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TACSAT-4 SOLAR CELL EXPERIMENT: TWO YEARS IN ORBIT

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ABSTRACT

The TacSat-4 spacecraft flies in a highly elliptical, 4-hour orbit, passing through proton and electron radiation belts 12 times per day. The TacSat-4 Solar Cell Experiment (TSCE) measures I-V curves on two, 3-cell strings of triple-junction cells, in flat-plate and concentrator configurations. Two additional triple-junction cells are measured at short circuit, testing a replacement cover glass technology. This paper reports on the first two years of experiment operations.

1. INTRODUCTION

The TacSat-4 spacecraft operates as a communication satellite enabling advanced communications capabilities. [1] TacSat-4 also carries a radiation spectrometer known as CEASE and the TacSat-4 solar cell experiment (TSCE). [2, 3]

TacSat-4 was placed in a highly elliptical orbit on 27 September 2011 with an apogee of 12050 km and perigee of 700 km, at an inclination of 63.4 degrees. Using the AP-8 and AE-8 radiation environment models, it is estimated the orbit creates radiation damage equivalent to 1.2E+16 1MeV e-/cm^2 to a solar cell with a 6 mil cover glass after just one year. [4, 5] It would take over 60 years in GEO to suffer an equivalent amount of radiation damage. It is in this environment that the TSCE measured solar cells in flat-plate and concentrator configurations.

2. EXPERIMENT DESCRIPTION

The spacecraft has two solar arrays, oriented along the +Y and –Y directions. These solar arrays track the sun in two axes with an accuracy of ±5°. The –Y wing has a 3-cell string of Emcore BTJM cells on Ge substrates thinned to 100 micrometers, with 150 micrometer CMG cover glass, mounted directly to the solar array honeycomb substrate. There is also a single BTJM cell, with a POSS® coverglass replacement, attached to an open weave fabric known as Vectran, mounted to a frame. [6] A photograph of the –Y wing test objects is shown in Fig. 1.

The +Y wing has a 3-cell string of Emcore ATJM cells with 508 micrometer coverglass mounted under a single-element molded linear Fresnel lens made of DC 93-500,

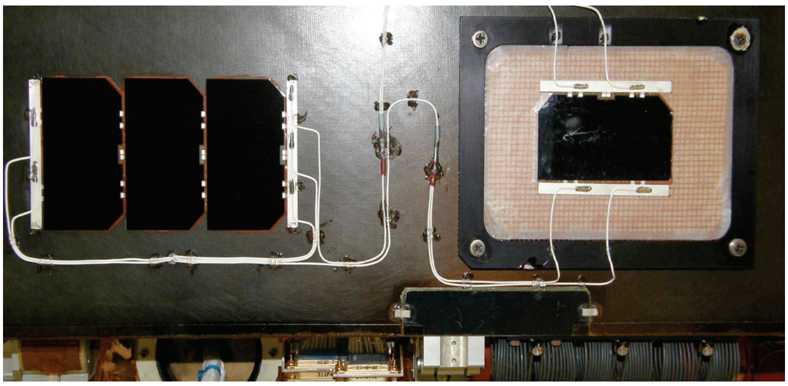

Figure 1) Flat-plate string (left) and solar cell with POSS coverglass replacement.

Figure 2) Stretched lens array (left) and BTJM "control" cell with CMG coverglass.

providing 6.34X concentration. The lens is protected from UV darkening by a UV rejection coating. A single BTJM cell with a 150 micrometer CMG cover glass mounted in a similar fashion as the BTJM cell with the POSS® cover glass replacement on the –Y wing, serves as a control cell for the POSS® cover. A photograph of the +Y wing test objects is shown in Fig. 2.

The TacSat-4 bus provides switched 28V power and four A/D channels to the TSCE electronics. When the TSCE is energized, the electronics cyclically bias the solar cell string though its I-V curve using an electronic load and alternately measure the two single cells at short circuit current (Isc). Each biasing cycle lasts one second. The electronics condition the current and voltage signals to conform to signal ranges of the A/D channels provided by the TacSat-4 bus. The bus then samples the A/D channels at an effective rate of 150 Hz for ten seconds. [7] Fig. 3 shows typical I-V curves for the two solar cell strings. Data collection occurs when operations permit. During the first three months of spacecraft operation the experiment was only operated occasionally. Once the spacecraft had completed the checkout phase, data sets were collected daily.

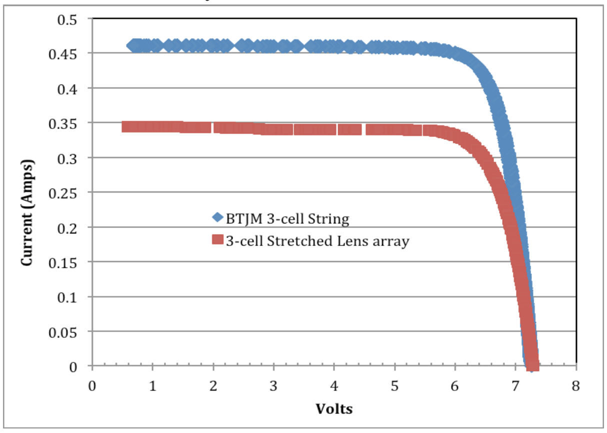

Figure 3) Typical I-V curves captured by the TSCE.

3. DATA ANALYSIS

3.1 Operations and Observed Artifacts

The TacSat-4 orbit is highly elliptical and endures thermal cycles that vary significantly with altitude and eclipse period. At perigee, the solar array temperature was observed as high as 70°C. At apogee the temperature was typically 50°C. As the TSCE was a secondary payload, data collection times were scheduled not to interfere with primary operations, thus the I-V curves were collected at various altitudes.

Fig. 4 shows an example of the variation in open circuit voltage (Voc) of the BTJM string with altitude. In the

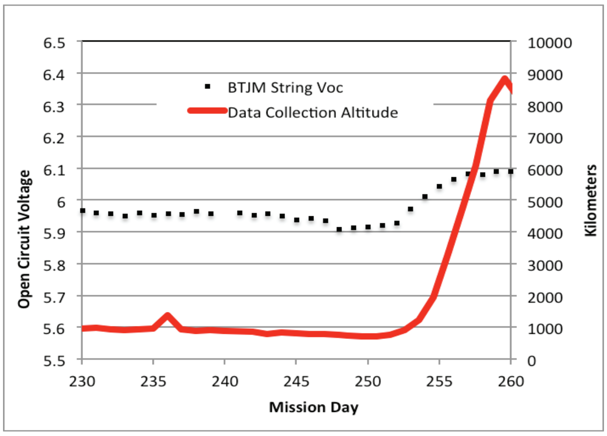

Figure 4) A plot of BTJM string Voc vs. altitude. Implying a significant temperature change with altitide.

interval shown, and using the BTJM temperature coefficient for Voc of 6.5mV/°C per cell, the implied temperature difference of an I-V curve collected at 900-km vs. 8800-km is 7°C. Most of the data collection over the two years occurred at altitudes above 8000-km where the temperature is relative stable, between 50°-55°C. But there are several periods where I-V curves collected at lower altitudes are apparent in the data.

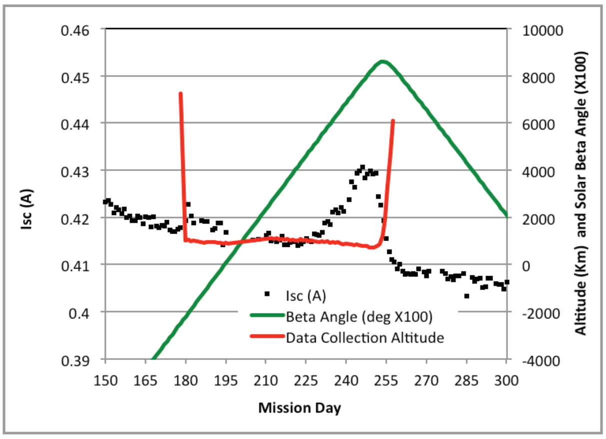

Figure 5) The effects of low altitude and high solar beta angle on the solar cell current.

Solar cell current is a much weaker function of temperature than cell voltage, but temperature and albedo illumination effects can be seen in the current data. Fig. 5 illustrates the artifacts to Isc due to a confluence of factors; high solar beta angle, and low altitude. When the solar cells are facing the sun under these conditions, the cells have a substantial view of the earth, creating a significant rise in solar cell current from earth albedo. On mission day 178, the data acquisition altitude drops from > 4000-km to ~900-km and a slight increase in current is seen at this transition due to increased temperature at lower altitudes. But as the beta angle rises from +46° on Day 225, to over +86° on Day 253, the solar cells see more and more of the illuminated earth creating a nearly

4% increase in current on Day 253. As the data acquisition altitude increases though, starting on Day 254, the albedo illumination contribution decreases in spite of the +80° beta angle. So for a significant albedo contribution to the current, both low altitude and high beta angle are required.

Correcting these data for temperature and albedo artifacts is beyond the scope of this paper. We present the explanation for these artifacts here so the reader can view the data set with an understanding of the origin of the artifacts and be able to see past them and recognize the underlying trends in these data.

Data presented here are corrected for sun-earth distance but not for temperature or albedo effects. Although temperature sensors were mounted to the experiment, and temperature measurements were made, it was not possible to record the temperature at the moment I-V curves were taken. The temperature of the solar arrays can vary by more than 30°C, even while continuously in the sun, due to varying amount of earth albedo between apogee and perigee.

Most of the data were collected above 8000-km at temperatures between 50-60°C. But there are notable excursions due to data collected at lower altitudes. We are confident though the underlying trends in these data are apparent even in the presence of these low altitude induced artifacts.

3.2 Results for the BTJM flat plate string

The solar cell data presented are shown along with predictions using the AP/E-8 and AP/E-9 radiation models as well as predictions modeled using particle fluence measurements from the on-board radiation spectrometer, CEASE.

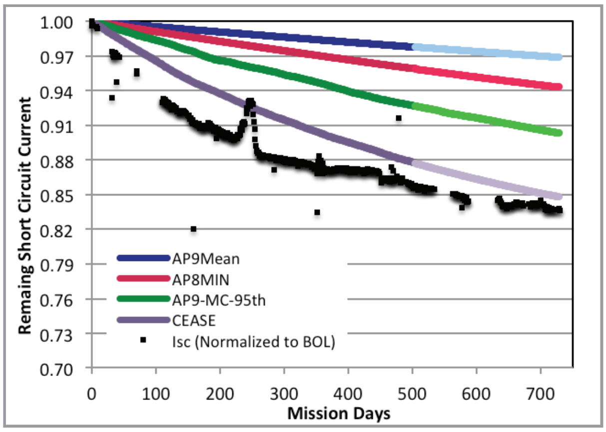

Figure 6) Remaining Isc of the BTJM cells compared to predictions using AP-8 and AP-9 radiation models as well as predictions using the measured data from the CEASE instrument.

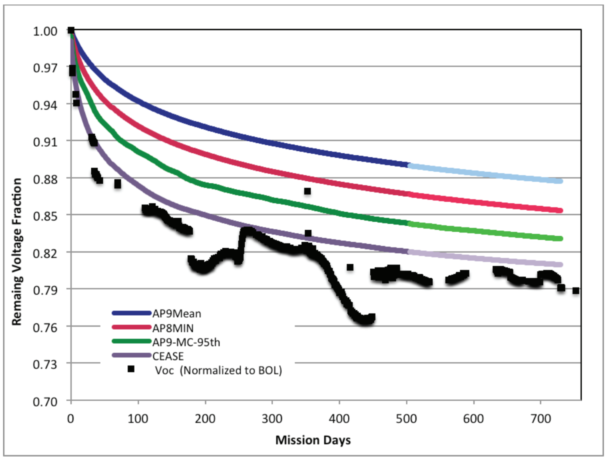

Figure 7) Remaining Voc fraction of the BTJM cells compared to predictions using AP-8, AP-9 and measured data from the CEASE instrument.

The graph in Fig. 6 plots Isc normalized to the beginning of life (BOL) value as a function of time in orbit for the BTJM string of cells labelled as black squares. These data are compared to radiation damage simulations using the SCREAM code with the electron and proton environments of AP/E-8 and AP/E-9. [9] The AP-8 case uses the AP8MIN environment and the AP-9 cases were run in Monte Carlo mode (100 simulations) and are represented by the mean case and the 95th percentile worst case. The solar cell degradation based on the radiation environment as measured by CEASE is also shown in Fig. 6 and is better matched to the BTJM data. CEASE spectra were only available through the first 500 days of the

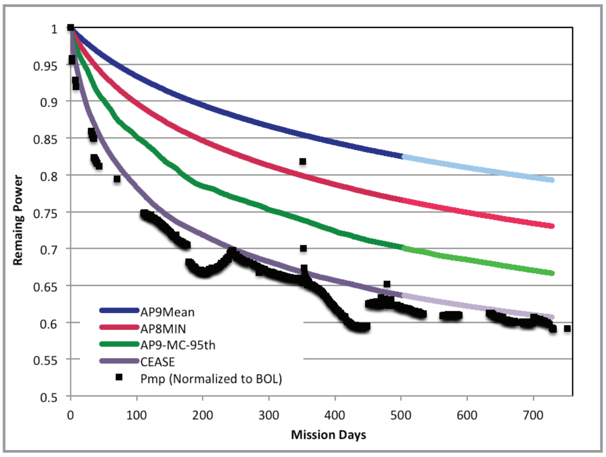

Figure 8) Remaining maximum power fraction of the BTJM cells compared to predictions using AP-8, AP-9 and measured data from the CEASE instrument.

mission at the time of this writing. Beyond day 500, the CEASE results are extrapolated from the last measurement set. This is indicated in the figure by lighter color shades of the lines representing the modeled solar cell response. It is notable that both radiation models, AP/E-8 and AP/E-9 significantly under predict the damage. It should also be noted that these degradation calculations only consider degradation to the solar cell itself due to displacement damage, and not any darkening effects of the coverglass and/or coverglass adhesive. These would be additive to any loss seen in the degradation to the solar cell.

The same type of plot in Fig. 6 is shown for the BTJM Voc in Fig. 7. Again, except for the artifacts due to temperature discussed above, the measured BTJM data agrees very well with the modeling results using the on-orbit CEASE radiation spectra.

Fig.8 shows the modeling results for the remaining maximum power (Pmp) as a function of time with the measured data for the BTJM string. The influence of the voltage artifacts are seen in this plot as well as the consistent trends of the established AP-8 and AP-9 environments under predicting the damage by a significant amount.

As trusted and well used as the AP-8 AP-9 models are, they are only as good as the experimental data they are based on. The TacSat-4 mission, with it's unusually harsh orbit, will help fill in portions of the radiation spectra not previously characterized.

3.3 Results for the Stretched Lens Array

Analysis of the stretched lens array is more complex than that of the BTJM string due to the 6X linear fresnel lens. As previously reported, the lens began to suffered a mechanical failure approximately six months into the mission. During the first 6 months before any lens failure, the Stretched Lens Array suffered about 13% power loss, compared to about 30% power loss for the one-sun cells, as expected due to the thicker cover glass. Thereafter, the three cells illuminated by the lens suffered increasingly different illumination levels as the lens began to mechanically fail under the combined effects of thermal and mechanical stresses along with radiation embrittlement of the weak silicone lens material. Newer, more robust lens designs mitigate the observed mechanical failures. This paper focuses more on the results after the complete lens failure in the 14th month of the mission.

The lens failed completely, on 21 November 2012 (Mission Day 421). At which point, it is essentially a flat-plate ATJM string under a 508 micrometer coverglass, directly comparable to the BTJM flat plate string with 150 micrometer coverglass.

The remaining power vs. time on orbit is shown for the stretched lens array (SLA) with and without the lens in Fig. 9. The remaining BOL power fraction was determined either with the concentrator lens or without (using the one-sun value). Here to, modeling results comparing

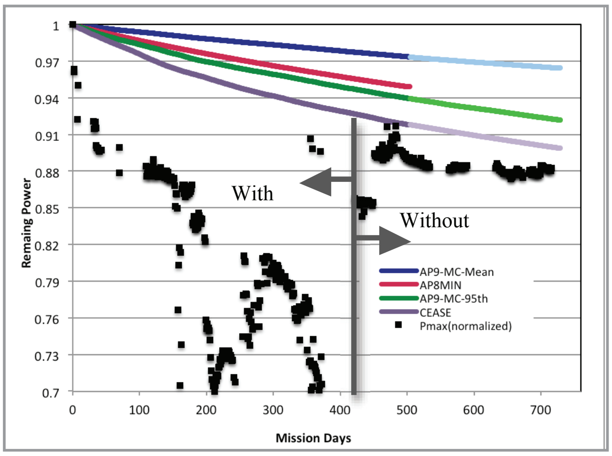

Figure 9) Remaining power fraction of the ATJM cells compared to predictions using AP-8 and AP-9 radiation models as well as predictions using the measured data from the CEASE instrument.

CEASE and AP/E-8 and AP/E-9 models are presented.

The modeled vs. measured data show the same trend as the BTJM cell, with the CEASE spectra matching the data more effectively. What is striking though is the level of protection offered by the thicker coverglass. At the two-year mark for the BTJM string with the thinner coverglass, the remaining power was only 60% of the BOL value, while the ATJM cell with a much thicker, 508 micrometer coverglass retained 88% of BOL performance.

3.4 Results for the POSS® Replacement Cover Glass

Two BTJM cells, each measured at short circuit, had one cell with a 150 micrometer CMG coverglass and the other with a POSS® coverglass replacement. The thickness of the POSS® cover was chosen to give the equivalent radiation shielding as the 150 micrometer CMG cover glass.

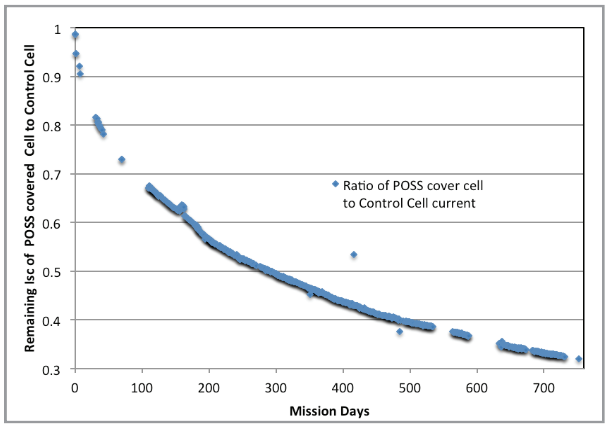

Figure 10) Ration of Isc of the Cell with POSS® cover compared to the control cell with a 150 micrometer CMG cover glass.

In Fig. 10 a plot of the ratio between the shorted BTJM cell with 150 micron CMG coverglass compared to the BTJM cell with POSS® cover. This gives a measure in the relative transmission between the two coverglass materials. The POSS® suffered a 67% loss in current compared to the cell with CMG coverglass after two years. At the time this material was chosen for the experiment its radiation hardness was not well understood. Since then ground testing of POSS® material show it to be radiation soft. This experiment thus confirms ground test results. [10]

4. SUMMARY

The TSCE measured I-V curves of solar cells in flat-plate and concentrator geometries. The experiment showed that the solar cell degradation rate was much higher than what is predicted by current radiation models. The CEASE radiation spectral data dramatically illustrated that the failing was not with the radiation response of the solar cells but rather with the accuracy of the radiation model predictions. The TSCE also demonstrated the utility of using thick coverglass in a high radiation environment, which allowed the solar cells to retain 88% of the BOL power compared to 60% of the BOL power when using thinner coverglass.

5. ACKNOWLEDGMENTS

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