

PERFORMANCE OF HIGH-EFFICIENCY ADVANCED TRIPLE-JUNCTION SOLAR PANELS FOR THE LILT MISSION DAWN

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ABSTRACT: Dawn, a NASA Discovery Mission, is planned to operate and gather information and data within the solar system's Asteroid belt. The large distance between the sun and the rocky bodies within the Asteroid belt creates a low-intensity illumination and low-temperature conditions commonly referred to as LILT. To meet the mission power requirements under LILT conditions, very high-efficiency multi-junction solar cells were selected to power the spacecraft to be built by Orbital Sciences Corporation (OSC) under contract to JPL. Emcore's InGaP/InGaAs/Ge advanced triple-junction (ATJ) solar cells, exhibiting an average air mass zero (AM0) efficiency of greater than 27.6% (one-sun, 28°C), were used to populate the solar panels [1]. The two solar array wings, built by Dutch Space, with 5 large-area panels each (total area of 36.4 m²) are projected to produce between 10.3 kWe and 1.3 kWe of end-of-life (EOL) power in the 1.0 to 3.0 AU range, respectively. The details of the solar panel design, testing and power analysis are presented.

Keywords: Multijunction Solar Cell, High-Efficiency, Space Cells

1 BACKGROUND

NASA's Discovery Mission Dawn is scheduled to launch in mid 2006. Its mission is to characterize the conditions and processes of the solar system's earliest epoch by investigating in detail two of the largest protoplanets remaining intact since their formations, Ceres and Vesta. The spacecraft's trajectory toward the asteroid belt is shown in Fig. 1. The mission life is envisioned to be 10.5 years. Under contract to JPL, Orbital Sciences Corporation is responsible for design, manufacturing, integration and testing of the Dawn spacecraft and support its launch and flight operations (Fig. 2). Dutch Space is responsible for the manufacturing and testing of the solar arrays, while Emcore provided the photovoltaic assembly for the mission. Ceres and Vesta reside in the extensive zone between Mars and Jupiter called the asteroid belt. The distance between the asteroid belt and the sun, in the order of 2-3 astronomical units (AU), necessitates efficient operation of the solar arrays under the low-intensity, low-temperature (LILT) conditions.

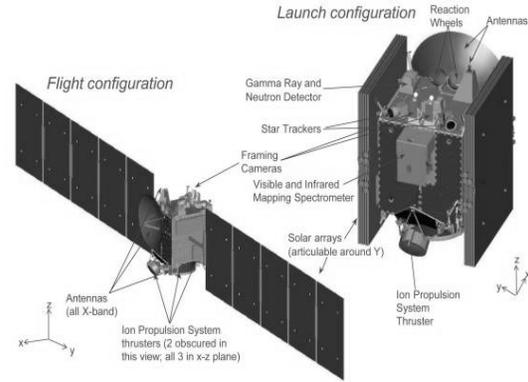


Fig. 2. Dawn Spacecraft Schematic

In the time span of 1950's through the mid 1990's, the need for power in space had been dominantly provided by silicon solar cells. In the past decade, however, high-volume manufacturing of high-efficiency III-V material based multi-junction solar cells has enabled this alternative technology to gradually become dominant for space power generation [1-4].

The solar array for the Dawn mission is planned to provide power under greatly varying illumination and temperature conditions. The sun intensity will vary approximately from 136.7 mW/cm² to 15.2 mW/cm² (i.e., 1 – 3 AU), while the calculated operating temperature of the solar array varies from +60°C to –88°C. Solar arrays populated with Emcore's InGaP/InGaAs/Ge advanced triple-junction (ATJ) solar cells were selected to provide primary electrical power for the Dawn mission. These cells, while exhibiting >27.5% beginning-of-life (BOL) minimum average efficiency under 1 AU (one sun), air-mass zero (AM0) illumination conditions at 28°C, are projected to demonstrate >30% conversion efficiency under LILT conditions.

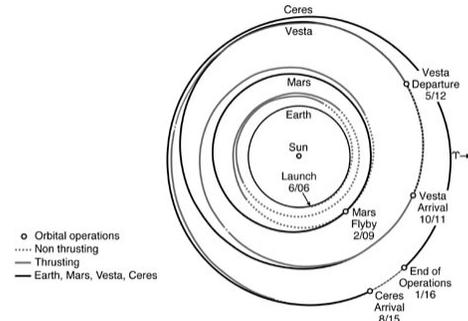


Fig. 1. Typical Dawn Trajectory Toward Ceres & Vesta

2 ADVANCED TRIPLE-JUNCTION (ATJ) SOLAR CELLS

It is well known that typical space solar cells designed for one sun operation may behave quite differently under LILT conditions. Historically, some space silicon cells have exhibited an illuminated current-voltage (I-V) characteristic with an unusual shape under LILT testing. This is referred to as the “flat spot” phenomenon [5]. This phenomenon causes these cells to exhibit a lower performance, at or near the maximum power point, than expected under LILT conditions. A similar effect has been observed in some of the lowest grade multi-junction GaAs cells, within the normal distribution of efficiencies in the cell production. This seems to be correlated to the shunt resistance (Rsh), in that cells with lower fill factor (FF) values are the only cells that have a potential to show this effect. One of the factors that affect Rsh is defect sites within or at the edge of the semiconductor layers.

It is well known that under 1x AM0 intensity, the solar cell performance is enhanced at lower operating temperatures. As might be expected from cells having below nominal values of Rsh, the lower-than-expected performance observed with some cells under LILT is emphasized under the conditions of low intensity flux, and not low junction temperatures. The LILT behavior of the solar cells can therefore be well characterized by only measuring the cells under low intensity light illumination levels at room temperature and subsequently applying temperature coefficient values which have been measured by JPL under LILT conditions. Consequently, the Emcore ATJ solar cells, manufactured for the Dawn mission, were all tested and electrically graded under low-intensity conditions at 28°C (instead of at 1x AM0).

This test methodology also removes the onerous condition of measuring large number of cells at below 0°C temperatures in a manufacturing line. The same testing and grading principals were applied to the production of 11,480 large-area (27.5 cm²) ATJ CIC (coverglass-interconnected-cell) assemblies for the solar panel build. The photograph of a Dawn ATJ CIC is shown in Fig. 3.

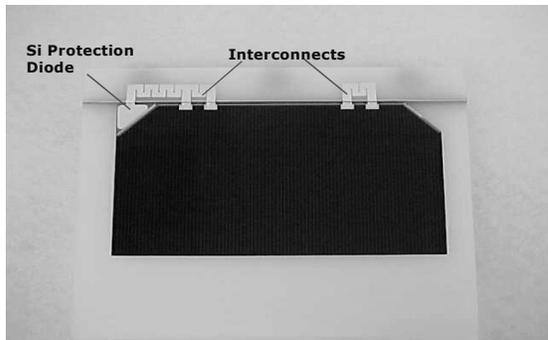


Fig. 3. ATJ production CIC – area of 27.5 cm²

Solar cells with higher FF values when tested under AM0, 1x intensity, maintained or showed improvement in FF under low intensity testing. On the other hand, low FF cells (i.e., <80% at 0.277x intensity)

tested under 1x intensity, sometimes exhibited a greater degree of FF degradation under lower intensities. The low intensity measurement of all cells and CICs was performed under 0.277x AM0 illumination. It was concluded from this test that even the lower-grade cells exhibit an acceptable performance under low-intensity conditions, and that the power demand of the Dawn spacecraft could be met using the typical range of the ATJ cell performance distribution. This typical performance range under 1x AM0 is shown in Fig.4.

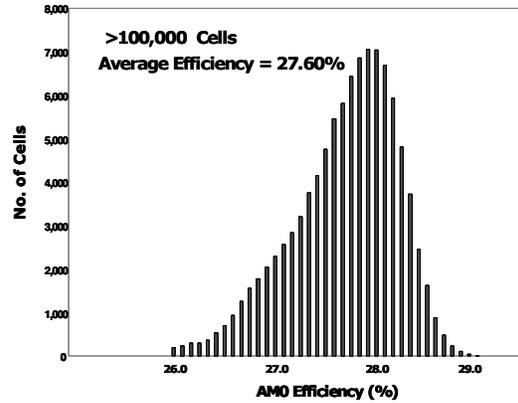


Fig. 4. ATJ production cell AM0 efficiency histogram

In the following sections, the power analysis methodology and the results of flight panel testing under Dawn illumination conditions are presented.

3 SOLAR PANEL CONFIGURATION

As mentioned earlier, the Dawn solar array consists of two wings, with 5 solar panels per each wing. One wing configuration is schematically shown in Fig. 5.

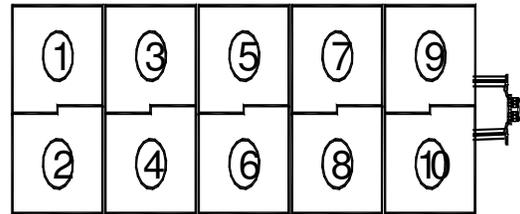


Fig. 5. Schematic solar wing configuration (circled numbers denote circuit numbering)

As shown in the figure, each panel is comprised of two circuits. Each circuit contains 14 strings. Total of 28 strings are bonded to every panel, with 41 cells connected in series per each string, bringing the total number of cells in each panel to 1,148 cells. All rectangular panels have the same dimensions: 2.265 x 1.608 m, resulting in a panel area of 3.64 m². Photographs of one representative panel, as well as, the unassembled +Y wing are shown in Fig. 6 and Fig 7, respectively.

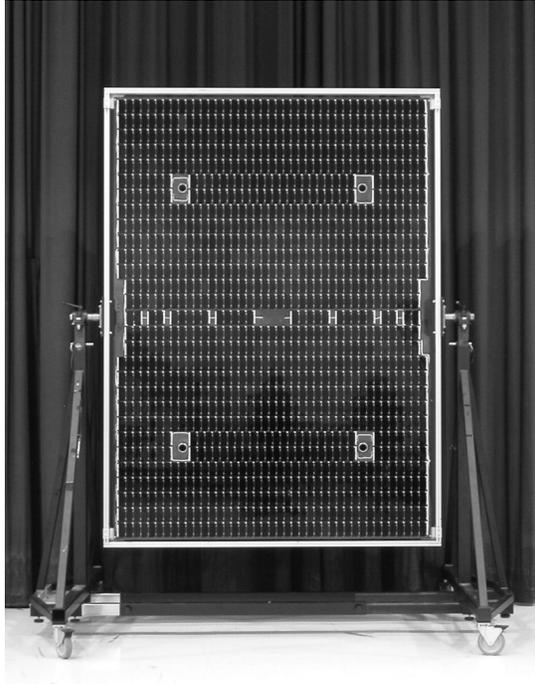


Fig. 6. Photograph of a Dawn panel (one of 10) populated with 1,148 large-area (27.5 cm²) ATJ solar cells



Fig. 7. Photograph of unassembled +Y wing consisting of 5 panels

4 POWER REQUIREMENTS & ANALYSIS

The Dawn spacecraft has a maximum power point tracker for maximum performance over the large intensity and temperature ranges. The power requirements and the calculated power for the Dawn mission at the array level are summarized in Table I, taking into account the predicted temperature of the array at the applicable sun distance.

Other requirements included array maximum power voltage (V_{mp}) to be greater than >85 V & <140 V & BOL short-circuit current (I_{sc}) < 7.5 A. The calculated

power values shown in Table I were the result of a comprehensive power analysis that was performed to predict the array level power. The solar array power analysis predicts the array electrical performance at all relevant stages during the mission by simulating the I-V curve generated over the required temperature range, sun intensity, and environmental conditions and loss factors, i.e. radiation, micrometeorites, etc. The solar array model allows for the generation of an I-V curve at the cell, string, circuit, panel, and array levels. Performance parameters such as I_{sc} , V_{oc} , maximum power point current (I_{mp}), maximum power point power (P_{mp}), and power or current at any given voltage may be determined from these generated I-V plots.

Table I. Dawn requirements & predicted power as a function of distance from the sun

Sun Distance (AU)	Intensity (AM0)	Required Power (W)	Calculated Power (W)
1.00	1.000	3,600	10,317
1.77	0.319	3,650	3,804
2.25	0.197	2,350	2,449
2.60	0.148	1,770	1,781
3.00	0.111	1,300	1,323

In the model, as in the solar panels, the cells are connected in series to form strings and the strings are connected in parallel to form circuits. In order to calculate the array power, the individual solar cell power outputs at any given stage during the mission is multiplied by the number of cells in the array and all pertinent current and voltage drop losses are applied. The voltage output of a circuit is calculated by multiplying the number of cells connected in series in a single string by the voltage output of a single cell. The current output of a circuit is calculated by multiplying the number of strings connected in parallel by the current output of a single string. Additional voltage losses due to wiring, connectors, and blocking diodes are then applied to the final results.

The results of the analysis rely on the actual measurement of the electrical performance parameters (i.e., V_{oc} , I_{sc} , V_{mp} , and I_{mp} at 0.277x sun intensity and 28°C for cells manufactured for the Dawn program. The CICs were electrically graded at a load voltage (V_{spec}) of 2.205 V. The minimum average illuminated CIC current at this load voltage (I_{spec}) was slightly greater than 121 mA, and the bin width was set at 1mA.

The Dawn solar array power analysis was therefore performed for the 0.277x case (1.9 AU) using the actual CIC test data, while the performance parameters (including temperature coefficients) for other lower-intensity AU cases of interest (i.e., 2.25, 2.6, and 3.0 AU) were extrapolated from the 1.9 AU case. The extrapolation was performed using a sampling of actual ATJ CIC measurement data taken under LILT conditions. Several representative ATJ CICs were measured at JPL under low intensity and low temperature conditions corresponding to the Dawn mission profile, enabling both BOL & EOL characterization of the CICs under operational conditions.

5 PANEL LEVEL ELECTRICAL RESULTS

The BOL electrical performance of the panels were measured with a large-area pulsed solar simulator (LAPSS) at 28°C under four different AM0 sun intensities: 1.0x, 0.277x, 0.20x & 0.125x. The actual measurement results exceeded power analysis prediction results under the same conditions, i.e., illumination intensity and temperature. A summary of the combined LAPSS test results for all 10 panels, comprising the unassembled +Y wing and -Y wing, as a function of sun intensity are presented in Tables II. The values in the second column of the table represent predicted combined power of both wings calculated at 28°C under the indicated sun intensities, such that they could be directly compared to the actual measured values under the same conditions shown in the last column. This is followed by a representative example of an I-V plot of one circuit at 0.277x intensity in Fig. 8.

Table II. Summary of combined LAPSS results for all 10 Dawn panels (+Y & -Y Wings)

Intensity (AM0)	Predicted Power – per Analysis (W)	Measured Power – per LAPSS (W)
1.00	11,135	11,723
0.277	2,990	3,096
0.20	2,114	2,179
0.125	1,245	1,327

As shown in Table II, the measured BOL power at all intensities meet or exceed the power predictions based on analysis.

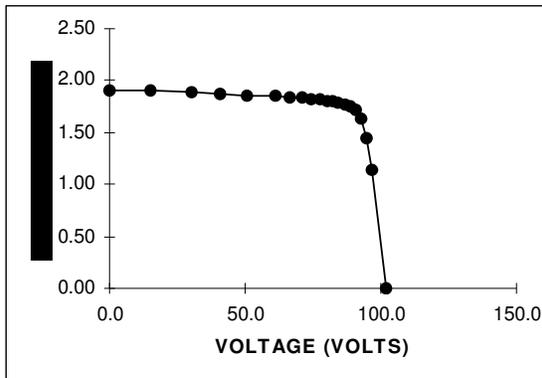


Fig. 8. BOL I-V plot of one Dawn circuit at 0.277x, 28°C

In addition to electrical health check and visual inspection, several other functional tests were performed on all panels. These included:

- Mass measurements
- Protection diode functionality Infra-red (IR) test
- Insulation resistance
- Functionality of bleed resistors, blocking diodes & thermal sensors

6 SUMMARY

Solar panels were built and tested for the Dawn spacecraft for a LILT mission to the Asteroid belt. High-efficiency ATJ cells were used to populate the panels. All cells were binned under a 0.277x AM0 low-intensity & 28°C conditions at Emcore. A sampling of CICs was also tested at JPL under the LILT mission profile. The results were used to perform a comprehensive power analysis of the mission incident intensity and temperature conditions. The electrical performance measurements of the completed solar panels demonstrate that the power requirements of the Dawn mission will be met.

7 REFERENCES

- [1] M.A. Stan, D.J. Aiken, P.R. Sharps, N.S. Fatemi, F.A. Spadafora, J. Hills, H. Yoo, and B. Clevenger. "27.5% Efficiency InGaP/InGaAs/Ge Advanced Triple Junction (ATJ) Space Solar Cells For High Volume Manufacturing," 29th PVSC, New Orleans, May 2002.
- [2] N. S. Fatemi, et al., "High-Efficiency Advanced Triple-Junction Solar Cells With Monolithically Integrated Bypass Diode," 19th European Photovoltaic Conference (PVSEC), June 7-11, 2004, Paris, France.
- [3] N. H. Karam, et al., "High efficiency GaInP₂/GaAs/Ge dual and triple junction solar cells for space applications," 2nd World Conf. & Exhibition on Photovoltaic Solar Energy Conversion, 6-10 July, 1998, Vienna, Austria, p.3534.
- [4] Y. C. M. Yeh, et al., "Advances in production of cascade solar cells for space," 26th PVSC, Sept. 30-Oct. 3, 1997, Anaheim, CA, p.827.
- [5] V.G. Weizer & J.D. Broder, "On the cause of the flat-spot phenomenon observed in silicon solar cells at low temperatures and low intensities," *J. Appl. Phys.* Vol. 53 (8), Aug. 1982, pp. 5926-5930.