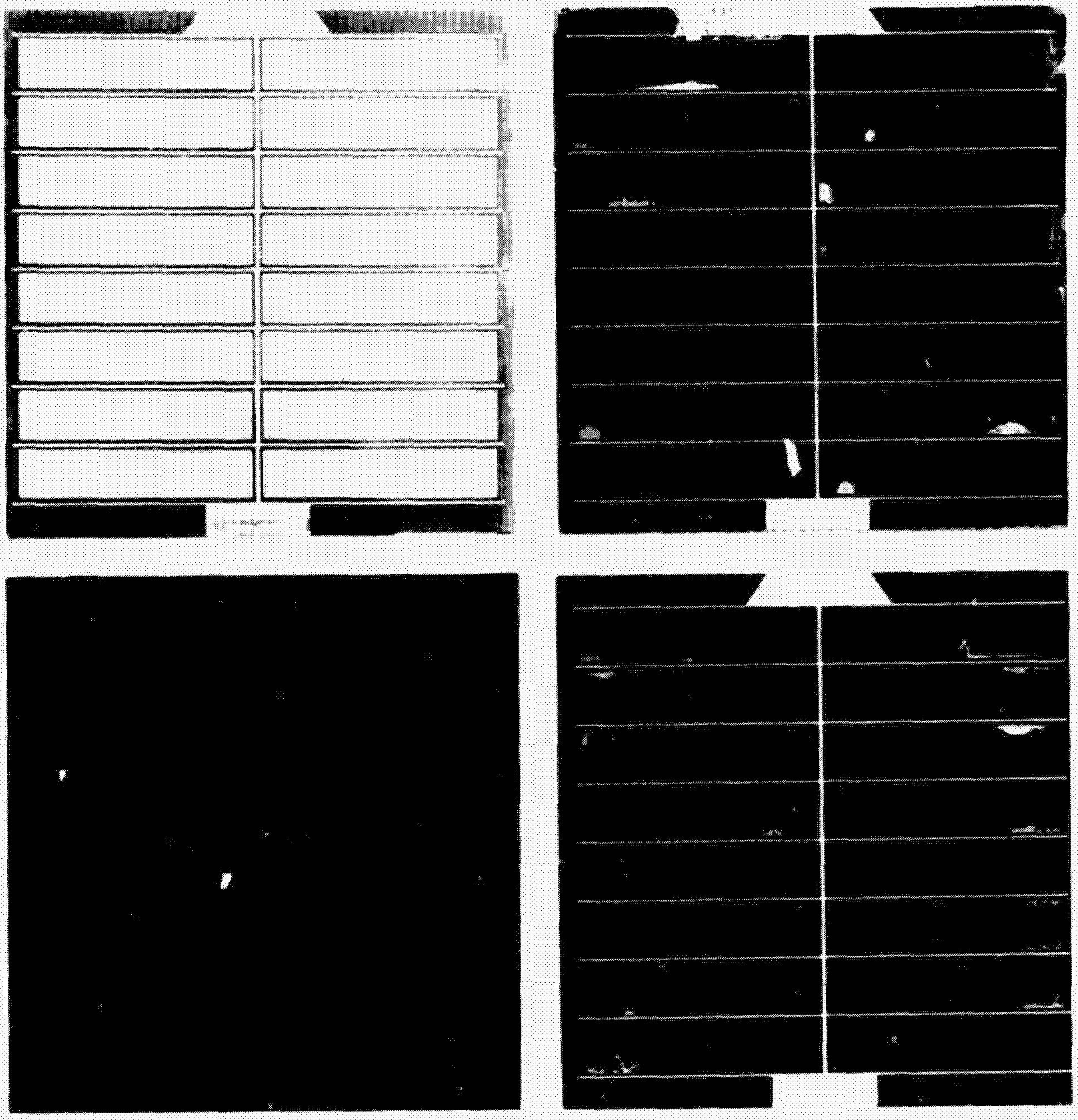

Figure 5. Submodules, Front and Back View, with Hot-Spot Erosion Shown

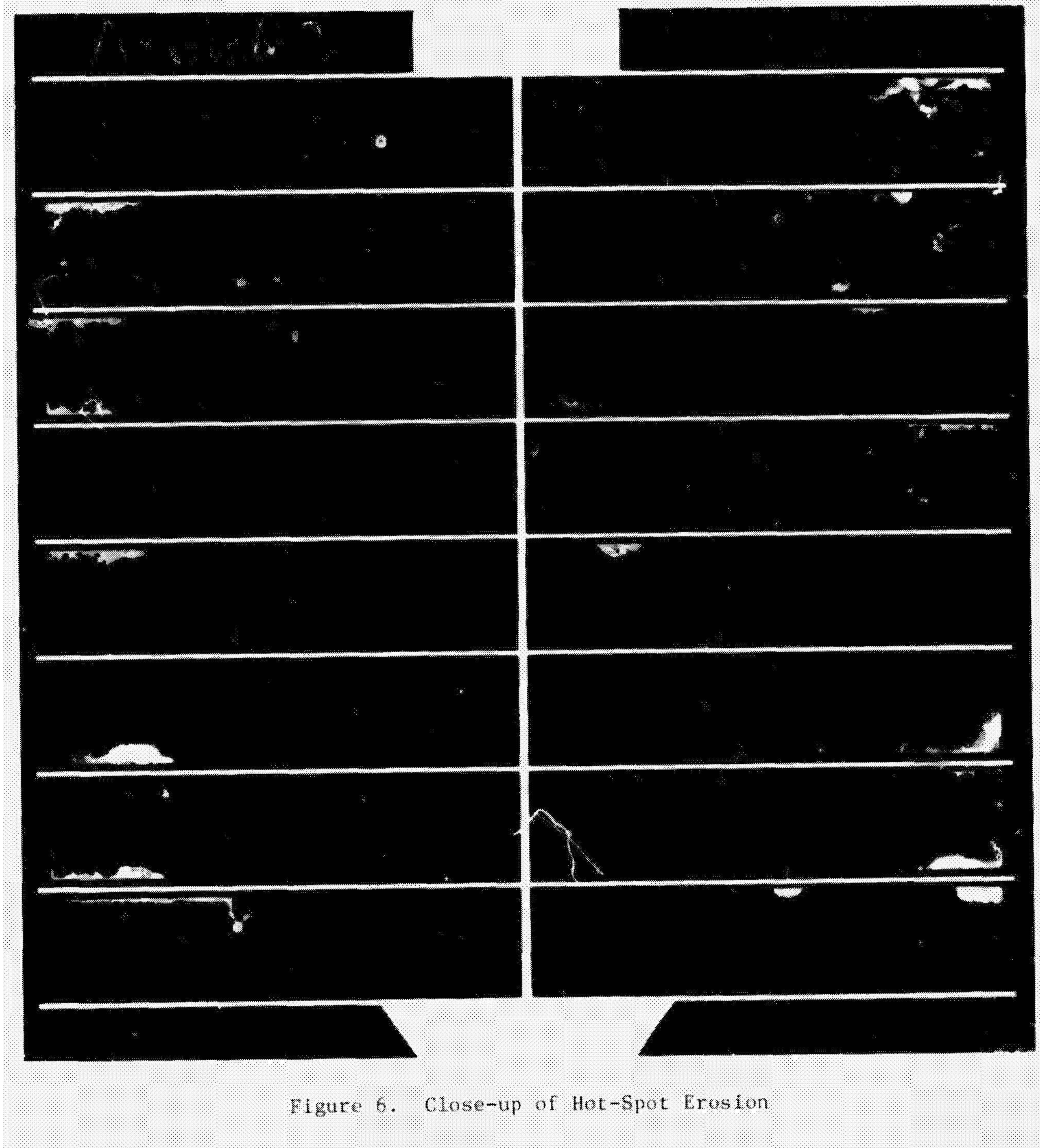

Figure 6. Close-up of Hot-Spot Erosion

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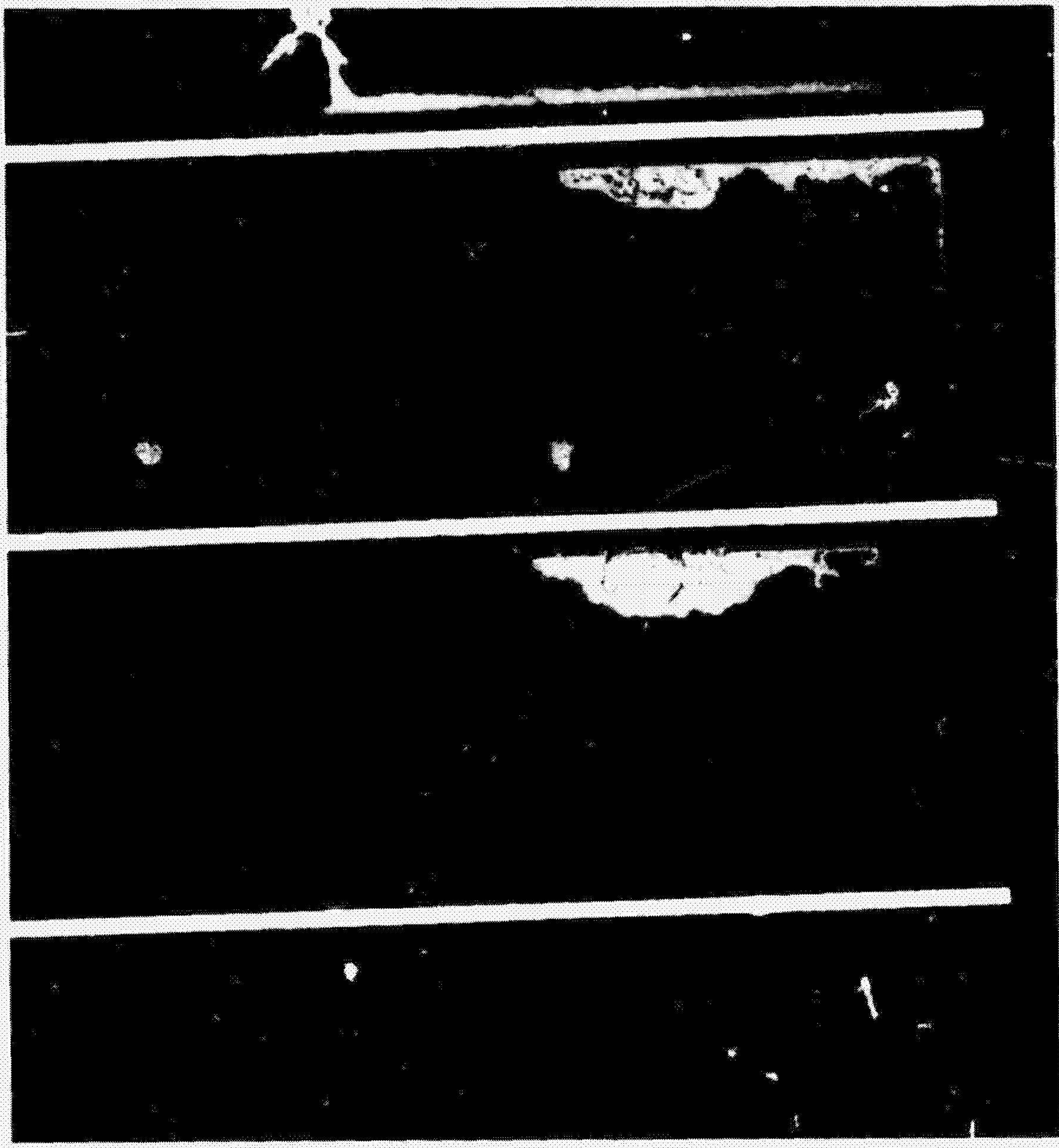
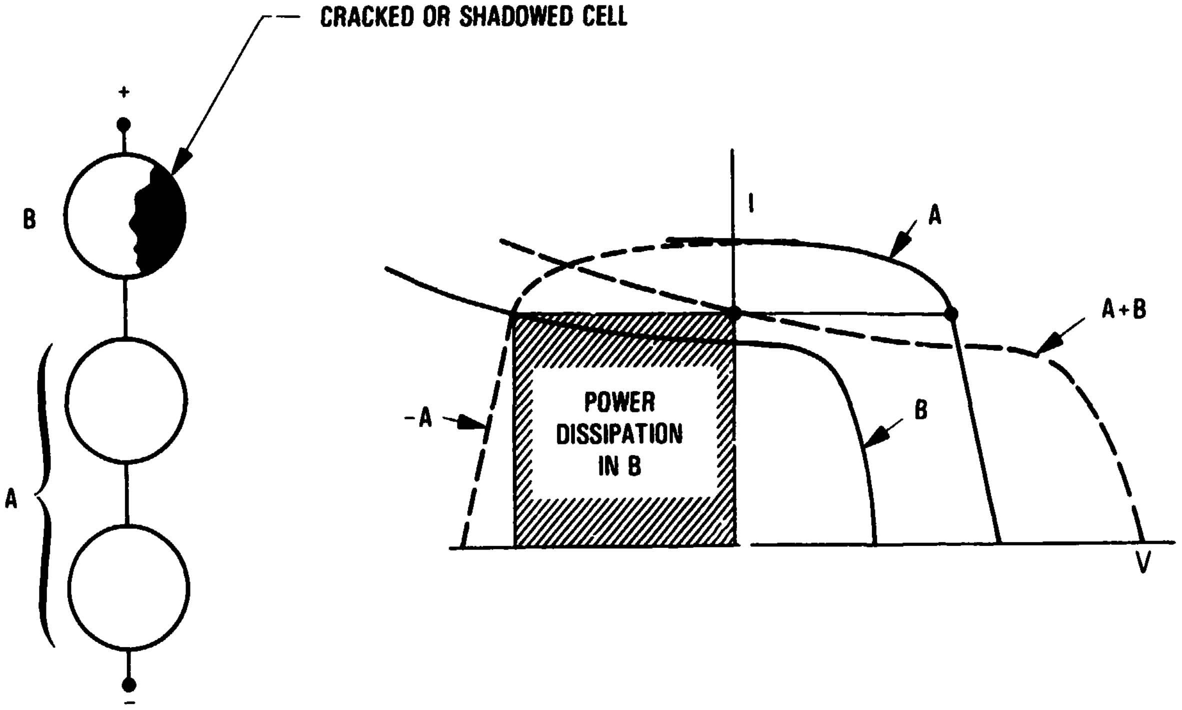
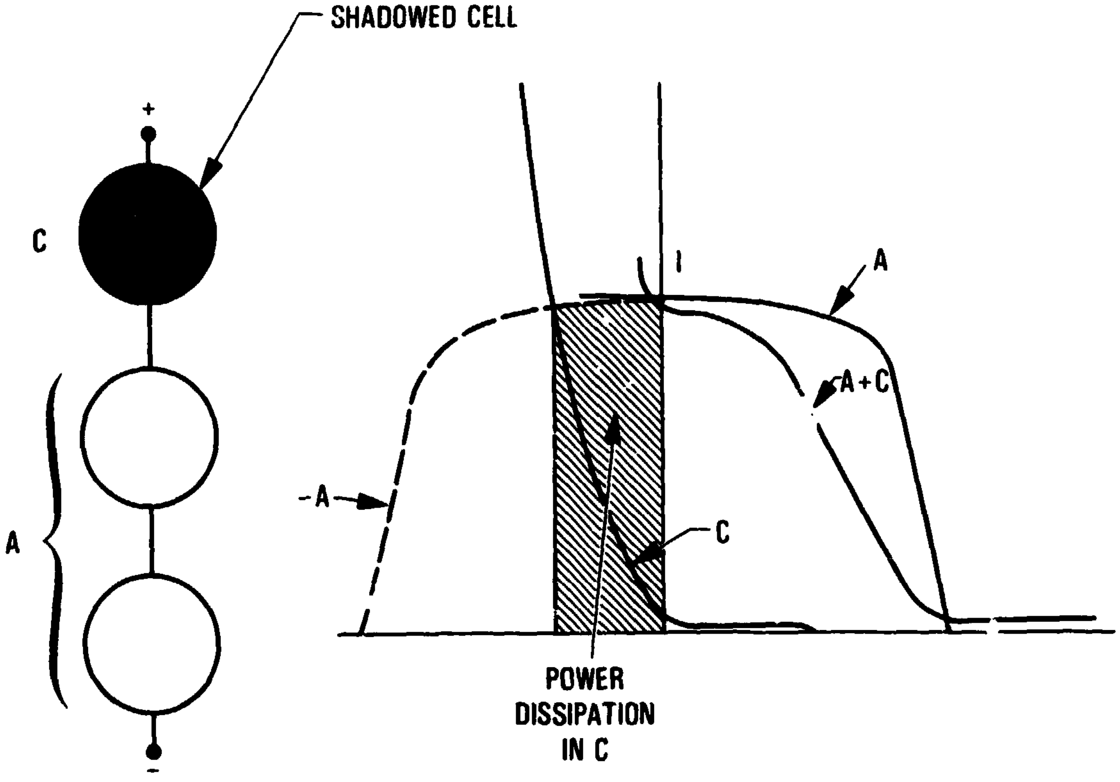


Figure 7. Close-up of Cell Erosion

VISUALIZATION OF HOT-SPOT CELL HEATING WITH HIGH-SHUNT-RESISTANCE CELL



VISUALIZATION OF HOT-SPOT CELL HEATING WITH LOW-SHUNT-RESISTANCE CELL



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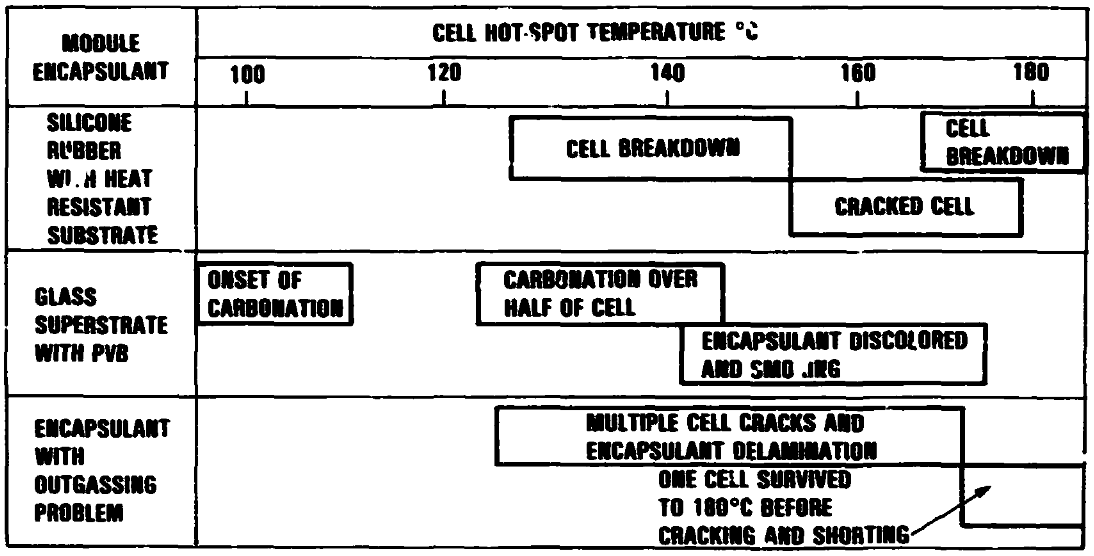
OBSERVED MODULE RESPONSE VS CELL TEMPERATURE



MODULE ENCAPSULANT

CELL HOT-SPOT TEMPERATURE °C

100

120

140

160

180

SILICONE RUBBER WITH HEAT RESISTANT SUBSTRATE

CELL BREAKDOWN

CELL BREAKDOWN

CRACKED CELL

GLASS SUPERSTRATE WITH PVB

ONSET OF CARBONATION

CARBONATION OVER HALF OF CELL

ENCAPSULANT DISCOLORED AND SMOKING

ENCAPSULANT WITH OUTGASSING PROBLEM

MULTIPLE CELL CRACKS AND ENCAPSULANT DELAMINATION

ONE CELL SURVIVED TO 180°C BEFORE CRACKING AND SHORTING

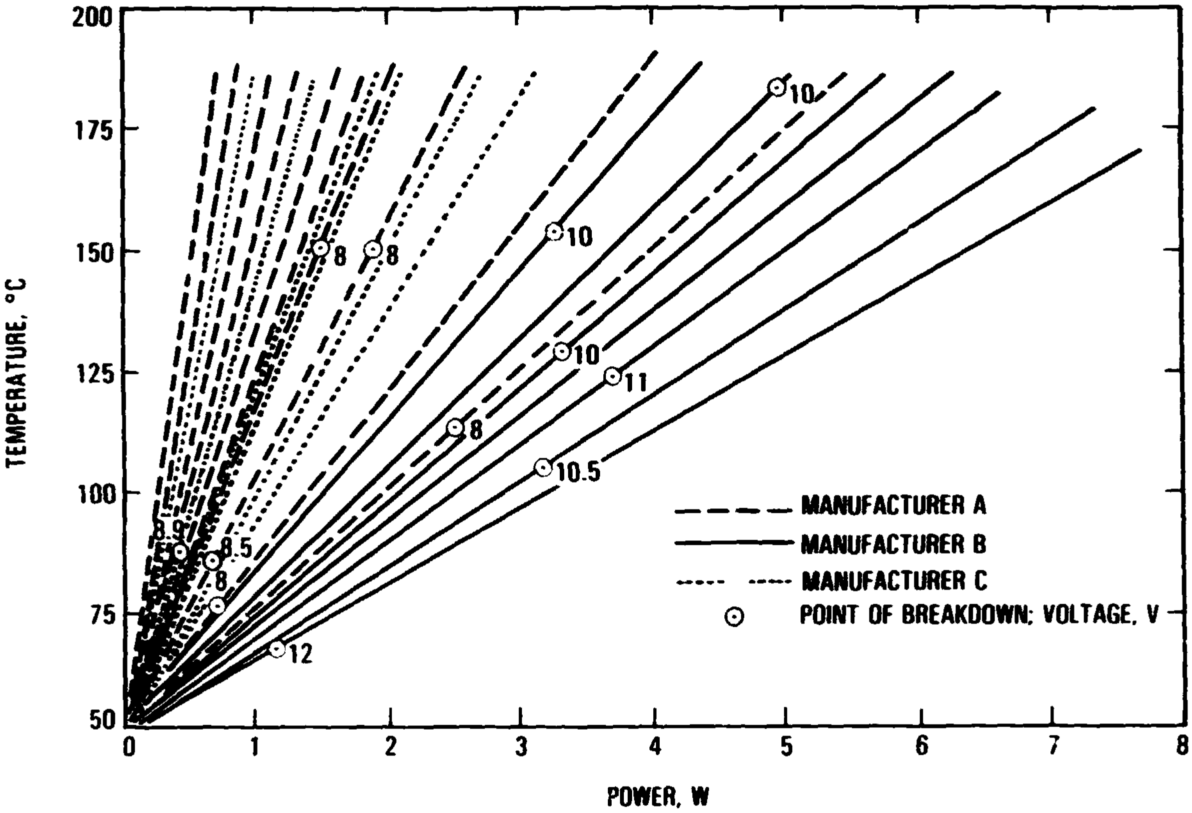
CONCLUSION:

- Hot-spot temperatures should be kept below approximately 120°C

Flat-Plate Solar Array Project

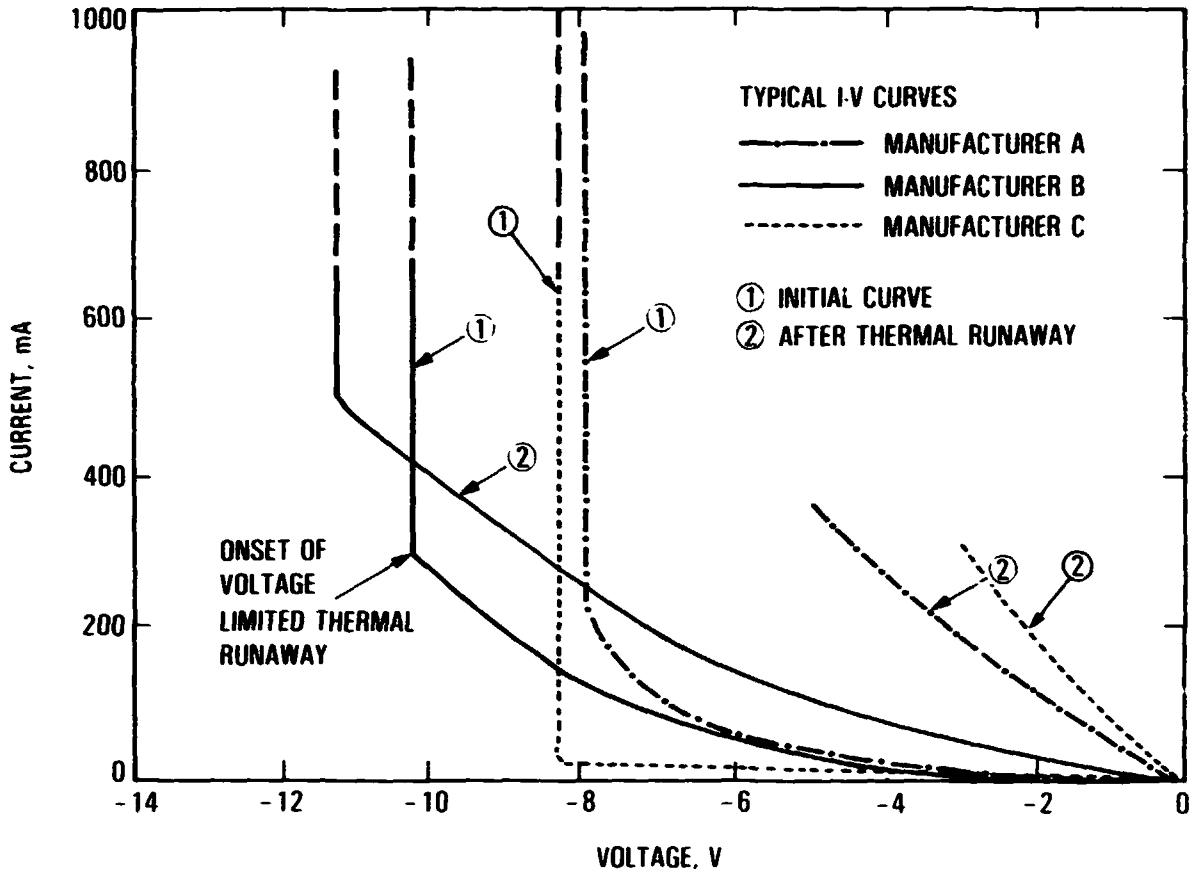
HOT-SPOT TEMPERATURE VS POWER

(UNENCAPSULATED a-Si SUBMODULES, NO ILLUMINATION)



Flat-Plate Solar Array Project

AMORPHOUS-CELL REVERSE-QUADRANT I-V CURVES



DISCUSSION

HARTMAN: Did you see any cells repair themselves if you applied a pulse?

GONZALEZ: We have seen some of that in the pulse testing. That's the only test where we did any front-quadrant I-V curves. We have seen some strange changes in those I-V curves, changes that occur when you just let the cell sit for a while and then continue to test. After it gets a pulse sometimes it gets better. Yes, there are changes.

KNIAZZEK: Can you describe what the effects were that you showed photographs of? What was the morphological change that you photographed?

GONZALEZ: That, I can't get into in detail. You will have to talk to one of the cell manufacturers. The only thing I can see is that the entire material of the cell was eroded away like a volcanic eruption. If you look at the 200X picture -- it just kicked out of there. Now, what's happening actually in the cell I don't know, except that physically it is just being -- it just eroded it, just blew the stuff away.

TURNER: First of all, your concern that the test really should be done illuminated as opposed to in the dark is well warranted. Because it may turn out there is not a significant difference, but one of the significant differences between amorphous cells and crystalline cells is that superposition holds in crystalline cells, that is, their dark I-V curve can be translated to produce the light I-V curve, and that's in general not true of amorphous cells. It's quite a different device in the dark than it is in the light.

GONZALEZ: I didn't mean to imply that we are proposing doing them in the absence of illumination, just that we are trying to get a handle on what's going on and that was the starting point.

TURNER: I understand. You have to start someplace. question is, with the design of these modules, they are usua a very narrow cell and very wide. Or very short and very wide, if you like. The opportunity for causing shadowing would seem to be different -- I don't know how different -- than it is in the case of crystalline modules, which are blocks, and if you have a lion walking across it with muddy prints then he could cause problems. Well, that did happen at Mt. Laguna. I wonder if anybody has attacked the problem of the probability of occurrence of the kind of shadowing that might cause a problem? If, for example, you say the worst case is the one where a module might blow out what you have to do is to hold a pencil two-thirds of the way across one, and only one, cell in the proper orientation. Has anybody wrestled with that problem?

GONZALEZ: I refer you to the work we did about a year ago that Jim Arnett from ARCO was involved in, and that's with the SMUD arrays, where we looked at the types of shadows and what they would do, so some work has been done on that. Not for amorphous; I thought you meant that as a question in general.

TURNER: Particularly because of these modules, which would seem to be less susceptible, but it can be tricky; a telephone line could certainly cause complete shadow.