Thermal Cycle Testing of the PowerSphere Engineering Development Unit

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Abstract

During the past three years the team of The Aerospace Corporation, Lockheed Martin Space Systems, NASA Glenn Research Center, and ILC Dover LP have been developing a multifunctional inflatable structure for the PowerSphere concept under contract with NASA (NAS3-01115). The PowerSphere attitude insensitive solar power-generating microsatellite, which could be used for many different space and Earth science purposes, is ready for further refinement and flight demonstration. The development of micro- and nanosatellites requires the energy collection system, namely the solar array, to be of lightweight and small size. The limited surface area of these satellites precludes the possibility of body mounting the solar array system for required power generation. The use of large traditional solar arrays requires the support of large satellite volumes and weight and also requires a pointing apparatus. The current PowerSphere concept (geodetic sphere), which was envisioned in the late 1990's by Mr. Simburger of The Aerospace Corporation, has been systematically developed in the past several years.[1-7] The PowerSphere system is a low mass and low volume system suited for micro and nanosatellites. It is a lightweight solar array that is spherical in shape and does not require a pointing apparatus. The recently completed project culminated during the third year with the manufacturing of the PowerSphere Engineering Development Unit (EDU). One hemisphere of the EDU system was tested for packing and deployment and was subsequently rigidized. The other hemisphere was packed and stored for future testing in an uncured state. Both cured and uncured hemisphere components were delivered to NASA Glenn Research Center for thermal cycle testing and long-term storage respectively. This paper will discuss the design, thermal cycle testing of the PowerSphere EDU.

I. The PowerSphere EDU Design

The Engineering Development Unit design of the PowerSphere solar array consists of one semi-spherical dome (0.6-meter in diameter) that is connected to the centrally located spacecraft bus through an ultra lightweight UV cured isogrid composite boom (See Fig. 1). The isogrid composite boom, which is integrated with flexible wiring harnesses for power and signal transmission between the solar array instrument deck and the spacecraft bus, is tightly folded into the spacecraft bus prior to deployment and rigidization. The semi-spherical EDU consists of two different subassemblies, namely Sub-Module A (See Fig. 2) and Sub-Module B (See Fig. 3), which together form a geodetic spherical shape of hexagon and pentagon solar panels. A complete EDU semi-spherical dome requires three "Sub-Module A" assemblies and one "Sub-Module B" assembly.

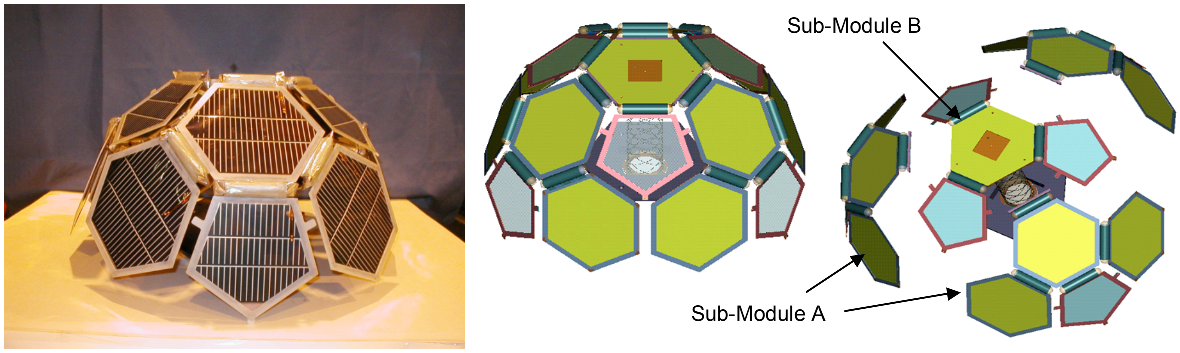

Figure 1. PowerSphere Engineering Development Unit

Each Sub-Module A assembly consists of three hexagon and one pentagon solar panels. Solar panels are integrated with flex-circuit blanket, which is on the backside of the solar panels, to form one subassembly component before integrating with mechanical hardware. Each Sub-Module A is equipped with a quick disconnect feature to simplify manufacturing process and to allow component replacement at the sub-module level if a module fails during assembly or testing.

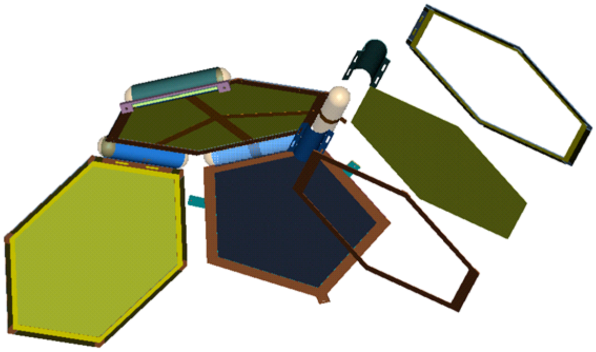

Figure 2. PowerSphere Sub-Module A Assembly

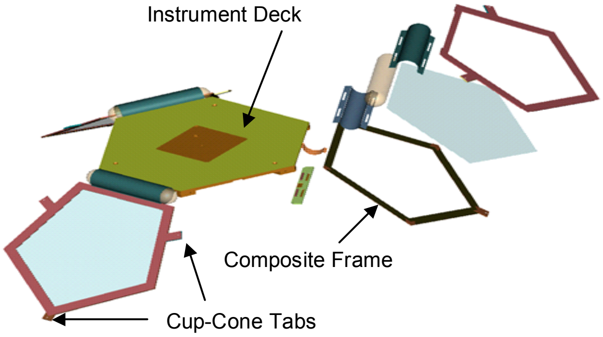

Figure 3. PowerSphere Sub-Module B Assembly

The Sub-Module B assembly consists of three pentagon solar panels that are fully integrated with the instrument deck. The mechanical interface between Sub-Module A and B is a bolted connection. The electrical interfaces between the two subassemblies are accomplished by using low profile connectors manufactured by Molex. The instrument deck is designed and fabricated with patch antenna interfaces and launch restraint features. The composite frames for the solar panels of both sub-modules are equipped with cup-cone interface tabs for launch restraint tie down.

II. EDU Component Manufacturing and Assembly

During this phase of the PowerSphere program, two EDU semi-spherical domes were produced. One hemisphere went through packing and deployment trial, rigidization of structural components, and thermal cycling tests. The other hemisphere was packed and stored at the subassembly level at NASA Glenn for future testing. Each hemisphere of the PowerSphere requires 15 solar cells, 9 hexagon cells and 6 pentagon cells. The Aerospace Corporation processed a total of 32 cells, which were manufactured by Iowa Thin Film Technologies. The cell processing at Aerospace Corporation included the deposition of the silver contacts on the top of the solar cells and a copper bus bar on the back of the cells. After initial processing at Aerospace Corporation the cells were shipped to Lockheed-Martin for deposition of the wrap around contacts. The cells were then shipped back to Aerospace for installation of the Tefzel cover over the top of the cells. I-V curves were performed on each cell before and after installation of the Tefzel covers. The cells were then shipped to Lockheed-Martin for laser welding to the flex circuit harness. Thirty cells were assembled into the EDU with two spares. The completed sub-module cells were shipped to ILC Dover LP for final assembly and integration.

One center column is used to connect and support each hemisphere onto the PowerSphere bus. Due to the anticipated low loading conditions, isogrid booms are used for the center columns. ILC fabricated three 0.3-meter [12 inch] long, 76.2 mm [3 inch] diameter isogrid booms for the EDU (See Fig. 4). They were made from three rovings of 449-A S-glass impregnated with ATI-P600-2 UV curing epoxy resin (Adherent Technologies) and were encapsulated in 1mil thick Mylar Type LBT-2 Film. Two of the isogrid booms were cured in sunlight while one was left uncured for the packed EDU hemisphere. The two cured isogrid booms were indexed and integrated with four flex circuit strips for connecting the power and signal of the spacecraft to and from the solar array.

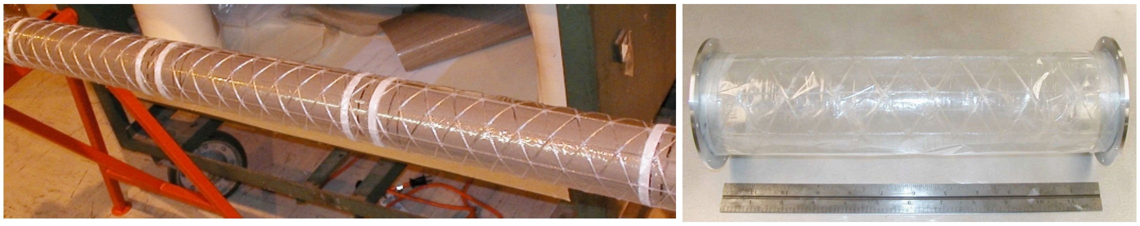

Figure 4. Isogrid Center Column Manufacturing

Thirty UV rigidizable fiberglass hinges were fabricated for the hemisphere assembly (See Fig. 5). Each hinge has a bladder made from a thin film material that is inflated to bring the corresponding solar panel to the correct angle. Once each hinge is inflated the UV resin rigidizes via sunlight to permanently hold the shape. The dimensions on twelve of the hinges are designed for supporting the deployed pentagon frames at the correct angle while the remaining 18 are designed for the hexagons. To control the deflection of each hexagon and pentagon solar cell on the PowerSphere they are supported with G10 frames on all sides. The UV rigidizable hinges are attached to these G10 frames. The flex-circuit, which transmits power from the individual solar cells to the spacecraft, runs through each hinge. The Hemisphere was assembled in two sections: Sub-Module A and Sub-Module B components.

After the completion of both Sub-module B's and all six Sub-module A's, the EDU hemisphere was assembled (See Fig. 6). Assembly of the hemisphere was completed by mechanically attaching the Sub-module A's onto their corresponding locations on a Sub-module B. After the sub-modules are secured, the flex-circuits from each sub-module were plugged into their designated receptacles located on the flex-circuit bonded to the Sub-module A (which can be seen in Figure 15).

III. EDU Packing and Deployment Trials

Figure 5. UV Rigidizable Hinge Manufacturing

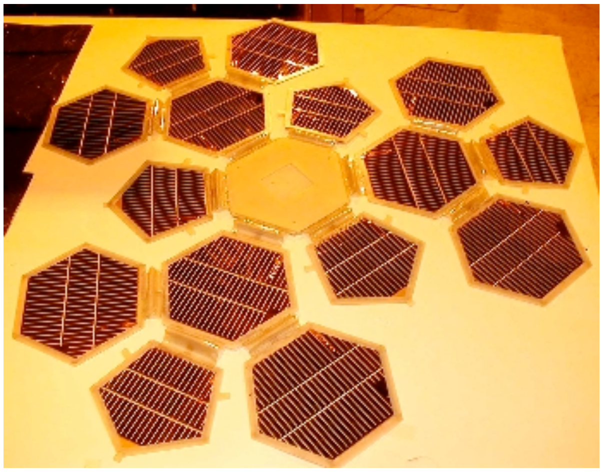

Figure 6. Fully Assembled EDU Hemisphere Components in Flat Layout

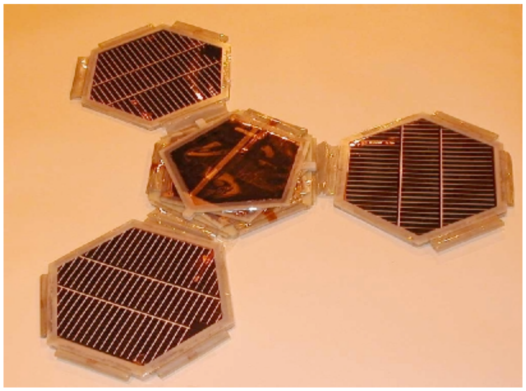

Figure 7. Completed Hemisphere Assembly with Folded Sub-Modules

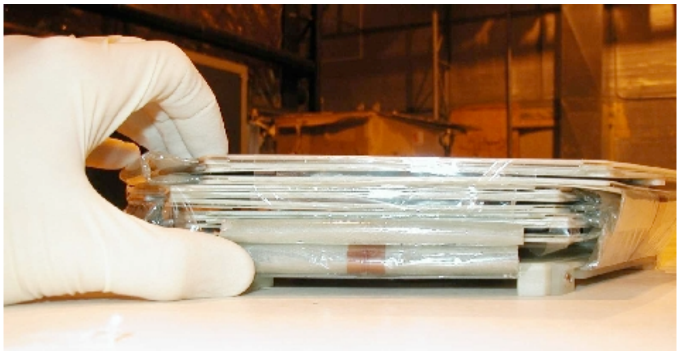

Figure 8. Fully Packed Hemisphere Assembly

After the final assembly of one EDU hemisphere, folding and packing trials were conducted to ensure that the hemisphere would pack as designed (See Fig. 7 and 8). Due to the tight fit between packed layers, tape was used to hold down the previously packed and aligned frame while the next frame was packed and aligned correctly over it. Alignment of the frames during packing involved lining up the cup-cone tabs on the G10 frames. The hexagonal frames were also required to line up with the edges of the Instrument deck.

However, as can be seen in Figure 8, the thickness tolerances in the PowerSphere EDU solar panel made it difficult to fold the hemisphere to the designed thickness. The limiting component in the final fold is the length of the flex-circuit and the Mylar bottom hinge, which can be seen, stretched taut at the right of Figure 8. This packing inaccuracy was the result of an underestimation of how much room the resin-impregnated fiberglass hinges would take up in the folded configuration. This problem will be addressed in the redesign by better thickness control of the solar panel during fabrication as well as changing the design to accommodate a longer Mylar bottom hinge.

Figures 9 and 10 show the z folding and packed configuration of a center column into the spacecraft bus. The design requirement for the isogrid packing, measured between the outside of the endcaps was 47.5 mm [1.870 inches]. The actual packed height of the manufactured isogrid and endcaps was approximately 33.5 mm [1.320 inches]. Thus, the packing height requirement was met for the z-folded center column.

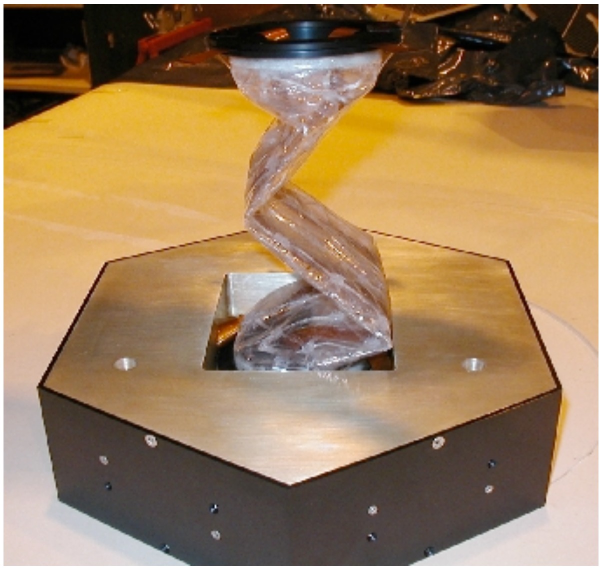

Figure 9. Z-folding of the Center Column into the Spacecraft Bus

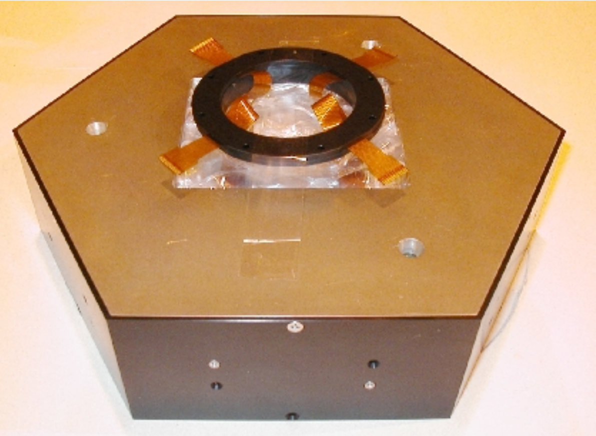

Figure 10. Packed Center Column in the Spacecraft Bus

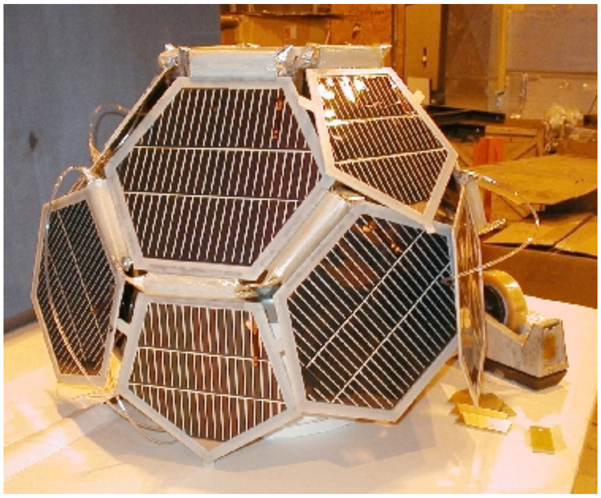

Figure 11. EDU Hemisphere after Deployment

Plastic tubing and the bladders that are integrated into the hinges are used to facilitate the deployment of the EDU hemisphere. Due to the protrusions of the tubing, which were necessary to allow the full freedom of motion for the hemisphere to deploy, several difficulties were encountered during the deployment trials. The deployed EDU hemisphere is shown in Figure 11. The sub-module frames would frequently get caught on the tubing. However, the pressure in the hinges, which varied between 13.8 to 27.6 KPa [2 to 4 psi], under 1-g condition, was sufficient to open up the hemisphere from a packed state. The hemisphere successfully deployed, thus demonstrating the feasibility of the stowage concept. In Figure 11, it is evident the effect that gravity has on the EDU structure, as the hinges are unable to hold up the outlying frames to the correct angle. Given the "microgravity" environment of space as well as the rotational motion of the PowerSphere, the hinges would be able to support the solar panels to the proper angles. A zero gravity deployment experiment will be the natural next step to fully validate this stowage concept.

After the deployment trials, the EDU was cured in sunlight. Due to the effect of gravity, spacers based on the designed distance between the frames were secured between every pair of adjacent panels to help the EDU maintain its hemispherical shape while the hinge bladders were inflated and cured. These spacers can be seen in Figure 12 and 13. The cure time for the EDU hinges is approximately one hour in sunlight, though it was cured longer to ensure that the UV reached every part of every hinge for a complete cure. After the EDU was rigidized, it was disassembled, packed and shipped to NASA Glenn Research Center for thermal cycling test.

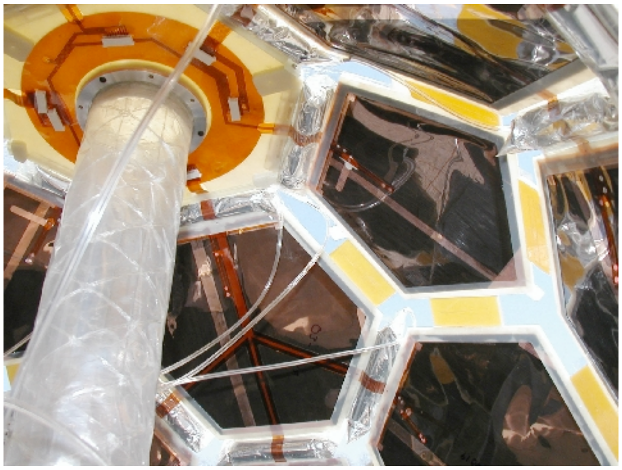

Figure 12. Interior of Hemisphere while Being Cured in Sunlight

Figure 13. Curing of the EDU Hemisphere in Sunlight

IV. Thermal Cycling Test Results

The PowerSphere project objective was to develop the spherical deployable structure and interconnect method for thin film solar cells. The development of **space qualified thin film solar cells** was not a part of this contract. Thus the purpose of the thermal cycle test was to prove that the spherical support structure, integrated flex circuit harness, and flex harness to thin film solar cell interconnect would survive the thermal environment on orbit. To verify that the items listed above survived the thermal cycle testing I-V curves of the individual solar cell panels were measured before, during and after performance of the thermal cycle test. In addition the I-V test was performed six months after completion of the thermal cycle test to verify that the PowerSphere structure and interconnect did not degrade with time. The results of all of the I-V testing on three of the thermal cycled cells are found in Figures 14, 15 & 16.

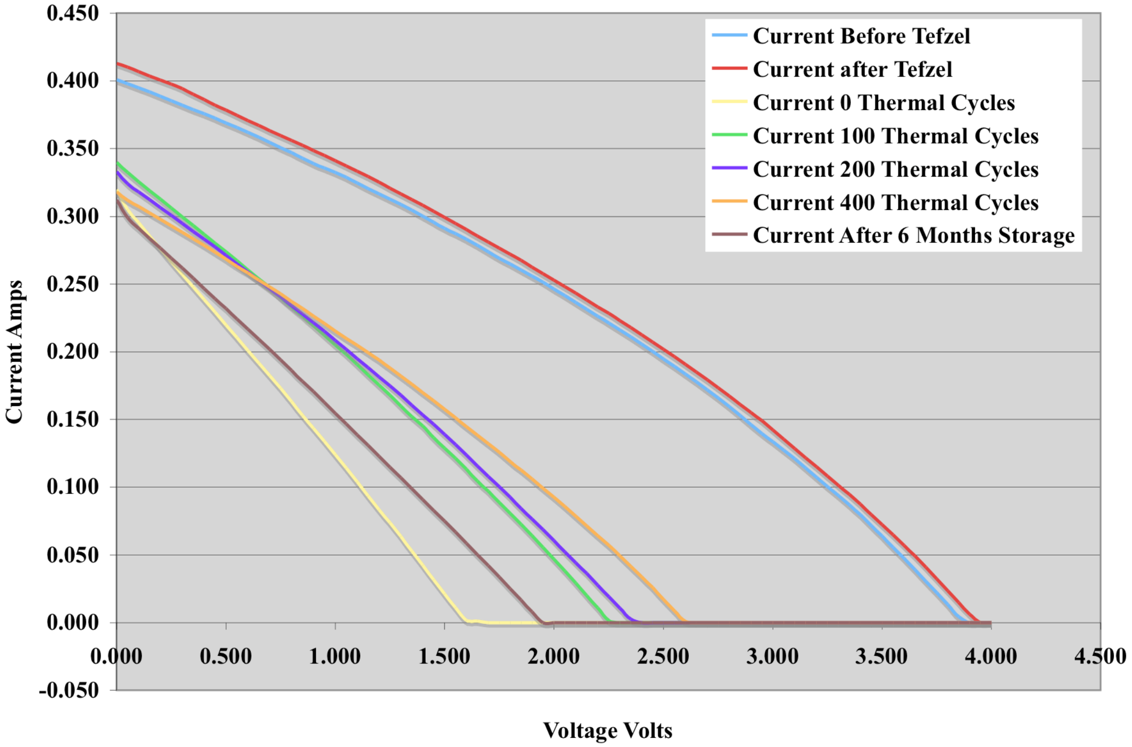

Figure 14 I-V Curves for Pentagon Cell

A fully deployed and rigidized hemisphere of the PowerSphere was delivered to the NASA Glenn Research Center for thermal cycling test. The solar array system was shipped unassembled and then reassembled at Glenn. The complete deployed hemisphere could not fit into the thermal cycle chamber. Thus a single Submodule A consisting of three Hexagonal panels and one Pentagonal panel was thermal cycled. It was discovered that Hexagonal panel 1 was damaged during shipment from ILC Dover to NASA Glenn and the electrical connection to the solar cell through the flex harness was broken. The hemisphere was shipped in its rigidized deployed state, which made it susceptible to transportation damage.

The thermal cycle time was about 3 hours for a +80ºC to -80ºC temperature range cycle. The I-V performance of the individual cells on each sub-module was measured and recorded before the cycling test and after 100, 200, and 400 cycles. A final measurement of the I-V performance was made after six months of storage after completion of the 400 thermal cycles.

Observations regarding the I-V testing results show that there was some damage or degradation of the solar cells during the laser welding of the solar cells to the flex harness and assembly of the solar cells into the PowerSphere support structure. The specific processes responsible for the observed degradation are not known as I-V curves were not performed during the integration and assembly process.

The performance of the solar cells during thermal cycling varied from some improvement with thermal cycling to some degradation. The same was true for the six-month storage period. Thin film solar cells that were used in the fabrication of the PowerSphere Engineering development unit are not representative of solar cells, which are currently available.

However, the results of the thermal cycle test verified that the PowerSphere support structure, thin film solar cell interconnects and flex harness can survive the expected orbital thermal cycle environment without degradation. Visual inspection of the Submodule A performed after completion of 400 thermal cycles did not show any delimitation in the hinges or the interface between the solar cells and the solar cell frames. Figures 17 & 18 are photos of the thermal cycled PowerSphere.

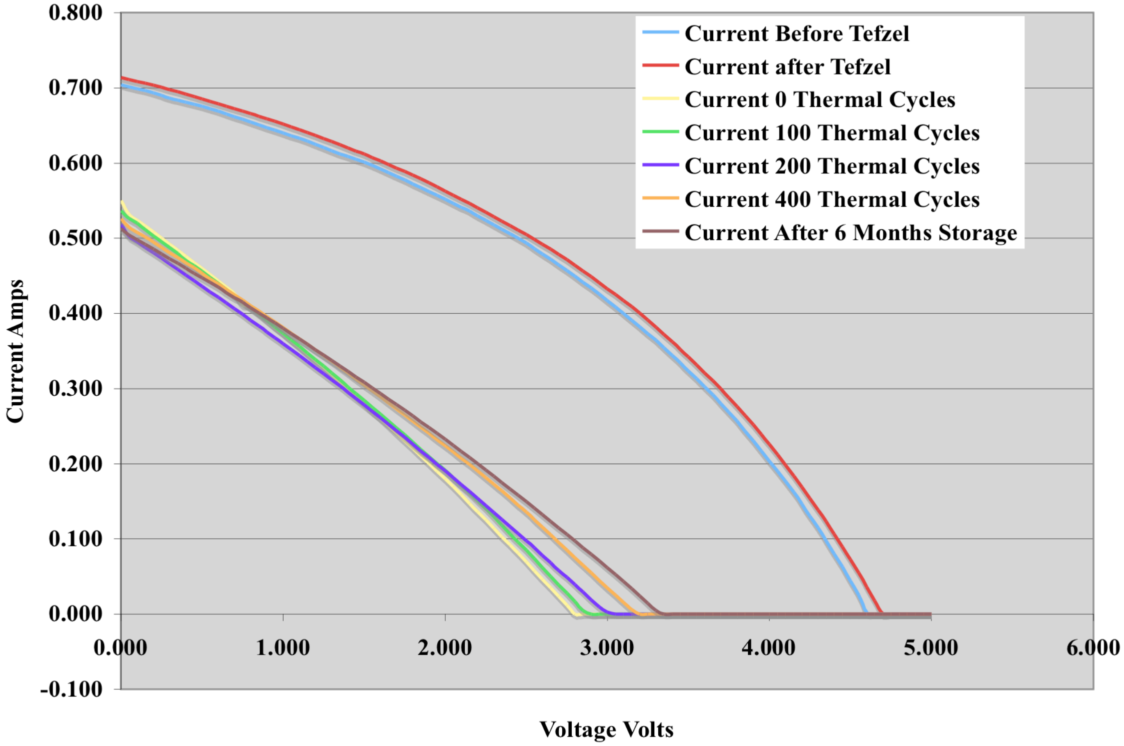

Figure 15 I-V Curves for Hexagon 2

V. Conclusions and Recommendations

The PowerSphere concept was envisioned in the late 1990's and has progressively gained maturity over the past several years and has reached the TRL of 4 to 5 (in system level) at the end of the PowerSphere program in 2004. The fabrication and testing of the Engineering Development Unit further proved the feasibility of the PowerSphere design. Significant progress has been accomplished in the past three years through the systematic development of the PowerSphere solar array system. What began as a solution to eliminate the problem of power choke in nano- and microsatellites has advanced the development of several technological areas that will directly benefit the development of ultra lightweight structures in space.

The development of multifunctional structure for PowerSphere pushed the developments of thin film solar cell process, integrated flex-circuit for thin film solar cell application, UV rigidizable support structures and hinges, and electrostatic discharge coating applicable for thin film and capable of folding.

The successful development of the integrated flex-circuit, accomplished by Lockheed Martin Space Systems, provided a lightweight solution to transfer power and signal to and from the solar array and the instrument deck to the spacecraft bus and still allowed tight folding required for compact stowage. This technology, which was developed for thin film application, worked well with space rigidizable-inflatable structures, particularly where folding and flexing is required. Missions requiring power and/or signal transfer through large structures over long distance would benefit from this technology.

The UV rigidizable-inflatable isogrid structure and hinge developments, accomplished by ILC Dover LP, gave space structural engineers a low cost and low (to no) power structural system capable of high compaction ratio. UV rigidizable structures are particularly valuable when power for deployment is limited or not available.

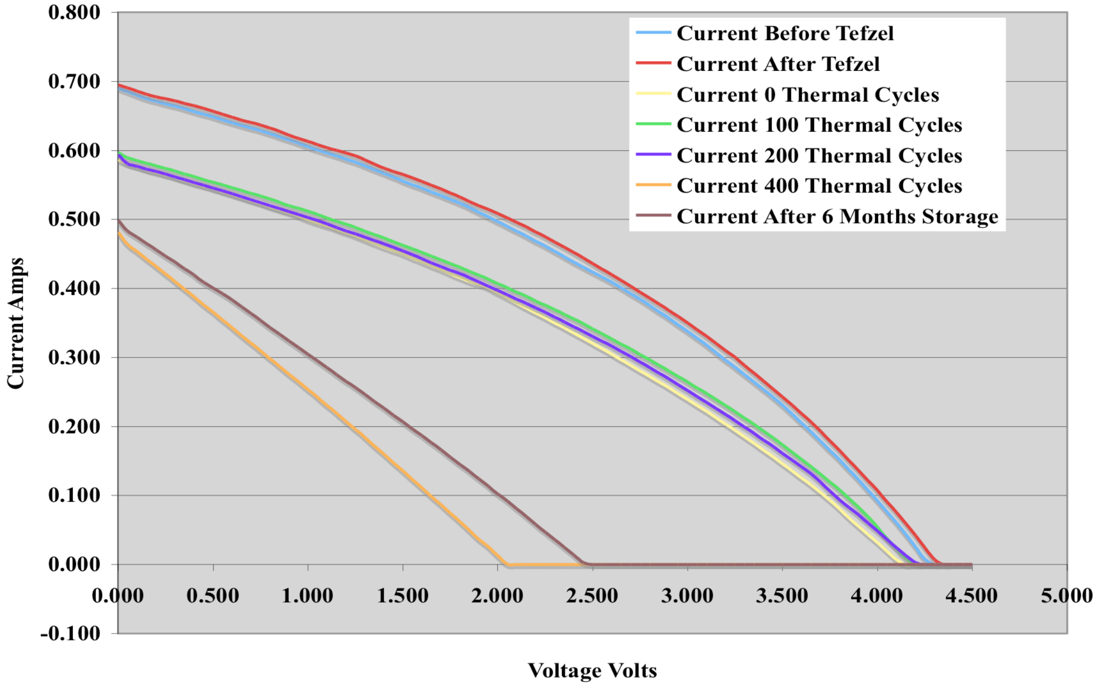

Figure 16 I-V Curves for Hexagon 3

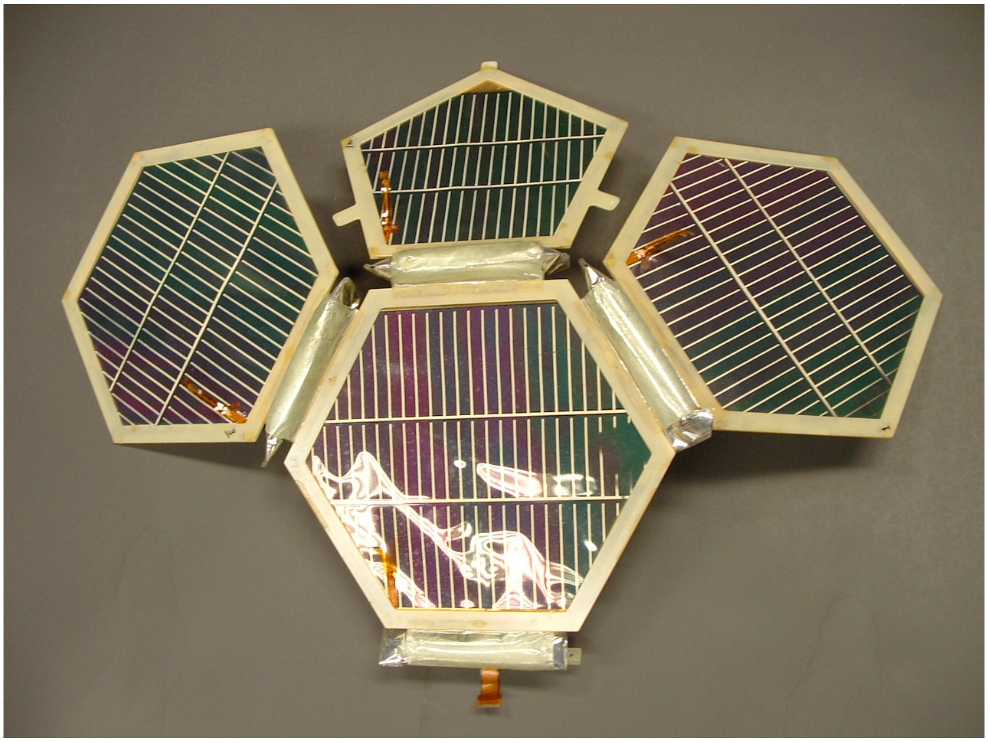

Figure 17 Post Thermal Cycle Test Photo of PowerSphere Submodule A Front Side

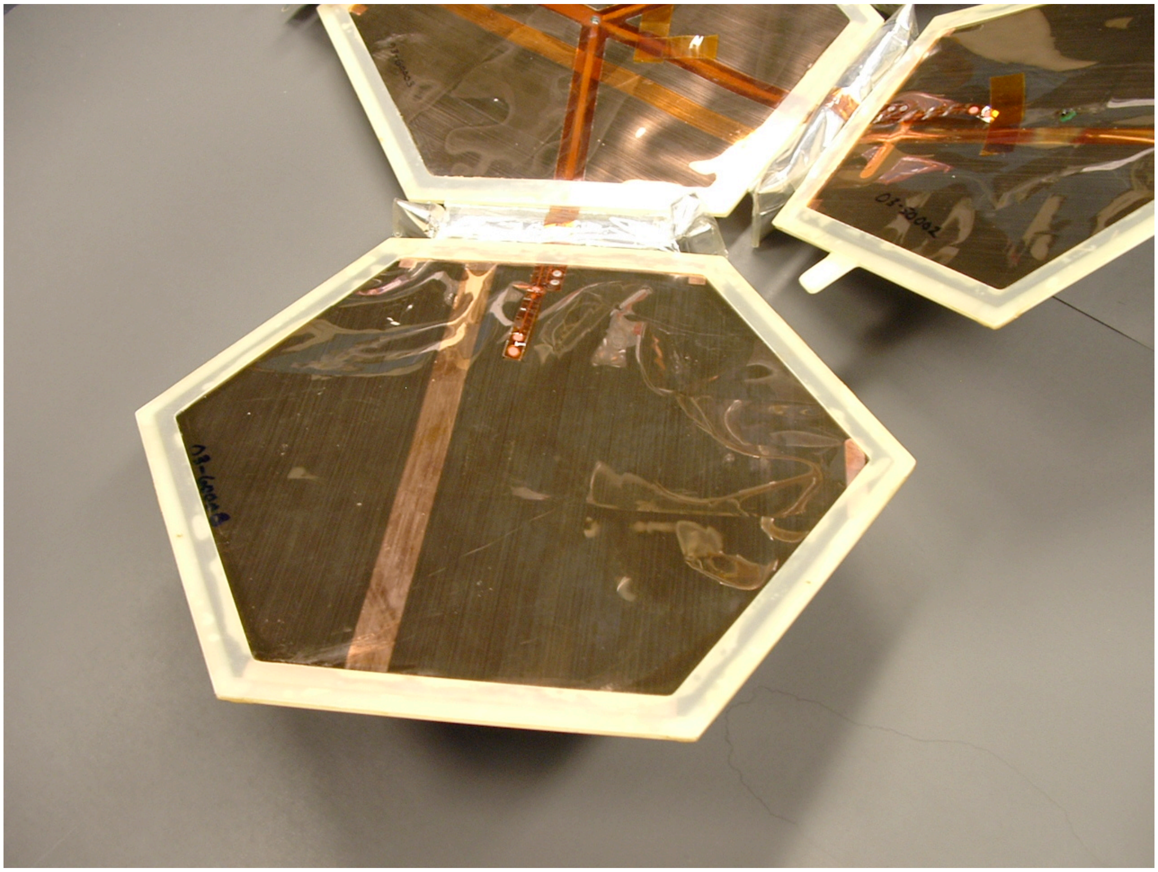

Figure 18 Post Thermal Cycle Test Photo of PowerSphere Submodule A Back Side

The authors conclude that PowerSphere mass performance, fabrication, launch stowage and deployment feasibility have been demonstrated. Furthermore, the initial steps toward space qualification have been taken regarding thermal cycling capability and resistance to orbital atomic oxygen and electrostatic discharge environments. We recommend further development in the areas of low-g deployment testing (aboard NASA KC-135 aircraft) and stowed vibro-acoustic testing followed by a thermal-vacuum 1-g deployment and thermal-electrical performance measurements. The PowerSphere system and the associated technologies are ready for further refinements and flight demonstration.

Acknowledgment

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References

1. Prater, A., Simburger, E. J., Smith, D. A., Carian, P. J., and Matsumoto, J. H., The Aerospace Corporation, “Power Management and Distribution Concept for Microsatellites and Nanosatellites,” Proceeding of IECEC, August 1-5, 1999.

2. Gilmore, D. G., Simburger, E. J., Meshishnek, M. J., Scott, D. M., Smith, D. A., Prater, A., Matsumoto, J. H., and Wasz, M. L., The Aerospace Corporation, “Thermal Design Aspects of the PowerSphere Concept,” Proceedings of Micro/Nano Technology for Space Application Conference, April 11-15, 1999.

3. Simburger, E. J., Matsumoto, J. H., Hinkley, D. A., Gilmore, D. G., Giants, T. W., and Ross, J., “Multifunctional Structures for PowerSphere Concept,” 42nd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics, and Materials Conference & Exhibit, Seattle, Washington, April 16-19, 2001.

4. Simburger, E. J., Matsumoto, J. H., Lin, J. K., Knoll, C. F., Rawal, S. P., Perry, A. R., Barnett, D. M., Peterson, T. T., Kerslake, T. W., and Curtis, H. B., “Development of a Multifunctional Inflatable Structure for the PowerSphere Concept,” AIAA-2002-1707 43rd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics, and Materials Conference & Exhibit, Denver, Colorado, April 22-25, 2002.

5. Simburger, E. J., Giants, T. W., Matsumoto, J. H., Garcia III, A., Liu, S. H., Lin, J. K., Scarborough, S. E., Rawal, S. P., Perry, A. R., Marshall, C. H., Peterson, T. T., Kerslake, T. W., and Curtis, H. B., “Engineering Development Model (EDM) Testing of the PowerSphere,” AIAA-2004-1570 45th AIAA/ASME/ASCE/AHS Structures, Structural Dynamics, and Materials Conference, Palm Springs, CA, April 19-22, 2004.

6. Simburger, E. J., Matsumoto, J. H., Giants, T. W., Tueling, M., Ross, J., Lin, J. K., Knoll, C. F., Rawal, S. P., Perry, A. R., Marshall, C. H., Barnett, D. M., Peterson, T. T., Kerslake, T. W. and Curtis, H. B., “Development of Flex Circuit Harness for the PowerSphere Concept,” 29th Photovoltaics Specialist Conference, IEEE, New Orleans, LA, May 20-24, 2002.

7. Hambourger, E. P., Kerslake, T. W. and Waters, D., "ITO-MgF2 Film Development for PowerSphere Polymer Surface Protection," paper AIAA-2004-5639, 2nd International Energy Conversion Engineering Conference, Providence, Rhode Island, Aug. 16-19, 2004.