Thin Film Technology Development for the PowerSphere

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Abstract

The Aerospace Corporation, NASA Glenn Research Center, Lockheed-Martin, and ILC Dover over the past two years have been engaged in developing a *Multifunctional Inflatable Structure for the PowerSphere Concept* under contract with NASA (NAS3-01115). The PowerSphere concept consists of a relatively large spherical solar array, which would be deployed from a microsatellite.[1–8] The PowerSphere structure and the deployment method was patented by the Aerospace Corporation (U.S. Patent Numbers 6,284,966 B1 and 6,318,675). The work on this project has resulted in a number of technological innovations in the state of the art for integrating flexible thin-film solar cells with flex circuit harness technology and inflatable ultraviolet-light-rigidizable structures. The specific power, specific volume, for the PowerSphere are presented in Figures 1 and 2 as a function of solar cell technology and efficiency.

The PowerSphere will enable microsatellite missions across NASA enterprises and DoD missions by providing ample electric power at an affordable cost. The Powersphere design provides attitude-independent electric power and thermal control for an enclosed microsatellite payload. The design is scalable, robust in high radiation environments and provides sufficient electric power to allow the use of electric propulsion. Electric propulsion enables precise positioning of microsatellites which is required for inspectors that would be deployed to inspect the International Space Station, Space Shuttle or large unmanned spacecraft. The Powersphere allows for efficient launch packaging versus deployed volume as shown in Figure 3.

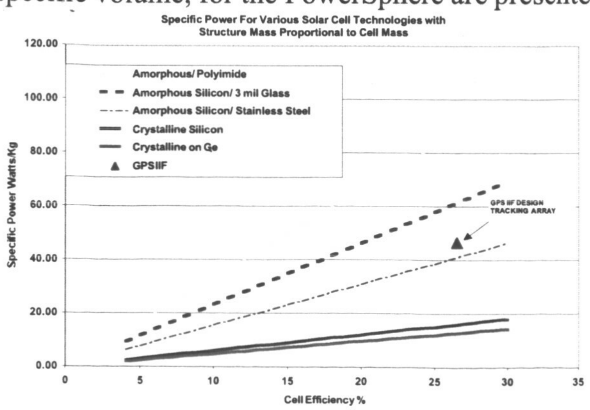


Figure 1. Specific Power of PowerSphere as a Function of Solar Cell Technology and Solar Cell Efficiency

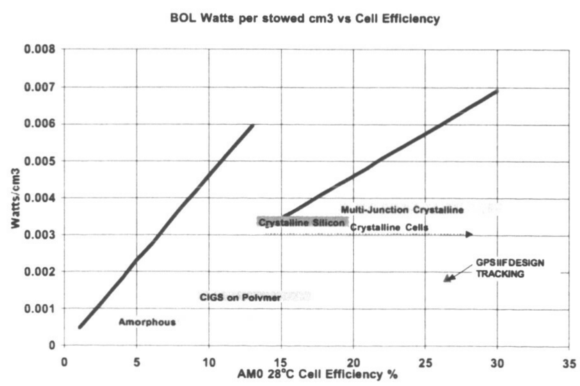


Figure 2. Specific Volumer of PowerSphere as a Function of Solar Cell Technology and Solar Cell Efficiency

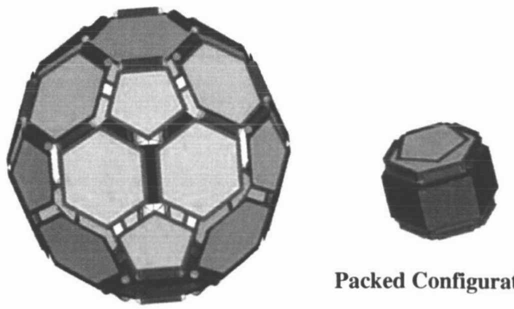


Figure 3. Stowed and Deployed PowerSphere

The PowerSphere microsatellite could be used across all of NASA's enterprises. Potential missions for PowerSphere microsatellites for the Space Science Enterprise would be measurement of the terrestrial magnetosphere, solar magnetosphere, extraterrestrial sample return, minor body detection, and interferometric astronomy. Missions for the Earth Science Enterprise would be global precipitation measurement, soil moisture measurement, ocean salinity measurement, cold land processes measurement, vegetation growth monitoring, earthquake detection, VLBI / SAR Imaging, and temporal gravity field measurement. For the Human Exploration and Development of Space Enterprise the missions would be remote hardware inspection and satellite inspection. Finally mass produced microsatellites can be an affordable vehicle for bringing the exploration of space into our nation's high school classrooms. High schools with funding through NASA's Education/Public Outreach program could engage students to design and fly science experiments in low earth orbit. This use of PowerSphere microsatellites would promote the teaching of space science and provide the students with hands on experience in designing the student science payload, gathering data from the student's satellite, and evaluating the data.

The present development contract, which will be completed in June of 2004, will advance the TRL level of the PowerSphere to TRL 4 with completion of environmental testing of the Engineering Development Unit. The PowerSphere utilizes the following new technologies:

* Thin-Film Photovoltaics
* Flex Circuit Thin-Film Solar Array Technology
* Inflatable Deployment Systems
* UV-Rigidizable Structures
* ITO/MgF ESD-AO Coating for Polymer Structures
* Distributed Power Management and Distribution System

Thin-Film Solar Cell Technology

The Aerospace Corporation in partnership with Iowa Thin Film Technologies has developed a thin-film solar cell fabricated on a polyimide substrate suitable for space applications. In order to make the Iowa Thin Film Technologies commercially fabricated solar cell suitable for space use two changes have been made in the manufacturing process. The first change is the use of aluminum instead of stainless steel on the backside of the polyimide. This aluminum layer (used for manufacturing convenience) is easily etched to reveal the high- emissivity polyimide back surface necessary to reduce the temperature of the array. The second change is the use of high-conductance vapor-deposited silver front contacts capable of surviving the space environment. The finished bare cells are monolithically interconnected to provide required array voltage.

Presently, these cells are covered with a 1.5-mil (38.1 μm) thick sheet of Tefzel, which is bonded to the cell with a pressure-sensitive adhesive. Finally, the front and backsides of the finished cell blankets are coated with 500 Å of ITO/MgF_2. The thickness of the finished solar cell blanket is 4 mils (101.6 μm), and the area density is 0.018 g/cm^2. Figure 4 is a photograph of a Aerospace/Iowa Thin Film solar cell module with 3 monolithically interconnected dual junction solar cells, and Figure 5 is the I/V curve for this module. As shown in Table 1,

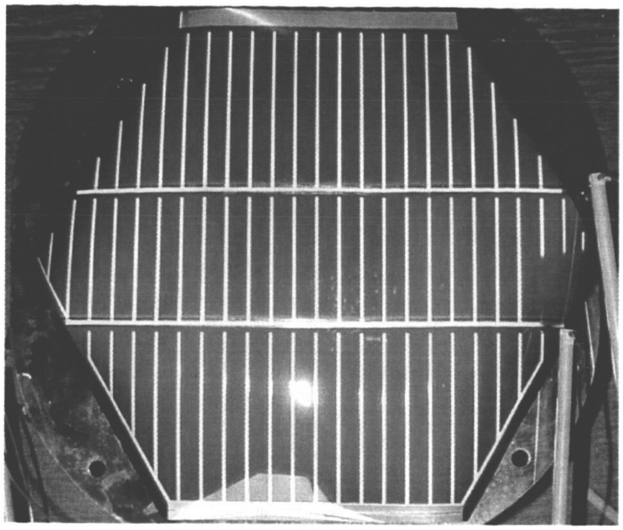


Figure 4. Photograph of Iowa Thin Film Technologies/Aerospace Hexagonal Amorphous Silicon Solar cell Module

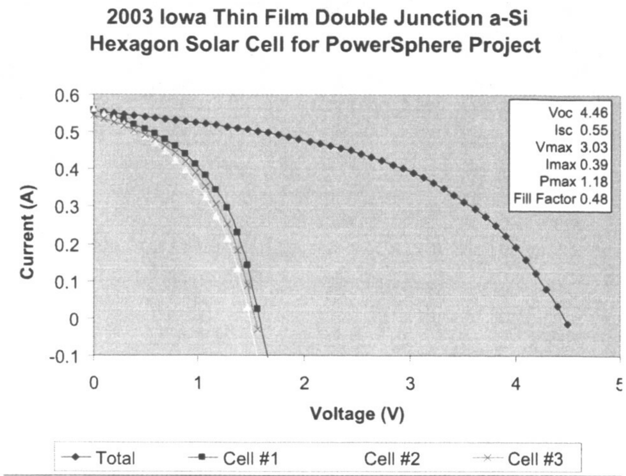


Figure 5. I/V Curve for Iowa Thin Film Technologies/Aerospace Hexagonal Amorphous Silicon Solar cell Module

Table 1. Performance Parameters for Iowa Thin Film/Aerospace Dual Junction Amorphous Silicon Solar Cell	
Voc	4.460 V
Isc	0.555 A
Jsc	0.0016 A/cm2
Vmax	3.033 V
Imax	0.388 A
Pmax	1.177 W
Fill Factor	0.476
Efficiency	2.51%
PV Cell Temperature	28.9°C
PV Cell Area	347 cm2

the efficiency of the monolithically interconnected module was measured to be 2.51% AM0 using Aerospace's X-25 Solar Simulator.

Presently, the Air Force Research Laboratory has a Phase 2 SBIR with Iowa Thin Film Technologies to improve the efficiency of their amorphous silicon solar cell from its present 2.5% AM0 to 8% AM0. This work is scheduled to be completed by 2005. The Air Force Research Laboratory is funding work at Unisolar to transition their cell design from stainless steel to a polyimide substrate, and laboratory scale cells have been produced with efficiencies in the 10% range. It is expected that production modules using the Unisolar technology would be in the 8% range. Figure 6 is a photograph of the Unisolar Triple Junction Amorphous Silicon Solar Cell tested at Aerospace and Figure 7 is the I/V curve for this cell. Cells from both of these manufacturers will be considered for the PowerSphere Flight Qualification Unit.

Another factor that must be considered when selecting a particular cell technology would be the radiation environment for a particular mission and the mission life. Preliminary results from radiation testing of thin-film amorphous silicon solar cells show that radiation degradation is much less than that for either silicon or multi-junction GaAs solar cells. In high-radiation orbits (e.g. 2800 km) an 11% BOL a-silicon cell would have higher EOL efficiency than GaAs or InP.[9]

Flex Circuit Thin-Film Solar Array Technology

A patent application for the solar cell interconnect to the PowerSphere flex harness design developed by Aerospace and Lockheed-Martin has been submitted to the U.S. Patent Office. It consists of solar cells with a copper contact that wraps around the edge of the polyimide substrate to the backside of the solar cell, as shown in Figure 8. The contact on the back of the polyimide is welded

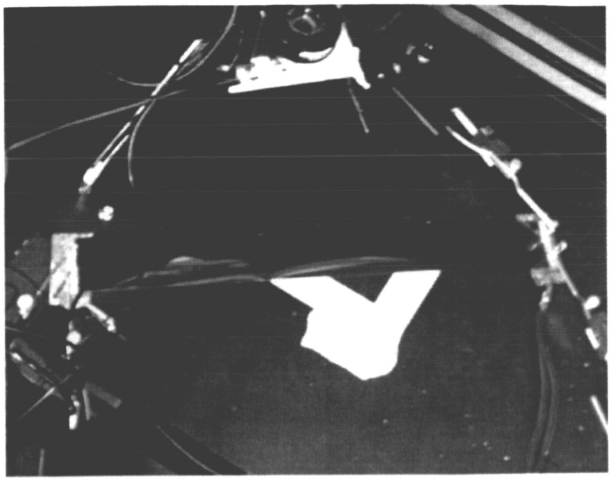


Figure 6. Photograph of Unisolar Triple Junction Amorphous Silicon Solar cell Module

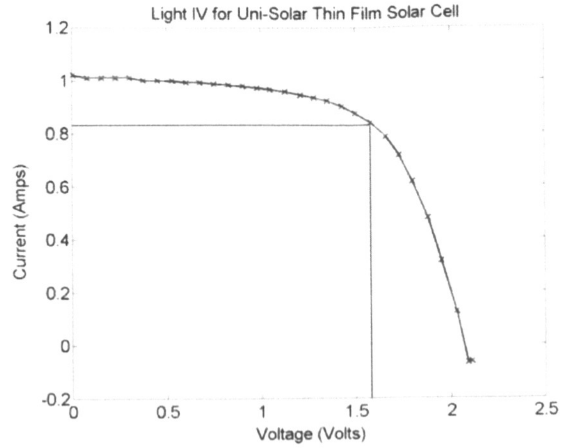


Figure 7. I/V Curve for Unisolar Amorphous Silicon Solar cell Module

Table 2. Performance Parameters for Unisolar Triple Junction Amorphous Silicon Solar Cell	
Voc	2.1012V
Isc	1.0153A
Jsc	0.0078 A/cm2
Vmax	1.5804 V
Imax	0.8393 A
Pmax	1.326 W
Fill Factor	0.622
Efficiency	7.53%
PV Cell Temperature	35.1°C
PV Cell Area	130.40 cm2

to the copper pad on the flex blanket. Welding the solar cells to the flex blanket provides both an electrical and mechanical joint. This method is quite robust and well suited for multiple applications. The welded interconnect between the flex harness, and the solar cell modules will be encapsulated into the bond material between the modules and the support frames. This will provide additional mechanical support to the solar cell-to-flex blanket welded interconnect.

Multifunctional Inflatable Ultraviolet Rigidizable Hinge

Details of the multifunctional, inflatable, ultraviolet-light-rigidizable hinge design for which Aerospace, ILC Dover, Lockheed-Martin and NASA Glenn has submitted a patent application to the U.S. Patent Office are as follows. The top hinge is a laminate of UV rigidization material encased between two film layers. The UV rigidization material must be encased in film to mitigate outgassing or adherence to itself when packed. The bottom hinge is a single layer of film. The top and bottom hinge widths span the length of the cylindrical portion of the bladder and bond to the solar panel frames. The diameter of the hinge is dependent on the maximum stack height. The run-length of the bottom hinge must be enough to span the stack height. The bladder is indexed to the top hinge, the frame sides, and the bottom hinge. The indexing reduces the peel force on the hinge to frame bond and helps maintain the accuracy of the hinge angle.

The flex circuit, which is fully integrated with the solar cell blanket, is incorporated into the hinge lay- up between the bladder and the bottom hinge. The use of the flex circuit in conjunction with UV-rigidizable material for the hinge assembly allows the Multifunctional Inflatable Solar Array Structure to be efficiently packed. The hinge consists of Owens Corning's 449 1250 S-2 glass fabric impregnated with Adherent Technologies' ATI-P600-2 UV curable epoxy resin[6]. The tubes

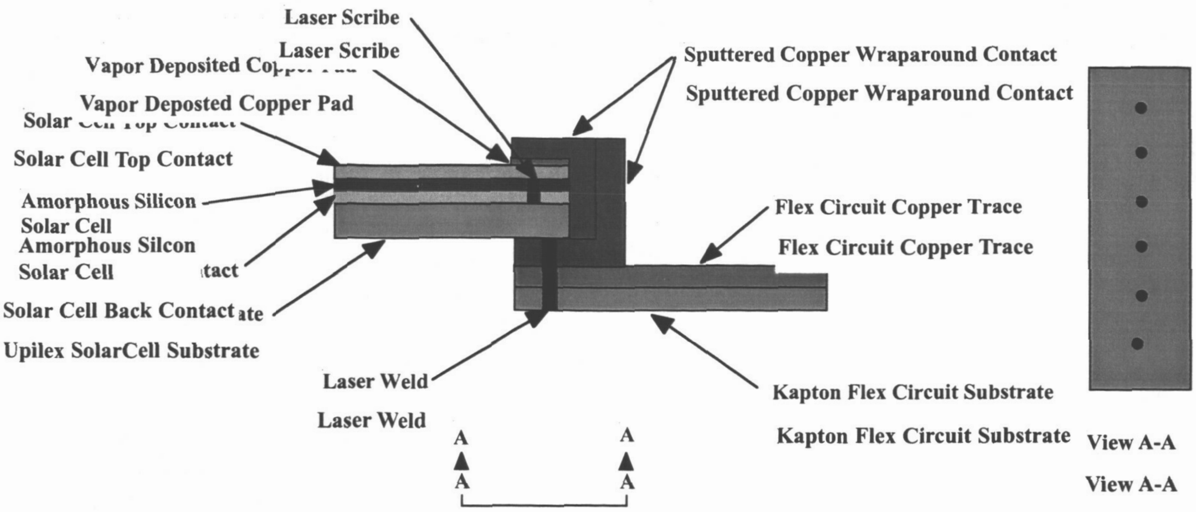


Figure 8. Design of warp around thin-film solar cell/flex harness interconnect.

are bonded onto the flanges, inflated, and then cured using UV energy from the sun. The use of the flex circuit in conjunction with UV-rigidizable material for the hinge assembly allows the Multifunctional Inflatable Solar Array Structure to be efficiently packed. Figure 9 provides the cross-section of the hinge developed for the PowerSphere project.

A number of experimental hinges were fabricated for the PowerSphere development effort for the purpose of defining the hinge manufacturing process and to determine how accurately they could be fabricated, as shown in Figure 10. Patterns were generated using AutoCAD for the bladder, the top hinge layer, and the bottom hinge layer. The computer-generated patterns were used to precision cut and mark the film materials on a wheel cutter. After the manufacturing trials, the patterns were adjusted as necessary, and a hinge was fabricated and inflated to approximately 1 psi. Using a template, the hinge angle was measured and determined to be 40.5°. This meets the requirement of the hinge design angle of 41.8±2°.

Ultraviolet Rigidizable Inflatable Booms

A Multifunctional Ultraviolet Rigidizable Inflatable Center Column was developed for the PowerSphere. The rigidizable inflatable center column must pack into a small volume, deploy the

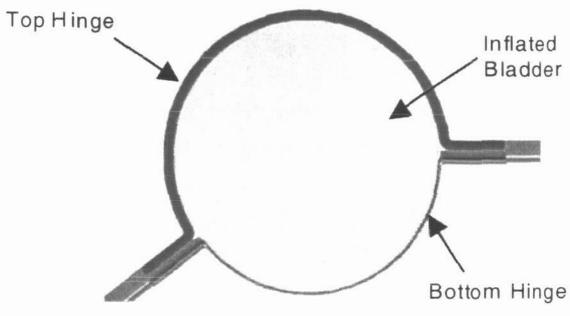


Figure 9. Hinge cross section.

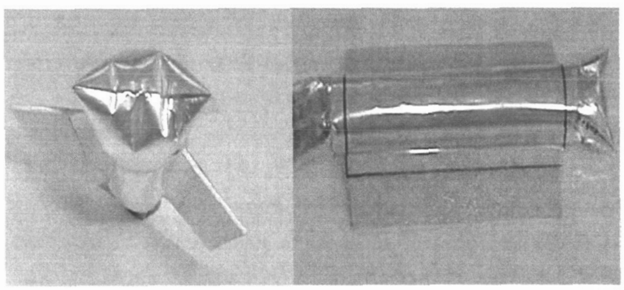


Figure 10. Inflatable hinge fabrication experiment.

solar panel assembly, and must be the structural component connecting the solar panels to the spacecraft. The center deployment column is an inflatable UV rigidizable isogrid boom consisting of a grid work of UV-curable composite tows integrated into an air-tight, UV-transparent, thin-film lay-up as shown in Figure 11. The flex circuit is integrated into the internal bladder of the column wall. As with the hinge, the center column is very flexible in the uncured state. This allows for compact z-fold packing. After inflation, UV radiation will cure the center column into a rigid structural component.

The center column interface design involves integrating the uncured UV rigidization material to a flange. The UV rigidization material is in the form of tows that must be accurately wound onto a mandrel in the isogrid pattern. The tows must be kept under tension to maintain the isogrid pattern. Furthermore, the transition of the tows to the flange must be as smooth as possible; i.e., the bending in the tows at the interface to the flange must be minimized. The UV- rigidizable tows must be encased in film such that it does not off-gas or bond to itself when packed.

A center column shown in Figure 12 was fabricated for the PowerSphere project using a modified filament winding operation. Patterns were generated in order to manufacture 3-in.-dia, 12-in.-long isogrid booms that will be used as test specimens and engineering models. Both the bladders and anti-blocking layers were precision cut and marked on a wheel cutter. The bladders and anti-blocking layers are fabricated from 2-mil-thick Mylar. The tows consist three rovings of Owens Corning's 449 1250 S-2 glass fiber impregnated with Adherent Technologies' ATI-P600-2 UV-curable epoxy resin. The tubes are bonded onto the flanges, inflated, and then cured using UV energy from the sun.

Inflation Methods

The PowerSphere will use a passive inflation method utilizing a material's vapor pressure for gas generation. Relatively small amounts of a given material (in either a solid or liquid state) can be applied to the inside of a tube. Once the external pressure is less than the vapor pressure of the material, the tube will inflate via the material's inherent pressure. The material will continue to vaporize until equilibrium is reached. This method does not require a power source for initiation, only a specific temperature to meet the necessary pressure. Nor does it require added spacecraft room as with a compressed gas bottle for example.

The inflation material search for the PowerSphere project focused on material compatibility and vapor pressure. The main material interface of the inflation material is with the bladder material, Mylar. The inflation material's compatibility with the materials of the entire PowerSphere system was also considered. The maximum allowable pressure of the bladders is limited by their seam strength. Due to the smaller radius of the hinges compared to the inflatable booms, the hinges can withstand greater pressure. Therefore, a different inflation material will be used for the

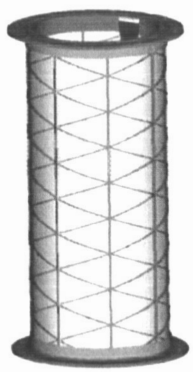


Figure 11. Center column.

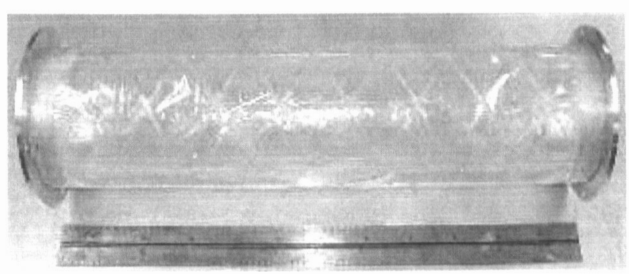


Figure 12. Isogrid center column.

hinge vs. the inflatable booms. The minimum pressure needed in the hinge and the center column for inflation and maintaining proper shape before rigidization is 0.5 psi. The maximum pressure/temperature for the hinge is at most 22.5 psi at 80°C. The maximum pressure/temperature for the center column is at most 7.5 psi at 80°C.

The recommended choice for the hinge inflation material is the mixture of 3-methylpentane and hexane. It meets the maximum pressure limit of 22.5 psi, has good material compatibility, and is inexpensive. This mixture's vapor pressure is equal to the minimum pressure, 0.5 psi, at –11°C. Therefore, the low-temperature deployment for the hinges is limited to –11°C.

The recommended choice for the boom inflation material is heptane. It is within the maximum pressure limit of 7.5 psi, has good material compatibility, and is inexpensive. Heptane's vapor pressure is equal to the minimum pressure, 0.5 psi, at 16°C. Therefore, the low-temperature deployment of the center column is limited to 16°C.

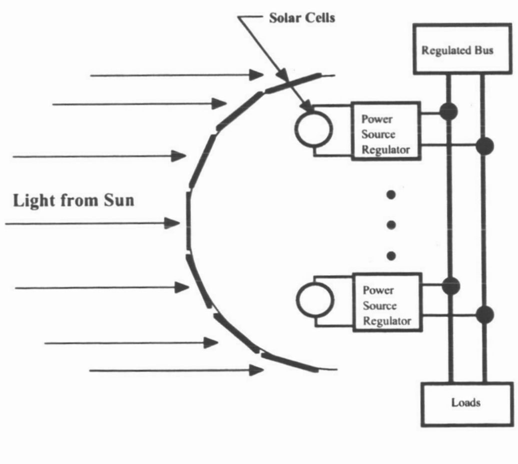
Electro Static Discharge and Atomic Oxygen Protection

The PowerSphere preliminary design calls for all exposed surfaces to be coated with an ITO-MgF_2 film. This film serves the dual purpose of atomic oxygen (AO) protection and electrostatic discharge control. A test plan was developed to provide a preliminary indication of film durability on flexible polymer structures such as solar cell panels, center columns, and panel hinges.[11,12]

For the PowerSphere application, it would be desirable to have a ~500Å ITO-MgF_2 film thickness for Atomic Oxygen robustness to maximize electric power production. While increased thickness of the ITO-MgF_2 coating would increase Atomic Oxygen protection on the solar cell panels, increasing film thickness from 500Å to 1000Å would decrease solar transmittance by ~12% (from 0.88 to 0.77). The optimal thickness for the ITO-MgF_2 coating will be optimized with further refinement of the PowerSphere design.

Distributed Power Management and Distribution (PMAD) System

The PowerSphere Solar array consists of 32 individual panels, which forms a geodetic sphere. Each panel on one half of the sphere is illuminated with various amounts of sunlight while the other half is not illuminated. The configuration for the PowerSphere solar array is such for the illuminated half of the PowerSphere each of the 16 solar cell panels will each receive a different amount of incident light. The individual solar cell panels will each be producing a different amount of current. Traditionally individual solar cells have been connected in series to develop sufficient voltage, which could then be delivered to the centralized Power Management and Distribution (PMAD) system. For a spherical solar array this arrangement is impracticable, as the solar cell generating the smallest amount of current will limit the power output of all of the other cells connected in series with it. This mismatch in current production is solved by the direct connection of each solar cell panel to the regulated bus via a microelectronic dc-dc converter. This direct connection eliminates the need for series connections of the cells located on different panels to produce sufficient voltage to supply the bus. This configuration shown in Figure 13 makes



Solar Cell Connection Scheme forSolar Power Sphere

Figure 13. PowerSphere PMAD Configuration

a spherical solar PowerSphere practicable and was patented by The Aerospace Corporation Patent number 6,127,621.

In addition to having individual DC-DC converters for regulating the Solar array the PowerSphere will utilize a ring bus where the six Li-Ion battery cells will each have a battery charger/boost regulator for interfacing with the 5 volt regulated bus. This PMAD configuration was patented by the Aerospace Corporation U.S. Patent Number 6,396,167. Figure 14 provides a top-level schematic for the PowerSphere microsatellite PMAD system.

Conclusions

The present team of Aerospace, NASA Glenn, Lockheed-Martin and ILC Dover has made significant progress in developing the various technology elements required to achieve a low cost low-mass attitude insensitive solar array for micro satellites. These technology developments will have application for many different gossamer structures not just the PowerSphere. The methods for making connections between thin film solar cells deposited on a polymer substrate will be applicable to much larger flat arrays, isogrid booms which use inflation for deployment are being considered for a number of advanced large space structures, inflatable deployment hinges which rigidize after deployment are simpler in design and eliminate mechanical backlash for large deployable structures, the ITO-MgF_2 coating offers an improvement over pure ITO for controlling electrostatic discharge on insulating exterior surfaces of spacecraft and finally the distributed PMAD system has the potential of greatly reducing the mass of the wiring harness of future spacecraft.

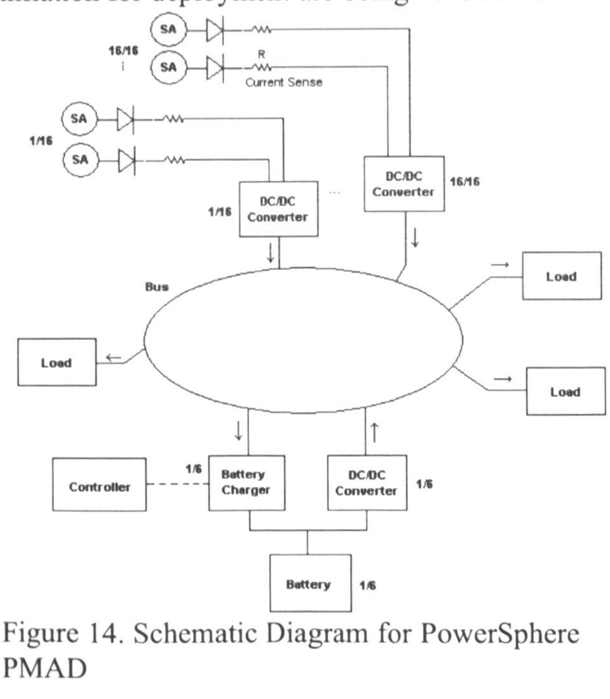


Figure 14. Schematic Diagram for PowerSphere PMAD

Acknowledgement

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