

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

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**ABSTRACT**

NASA's Discovery Mission Dawn is designed to operate within the solar system's Asteroid belt, where the large distance from the sun creates a low-intensity, low-temperature (LILT) condition. 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 with 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, to be built by Dutch Space, with 5 large-area panels each (total area of 36.4 m<sup>2</sup>) 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.

**BACKGROUND**

In mid 2006, NASA's Discovery Mission Dawn is scheduled to launch its mission to characterize the conditions and processes of the solar system's earliest epoch by investigating in detail two of the largest proto-planets 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 provides the photovoltaic assembly for the mission. Ceres and Vesta reside in the extensive zone between Mars and Jupiter called the asteroid belt. The large distance between the asteroid belt and the sun, in the order of 2-3 astronomi-

cal units (AU), necessitates efficient operation of the solar arrays under the low-intensity, low-temperature (LILT) conditions.

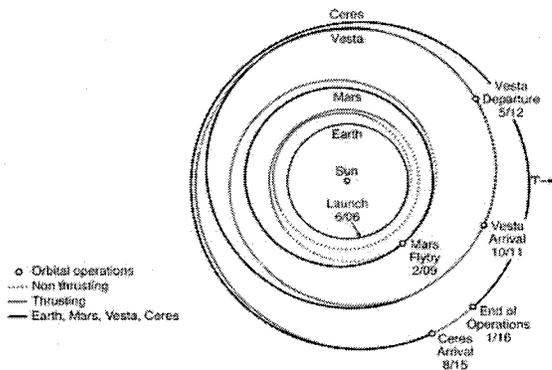


Fig. 1. Typical Dawn Trajectory Toward Ceres & Vesta

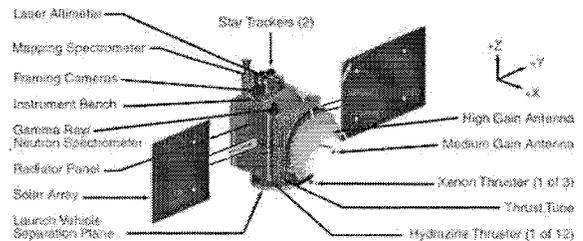


Fig. 2. Dawn Spacecraft Schematic

Historically, the need for power in space has been dominantly provided by silicon solar cells. In the past several years, however, high-volume manufacturing of high-efficiency multi-junction solar cells has enabled the use of this alternative technology 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/cm<sup>2</sup> to 15.2 mW/cm<sup>2</sup> (i.e., 1 – 3 AU), while the calculated operating temperature of the solar array varies from -88°C to +60°C. Solar arrays populated with Emcore's InGaP/InGaAs/Ge advanced triple-junction (ATJ) solar cells are 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. Efficiencies of greater than 34% have been recorded at JPL for an ATJ cover-glass-interconnected-cell (CIC) under incident space illumination intensity of 21.9 mW/cm<sup>2</sup> (representing 2.5 AU distance from the sun) and operating at a temperature of -100°C.

### 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. For example, by employing a "guard ring" diffused layer around the perimeter of Si space cells used for the Rosetta mission, the edge defect sites are in effect passivated, eliminating the "flat spot" that is normally observed under low intensity illumination in some cells [6].

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 cm<sup>2</sup>) ATJ CIC (coverglass-interconnected-cell) assemblies for the solar panel build. The photograph of a Dawn ATJ CIC is shown in Fig. 3.

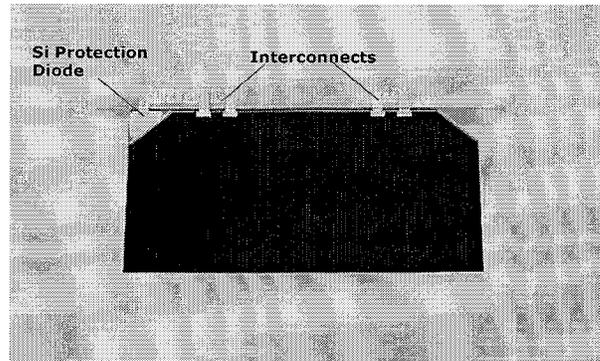


Fig. 3. ATJ production CIC – area of 27.5 cm<sup>2</sup>

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.

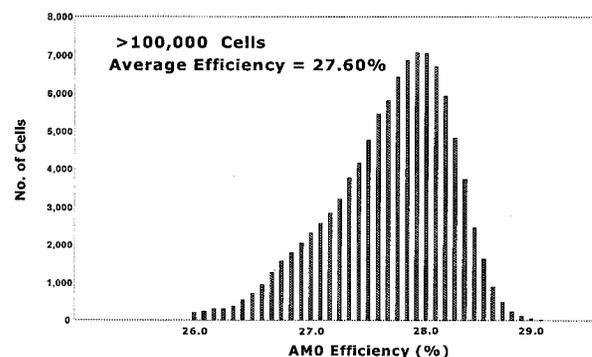


Fig. 4. ATJ production cell AM0 efficiency histogram

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

## 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.

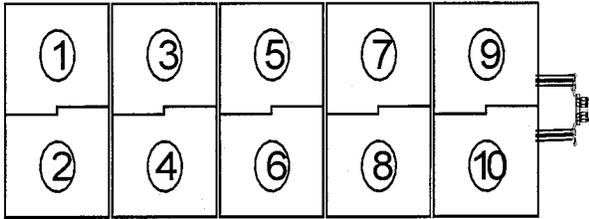


Fig. 5. Schematic solar wing configuration (circled numbers denote circuit numbering)

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 m<sup>2</sup>. A photograph of one representative panel is shown in Fig. 6.

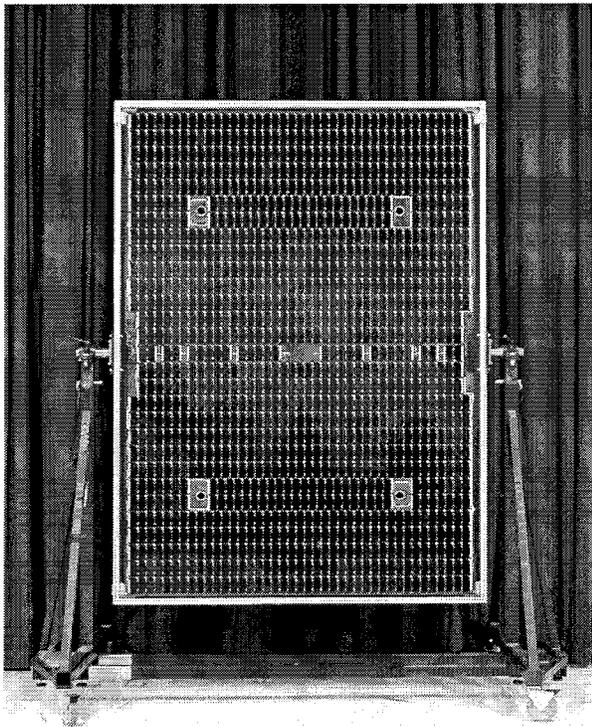


Fig. 6. Photograph of a Dawn panel (one of 10) populated with 1,148 large-area (27.5 cm<sup>2</sup>) ATJ cells

## 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.

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

Other requirements included array EOL maximum power voltage ( $V_{mp}$ ) >85 V, BOL open-circuit voltage ( $V_{oc}$ ) <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.

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 cur-

rent at this load voltage (I<sub>spec.</sub>) 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.

### 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. A summary of the LAPSS test results for 5 panels (+Y Wing) are presented in Table II. The values in the second column represent predicted power of one wing 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. 7.

Table II. Summary LAPSS results for +Y Wing

Intensity (AM0)	Predicted Power – per Analysis (W)	Measured Power – per LAPSS (W)
1.00	5,568	5,852
0.277	1,495	1,551
0.20	1,057	1,082
0.125	622	663

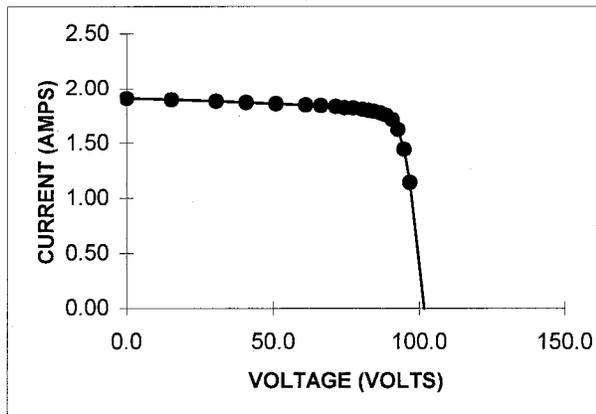


Fig. 7. BOL I-V plot of one Dawn circuit at 0.277x, 28°C

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

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

### 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.

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