PRELIMINARY LOW TEMPERATURE ELECTRON IRRADIATION OF TRIPLE JUNCTION SOLAR CELLS

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INTRODUCTION

For many years extending solar power missions far from the sun has been a challenge not only due to the rapid falloff in solar intensity (intensity varies as inverse square of solar distance) but also because some of the solar cells in an array may exhibit a LILT (low intensity low temperature) degradation that reduces array performance. Recent LILT tests performed on commercial triple junction solar cells have shown that high performance can be obtained at solar distances as great as ~ 5 AU[1]. As a result, their use for missions going far from the sun has become very attractive. One additional question that remains is whether the radiation damage experienced by solar cells under low temperature conditions will be more severe than when measured during room temperature radiation tests where thermal annealing may take place. This is especially pertinent to missions such as the New Frontiers mission Juno, which will experience cell irradiation from the trapped electron environment at Jupiter. Recent testing[2] has shown that low temperature proton irradiation (10 MeV) produces cell degradation results similar to room temperature irradiations and that thermal annealing does not play a factor. Although it is suggestive to propose the same would be observed for low temperature electron irradiations, this has not been verified.

JPL has routinely performed radiation testing on commercial solar cells and has also performed LILT testing to characterize cell performance under far sun operating conditions. This research activity was intended to combine the features of both capabilities to investigate the possibility of any room temperature annealing that might influence the measured radiation damage. Although it was not possible to maintain the test cells at a constant low temperature between irradiation and electrical measurements, it was possible to obtain measurements with the cell temperature kept well below room temperature. A fluence of 1E15 1MeV electrons was selected as representative of a moderately high dose that might be expected for a solar powered mission. Fluences much greater than this would require large increases in array area and mass, compromising the ability of PV to compete with non-solar alternatives.

PROCEDURE

Although radiation tests are typically performed at room temperature (28C), the JPL irradiation test chamber does have a capability for testing at various temperatures, with a low temperature near liquid nitrogen levels (-180C). There is also an available light source and optically clear quartz window that allows illumination of the solar cells during irradiation. However, the light source does not presently meet the optical spectra requirements needed to accurately measure triple junction solar cells. The Dynamitron irradiation test plate and the X-25 solar simulator LILT test plate are of the same configuration so that cells can be firmly mounted in either chamber. Since the Dynamitron radiation facility and the X-25 Solar Simulator are located in separate areas of the Cell Characterization Test Laboratory, the test procedure required transport of the cold and irradiated test plate from the Dynamitron test chamber to the X-25 LILT test chamber to ascertain the impact of the irradiations on the solar cells.

Various methods were examined to transport the samples between tests facilities without any significant heating of the test plate and to avoid or minimize moisture condensation. Following the irradiation, the chamber was returned to ambient pressure (with a dry nitrogen back fill) and opened. The test plate was then wrapped in aluminum foil during transport. It was removed when the plate was mounted in the X-25 solar simulator test chamber which was being purged with dry nitrogen. The access port was then closed and pump down initiated. The foil was intended to minimize direct contact of the cell/cover front surface with the ambient room air.

During trials of transport methods, a surrogate plate was monitored for temperature in order to observe any changes occurring during the dismounting of the test plate from the Dynamitron and ~ 1 minute transit to the X-25. Due to the large heat capacity of the 1/8 inch thick copper test plate, it was possible to perform the exchange between test chambers with only a slight warming of the test plate. The initial test procedure used a covered aluminum pan with a layer of liquid nitrogen in the bottom, but due to the above mentioned temperature stability the approach for the actual testing used a plain covered cardboard box filled with Styrofoam "popcorn". Not elegant, but less of a possible hazard than carrying liquid nitrogen.

For these tests a small number of production triple junction solar cell CICs (solar cell-interconnect-coverglass) were purchased from the two U.S. Space cell manufacturers, Emcore and Spectrolab. The CICs are the basic component provided by the manufacturers for array assembly. The CICs also had rear contact tabs attached by the manufacturers using space qualified processes to enable JPL test fixture assembly. The cells were tested under (AM0) air mass zero (Space) conditions at JPL, and CICs were then selected to assemble two test plates for each manufacturer (four cells per test plate). The standard test plate (Figure 1) consists of a 1/8" thick copper plate machined to provide a central location for the radiation dose measuring Faraday cup, and a number of smaller holes for insertion of terminal posts. The terminals are used for hard wiring the solar cells to the posts and attached electrical connector to ensure stable electrical connections. The CICs are bonded to the substrate with a thermally conductive silicone adhesive. A separate connection is made to a thermocouple fixed to the surface of a top contact tab where it is attached one of the test CICs. The cells were all retested electrically following the plate assembly, both at AM0/room temperature and LILT conditions. This is a standard procedure performed for all JPL LILT tests.

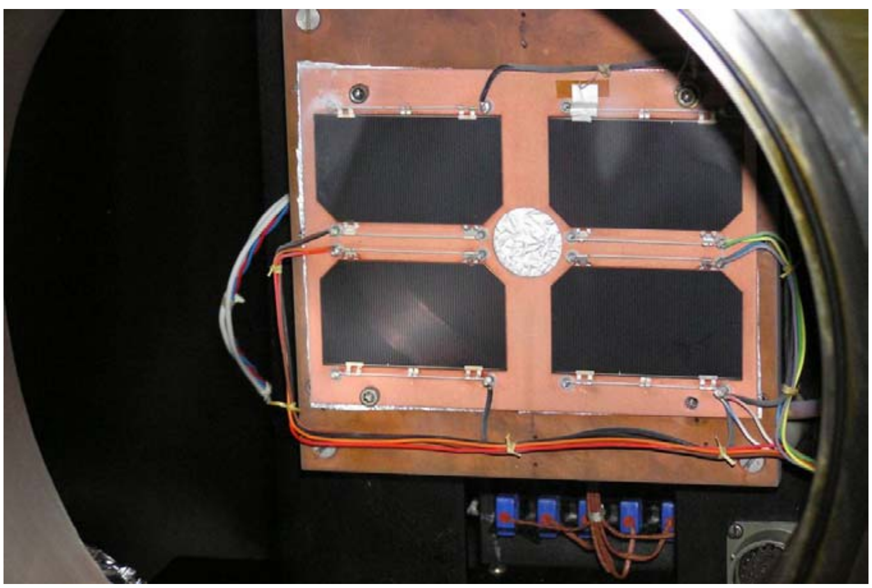

Figure 1. Typical Test Plate in X-25 Solar Simulator Test Chamber

A test plate was installed in the Dynamitron electron accelerator test chamber. (Figure 2) The test chamber was then pumped down to 4x10-5 torr or better and the test plate temperature was reduced to -120C, at which time the irradiation began. When the required 1E15 1 MeV electron equivalent dose was reached, and the accelerator shut down, the test chamber was back filled with nitrogen gas to return the pressure to ambient levels.

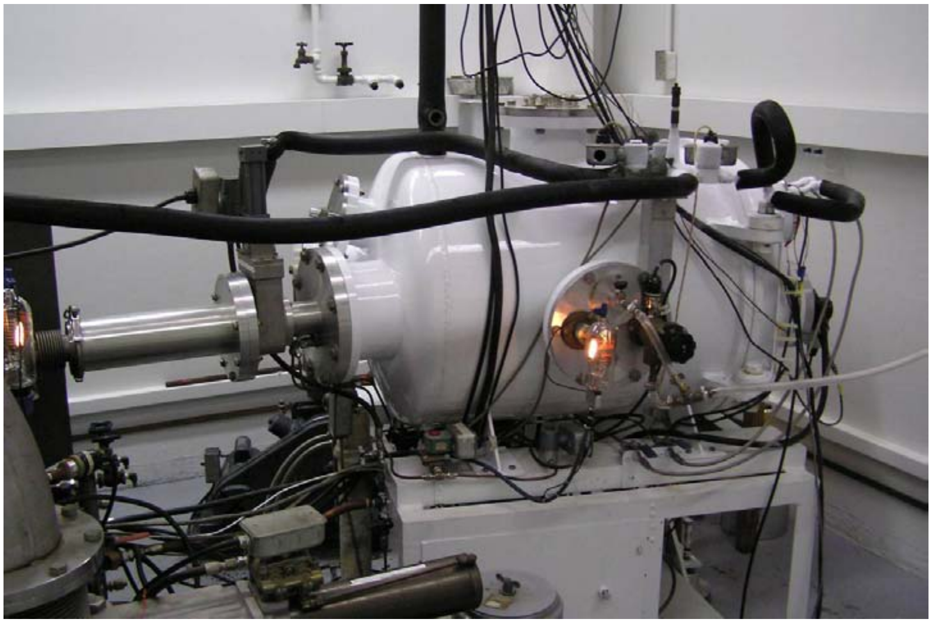

Figure 2. Dynamitron Cell Irradiation Test Chamber

The chamber was then opened maintaining a low volume flow of nitrogen gas over the test plate and aluminum foil was wrapped around the front of the cold test plate. After disconnecting the plate from the plate holder the covered test plate was quickly transferred to an insulated box and carried to the X-25 test chamber (Figure 3) in an adjacent room. Once in the X-25 test chamber, which was being purged with dry nitrogen, the foil was removed and the plate attached to the temperature control mounting block. Then the quartz access window was reattached to initiate the pump down to 4x10-5 torr. During this time the temperature of the test plate remained below -80C. Once the vacuum level was achieved, the test plate temperature was increased to ~ -70C in order to sublimate a thin layer of frost from the CICs, and then returned to -120C. The cycle from ~ -80C to -70C and back to -120C typically required 40 minutes duration.

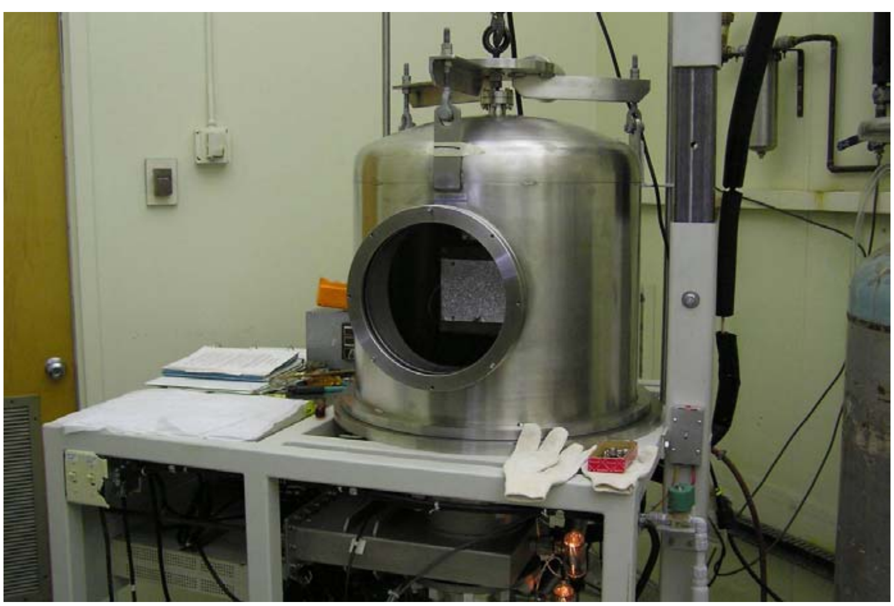

Figure 3. X-25 Vacuum Test Chamber

Once at -120C, all cells on the test plate were measured at an intensity of 4.7 mw/cm^2. The cell temperatures were then increased to 28C and maintained for approximately 45 minutes while the illumination intensity was increased to 136.7 mw/cm^2 (AM0). Slow heating and cooling rates were used to minimize thermal shock. Then the cells were returned to LILT conditions (4.7mw/cm^2 and -120C) for the second measurement. This process was repeated for each test plate. The time line for the second Spectrolab test plate is shown below in figure 4. This plate had the lowest radiation flux and consequently the longest irradiation time.

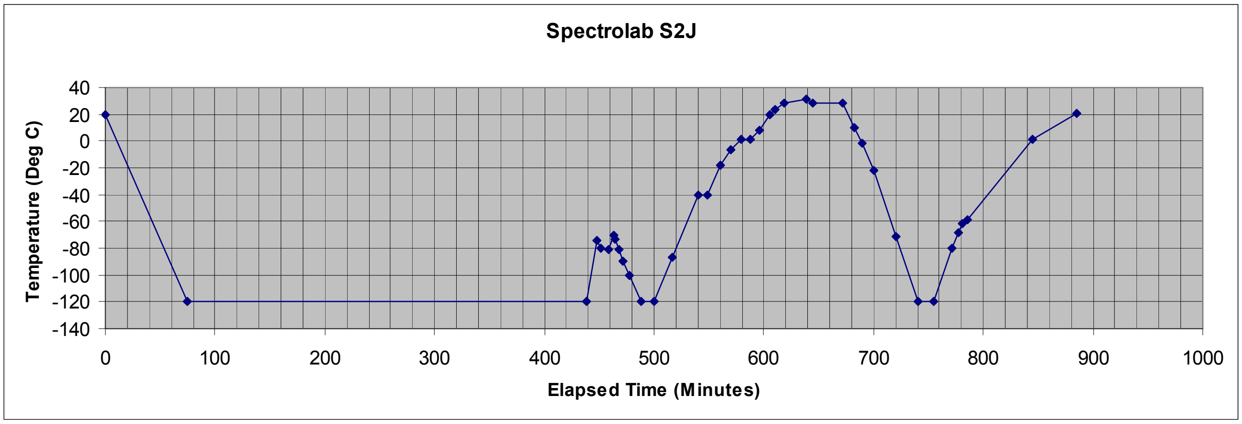

Figure 4. Spectrolab Test Plate S2J Temperature Timeline

The short interval starting at 440 minutes is the start of the frost sublimation phase, with the first LILT electrical measurement at ~485 minutes. High temperature exposure begins after this with the second LILT electrical measurement at ~740 minutes.

RESULTS

Results were somewhat mixed in that while the cells on one of the four test plates showed notable improvement following a exposure to room temperature, the other test samples (including one plate for the same manufacturer and two for the other) showed little to no change. This fluence typically results in approximately 15% power loss after room temperature irradiations. Cells irradiated at -120C and tested at that temperature showed losses comparable to or worse than the 28C test data. Exposure to room temperature improved the performance loss of the most degraded cells to levels near the room temperature irradiated values. In the extreme case the average cell efficiency on one test plate recovered 3.7 percentage points after room temperature exposure. The change in cell efficiency following the soak at 28C for the other three test plates ranged from 0 to 2.4%, values close to the estimated measurement of 2%.

The first plate tested showed a light haze contamination on the front surface of the CICs. This was traced to the Dynamitron test chamber where a section of Tygon tubing slipped into the edge of the electron beam. (This was eliminated for subsequent tests). The initial average power degradation was 12.6% which was reduced slightly to 12.0%, following the 28C temperature soak. The improvement was recorded in the voltage and fill factor primarily, with no change in Isc (short circuit current). This would be consistent with a slight variation in before and after temperature (approximately 1^{o} C) than with radiation annealing. The magnitude of the change is in the range of test accuracy. It was also noted that the degradation from the 1E15, 1 MeV electrons was less than the manufacturer's listed degradation of 14%. For the second plate of that same cell manufacturer, both the before and after 28C soak degradations were 14.9%. This plate had one cell with poorer LILT performance before irradiation and the data was re-examined with that one cell eliminated to see if it had any impact on the average change. As a result, the before "annealing" power degradation of the three remaining "good LILT" cells increased to 14.5% with an improvement to -12.5 % after the 28C soak, consistent with the plate 1 degradation. Again, the final degradation was slightly less than the manufacturer's data of 14% (obtained using room temperature irradiations) with the degradation before the 28C thermal soak in approximate agreement with the published value (based on 28C irradiation testing).

The results for manufacturer B were somewhat different. For one plate the average cell degradation following irradiation was 19.9%, improving to 17.3% degradation after ~ 1 hour 28C soak, and then to a degradation of 16.2% with an additional ~117 hour soak at 28C. This resulted in a total gain (after 118 hours) of 3.7 percentage points in cell efficiency corresponding to a 19% reduction in the irradiated power loss. For this plate improvements were noted in current and voltage. The final degradation agrees with the manufacturer's published data of 16% based on room temperature irradiation. Although this result was in line with an explanation of modest annealing, the second plate for manufacturer B showed different behavior. Although the initial degradation was measured at 20.6%, the value after the 28C soak (1 hour) was 19.5%, for a gain of 1.1 percentage point in cell efficiency, within measurement error. The 19.5% degradation after thermal soak was still below the manufacturer's published data.

DISCUSSION

Ideally, irradiation at -120C and in situ electrical measurements at that same temperature would be the best method for performing these tests. Due to the need to use two separate chambers with a quick transfer between them, it was necessary allow a short term temperature increase to -70C, still well below room temperature. The fluence of 1 E15 1MeV electrons typically incurs losses of approximately 15% in cell power in room temperature testing. Based on estimates of LILT measurement errors, changes of 2% are not considered significant. Additional potential sources of error include the impact of the cell transfer and coverglass adhesive anomalies (both discussed below). For each manufacturer, one test plate showed power changes of less than this amount after room temperature thermal soak. Also for each manufacturer, one test plate showed small improvements after the room temperature soak with improvements of 2.4 to 4.6% in cell power. For one manufacturer this increase was noted only after removing one cell from the data. Excluding the one test plate with the 4.6% improvement in power following the room temperature soak, the evidence would strongly suggest that room temperature annealing was not a significant factor. For manufacturer A, the measured cell degradation prior to any soak at room temperature was equal to or less than the data published by the manufacturer for room temperature irradiation. For manufacturer B, initial degradations following irradiation were greater than shown in the published data; with degradation values corresponding to published data only occurring after the room temperature soak (for one of the two plates). It is possible that there is a difference in the role of room temperature annealing between the performances of the two manufacturer's cells and testing of additional cells would be needed to better establish this. Short of that, a small margin can be added to the expected degradation for missions that undergo low temperature irradiation to account for the changes observed in these tests.

As mentioned earlier, similar low temperature irradiations of triple junction solar cells, using high energy protons, showed no indication of thermal annealing. Normally the high energy protons would be expected to show similar results in the cells as the 1 MeV electrons. Those tests had some difference from the tests described herein which may explain the differences in results: The cells were manufactured by a Japanese company, Sharp Corporation, and the irradiation and electrical testing was done in a single vacuum system, with no need for a physical transfer.

The transfer of cooled cells from the Dynamitron test facility to the X-25 test chamber limited the ability to maintain temperatures to the -120C irradiation temperature. Although it was possible to keep the temperature rise during the transit to within 10-15C of the -120C test temperature, the moisture condensation on the cells required a subsequent increase to approximately -70C in the X-25 vacuum test chamber for condensation removal prior to the initial -120C cell measurements. For this reason, testing of the last three plates allowed the temperature during transfer to rise as high as ~-70C, the temperature they would need to be at during for condensation removal. These temperatures were well below the more typical room temperature irradiation testing of 28C. Furthermore the rapid transfer from Dynamitron to the X-25 meant that the test cells were between -70C and -120C for approximately an hour, generally shorter than the time between room temperature irradiation in the Dynamitron and X-25 measurements, which can range up to a day or so. In addition to the above discussed measurement constraints, some unusual CIC behaviors were also observed in the course of these tests that compromise the test accuracy.

When the test cell temperatures were increased to ~28C in the X-25 test chamber following the minus 70C condensation removal and the initial -120C post-irradiation electrical performance measurements, adhesive bubbles were noted on some of the cells. This was evident as a large bubble or a number of small bubbles between the cover slide and cell. This did not become noticeable until the cell temperature was close to room temperature. The initial bubble could become fairly large (few cm. in diameter) and would typically shrink as the bubble perimeter reached the cover/cell edge (Figure 5).

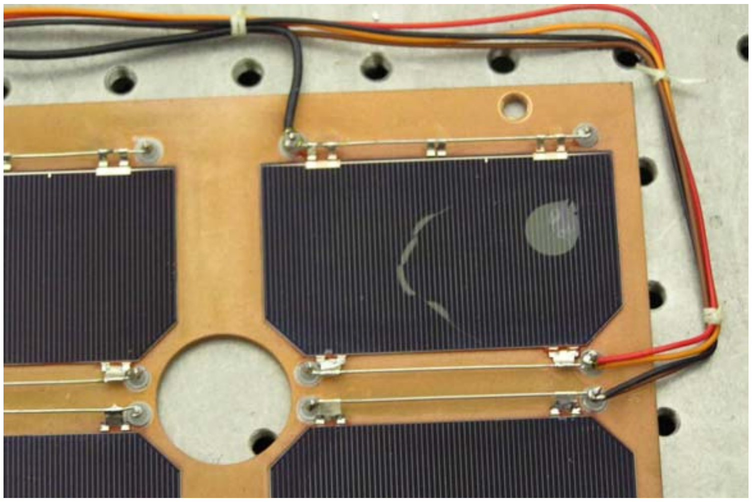

Figure 5. Coverglass “Bubble”

Upon re-cooling to -120C, the bubble size would shrink to less than ~one cm. radius. The cell area affected by the bubbles was estimated at less than 10% so that any impact on cell performance would be small. It was assumed that this was the source of some of the data uncertainty, although examination of test results for cells with and without bubbles did not show any clear differences. This behavior was not expected and has not been observed on previous LILT testing over similar temperature ranges. Cover and cell bubbles have been observed on flight array programs during the mid 1990s, when very large area solar cells became commonplace. The manifestation of this was called “blow-out” since the central portion of the cover and also solar cell would actually break out as if pushed from below during thermal cycling. It was attributed to incomplete curing of the adhesive near the cell central regions. A high temperature vacuum bake-out was developed to accelerate the curing and is used on modern solar arrays. This bake-out is not done for cells used in JPL LILT testing and “bubbles” have never been noted previously in any JPL testing of individual cells. The primary difference in these tests compared to previous LILT testing was the transfer between test chambers and the frost deposit on the CICs. The frost and/or ice deposit certainly is a candidate for the cause of the unusual bubble occurrences, although a mechanism has not been identified.

CONCLUSION

The comparable cell degradations measured in these low temperature tests and in standard room temperature testing suggests the conclusion that there is no <u>significant</u> thermal annealing from low temperature electron irradiation although small annealing improvements can not be ruled out.. However, this comment only refers to temperatures above approximately -70C, the frost removal soak temperature. Although the intention was to confirm or deny annealing occurrence at irradiation temperatures on the order of -120C, a condition comparable to a Jupiter orbital environment, this was not possible. The source of the difference in behavior for plates with the same manufacturer’s cells is not known. Uncertainties in these test results due to the test plate transfer can be removed by spectral modification of the cell illumination source in the Dynamitron test facility to allow for accurate in situ measurements of triple junction solar cells. This would then allow electrical testing of the cells to be performed in the Dynamitron test chamber immediately following the irradiation without changing the cell temperatures. Such testing would remove the influence if any, due to the transfer, between test chambers. Funding for this modification is being pursued for possible future testing.

Although the low temperature irradiation conditions are limited to a small number of potential missions, Jupiter orbiters, for example, the increasing attractiveness for PV power systems at these extended solar distances makes the resolution of any annealing behavior critical. Testing costs to resolve this are anticipated to be minimal especially when compared to any array cost required for such a mission.

ACKNOWLEDGEMENT

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REFERENCES

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