INITIAL ON-ORBIT PERFORMANCE ANALYSIS OF INVERTED METAMORPHIC (IMM3J) SOLAR CELLS ON MISSE-7

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ABSTRACT

Prototype Inverted Metamorphic (IMM3J) cells were grown and fabricated and assembled onto an experimental flight coupon for inclusion on the 7th Materials International Space Station Experiment (MISSE-7). This paper examines the first eleven months of on-orbit data of prototype IMM3J solar cells in a low earth orbit (LEO) environment. The prototype IMM3J solar cells show excellent electrical and mechanical stability over the first eleven months in orbit with 97-98% in Jsc and maximum power (Pmp) retention for the four actively measured IMM3J solar cells. The loss in Jsc and Pmp is likely due to etching of the anti-reflective glasscover coating due to atomic oxygen.

INTRODUCTION

In recent years, Inverted Metamorphic (IMM) solar cell technology has emerged as a candidate for the next generation of advanced solar cell technology for aerospace applications [1]. In order to further investigate the performance of IMM solar cell technology in a real operational environment, a flight coupon was fabricated with prototype Inverted Metamorphic (IMM) solar cells (circa 2008) from Spectrolab.

The coupon was delivered to the Naval Research Laboratory (NRL) in 2008 for inclusion on the Seventh Materials on the International Space Station Experiment (MISSE-7). The coupon was delivered to the ISS by the space shuttle.

The Spectrolab MISSE-7 coupon consists of eight Inverted Metamorphic (IMM) triple junction 2 cm x 2 cm solar cells of which four cells have active on-orbit telemetry. This coupon was deployed on the space shuttle flight (STS-129) on November 16, 2009 and was successfully retrieved in May 2011 on the penultimate space shuttle flight.

This advanced solar cell technology has been developed under AFRL funded programs at Spectrolab and provides a snapshot in time of this advanced solar cell technology. Initial analysis of on-orbit data is reviewed in this paper.

MISSE-7 FLIGHT EXPERIMENT

The MISSE-7 flight coupon was fabricated in 2008 and delivered to NRL for integration for launch into the International Space Station (ISS) via space shuttle delivery. The coupon is mounted on the exterior of the International Space Station (ISS) and is in a low earth orbit (LEO). There are no backside components on the coupon so that the coupon fits within the Forward Technology Solar Cell Experiment (FTSCE) compartment. The US Naval Research Laboratory (NRL) was tasked with coupon preparation for launch and all aspects of on-orbit telemetry.

MISSE-7 COUPON FABRICATION

The fully fabricated Spectrolab MISSE-7 coupon is shown is Figure 1. Cells denoted A1, A3, A6, and A8 (the four corner cells) have active telemetry while the others are passive ride-alongs. CIC features include bypass diode protection, 5 mil CMG coverglass, and an all welded design.

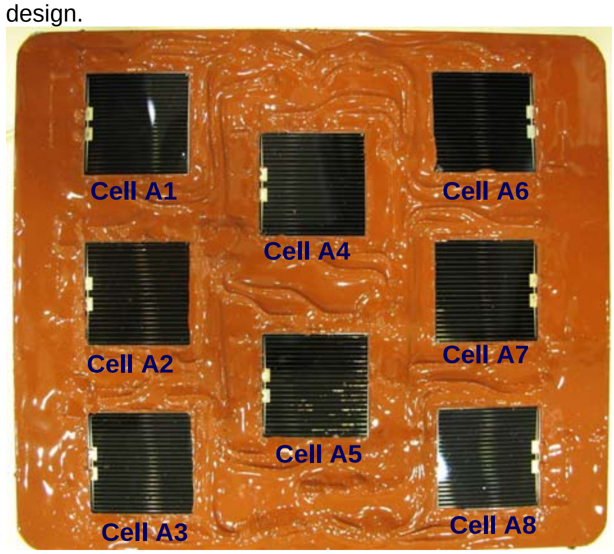

Figure 1 MISSE-7 flight coupon consisting of 8 IMM3J solar cells. Cell size is ~ 2 cm x 2 cm.

The front side of the coupon is fully grouted. The IMM cells are circa 2008 development efforts and provide a snapshot in time of IMM solar cells.

Pre-flight Characterization

The MISSE-7 flight coupon was characterized with a Large Area Pulsed Solar Simulator (LAPSS) using UTJ setup standards as balloon flight calibrated IMM standards were not available at the time. Figure 2 shows room temperature LIV curves for the four active cells (A1, A3, A6, and A8). LIV performance is nominal and represents the state of IMM3J performance during the early 2008 timeframe. Nominal efficiency for these cells is ~ 26 to 27%.

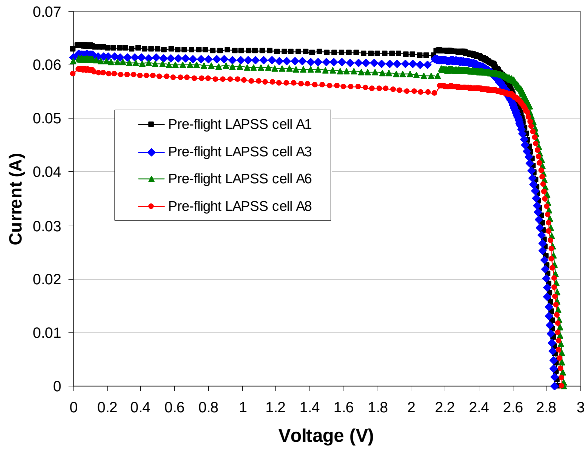

Figure 2 Pre-flight LAPSS characterization at Spectrolab.

ON-ORBIT TELEMETRY

The MISSE-7 coupon was launched on space shuttle flight STS-129 on November 16, 2009. The coupon became operational shortly after launch. The MISSE-7 coupon was retrieved in May 2011.

Figure 3 shows the temperature profile (leftside) and sun angle (rightside) over the initial eleven months the IMM3J solar cells were in orbit. The higher the sun angle the lower the cell temperature.

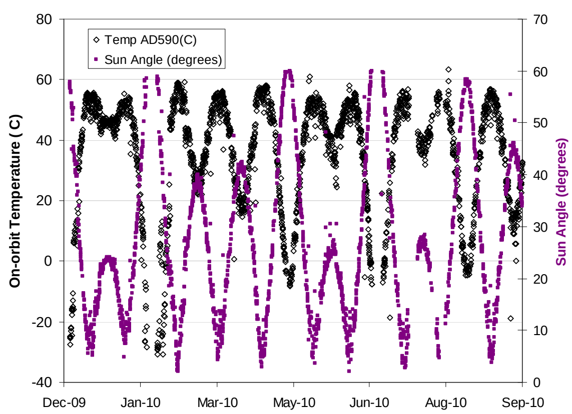

Figure 3 Temperature profile (leftside) and sun angle (rightside) for the first eleven months on orbit as determined by AD590 temperature sensor mounted within the coupon.

Temperature was determined by an AD-590 temperature sensor located within the coupon from the back. The maximum and minimum temperatures ranged from 67°C to -64°C. Additionally there is a sun-earth distance correction that is used in the data corrections.

Data Corrections

Initial data filtering included removing measurements taken greater than 60 degrees, non-measurements, and FF <0.5 or greater than 1. Close examination shows some potentially outlier measurements that do not fall on the main curve, however these were left in for this analysis.

Data corrections for Isc and Imp are applied for sun-earth distance (intensity), sun-angle, and temperature as described in [2]. Figure 4 shows the on-orbit Isc, and the angle and intensity corrected Isc.

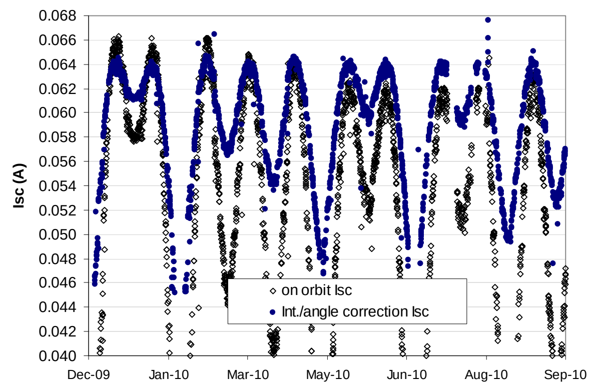

Figure 4 On orbit Isc and sun angle and intensity corrected Isc.

The sun angle and intensity corrected Isc reduces the scatter in the on-orbit data; however temperature effects are still present in this figure. Temperature corrections to Isc and Imp where applied next to produce preliminary intensity corrected Isc and Imp.

The temperature coefficients derived from the flight data using the intensity/angle corrected Isc vs. T are shown in Figure 5.

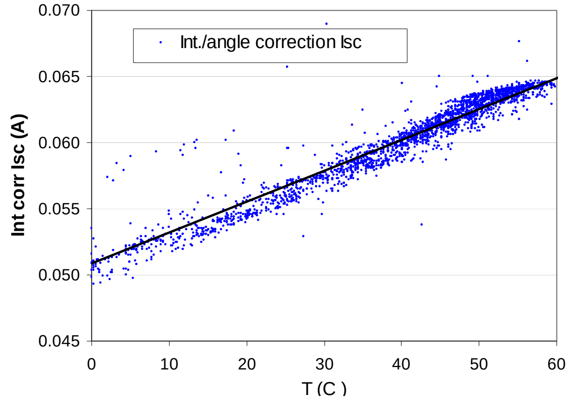

Figure 5 Isc temperature coefficients were calculated from intensity/angle corrected Isc vs. T from the flight data.

Imp was calculated in a similar manner. An interesting observation is that the Isc and Imp temperature coefficients are ~5X larger than expected. Ground characterization of the cells is planned to determine the source of this discrepancy.

Figure 6 shows the on-orbit Isc, sun angle and intensity corrected Isc, and the temperature corrected Isc. Applying all the corrections reduces the data to a relatively constant value for Isc. The dashed line represents the Isc value as determined by pre-flight LAPSS characterization.

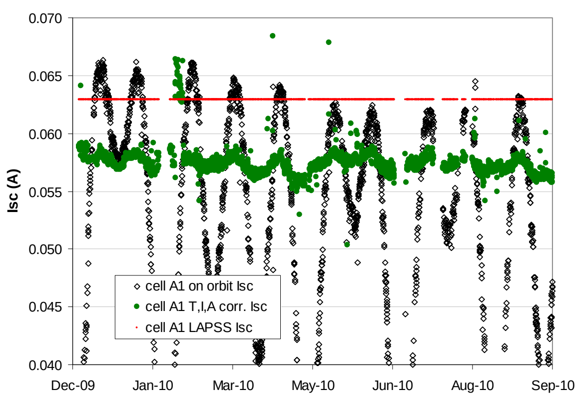

Figure 6 On orbit Isc, Int./angle corrected Isc, and temperature corrected Isc. The dashed line represents the Isc value as determined by pre-flight LAPSS measurement.

The change in Voc as a function of intensity change was calculated for each data point using equation (1)

$$\Delta Voc = \frac{nkT}{q}\ln(X) \qquad (1)$$

where *k* is Boltzmann's constant, *q* is the electron charge, *n* is the diode ideality factor, *T* is the temperature in Kelvin and *X* is the ratio of intensity corrected Isc to on orbit Isc. It should be noted this Voc correction is per junction so it is multiplied by 3 in this case. Changes in Vmp due to intensity changes were calculated in the same manner. The changes in Voc and Vmp due to intensity are relatively small in this case as they are proportional to the natural logarithm of intensity ratio. Figure 7 shows the on-orbit Voc and intensity Voc. Note the change is quite small. A diode factor of 1.5 per junction was used in the calculations. Temperature effects are still present in the data.

Figure 7 compares on orbit Voc, intensity corrected Voc and temperature corrected Voc for the eleven month data set. Also shown is the pre-flight LAPSS Voc for reference. The Voc collapses to a nearly constant value. In some places the Voc drops off, which corresponds to high angle measurement equation (1) may not be entirely valid over the full angle range.

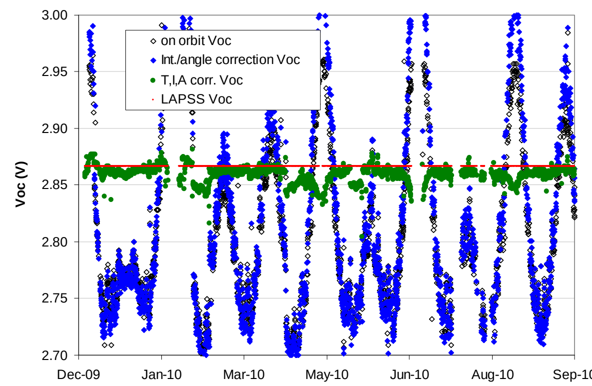

Figure 7 On orbit Voc, intensity corrected Voc, and temperature corrected Voc. Preflight Voc is shown as straight line.

The Vmp data was corrected in a similar manner and is shown in Figure 8.

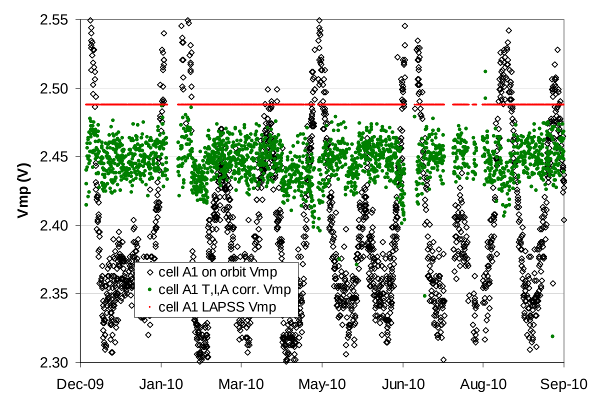

Figure 8 On orbit Vmp, intensity corrected Vmp, and temperature corrected Vmp.

It is not yet clear why the corrections due not give values closer to the pre-flight determined values except for Voc. Calculating the resulting temperature coefficient after applying equation (1) for n = 1, 1.5, and 2 gives Voc temperature coefficients in the range of ~ -0.005-0.006

mA/°C which are in the right range for three-junction solar cells. An alternate approach is to use preliminary laboratory determined intensity and temperature coefficients to apply to the on orbit data set. Values of n between 1 and 1.5 seem to fit the data the best. It should not be inferred that inverted metamorphic solar cells have an average diode factor between 1 and 1.5. This was only used as a fitting parameter and careful laboratory characterization needs to be performed to accurately determine diode factors for IMM.

Proceeding with the data reduction, Pmp was calculated from the product of Vmp and Imp. Figure 9 shows the results for cell A1 which yield a nearly constant value for Pmp given all the intensity, angle, and temperature corrections applied over the first eleven months in orbit.

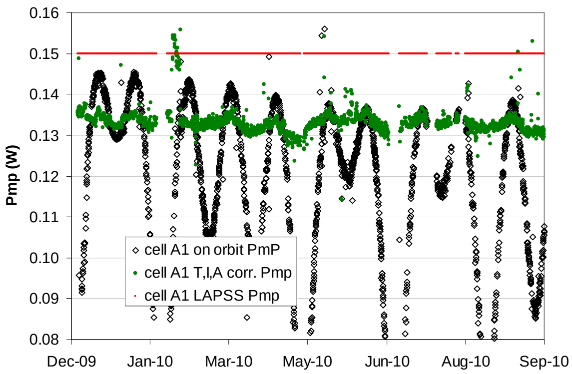

Figure 9 On orbit Pmp, intensity corrected Pmp, and temperature corrected Pmp.

Corrected data points which fall from the main curve correspond to high incidence angles (and low temperatures) where the corrections may not be entirely valid.

Results and Discussion

Table 1 summarizes the pre-flight LAPSS IV parameters vs. average, standard deviation, and % difference for the four IMM3J solar cells for the first eleven months in orbit for data corrected up to 60 degrees from normal. The corrected Isc, Imp, and Pmp give lower values than that determined from LAPSS.

Table 1 – Preflight LAPSS vs. average, standard deviation, and % difference for the four IMM3J solar cells for first eleven months in orbit.

		Isc	Imp	Voc	Vmp	Pmp	FF
		(mA)	(mA)	(V)	(V)	(W)	
Cell A1	LAPSS	62.9	60.1	2.867	2.488	0.150	0.829
	Avg.	57.4	54.2	2.867	2.454	0.133	0.808
	Std.	1.6	2.5	0.050	0.039	0.004	0.008
	%difference	-8.77	-9.75	0.01	-1.38	-11.31	-2.48
		Isc	Imp	Voc	Vmp	Pmp	FF
		(mA)	(mA)	(V)	(V)	(W)	
Cell A3	LAPSS	61.4	58.7	2.85	2.469	0.145	0.828
	Avg.	55.3	52.2	2.835	2.432	0.127	0.809
	Std.	3.1	4.4	0.051	0.059	0.016	0.033
	%difference	-9.98	-11.13	-0.52	-1.51	-12.46	-2.29
		Isc	Imp	Voc	Vmp	Pmp	FF
		(mA)	(mA)	(V)	(V)	(W)	
Cell A6	LAPSS	60.6	57.1	2.902	2.609	0.149	0.847
	Avg.	54.9	51.3	2.884	2.522	0.129	0.817
	Std.	1.6	1.5	0.052	0.016	0.004	0.003
	%difference	-9.37	-10.18	-0.63	-3.33	-13.18	-3.58
		Isc	Imp	Voc	Vmp	Pmp	FF
		(mA)	(mA)	(V)	(V)	(W)	
Cell A8	LAPSS	58.3	54.5	2.891	2.596	0.141	0.838
	Avg.	53.6	49.2	2.871	2.561	0.126	0.818
	Std.	1.5	1.4	0.054	0.019	0.004	0.007
	%difference	-8.00	-9.71	-0.70	-1.36	-10.63	-2.35

While there are differences in the corrected values to the pre-flight values, the corrected on-orbit values seem relatively constant. As noted before, balloon flight standards were not available for this cell architecture.

Another more important way to look at the data is to track the average over the course of the on-orbit flight time. Figure 10 shows the normalized average corrected Isc, Voc, and Pmp by month over the first eleven months in orbit for cell A1 showing good retention for these parameters.

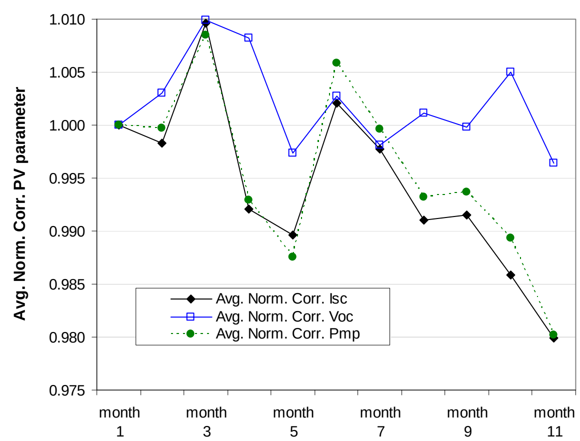

Figure 10 Average normalized corrected PV parameters normalized to first's month's value for first eleven month's in orbit.

The Voc retention for these cells is excellent over the time the cells have been in orbit. The normalized Voc is stable within measurement error. The Jsc and Pmp both have 97-98% retention for the four cells. The change in Jsc could be due to atomic oxygen etching of the antireflective coating on the coverglass of the cells. The maximum power (Pmp) tracks closely with Jsc and could be due to the reflectance change of the coverglass coating. The other three cells (A3, A6, and A8) give similar results to cell A1. The remaining seven months of on-orbit data will also need to be analyzed.

Post flight laboratory LAPSS characterization will need to be performed on this coupon once it's returned to Spectrolab. Unfortunately control cells were not included on this coupon for comparison. These prototype IMM3J solar cells show excellent electrical and mechanical stability in this space environment based on this data set. Additional effort is needed to understand the ~ 5X higher Isc and Imp temperature coefficients than expected based on the values calculated from this data set. Post laboratory LAPSS characterization should help with the overall data fitting of this on orbit data set.

It should be noted these cells are early prototypes and IMM3J solar cell development has since demonstrated a number of performance and process improvements since these early demonstration cells. Newer IMM3J devices are scheduled to be flown on the upcoming MISSE-8 flight.

Next Steps

The MISSE-7 coupon was retrieved on space shuttle flight STS134 in May 2011 and has acquired an additional six months worth of flight time and data. Additional work will involve analyzing the additional flight data and comparing to post flight LAPSS characterization at Spectrolab. Additional data analysis could investigate applying preliminary temperature coefficients determined on a later generation of IMM3J cell.

SUMMARY

Prototype (circa 2008) IMM3J solar cells were fabricated for the MISSE-7 flight coupon. The coupon consists of eight 2 cm x 2 cm IMM3J solar cells; four of the cells had active telemetry. Preflight LAPSS LIV characterization was performed on all the cells.

Intensity, incidence angle, and temperature corrections were performed on all the four active telemetried cells for the first eleven months in orbit. Based on this initial data set, analysis of on-orbit data show that IMM3J solar cells are electrically well behaved (and predictable) in terms of intensity, incidence angle, and temperature performance as expected of multijunction solar cells. These prototype inverted metamorphic (IMM3J) solar cells show excellent electrical and mechanical stability based on this data set and flight environment.

Additionally IMM3J solar cells show a high degree of stability on-orbit with 97-98% maximum power retention in performance within measurement and data correction error for this LEO environment. The change in Jsc and Pmp could be due to the etching of the coverglass antiflective coating due to the high atomic oxygen environment.

Further analysis will be performed on the additional six months of data from the remainder of the mission and post-flight LAPSS will be measured once the coupon is returned to Spectrolab.

Acknowledgements

The AFRL Space Vehicles Directorate provided the coupon substrate and this work was supported under contract F9453-06-C-0344. The authors wish to acknowledge the Naval Research Laboratory (NRL) and the entire multijunction team at Spectrolab.

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