The Environmental Performance at Low Intensity, Low Temperature (LILT) of High Efficiency Triple Junction Solar Cells

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A number of JPL missions, either active or in the planning stages, require the accurate LILT (low intensity - low temperature) characterization of triple-junction solar. Although triple junction LILT performance was reported as recently as 2002, there has been an evolutionary advance in cell technology by both U.S. space cell manufacturers that, for mission design purposes, effectively obsoletes the earlier data. As a result, JPL initiated a program to develop a database for the LILT performance of the new high performance triple junction solar cells. JPL obtained Emcore Advanced Triple Junction CIC assemblies and Spectrolab Ultra Triple Junction CIC assemblies. These cells were tested at temperature-intensity ranges designed to cover applications between 1 and 5.18 AU solar distances. 1 MeV electron irradiations from 2.5 E14 to 1 E15 were performed on the cells to evaluate the combined effect of particulate radiation and LILT conditions. The effect of LILT conditions was observed to incur an increase in the variation of cell performances such that at simulated 5.18 AU conditions the average performance was approximately 30% with the best cells measuring between 32 and 34% efficiency. The 30% average efficiency compares with approximately 25% average efficiency measured on earlier technology triple junction solar cells.

Nomenclature

LILT	=	low intensity, low temperature
Isc	=	short circuit current
Pmax	=	maximum power
FF	=	fill factor
Voc	=	open circuit voltage
Vmp	=	maximum power voltage
Imp	=	maximum power current
AM0	=	air mass zero
CIC	=	cell-interconnect-cover
ATJ	=	advanced triple junction (Emcore)
UTJ	=	ultra triple junction (Spectrolab)
AU	=	astronomical unit (average distance between Earth and sun)

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I. Introduction

A number of JPL missions, some active (such as Dawn - an asteroid encounter mission) and some in planning stages, require the accurate LILT (low intensity - low temperature) characterization of triple-junction solar cells at solar intensities equivalent to those found between Earth and Jupiter. Although triple junction LILT performance was reported as recently as 2002[1], there has been an evolutionary advance in cell technology by both U.S. space cell manufacturers that, for mission design purposes, effectively obsoletes the earlier data. As a result, JPL initiated a program to develop a database for the LILT performance of the new high performance triple junction solar cells. A number of Emcore ATJ CIC assemblies and Spectrolab UTJ CIC assemblies were obtained. A test matrix was established for temperature and intensity conditions initially covering the range between 1 and 3 AU (Dawn mission environment). In the interest of minimizing the time necessary to complete the tests the conditions were selected to best meet the needs of the Dawn mission which was in the process of preparing the solar array procurement package. At the end of the LILT tests a decision was made to irradiate some of the test cells to the equivalent Dawn radiation environment, since it wasn't clear how the LILT and radiation effects would combine over the mission AU range. The radiation levels were then increased further using additional cells to provide data to JPL missions that were in planning phases. As a result, the triple junction cell data includes 1 MeV electron equivalent doses of 2.5 E14, 5 E14, and 1 E15. The cells for the later two exposures are different than those used in the first, but from the same lots the cell manufacturers delivered to JPL. In addition, the test matrix for LILT was also increased to encompass additional mission applications.

Below in Table 1 is the test matrix that was used for the temperature - intensity tests. This was devised to fully bracket the solar intensities and solar cell operating temperatures expected during the missions from Earth out to the orbit of Jupiter. It includes three temperatures (–70, –50, and –25 C) that are common to all intensities.

Intensity (mW/ cm²)	Distance (AU)	Temperature (C)
5.1	5.18	-170,-150,-120,-100,-70,-50,-25
15.17	3.0	-170,-150,-120,-100,-70,-50,-25
21.87	2.5	-170,-150,-120,-100,-70,-50,-25
37.87	1.9	-100,-70,-50,-25,0,28
60.69	1.5	-70,-50,-25,0,28
94.87	1.2	-70,-50,-25,0,28
136.7	1.0	-70,-50,-25,0,28

Table 1. Temperature-Intensity Test Matrix

II. Cell Selection

JPL requested the cell vendors, Spectrolab and Emcore, to deliver a minimum of 20 current technology flight-type triple junction solar cells. JPL further specified that these cells cover the range from low to high within the flight deliverable distribution. The average cell efficiencies of each manufacturer's cells was approximately 28% at AM0, 28C test conditions, in line with the advertised performance. From these, JPL selected four CICs each from the low, mid, and high ends of the distribution, giving a total of twelve (12) cells for each manufacturer to be used in the LILT testing. It should be noted that the bin ranges varied slightly between the two manufacturers. The actual cells used for the plate assembly were selected from those delivered, by JPL and the Dawn spacecraft prime contractor, Orbital Sciences, to clearly represent the three regions of the power distribution. Three test plates of four CICs each were assembled for each manufacturer. Each test plate consisted of cells from the same binning range, i.e., plate 1 for each vendor had cells from the low end of the cell distribution, plate 2, the mid range, and plate 3, the high range. Although in actual flight use, the majority of cells come from the mid range, JPL was interested in determining if any particular LILT behavior would be dependent on the initial cell performance. In this way at least four cells would be available in each of the three ranges and the results of any single cell anomaly or damage could be evaluated based on comparison with the remaining cells on the plate. This also meant that estimates of solar array power would not be accurately met by averaging twelve cells from each manufacturer. Rather, array performance analysis would need to take into consideration the relative weighing of each of the cell groups in the overall flight cell distribution. However, for the purpose of evaluating cell LILT behavior, the use of the three power groupings was felt to provide a good overall indication of LILT behavior for the small cell quantities involved. The remaining cells were kept to serve as controls or to be used for additional testing if necessary. All cells were re-measured at JPL under AM0 conditions to confirm the manufacturer's initial measurements. A set of test plates with the cells is shown in figure 1.

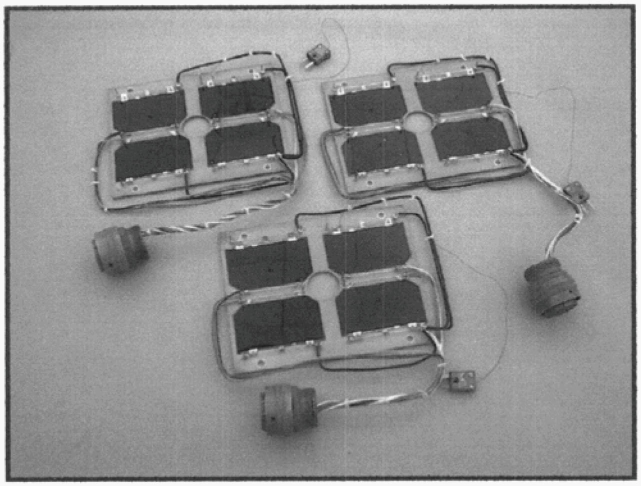

Figure 1. Typical Set of Test Plates

III. Test Facility and Procedure

A. Test Facility

A multi-junction modified, Spectrolab X-25 Mark II, short-arc Xenon, close-filtered, AM0 solar simulator was used in the electrical performance testing. The simulator multi-junction modification included a set of special, adjustable filters used to balance the X-25 spectrum when testing multi-junction solar cells. Balance is established when the balloon-flown calibration values for the top and middle iso-junction balloon reference cells, for the appropriate cell vendor, are measured following adjustment of the filters during setup of the X-25. Then the intensity of the solar simulator is set with the appropriate vendor's triple-junction balloon-calibrated reference cell. The calibration accuracy of the balloon-flown reference cells is +/-1%. Therefore, this is the absolute accuracy of the X-25 solar simulator intensity. The accuracy and repeatability of the equipment for measuring Isc, Imp and Pmp measurements of the CIC test cells is about +/-1%.

I-V curves were obtained with an active load (bi-polar power supply) that had a protective diode circuit across its output to limit reverse voltage across any CIC to 0.7 volts. When it is desired to lower the intensity, neutral density filters are used. The desired amount of filtering is achieved by selecting filters from a set of six (6) different grades of framed stainless steel window screen and a set of three (3) aluminum discs with uniform patterns of different-sized holes. The lamp power is never adjusted, because this would change the spectral distribution of the light source. A specific intensity may require one or more screens and sometimes one (1) of the discs. Use of different filters will cause the X-25 intensity uniformity pattern to be slightly different, although the X-25 intensity uniformity is always better than +/-1% over the 6.5 inch x 4.5 inch test plates. Because of the differing uniformity pattern, it is not recommended that an <u>individual CIC's</u> characterization data be used to study changes in the CIC's parameters such as Isc, Imp and Pmp versus intensity.

B. Pre-Irradiation Test Description

Initially the CICs were checked for shorts and examined for cracks to ascertain their condition. No physical damage was noted and the electrical measurements agreed with the manufacturers' data. After being bonded to copper test plates, and hard-wired to terminal posts, they were similarly rechecked and found to still be in excellent condition. Then each CIC was tested for electrical isolation from its test plate, which resulted in all measurements being greater than 200 megohms.

Electrical measurements were made through a connector, which was wired directly to the CICs via terminal posts. This approach was used to avoid any errors that might occur through the use of pressure contacts. The pre-irradiation characterization tests were performed at the temperatures and intensities specified in the Temperature-Intensity Test Matrix, shown as Table 1. Twelve (12) of each vendor's CICs were bonded to three (3) separate test plates. Test plate #1 contained the four (4) lowest efficiency CICs, test plate #2 contained the four (4) middle efficiency CICs and test plate #3 contained the four (4) highest efficiency CICs. All cells are typical of cells delivered for space flight applications in terms of mechanical and electrical characteristics. During the testing, test plates were mounted on a temperature-controlled block inside a high-vacuum chamber. Illumination from the X-25 Mark II solar simulator entered the vacuum chamber through its fused silica window and stimulated the CICs at a normal incidence angle.

Intensity (mW/ cm²)	Distance (AU)	Temperature (C)
15.17	3.0	-100, -70, -50, -25
21.87	2.5	-100, -70, -50, -25
37.87	1.9	-100, -70, -50, -25
136.7	1.0	-100, -70, -50, -25, 0, 28

Table 2. Post-Irradiation Test Matrix

C. CIC Test Plate Irradiation

Following the initial characterization tests, test plates #1 and #3 for each vendor were subjected to 1 MeV electron irradiation in the JPL Dynamitron Accelerator. The cumulative fluence for each of the four (4) test plates was 2.5E14 e^-/cm^2. This is the 95% confidence level fluence with a Radiation Design Factor of two (RDF=2) for Pmp degradation during the intended Dawn mission.

D. Post-Irradiation Test Description

The post-irradiation characterization tests were performed at the temperatures and intensities specified in the Post-Irradiation Test Matrix, shown as Table 2. The range is limited because those specified in Table 3 were deemed to be the most critical in determining the suitability of the CICs for the Dawn Mission. As previously undertaken for the pre-irradiation characterization tests, twelve (12) of each vendor's triple-junction CICs was tested. This time, however, test plates #2 would be used as control samples to correct results obtained from the re-testing of the irradiated test plates #1 and #3. The post-irradiation, 1 AU dataset was repeated for one vendor's test plates to confirm results obtained in the first dataset.

IV. LILT Test Results

The test data for each manufacturer's cells were similar. There were some differences between the cells from the two manufacturers when the behavior of all tested cells were examined. For example, one manufacturer's cells showed a greater variance in power at LILT conditions, with higher and lower efficiencies than the other manufacturer (although the average was the same). However, in view of the limited cell quantities tested this cannot be considered statistically significant. Consequently, the comments in this section will be directed to the average of all cells tested.

The data in figure 2 shows the average cell efficiency as a function of solar distance (in Astronomical units) and includes the estimated cell operating temperature at the given solar distance. The results for the tested cells are compared to performances measured on triple junction cells approximately four (4) years ago[1]. The improvement in performance for triple junction cell performance is quite clear.

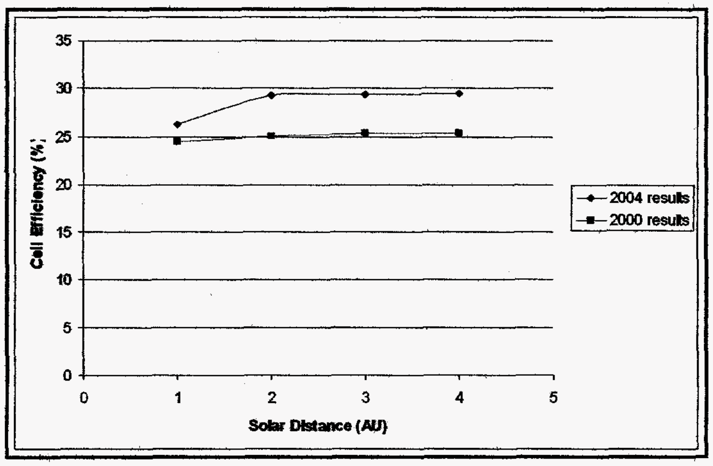

Figure 2. Average Cell Efficiency vs. Solar Distance

Cell operating voltages are critical for LILT missions since this parameter can change rapidly with AU. As a result, the power electronics need to accommodate the change in order to operate the array near maximum power. As is shown in figure 3, the triple junction cell has a moderate voltage change of approximately 35% over the range 1 to 5 AU, especially when compared to silicon solar cells. For the later, a voltage increase of approximately 75% occurs between 1 and 5 AU[1].

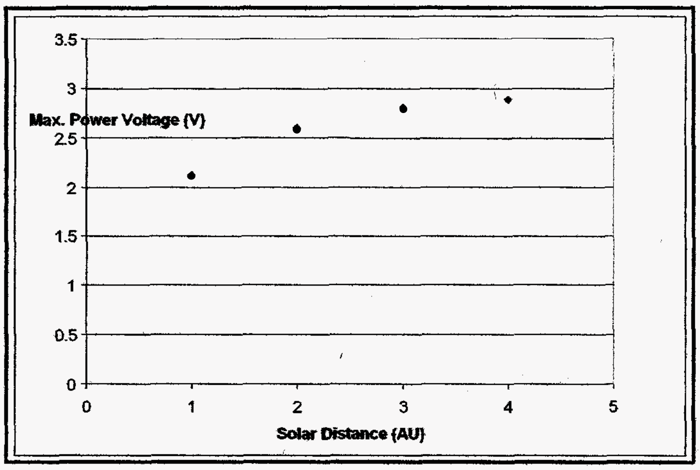

Figure 3. Average Cell Maximum Power Voltage vs. Solar Distance

The cell feature that most clearly identifies cells with anomalous LILT degradation is the fill factor. The fill factor is shown in figure 4. Although it is not identifiable from this curve, a small number of cells with excessive degradation in fill factor lead to a flattening and then reduction of the FF at higher AU values. Although a small percentage of cells exhibited this anomalous degradation, figure 5 illustrates the magnitude of such loss that can occur. As can be seen, the average performance of each plate at a given set of test conditions (intensity, temperature) falls within a small range that can be related to the initial selection of cells into low, medium, and high performance ranges. The figure also shows the stronger role of reduced intensity, compared to reduced temperature, on the LILT performance degradation. However, one plate exhibited larger than anticipated losses due to the inclusion of some cells with obvious "LILT degradation." In some cases this could be associated with a "low" cell shunt resistance and consequently this was most likely to show up in cells from the lowest power bins. This is an understandable LILT loss since a small shunt loss at AM0 will become an increasingly large component as the generated current decreases with the square of the solar distance. In some cases it may be a relatively larger shunt loss that "moves" a cell from a high or mid bin to the low bins. Not all LILT losses were directly attributable to shunting and there were some indications of classic "broken knee" curve shape, i.e., the cell I-V curve exhibited a noticeable and relatively sudden decrease in the characteristic diode shape. Due to the small sample size, it is not evident what percentage of cells exhibits this effect, although only a small number would be expected based on this data. Since the low bin cells will be a small fraction of those delivered (typically 60-75% of cells in flight hardware come from the middle bins, with smaller percentages in the higher and lower bins) the impact on overall array performance will be less pronounced than shown in the data here which awards equal weight to low, mid, and high bins.

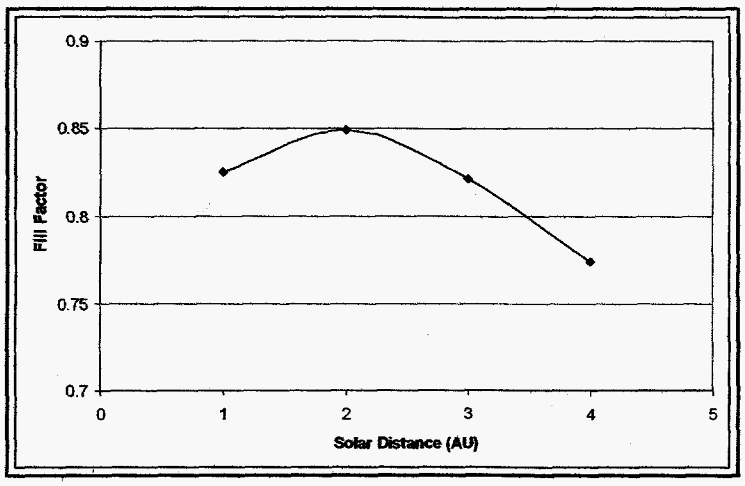

Figure 4. Average Cell Fill Factor vs. Solar Distance

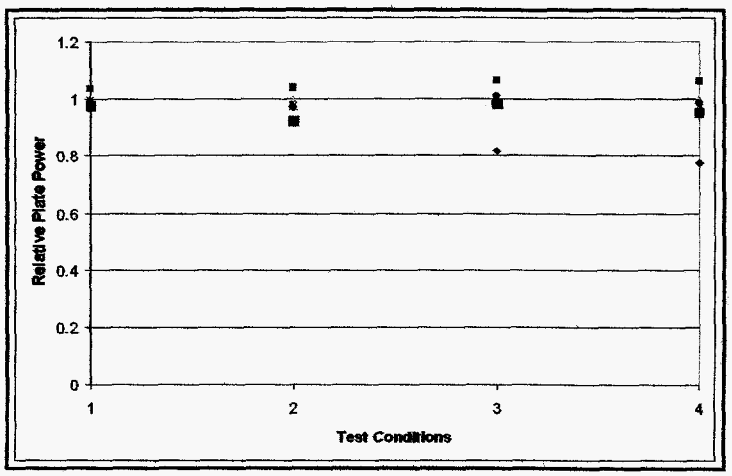

Figure 5. Average Plate Performance Normalized (at each test condition) to Mid Bin (2) Plate Value For the Following Conditions: 1-AM0, 28C; 2- AM0, -70C; 3- 3AU, 28C, 4- 3AU, -70C

V. Radiation Test Results

The principal environmental degradation for most interplanetary missions is charged particle radiation. Two questions arose when considering radiation damage for missions at solar distances with significant LILT conditions. First, is whether the radiation damage is the same when induced at low temperatures as at room temperature. The later question was beyond the scope of the testing program described here. In addition, for most LILT missions under consideration, radiation damage is attributable to solar flares and most likely to occur at solar ranges between 1 and 2 AU, where cell temperatures are not much lower than at Earth. Exceptions can occur, such as transit in the radiation environment close to Jupiter, but this was not investigated.

A second question is whether the degradation calculated at Earth can be directly applied at LILT conditions, i.e., are the same percentage losses in cell current, voltage, and power valid over a wide range of solar distances. Previous work[2] concluded that the percent of cell power lost to a given radiation fluence was much less at LILT conditions than at 1 AU, not only for earlier versions of 3-junction cells, but also for single junction III-V and silicon cells. Obviously, if this behavior could be verified it would provide for additional mission power at LILT conditions, where available power is often most critical.

In assessing this, JPL irradiated a group of test cells, using plate 1 (low binning) and plate 3 (high binning) cells from each manufacturer. This was done to leave plate 2 (median binning) as a control and as backup if additional tests were required. The group 1 and 3 cells were irradiated to 2.5 E14 1 MeV electrons, and tested out to 3AU LILT conditions, in support of the DAWN mission which had a 3AU maximum solar range limit. This was extended in an additional set of tests out to 5AU, after discussions with other programs. For this extension, an additional plate was assembled using four cells from each vendor, consisting of cells in the mid range of the distribution. These cells were subjected to fluences of 5 E14 and 1 E15 1 MeV electrons.

The results of the testing performed were surprising. In contrast with previously reported data, the percentage degradation of all test cells was found to be the same at LILT conditions as at the standard test conditions (AM0, 28C). Figure 6 shows this for cells tested to the fluence of 5 E14. Although the cell quantity in this data base is small, the results were consistent within the cells of each manufacturer and between the two manufacturers. The data strongly suggests that there is no reduction in degradation at LILT operating conditions. This was also observed at 5 E15 fluence and at 2.5 E14 fluence (performed on the larger quantity of cells). The cells from plates one (1), the lower power cells, exhibited greater variance due to the increased shunt resistances (compared to the plate 2 and 3 cells), but still showed average degradations under LILT conditions in agreement with the standard test conditions.

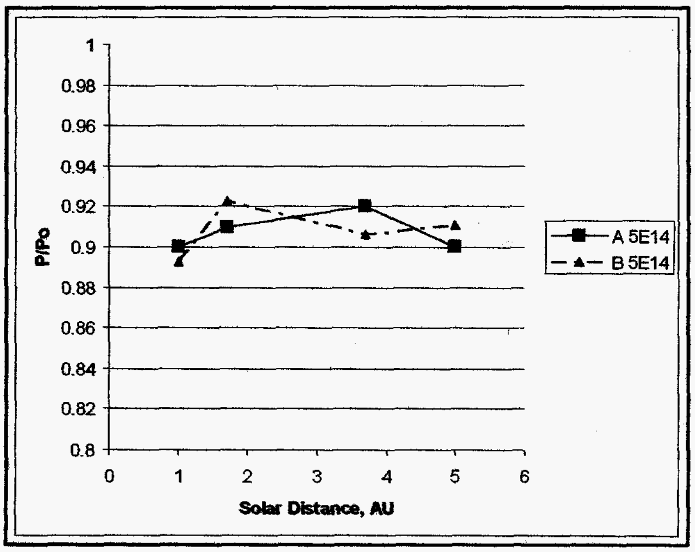

Figure 6. P/P_o at 5 E14 – 1 MeV electrons for Manufacturers A and B

The discrepancy between the data obtained in these tests and previous reported data is curious. It is difficult to explain this on the basis of characteristics of the advanced three (3) junction cells, since it was evident for both manufacturers, and also the previous results applied to a variety of cell types and manufacturers..

VI. Conclusions

In the four years since JPL previously examined three (3) junction solar cells, cell efficiencies (measured at AM0, 28C) have increased appreciably, from approximately 24% to 28% (AM0, 28C). The results of testing reported herein show that comparable improvements are observed at LILT conditions (up to 5AU equivalent). Average cell efficiencies from 3 - 5AU for both manufacturers' cells were measured to be approximately 29 -30%. This compares with data obtained in 2000, that showed ~25% efficiency over the same range. The efficiency from three (3) junction cells remains nearly constant over a wide AU range, with only an average 3-4 point efficiency increase measured as the solar distance increases from 1AU to 5 AU.

A few of the cells tested showed evidence of LILT degradation, i.e., a reduced performance due to a reduction in fill factor. Due to the same sample size, it is not possible to ascertain what fraction of a flight population would exhibit this.

The radiation testing provided results that were considerably different than had been published in 2002[2]. Whereas that data showed much reduced percentage loss in cell performance at LILT conditions than at Earth operating conditions, this work unambiguously showed that the percentage power lost under differing AU conditions was essentially the same.

Data that would allow for a more comprehensive determination of temperature coefficients and cell performance was not assessed in these tests. This was done primarily in the interest of reducing the testing duration to meet the DAWN program schedule. The lack of existing LILT cell data for the DAWN mission meant that the array procurement could not be initiated until appropriate data was available. To meet the schedule, the temperature-intensity test matrix was limited in scope to best fit the DAWN mission. For example, temperature data at 3 AU does not include the 28C "room temperature" condition since there was no reason to expect the array to operate at that value under low intensity illumination. In hindsight, an expanded matrix would have been valuable in reducing the amount of extrapolation required to complete the array performance analysis for various LILT conditions. Direct relationships from cell and array "room temperature" test conditions to LILT conditions would reduce analysis errors. Further LILT testing should also use larger sample sizes than the 12 cells tested for each manufacturer herein. This would reduce the impact on the results from a single cell. Quantities at least three times larger would tighten the error limits allowing for greater accuracy in predicting array performance. At the same time, there was fundamental consistency in the data that supports the conclusion of 29 - 30% cell efficiency from 3 to 5AU.

In order to have the data necessary to allow prediction of array performance at LILT conditions with accuracies comparable to that available for Earth orbiting spacecraft and missions to nearby objects such as Mars and Venus, additional LILT testing needs to be performed. Increased accuracy in array performance prediction would benefit from examining the influence of LILT degraded cells on a circuit. Although this might be somewhat similar to the impact of partial shadowing, the LILT degraded cells exhibit a curve shape change (reduced fill factor) rather than a short circuit current reduction (as is the case in partial shadowing). Obviously, this could be avoided if tools were available to remove the low percentage of cells that show large LILT losses.

Acknowledgments

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The authors wish to thank Emcore Corporation and Spectrolab, Inc., for providing the test cells. This work was performed by the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration.

References

[1]Stella, Paul M., Gregory L. Davis, Robert L. Mueller, Dmitri D. Krut, David J. Brinker, David A. Schieman, "The Performance of Advanced Solar Cells for Interplanetary Missions," *28th IEEE PV Specialists Conference Proceedings*, Anchorage, AK, 2000, pp. 1354-1357

[2]Gelderloos, C.J., K.B. Miller, R.J.Walters, G.P.Summers, S.R. Messenger, "Low Temperature Low Intensity Performance of Advanced Solar Cells," *29th IEEE PV Specialists Conference Proceedings*, New Orleans, LA, 2002.