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## Accelerated Stress Testing of Thin Film Solar Cells -- Development of Test Methods and Preliminary Results

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### 1.0 INTRODUCTION

The reliability characteristics of solar cells intended for low-cost terrestrial applications, either central power generation or distributed residential usage, will be a key factor in determining the economic feasibility of such systems. Typical cost models are based on a 30-year module life, which is generally accepted to mean that the power output of an array should not decrease by more than 10% during this period. The achievement of such a degree of system reliability requires the use of very stable cells. Clemson University, under JPL sponsorship, has had a program to assess the relative reliability attributes of silicon solar cell technologies through laboratory accelerated stress testing since 1977. Much information has been gathered on crystalline cells whose starting material was produced by a variety of techniques -- Czochralski, EFG, dendritic, and HEM. Recently attention has turned to thin film technology and this paper discusses the methodology of using accelerated testing to evaluate the reliability attributes of this type of cell. In this paper necessary conditions for initiating a comprehensive thin film test program including test samples, accelerating stresses, and electrical measurement techniques are discussed and some preliminary test results related to commercial a-Si cells are given.

Accelerated test methodology involves subjecting cells to stresses higher than normally encountered in hopes that naturally occurring degradation mechanisms, which might take years to detect in the field, can be detected in the laboratory within days or weeks. Cells are initially visually inspected and electrically measured, subjected to the desired level of stress, and then measured and inspected again. Changes which occur can then be assumed to be due to the effect of stress and through analysis of the observed degradation related to fundamental physical, chemical, or metallurgical changes. In this way accelerated stress testing can be used to uncover potential failure mechanisms in a relatively short period of time, permitting preventative measures to be taken.

For accelerated testing to provide useful results, however, three conditions must be met: 1) the samples being stressed must be representative of the manufactured population, 2) a stress window must exist, and 3) the measurement methods used must have a sufficient degree of repeatability. Each of these points will be discussed in detail as it pertains to the stress testing of thin film cells.

## 2.0 TEST SAMPLE CONSIDERATIONS

Thin film modules are fabricated monolithically, i.e. a number of interconnected cells are fabricated simultaneously on a single substrate or superstrate. Stress testing, however, is most effective when it seeks to examine the effect of stress on each individual cell rather than a complete module, since not every cell will be affected equally by the stress. This requirement for individually addressable cells means that in contrast to single crystal cells, where test samples could be taken directly from a manufacturer's current production prior to assembly and encapsulation, special test vehicles will need to be manufactured specifically for the purpose of accelerated testing.

These specially made test vehicles should be as nearly identical as possible to the monolithic structure, however. They should have the same composition of materials and be processed in the same way. The test vehicles should include simulated interconnects so the effect of stress on the metal interfaces can be examined. The role played by encapsulation is not at all clear in thin film cells, but because thin films are obviously subject to more rapid degradation through corrosive and dissolution effects than the thicker layers of crystalline cells, encapsulation can be expected to strongly influence a cells response to accelerated testing.

Final: an assured source of test samples representing state-of-the-art technology is required. The great value of crystalline cell testing was its ability to compare the reliability attributes of material and processing changes as they developed. Because of reasons stated above, the regular availability of 100-quantity lots of test samples will require considerably greater dedication to accelerated testing on the part of manufacturers than was the case for crystalline cells.

## 3.0 STRESS WINDOW AVAILABILITY

As noted above, the amount of stress applied to a cell must be sufficient to provide considerable acceleration of the degradation mechanism over that which occurs in real time. Typically one would like to achieve at least an acceleration factor of 100. With an acceleration factor of 100, effects occurring in 30 years will be observed to have the same magnitude in approximately 100 days. Determination of actual values of acceleration factors, in general, is difficult, but for the case of those degradation mechanisms which are a function of temperature only it is possible to use the Arrhenius equation to establish a relationship between high temperature stress and room temperature stress. Under these conditions the acceleration factor will depend on an activation energy as well as temperature. A mechanism with a high activation energy will have a much higher acceleration factor for a given temperature, as shown in the accompanying viewgraph. Most common degradation mechanisms have activation energies between 0.4 and 0.7 eV.

In an effort to achieve a high acceleration factor, or at any rate one which is at least 100, the tendency is to increase the stress temperature. This can only be done within limits, however, since certain thresholds may be exceeded at sufficiently high temperatures as to introduce new failure modes which did not occur at lower temperatures. An example of this behavior would

be the change of phase of a material, such as solder melting. The metallurgical leaching aspects of molten solder are completely different from the diffusion characteristics of solid solder. Consequently Arrhenius extrapolation is no longer possible when thresholds such as this are exceeded. The introduction of new failure mechanisms, in effect, places an upper limit on the magnitude of the accelerating stress which may be used. Thus the combination of minimum acceleration factor and maximum stress results a test "window" for some activation energies and not for others. In the graphical example shown in the viewgraph, where a minimum acceleration factor of 100 and a maximum temperature of 140 C were assumed, a window of testability can be seen to exist for an activation energy of 0.5 eV, but not for 0.4 eV.

Because there is no extensive history of accelerated testing on thin film cells, activation energies have not been determined and little is known concerning the existence of phenomenological thresholds which will limit stress. One technique for determining the upper stress limits for accelerated testing is to perform step stress testing. In step stress testing samples are consecutively subjected for equal lengths of time (steps) to ever increasing stress levels. It is possible to select the stress level magnitudes and times such that there will be little cumulative effect. Consequently a sudden change in the amount of degradation from one level to the next signals the existence of a phenomenological threshold and accelerated testing should only be performed at lower levels of stress. A classic example of this type of behavior was observed when some unencapsulated a:Si cells were subjected to unbiased temperature step stress testing as shown in the accompanying viewgraph. Obviously the threshold occurred between 130 and 140 C. Further work will be needed to determine the cause of this threshold.

#### 4.0 MEASUREMENT REPEATABILITY

The ability to make repeatable electrical measurements days, weeks, and months apart is essential to an accelerated test program. The greater the repeatability of the measurement instrumentation the smaller the changes which are able to be detected, and consequently the shorter the acceleration time that is needed to induce degradation. Measurement repeatability necessitates being able to accurately reproduce after stress the same temperature, contact, and illumination conditions that existed before stress.

Cell temperature control requires use of a shuttered light source combined with rapid data acquisition so that the temperature of the cell will not be influenced by its illumination. A constant flow of temperature controlled air is used to precondition the cells prior to illumination. Cell contacts should be of the Kelvin type with separate current carrying and voltage sensing contacts to eliminate the effect of varying contact resistance. Thin film cells do not have soldered leads attached, as was the case for crystalline cells, so pressure contacts must be made directly to the thin conductive films. Metal spring contacts tend to scratch the films so that the measurement process itself will introduce degradation. It has been found that conductive, elastic rfi gasket material is an excellent non-damaging contact material, particularly when jigs are designed so that conduction is across the width of the gasket rather than along its length.

Under the Clemson-JPL contract, a short interval measurement system,

embodying the Kelvin contact and temperature control principles mentioned above, was developed for characterizing crystalline cells up to 4-inches in diameter. This instrument, which has proven in practice to be repeatable to within 1%, cannot be used directly for a:Si cells because of the difficulty in reproducibly setting illumination levels over extended periods. This is due to the fact that ELH simulator lamps tend to change their spectral characteristics over time and stable, spectrally appropriate thin film reference cells are not available for adjusting the lamps' intensity, as was the case for crystalline cells. Various approaches are being followed in a number of different laboratories which will permit the simulation of thin film spectral characteristics using stable silicon cells. The ability to make accurate accelerated stress test measurements will need to await the outcome of this development effort.

At the present time accelerated test measurement data at Clemson is obtained by digitizing cells' IV characteristics and storing this information on floppy disks. It was found in measuring crystalline cells that valuable information concerning degradation mechanisms could be obtained from the shape of the characteristic in all three quadrants (reverse, power, and far-forward). The amount of data necessary for the complete comparison of before and after stress characteristics can quickly mount up, even for a modest test program. For some time reduced data quantities have been used in an effort to simplify this comparison and perhaps ultimately eliminate the need for ever increasing amounts of storage. The reduced parameters now being collected are Voc, Isc, Pm, Vm, and Im. Modelling work has indicated that the addition of the parameters Rs (series resistance), Rsh (shunt resistance), Io (effective diode leakage current), and n (diode ideality factor) will permit reasonably accurate modelling of the shape of the IV characteristic, at least in the power quadrant. Consequently effort is underway to automatically acquire these parameters and eliminate the need to store individual data points. Standard statistical packages are available which permit the statistical analysis of these reduced data parameters.

## 5.0 PRELIMINARY RESULTS

A comprehensive accelerated stress test program for thin film cells has not as yet been started. Initiation of such a program is dependent on successful completion of the steps outlined above, particularly the availability of an assured supply of representative state-of-the-art cell test structures. Consequently very little data is available at this time, but some preliminary measurements are underway in an effort to define an appropriate test schedule for a:Si cells. The test schedule which has been utilized in the past for crystalline cells is shown in the accompanying view graph and, while this schedule will need to be modified for a:Si and other types of thin film cells, it can serve as a point of departure for these initial investigations.

Having acquired a number of individually addressable, but unencapsulated a:Si cells, which were fabricated in multiples of 16 on a common superstrate, the first step was to subject them to unbiased step stress testing. This resulted in the data mentioned earlier which indicated a threshold effect occurring between 130 and 140 C. A crystalline reference cell was used for these measurements, which implies that measurement errors of a few percent were superimposed on the stress related changes, but nevertheless the data

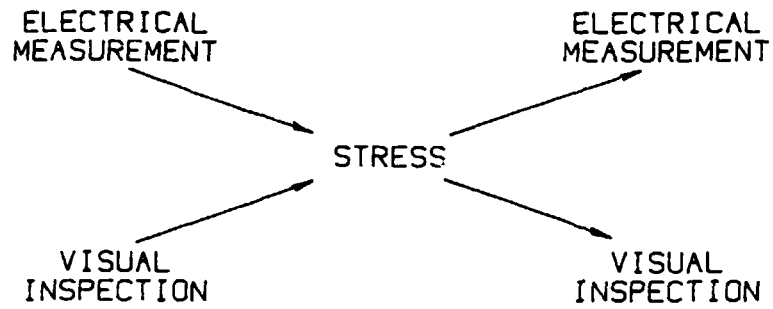
obviously supports the existence of a stress related transition temperature. It is not known at this time, however, if the transition temperature applies only to this type of cell construction or the reason for its existence.

In order to investigate the effect of high humidity on these cells a subgroup of 16 cells was subjected to the standard 85/85 test (85 C and 85% relative humidity). Initial measurement indicated that the cells could be divided into two classes -- "good" and "poor" -- on the basis of their power output. Good cells had relatively rectangular IV characteristics (good fill factors) with Pmax in excess of 20 milliwatts, while poor cells had Pmax less than 20 milliwatts. Thus far, data has been collected after 200 and 400 total stress hours with results as shown in the accompanying viewgraph. The two classes of cells behaved quite differently. During the first stress period the maximum power output of the poor cells increased by more than 50%, on the average, with only a slight further increase being observed during the second stress period, while the poor cells showed a slight decrease in Pmax after both stress levels. As shown in the viewgraph, poor cell improvement was accompanied by increases in Voc and FF, but not Isc. This test is continuing. More work will need to be done to define the degradation mechanism, but one phenomenon that will certainly be investigated is hydrogenation as a result of water vapor dissociation at the aluminum back contact.

As a second experiment to investigate the effect of high humidity, another group of 16 a:Si cells was subjected to pressure cooker stress (121 C, 15 psig H2O) for 25 hours, the minimum stress time in the crystalline cell schedule. Physical examination of the stressed cells indicated that most of the metallization and much of the silicon had been removed, although the ITO layer appeared to have remained in place. Obviously this length of stress was much too long for unprotected thin film cells. Next a second group of 16 cells was subjected to 1 hour of pressure cooker testing. Results closely paralleled the 85/85 tests described above, with good cells showing degradation and poor cells showing improvement. This test is now being extended to longer stress times.

## 6.0 SUMMARY

It is clear that if thin film cells are to be considered a viable option for terrestrial power generation their reliability attributes will need to be explored and confidence in their stability obtained through accelerated testing. Development of a thin film accelerated test program will be more difficult than was the case for crystalline cells because of the monolithic construction nature of the cells. Specially constructed test samples will need to be fabricated, requiring commitment to the concept of accelerated testing by the manufacturers. A new test schedule appropriate to thin film cells will need to be developed which will be different from that used in connection with crystalline cells. Preliminary work has been started to seek thin film schedule variations to two of the simplest tests: unbiased temperature and unbiased temperature-humidity. Still to be examined are tests which involve the passage of current during temperature and/or humidity stress, either by biasing in the forward (or reverse) directions or by the application of light during stress. Investigation of these current (voltage) accelerated tests will involve development of methods of reliably contacting the thin conductive films during stress -- a potentially difficult task.

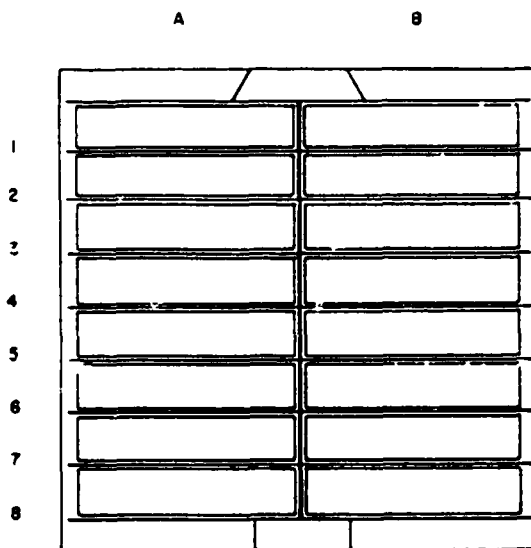


- REPRESENTATIVE SAMPLES
- STRESS WINDOW
- MEASUREMENT REPEATABILITY

ACCELERATED STRESS METHODOLOGY  
AND NECESSARY REQUIREMENTS

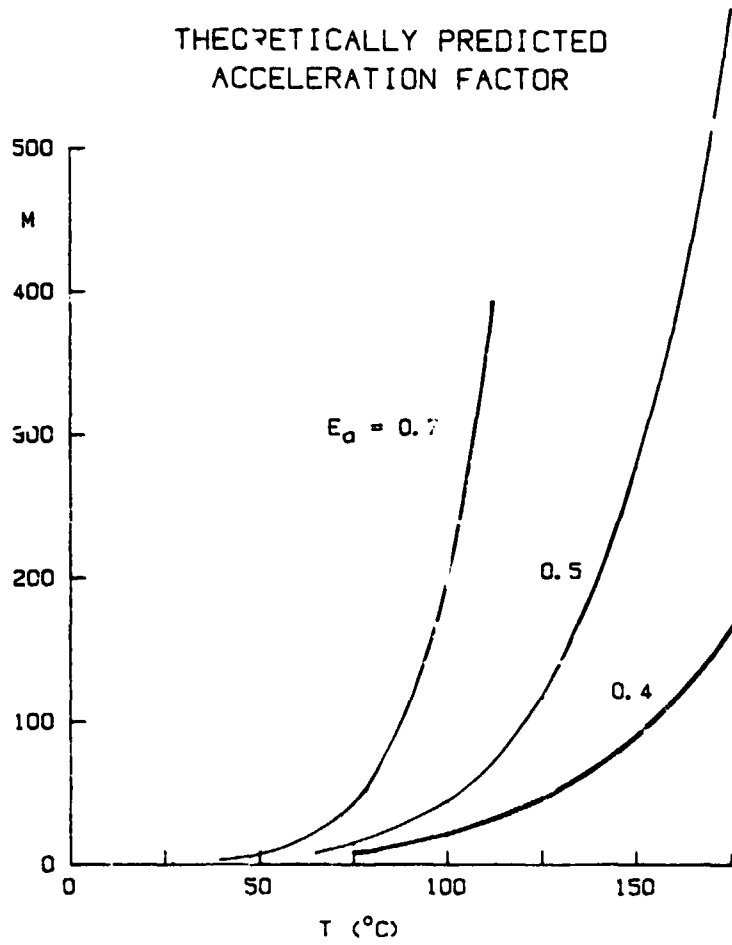
- TEMPERATURE CONTROL  
SHUTTERED LIGHT  
CONSTANT TEMP AIR FLOW
- REPRODUCIBLE ILLUMINATION  
REFERENCE CELL  
AREA UNIFORMITY
- KELVIN CONTACTS  
ELASTIC CONTACTS
- DIGITIZED DATA  
3-QUADRANT CHARACTERIZATION  
VOC, ISC, PM, VM, IM  
RS, RSH, IO, n

ACCELERATED STRESS TESTING  
MEASUREMENT CONSIDERATIONS

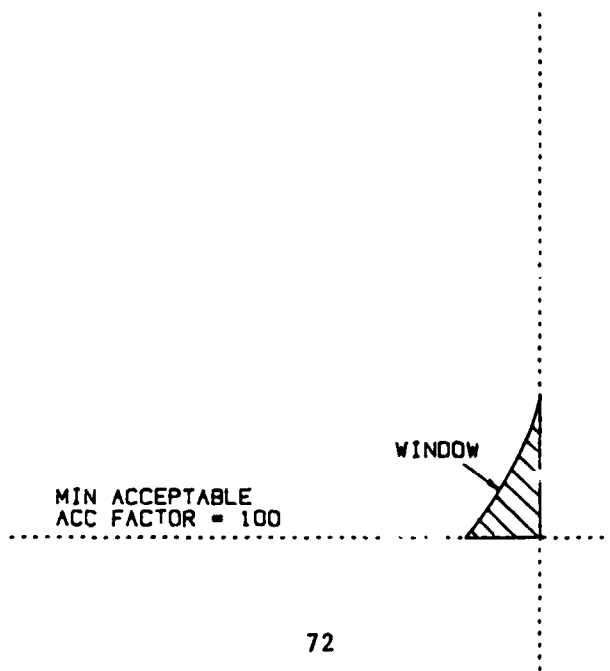


CONTACT LAYOUT FOR INDIVIDUALLY  
ADDRESSABLE  $\alpha$ -Si TEST STRUCTURE

THEORETICALLY PREDICTED  
ACCELERATION FACTOR



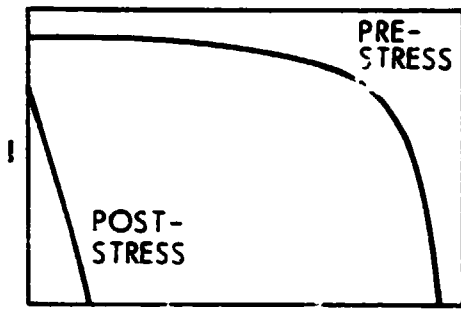
MAX STRESS  
TEMP = 140°C



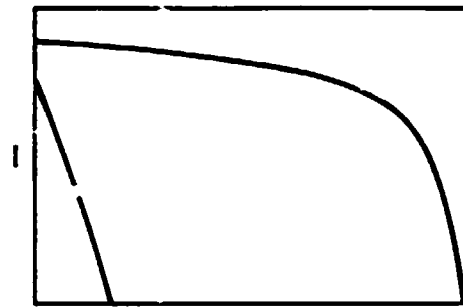


TYPE OF  $\alpha$ -Si CELL DEGRADATION BEING OBSERVED  
(20 HOURS AT 140 °C, OPEN CIRCUIT)

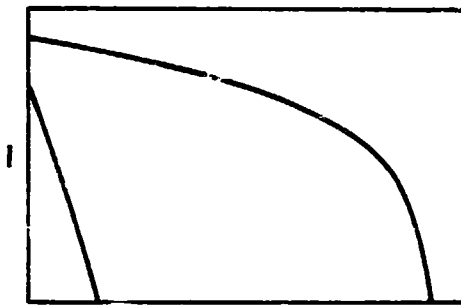
IV CURVES: PRE-STRESS AND POST-STRESS (8  $\alpha$ -Si CELLS IN ONE SUBMODULE)



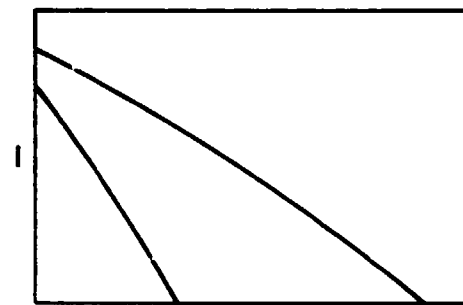
V CELL #1



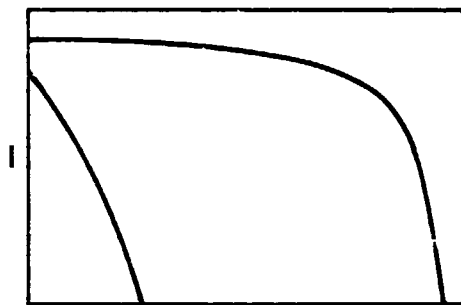
V CELL #5



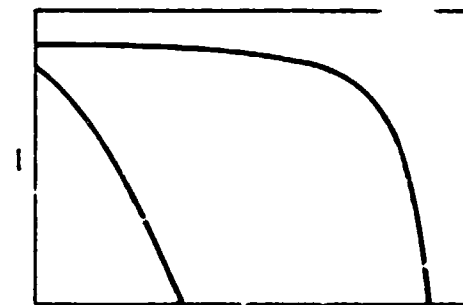
V CELL #2



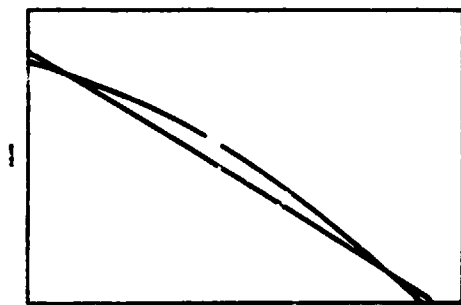
V CELL #6



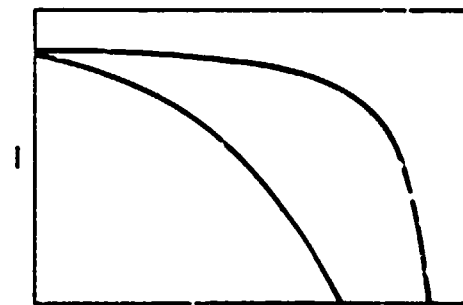
V CELL #3



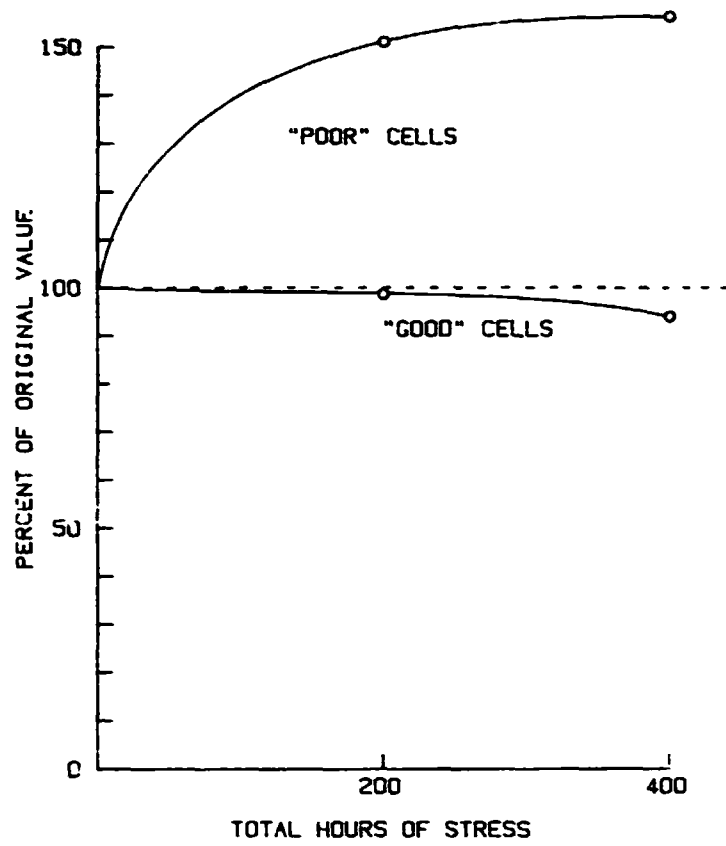
V CELL #7



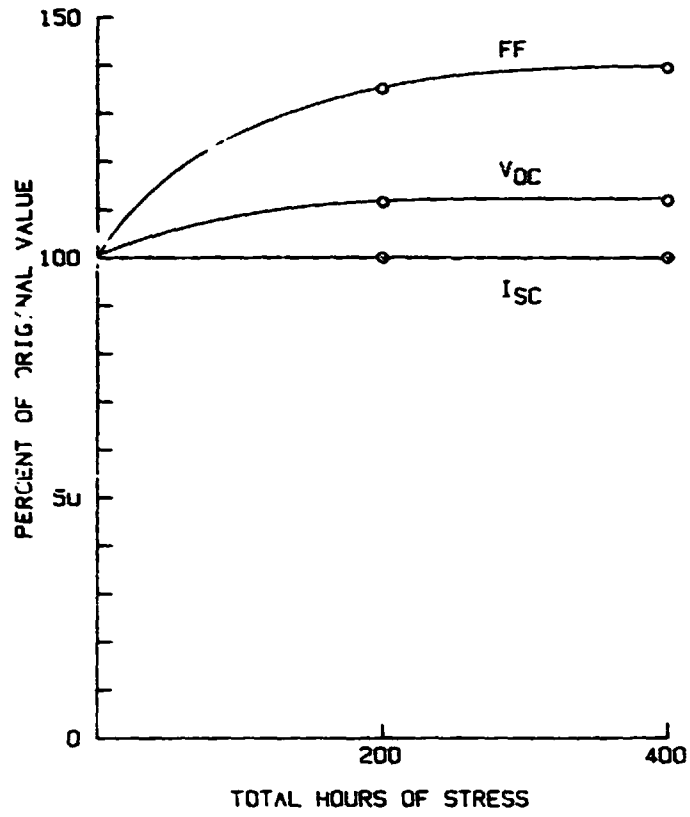
V CELL #4



V CELL #8



NORMALIZED  $P_M$  AS A FUNCTION OF 85/85  
STRESS TIME FOR  $\alpha$ -Si SOLAR CELLS



NORMALIZED I<sub>SC</sub>, V<sub>OC</sub>, AND FF AS A FUNCTION OF 85/85 STRESS TIME FOR "POOR" Si SOLAR CELLS

## DISCUSSION

**SULLIVAN:** With the actual increases in performances seen in the 85/85 environment, I assume the samples were removed from the environment and allowed to dry out for a certain period of time, or something like that. You tested an hour or so after you pulled them out of the chamber?

**LATHROP:** Yes. I don't know that we considered this critical, and we probably did not time it. But the test devices were taken out, and then within a reasonable time measured; I don't know what it is.

**WRONSKI:** Did the improvements deteriorate, just on standing, afterwards?

**LATHROP:** We did not measure that. We just measured them and stuck them back in the system, in the 85/85 chamber.

**WRONSKI:** I see. It would be interesting -- maybe it was an improvement.

**LATHROP:** That is a very good comment.

**JESTER:** For instance when you showed the 130°? I really didn't understand if you had humidity in that exposure?

**LATHROP:** That was just room ambient humidity. We could see a slight change in color. It was enough so that if you knew what you were looking for you could see it in a 35 mm slide, but, if I were to put it up here and show you, quickly, you might not detect it. We saw a very slight change -- no change in the contacts at all, however, that we could see, but a change in the color of the silicon.

**VASEASHTA:** Did you also run the spectral response to see which portion of the spectrum it degrades in?

**LATHROP:** No, we have not done that, but that would be an excellent thing to do. We need to do that.

**LESK:** It looks like in some of those, you removed a very bad shunt. Do you think this might become part of the manufacturing process?

(LAUGHTER)

**LATHROP:** I rather doubt it. I think it is too expensive in terms of time and all that kind of thing -- that is, burn-in. On the other hand, I have heard people discuss that -- upon certain kinds of stress they see modules improve, when you look at the overall module. What may be occurring there is that the bad cells in the module are getting better, and the good ones in the module are not getting any worse. This may occur. This is a different situation from what we see in crystalline cells, where you pick and choose and

you select and you start out with things that are already pretty uniform. In fact, when we get cells from the manufacturers, they are very close to being identical. Here we see cells that are very, very different. This may be a thing in the manufacture of these modules that is going to cause some concern.

ARNETT: Making sure I understand, in the data that you are showing us: you seem to be using the step test, where you are proceeding from step to step with increasing temperature to establish the point at which you begin to introduce new mechanisms. It is not clear from what you have told me that you wouldn't have seen the same thing that you saw as the normal means of failure if you had not continued for a longer period of time at one of the lower temperatures. Do you have data to show that the mechanism you are using to say that 130° is the maximum temperature you can use because it is a new mechanism -- do you have data that says that is the case, or is it something you would actually have seen if you just continued these other tests for a longer period of time? I'm not convinced that what you saw is a different failure mode.

LATHROP: I see what you are saying, but where it is just a relatively short time but quite a large temperature difference, namely 10°, if you look at the Arrhenius extrapolation of this you would not expect to see any effect of the previous stressing. In other words, the cumulative effect of the stresses up to 130°C -- prior to 130°C would be negligible compared with a 130°C step -- because of a consideration of time and temperature. I think that on these grounds my inclination is to say that it is a mechanism which is suddenly occurring. We have run some limited tests: we put them in ovens directly at 140°C, and zap, they go bad and we put them in lower temperatures and they haven't gone bad within the times that we have run. It is, in my thinking -- at least, it is a semi-valid sort of thing; we don't have much data on it, though, -- that it's possible there is a cumulative affect.

GAY: My only comment is one of caution about too rigorously associating interpretation of the results at 130°C, because modules are laminated at 150°C.

LATHROP: Right, but they are not laminated for 20 hours or so. Nevertheless, your point is well taken. This was one module that we used. Maybe that module is unique; it was from one manufacturer. Maybe that process on these modules was unique. I am just saying this is -- I am not trying to prove a point that there is an upper limit and one can run some fairly quick tests that allow you to see where that upper limit is. That's the only thing I am saying.