DESIGN AND DEVELOPMENT OF THE SPACE TECHNOLOGY 5 (ST5) SOLAR ARRAYS

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ABSTRACT

The National Aeronautics and Space Administration's (NASA's) Space Technology 5 (ST5) is designed to flight-test the concept of miniaturized "small size" satellites and innovative technologies in Earth's magnetosphere. Three satellites will map the intensity and direction of the magnetic fields within the inner magnetosphere [1]. Due to the small area available for the solar arrays, and to meet the mission power requirements, very high-efficiency multijunction solar cells were selected to power the spacecraft built by NASA Goddard Space Flight Center (GSFC). This was done in partnership with the Air Force Research Lab (AFRL) through the Dual-Use Science and Technology (DUS&T) program. Emcore's InGaP/InGaAs/Ge Advanced triple-junction (ATJ) solar cells, exhibiting an average air mass zero (AM0) efficiency of 28.0% (one-sun, 28°C), were used to populate the arrays [2]. Each spacecraft employs 8 identical solar panels (total area of about 0.3 m^2), with 15 large-area solar cells per panel. The requirement for power is to support on-orbit average load of 13.5 W at 8.4 V, with ±5% off pointing. The details of the solar array design, development and qualification considerations, as well as ground electrical performance & shadowing analysis results are presented.

INTRODUCTION

ST5 is a space technology development mission in the New Millennium Program (NMP). It is NASA's first experiment in the design of miniaturized satellite constellations. The mission will design, integrate and launch three spacecraft into orbits high above the Earth's magnetosphere (See Figure 1). Each spacecraft incorporates innovative technology and constellation concepts that will be instrumental in future space science missions. Each spacecraft measures 50 cm across and 28 cm high and weighs less than 25 kg. The mission was originally intended to be a secondary payload on an unspecified launch vehicle of opportunity but is now the primary payload on a Pegasus XL. The mission is scheduled for launch in late 2005. The mission duration is planned for 3 months [1, 3].

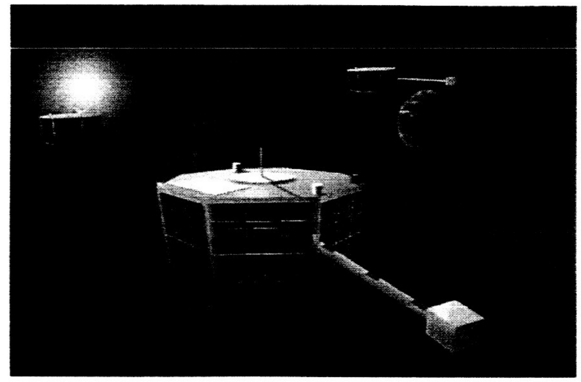

Fig.1. Early artist's conception of the three ST5 spacecraft.

The ST5 solar arrays consist of eight body-mounted solar panels mounted on each of three spacecraft. All of the panels are identical. This modular approach has proven advantageous in the past for multiple-spacecraft use [4]. Each panel is 16.5 cm wide and 28.6 cm long. Each substrate is 0.4 cm thick and consists of graphite facesheets, an aluminum honeycomb core, and Kapton insulator.

The ST5 solar panel procurement was a partnership between NASA GSFC and AFRL. The ATJ solar cells were selected for the ST5 mission by theNASA GSFC Applied Engineering Technology Directorate and the AFRL Space Vehicles Directorate based on their high conversion efficiency and production availability. These cells were developed under an AFRL Dual Use Science & Technology effort with Emcore Photovoltaics to further optimize the previous triple junction InGaP/GaAs/Ge solar cell design.

DRIVING REQUIREMENTS

The ST5 solar arrays are required to support an orbit average load of 13.5 W at 8.4 V at the power system bus after 3 months in an orbit with a perigee of 300 km, an apogee of 4500 km, and an inclination of 76°. In addition, the array must provide sufficient power to charge the battery during the sunlight period of the orbit. This translates to a requirement that the array provide 23.1 W at 9.2 V at the array string terminations assuming an April 5 launch (resulting in minimum sun intensity at end of life). The array must survive 290 eclipse cycles from -75°C to +55°C and 10 cycles from -75°C to +95°C.

The change from a mission of opportunity to a mission with a dedicated launch vehicle also resulted in a change of orbit. The original orbits were approximately 300 km x 30,000 km with inclinations ranging from 0° to 28°. The solar panels were sized for the original orbit. The new orbit results in slightly less array degradation than the original.

The presence of a magnetometer dictates that the solar array be magnetically clean. The magnetic field generated by each panel is constrained to no more than 0.005 nanotesla at a distance of 50 cm from any point on the panel. The magnetic cancellation circuit that meets this requirement is described below.

Each panel contains three circuit assemblies, comprised of 5 solar cells connected in series and bonded over a sheet of silver mesh with a sheet of protective acrylic kapton in between. The silver mesh is soldered to the return end of the string and then to the diode board. The silver mesh ensures that the return current flow is in the opposite direction to the power current direction. This configuration assures that the magnetic moment is minimized. In addition, all power and return wires to and from the diode board and connector are twisted to minimize magnetic moment.

Another requirement levied on this technology mission was that the resistance between the solar cell coverglass top surface and the solar cell surface or adjacent interconnect could not exceed 4 x 10^8 ohms. The following technique was used to accomplish this. The coverglass-interconnect-cell (CIC) is constructed using indium tin oxide (ITO) edge wrap coverglass along with a drop of conductive adhesive placed on each of two redundant 3 toe interconnects. The conductive adhesive provides a conductive path from the ITO edge wrap to the 3 toe interconnect of the CIC. A megohmmeter is used to measure the resistance between the tops of the coverglass and interconnect. This design yields a resistance that is consistently below 4 x 10^8 ohms.

SOLAR PANEL DESIGN AND DEVELOPMENT

General

The panel consists of three strings, each composed of 5 cells in series (see Fig. 4 & 5). Under each string is a strip of 0.001 inch thick silver mesh that is provided for magnetic moment cancellation and a 0.002 inch thick strip of acrylic kapton used as a protective barrier between the silver mesh and the CICs. The silver mesh, protective kapton and strings are bonded together via adhesive. The positive side of each string is connected to the anode side of a pair of blocking diodes with redundant 24 AWG wires. The 3 strings are bussed together on the cathode side of 3 pairs of diodes and then connected to a 9 pin connector with redundant 20 AWG wire. The negative side of each string is connected to the silver mesh which is connected to the negative bus bar of the diode board via 24 AWG wire. The diode board is attached to the connector using 20 AWG wire. All electrical connections are soldered.

Components

The main components employed for the flight panels builds are listed below:

- 28.0% efficient ATJ (Advanced Triple-Junction) n-on p $GaInP_2/InGaAs/Ge$ solar cells - 92.00 x 27.51 mm (24.58 cm^2)
- 0.508-mm Cerium-Doped Microscope Glass (CMG)/Antireflective (AR) Coating/ITO Coverglass
- Interconnects – 3 toe, silver plated Kovar
- Silver mesh
- Diode Boards – G10 Glass epoxy circuit board

Design Factors

The following factors were used to size the ST5 solar panels:

	Short-Circuit Current	Open-Circuit Voltage	Voltage at Max. Power	Max. Power	Current at Max. Power
Measurement Uncertainty	0.98	0.99	0.99	0.97	0.98
Coverglass Loss (ITO)	0.98	1.0	1.0	0.98	0.98
Assembly Loss	0.98	0.99	0.99	0.97	0.98
UV Darkening	0.976	1.0	1.0	0.976	0.976
Random Failures	0.99	0.99	0.99	0.98	0.99
Total BOL Loss Factor	0.941	0.980	0.980	0.922	0.941
Total EOL Loss Factor	0.909	0.970	0.970	0.882	0.909
Min. Solar Intensity	0.967	1.00	1.00	0.967	0.967
Max. Solar Intensity	1.033	1.00	1.00	1.033	1.033
Temp. Coefficients (%/°C)	0.053	-0.225	-0.225	-0.221	0.053

Array Output

The ST5 solar array, once the panels are mounted on the spacecraft, has eight facets, half of which are illuminated at a time (Fig. 6). The total array output is computed by summing the output of each facet for each spacecraft rotation angle.

A magnetometer and boom shadow the solar array on each spacecraft. To account for this shadowing, an analysis was performed using three-dimensional graphics software in conjunction with a model of the spacecraft. The spacecraft model was rotated through 360 degrees and the shadowing loss determined at each angle. The resulting effect on end of life power output is presented in Figure 2. Shadowing from the magnetometer and its boom results in a reduction of 3.6% in power at 9.2 V averaged over one spacecraft rotation. The BOL (beginning of life) and EOL (end of life) current-voltage and power-voltage characteristics of the array, averaged over one spacecraft rotation and including shadowing losses, are illustrated in Figure 3.

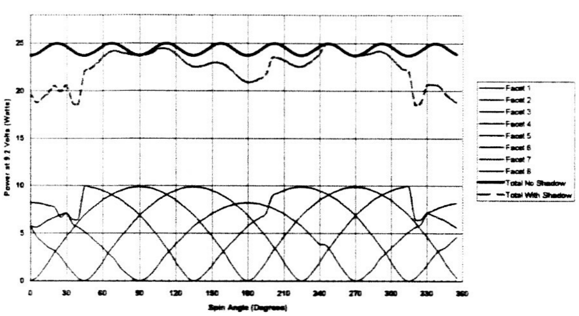

Fig. 2. ST5 EOL Solar Array Power vs. Spacecraft Spin Angle.

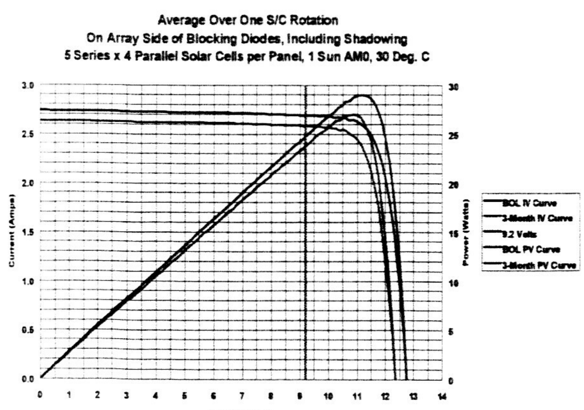

Fig. 3. ST5 Solar Array Current-Voltage Performance.

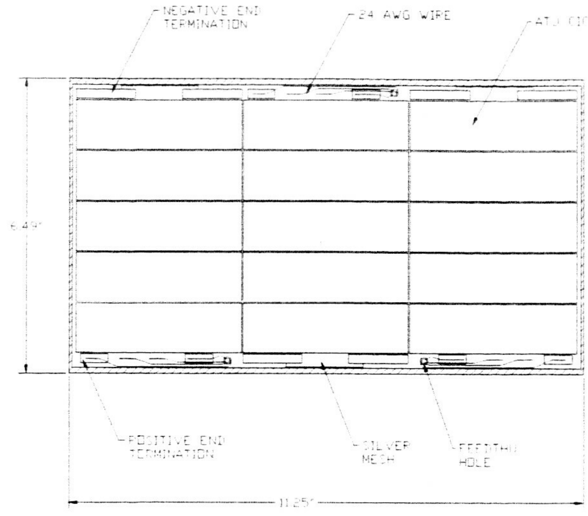

Fig. 4. ST5 Solar Panel Schematic

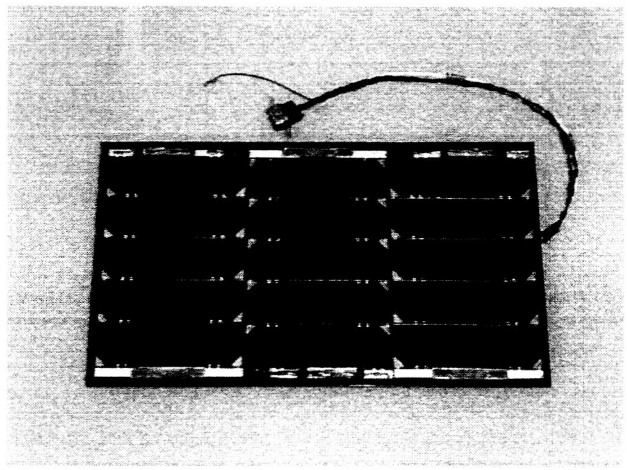

Fig. 5. ST5 Solar Panel Photograph

Fig. 6. Panel Integration of ST5 Spacecraft 1

TESTING

Qualification Coupon Level

The qualification coupon was subjected to the following environmental testing:

1. Random Vibration – 2 minutes in each of 3 orthogonal axes. The test parameters are shown in Table I.

Table I – Random Vibration Test Parameters

Frequency (Hz)	ASD Level (g^2/Hz)
20	0.03
80	0.3
600	0.3
2000	0.028
Overall	**17.11 g_{rms}**

2. 300 Ambient Pressure Thermal Cycles
    a. 10 cycles @ +120°C to -75°C
    b. 290 cycles @ +65°C to -70°C
3. 8 Thermal Vacuum Cycles
    a. 6 cycles @ +65°C to -70°C
    b. 2 cycles @ +120°C to -75°C
    c. Pressure ≤ 1×10^{-5} Torr
4. Thermal Vacuum Bake Out
    a. 96 hours @ 95°C
    b. Pressure ≤ 1×10^{-5} Torr

Flight Panel Level

The panels were subjected to the following environmental testing:

1. Random Vibration – 1 minute in each of 3 orthogonal axes. Test frequencies ranged from 20 Hz to 2000 Hz with an overall acceleration of 12.11 g_{rms}.
2. 8 Thermal Vacuum Cycles
    a. 6 cycles @ +65°C to -70°C
    b. 2 cycles @ +120°C to -75°C
    c. Pressure ≤ 1×10^{-5} Torr
3. Thermal Vacuum Bake Out
    a. 96 hours @ 95°C
    b. Pressure ≤ 1×10^{-5} Torr

Spacecraft Level

After integration to the spacecraft, the panels will be subjected to the following testing:

1. Panel Aliveness – Illumination of each panel with a halogen lamp and measure electrical output at each panel connector.

2. End-to-End Test – Illumination of solar array with a halogen lamp and verification that output registers through spacecraft telemetry.

3. Spacecraft Environmental Tests – Includes EMI/EMC, vibration, acoustic, and thermal vacuum tests.

4. Multijunction Large-Area Pulsed Solar Simulator (MJ LAPSS) Test – After spacecraft environmental testing, the electrical performance of each panel will be measured to determine whether any damage may have occurred due to environmental testing or handling.

5. Panel aliveness and end-to-end testing will be repeated at the launch site prior to integration to the launch vehicle.

CONCLUSION

The New Millennium ST5 mission to flight-test the concept of small-size satellites and innovative technologies in the earth's magnetosphere is on track for launch in December 2005. The high-efficiency ST5 solar panels have been fabricated, tested, and delivered for integration with the three spacecraft. The panels for Spacecraft 1 have been integrated. The remaining panels will be integrated to Spacecraft 2 and Spacecraft 3 in January and March 2005, respectively.

REFERENCES

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[4] J. Lyons, "SMEX•Lite Modular Solar Array Architecture", *37th IECEC, Washington, DC, Jul. 29-Aug. 2, 2002. pp. 20022-1-20022-5.*