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Inflatable Rigidizable Solar Array for Small Satellites

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INFLATABLE RIGIDIZABLE SOLAR ARRAY FOR SMALL SATELLITES

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Abstract

With today's high launch costs, and tightening launch opportunities, low mass, cost, and packaged volume can determine the mission feasibility. L'Garde has developed the Inflatable Torus Solar Array Technology (ITSAT) to supply power to the growing fleet of small satellites in the 1kW class making forays into the space market. The ITSAT configuration with low mass and stowage volume and the inherent reliability of inflatably deployed structures is an excellent solution for these low power applications. The ITSAT is able to provide power densities more typical of a much larger system, despite its small scale.

Utilizing L'Garde's next-generation stretched aluminum inflatable rigidizable tube technology, and Northrop Grumman's new polymer cover-glass photovoltaic cell technology, power densities as high as 105 watts/kg can be achieved for a 0.5kW class array. Further, the packaging efficiency inherent in inflatable structures allows the complete system to be packaged in 0.04 m^3 for a packaging density of 20kw/m^3. L'Garde's proto-flight unit, utilizing older technology 13.8% cells, is achieving 73W/kg, a production system with the same cells and upgraded components would achieve a power density of 93W/kg. However, when this lightweight structure is integrated with a competitive 28% efficient blanket the power density would rise to a very competitive 109W/kg.

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Introduction

The ITSAT configuration is the culmination of several programs [1-4]. The initial design work was conducted under an SBIR Phase I funded by DARPA, in which a feasibility study was conducted on various point designs for power systems for LEO, GEO, and Molnaya orbits, with array sizes from 100W to several kilowatts. The subsequent Phase II effort refined this design, generated detailed drawings, fabricated the hardware, and tested the components producing a proto-flight system, Figure 1. This phase included a successful deployment at temperatures of –90C in the Naval Research Laboratories (NRL) 9 meter vacuum chamber, and subsequent dynamics testing and thermal cycling in the deployed state.

Figure 1. ITSAT Solar Array

In 1999 an SBIR was awarded to prepare the ITSAT configuration for launch on the shuttle in early 2001. The flight experiment was sponsored by the Air Force who were interested in the ITSAT technology to provide power for their small satellite programs. Under technical direction from JPL, the Phase I effort further defined the flight experiment, and instrumentation while defining the qualifications required for flight. Soon after the award of the Phase II program, the shuttle flight manifest identified for the ITSAT flight was cancelled in favor of a Space Station Freedom payload. Instead, the remaining resources were used to prepare the ITSAT for a generic flight, should one become available, and integrate several new technology upgrades developed in the interim. Specifically, new lower mass and volume, higher strength helically-wound stretched aluminum laminate tubes were developed and retrofit to the system with no loss in structural strength and stiffness. A new more capable lower mass and volume inflation system was designed, fabricated, and retrofit to the system to further enhance it's competitiveness. Successful ambient deployment and launch vibration qualification tests were conducted to validate the new components and upgraded system. Additionally a new canister design has been developed to reduce the weight even further.

The result of these efforts is a flight ready system with a measured power density of 73 W/kg of on-orbit performance for a system generating 275W of B.O.L. power. This performance is achieved with older technology 13.8% efficient crystalline silicon cells. A production unit, incorporating improved components previously identified, will have a power density of 93 W/kg. With new technology polymer cover glass technology from TRW, a production ITSAT system generating 500W of power can reach power densities of up to 109 W/kg, a very competitive system without the complexities or constraints of concentrator hardware or cells.

ITSAT Design and development

Requirements

The ITSAT was designed in the 0.2-1.0kW range for a mission life of 3 years in LEO to GEO with the associated thermal and space environments. Structurally, the ITSAT is designed to handle 0.03g's in any axis, while maintaining relevant safety margins. The deployed array exhibits a natural frequency in excess of 1.0Hz. In the stowed configuration, it must be able to withstand the shuttle launch vibration environment of 12g's in all three axes.

Aluminum Laminate Struts

At the heart of the inflatable solar array concept are the inflatably deployed/rigidizable aluminum laminate struts [5,6]. These struts provide the force needed to fully extend the array during deployment, and after rigidization, provide the strength and stiffness to absorb the static and dynamic loads during the mission. The strut is a monocoque cylinder fabricated from a three-layer laminate consisting of an aluminum foil sandwiched between two layers of Kapton. Before inflation and deployment the laminate is very malleable and is easily flattened and packaged in a Z-folded arrangement. Upon inflated the strut returns to its cylindrical shape. Once deployed, the strut is inflated to its 206.84MPa rigidization pressure, the stresses are carried by the Kapton but are high enough to yield the aluminum, removing wrinkles and distortions introduced during packaging. The aluminum is work hardened during this process raising its modulus. Once rigidized, the internal pressure is vented leaving a straight, rigid, geometrically stable tube capable of supporting the mission loads.

Recently, L'Garde has improved the aluminum laminate concept substantially through the addition of a thin helical PBO wrapping around the tube. This helical wrapping supports much of the pressure load in the hoop direction allowing greater yielding in the longitudinal direction resulting a stronger, and more geometrically precise cylinder. Additionally, the spiral wrapping, as it supports much of the inflation pressure, has raised the burst margin of the tubes significantly to about 3.0, specifically, the burst pressure of over >620.53MPa is at least 3.0 times higher then the rigidization pressure.

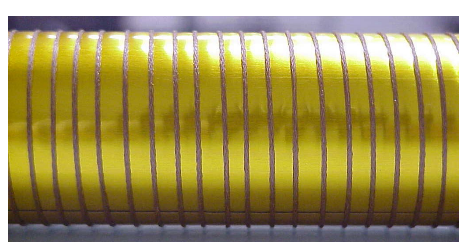

Figure 2. Aluminum Laminate Helical Winding

This innovation in the inflatably deployed, rigidizable struts has improved the ITSAT concept greatly. The new strut design allowed us to reduce the previous 10.16cm diameter tubes to 6.35cm while maintaining the same overall stiffness, and resistance to buckling. The addition of the chord mass is far outweighed by the reduction in tube diameter, volume, and endcap mass resulting in a substantial decrease in strut mass. Despite an increased rigidization pressure over the previous tube configuration, the reduction in internal volume of the new struts has resulted in a 45% decease in the required inflatant, allowing a similar decrease in the overall tank volume and mass.

As aluminum is a good conductor of heat it distributes heat quickly around it's perimeter, further, carefully selected coatings on the interior allow it to radiate heat within the structure itself very effectively distributing the energy. As thermal gradients are quickly dispersed within the structure MLI is not required for good thermal stability.

Canister

The canister and lid are built of 12.77mm and 3.18mm Nomex honeycomb with 0.13mm thick graphite-epoxy facesheets bonded on both sides. Reinforcements are used on all corner joints. The lid is constructed similarly, with a small flange overhanging all four sides. The finished canister weighs only 0.86 kg. and completely enshrouds and contains the stowed array and struts. The stowed dimensions are 16.25cm x 21.33cm x 113.28cm, with a stowed volume of 0.04m^3 including the inflation system which resides on the back of the canister.

Figure 3. ITSAT Composite Canister

A new lower mass canister has been designed. The new open configuration saves mass by leaving the walls open. Thin walled composite struts sized to withstand the launch vibration loads carry the packaged loads. "Stems" are incorporated to further constrain the packaged array during launch and ascent. The new design weighs only 0.54kg, saving 0.32kg of mass.

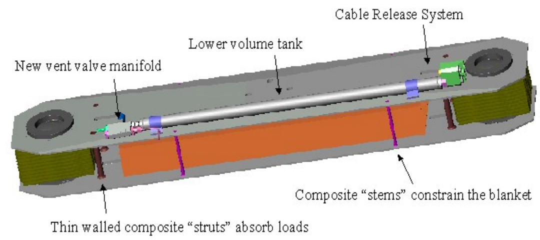

Figure 4. Updated Canister Design

Inflation System

A schematic of the 4-stage inflation system is shown in Figure 5. The inflation sequence consists of 4 distinct phases. During phase 1, the packaged and stowed configuration, the tubes are vented to ambient through a vent port. This allows any gasses trapped in the stowed tubes to escape during ascent so as not to prematurely inflate the structure before deployment. During Phase 2 of the inflation sequence, a novel shear pin and piston arrangement closes the vent port while simultaneously opening a low rate orifice path to the struts. The low rate was specifically chosen to provide the proper initial inflation rate of the tubes to allow a smooth and controlled strut deployment. During Phase 3, a high rate valve is opened, quickly raising the pressure in the deployed tube to the proper 206.84MPa required to ensure rigidization. Finally, during Phase 4, the vent valve at the opposite end of the tank is fired allowing the residual gas in the tank and tubes to vent to space through a zero thrust nozzle located at the base of the array.

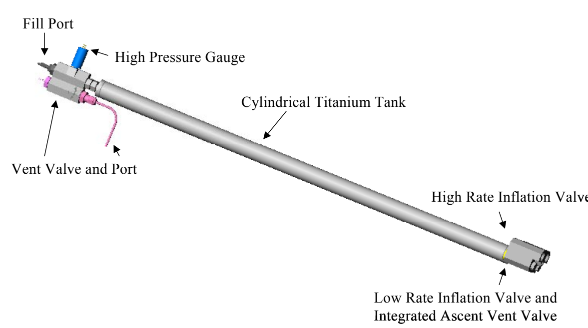

Figure 5. Update Inflation System

Array

The existing array uses 0.05mm Kapton as the blanket substrate, see Figure 1. The blanket is 10% populated with cells with the remainder populated with mass simulators including cover glass. The functional cells are interconnected to each other, with 31 cells per string. The interconnects are soldered cell-to-cell and allow for differential thermal expansion. In addition, resistance-temperature devices (RTDs) are mounted on the back of the working cells to monitor cell temperature. Cell temperature was measured and kept constant during electrical current-voltage (I-V) testing. Temperature measurements will also be required for on-orbit performance measurements. By-pass diodes are incorporated to allow for damaged cells and partial shading.

Thermal cycling of the blanket was a concern. To test the strength of the cell-to-substrate bond and the cover glass bonding, a sample of the solar blanket was sent to NASA Lewis Research Center for rapid thermal cycling. No damage or degradation occurred during the test. This coupon was cycled from –100°C to +80°C for a total of 2000 cycles.

To predict the power output of the fully populated array many factors were considered. The Silicon Crystalline cell chosen was rated at 13.8% efficient, but including mismatch, line, and temperature losses, the final B.O.L. efficiency was 11.38%. Including UV degradation, thermal cycling, cover glass and adhesive darkening, the E.O.L. efficiency is 9.16%. For a fully populated version of the existing blanket and array, the B.O.L. power is 274 watts, dropping to an E.O.L. power of 220 watts. The total blanket mass including lines, hinges, and tensioning chords is 1.1kg.

Array Enhancements

Recent work at L'Garde has focused on integrating the lightweight inflatable structure with new technology high efficiency cells. L'Garde and Northrop Grumman formed a team to investigate relevant cell technologies for the ITSAT array. Four cell technologies were selected for further investigation: high efficiency (26%) GaAs, high efficiency (16.5%) lightweight (3 mil) silicon, advanced amorphous silicon (9.5%), and copper indium gallium diselenide (CIGS, 10.14%). In addition, it would be beneficial to minimize the weight of shielding and thermal control materials. Thus, eliminating the cover glass on the solar cells helps reduce mass significantly. Northrop Grumman has been testing polymeric materials that may be substituted for the glass. While this is not a new idea (fluoropolymers were tested in the late 70's for cover material [7] and flown as adhesive [8]), the new elements for this are advanced plastics and, as important, protective coatings.

Seven polymers have been selected for additional space testing on the Materials on the International Space Station Experiment (MISSE) [9]. For purposes of simplicity in this presentation, Aclar, an advanced fluoropolymer, has been assumed to be the polymer medium. Each of the polymers is coated with a Northrop Grumman proprietary combination of metal oxides to result in a tenacious UV protective, very low energy proton protective, solar antireflective, and electrically conductive surface that provides ESD protection. (Proton protection is afforded by a thick layer and serves to reduce the quantity of particles, not spectrum of energies). The coating also serves to protect the polymer from atomic oxygen attack.

A study was conducted estimating the mass and performance of the above cells and optical treatments when applied to the ITSAT's 2.41m^2 (0.74m*3.25m) array. The results of the study are shown in Table 1. The highest overall system power densities were achieved using 28.1% efficient gallium arsenide Triple Junction cells. This cell efficiency has been demonstrated in limited production runs, and the cells are currently under qualification testing. With system losses the array is generating 503 watts giving the system a power density of 109 W/kg.

Table 1. Cell Study Results

Type	High η Si		GaAs/Ge	A-Si	CIGS
Vendor	ASE	Sharp	Emcore	Unisolar	Daystar
Type	2wiTHiEta	AHES	3J GaAs	3J	1J
Efficiency	16.80%	16.50%	28.10%	9.50%	10.20%
BlanketMass (kg)	0.96	0.74	2.10	0.74	0.55
BOL Power (W)	208.35	186.98	503.06	216.77	186.43
System Mass (kg)	3.48	3.26	4.62	3.26	3.07
System Power Density (W/kg)	59.84	57.33	108.97	66.55	60.70

Qualification Tests

Deployment

The ITSAT deployment sequence is depicted in Figure 6. Upon deployment initiation, twin pyro-cutters sever cables holding the ITSAT lid in place. Simultaneously, the inflation system slow rate pyro-valve is fired initiating the inflation sequence. The mass flow rate of the initial inflatant is chosen to ensure a positive steady deployment rate void of any extreme dynamics. As the tubes are slowly inflated, the extension of the tubes pull with them the folded array. The orthogonal folds in the Z-folded tubes and array tend to "guide" the system deployment in a linear fashion. Lanyards tying the array to the struts keep the components together and deploying in a controlled manner. Once fully deployed the inflated tubes tension the array to its proper 11.57N of tension. At this point, 60 seconds into the deployment sequence, the high rate inflation is initiated bringing the aluminum laminate tubes to their proper rigidization pressure. After the tubes have sustained rigidization pressure, a third pyro valve vents the gas to space through a zero thrust nozzle completing the deployment and rigidization sequence.

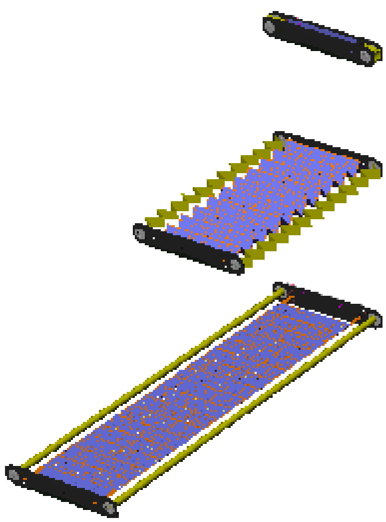

Figure 6. Deployment Sequence

Random Vibration

The packaged array has endured random Vibration tests to simulate the shuttle launch environment, Figure 7. These tests were conducted on L'Garde vibration machine and exposed the array to vibrations in all 3 axis (8.8g RMS, 12.45g peak, 20-2000Hz.). The tests indicated no visual damage to the structure and no degradation in cell continuity.

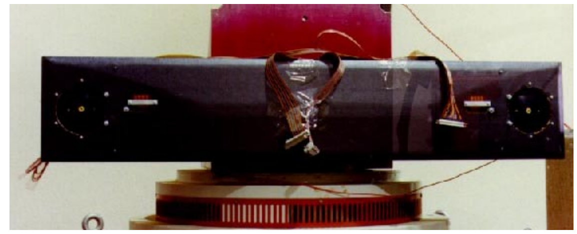

Figure 7. Random Vibration Tests

Thermal Vacuum Deployment

Thermal vacuum deployment tests were conducted at the NRL facility. The test was conducted in simulated eclipse conditions (vacuum with shrouds at –90°C) The ITSAT deployment test stand is shown in Figure 8. To simulate the effect of zero-G the test stand has a slight downward tilt to it to negate the effect of sliding friction of the lid. The deployment test performed flawlessly, and all equipment and sensors performed well. I-V tests performed before and after the deployment showed no measurable change in the cell performance.

Figure 8. Deployment Test Setup

Thermal Testing

For a 56 hour period, the deployed configuration was thermally cycled from –85°C to +70°C in vacuum conditions, see Figure 9. The front of the tubes were exposed to the shroud temperatures (-80°C), while the back surface was exposed to the cold plates (-180°C). The difference in the tube external surface was only 9°C even though they were exposed to a temperature difference of 100°C. The radiative and conductive heat transfer within the structure between the front and back surfaces of the tube is large enough to overcome the large difference in exposure temperature. Because of this small temperature gradient, no thermal distortions were measurable in the tubes under simulated worst-case thermal loading conditions. This feature underlines a key advantage of the aluminum laminate concept; no MLI is required to reduce thermal gradients.

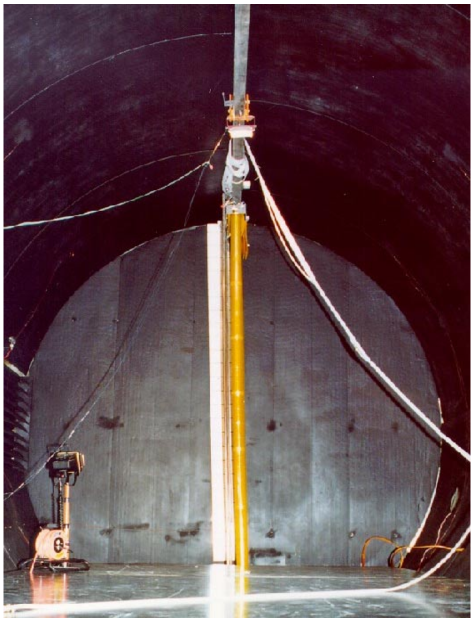

Figure 9. ITSAT in Thermal Vacuum Chamber

Dynamics Testing

While deployed in the thermal vacuum chamber dynamics testing was performed on the full system under simulated space conditions to determine the system natural frequency. By exciting the structure with a vibrator and measuring the tip deflections, a natural frequency of 1.04 Hz. was determined.

While thermal vacuum testing of the new configuration with the updated helically wound stretched aluminum laminate tubes has yet to be conducted, a system natural frequency of 1.03Hz. has been determined analytically using NASTRAN. No change in the system natural frequency was expected however, since the biggest driver of the lowest natural frequency mode is the array blanket itself which is governed by it's overall mass and it's 11.92N total longitudinal tension.

Summary

L'Garde has developed an inflatably deployed, rigidizable solar array for small satellites. Using new aluminum laminate rigidization and an upgraded and improved inflation system, the current structure and array, utilizing older generation 13.8% efficient cells, can achieve a credible 73W/kg of on-orbit power generation. Utilizing gallium arsenide 28.1% efficient cells, and Northrop Grumman's new polymer cover glass technology the power density can be further enhanced to 109 W/kg for a 4.62kg array capable of generating over 500W of power.

The existing hardware has been fully qualification tested for a shuttle mission. Qualification tests conducted include vacuum/thermal chamber deployment, launch vibration testing, thermal cycling, and dynamic testing.

The Inflatable Torus Solar Array Technology (ITSAT) was designed to supply power to the growing fleet of small satellites in the 1kW class making forays into the space market. The ITSAT configuration with low mass and stowage volume and the inherent reliability of inflatably deployed structures is an excellent solution for these low power applications. Further, it also represents a substantial savings for the satellite designer; the cost per watt is about one half that of competing mechanically deployed systems

Acknowledgments

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References

1) Malone P., Williams G., "Lightweight Inflatable Solar Array", Journal of Propulsion and Power, Vol. 12 No.5 1996

2) Veal G., "Inflatable Torus Solar Array Technology Program", L'Garde Technical Report, LTR-91-GV-022, December 1991

3) Freeland B., Bilyeu G., Veal G., Mikulas M., "Inflatable Deployable Space Structures Technology Summary", IAF-98-I.5.01, 49th International Astronautical Congress, Sept 28, Melbourne, Australia

4) Derbès B., "Case Studies in Inflatable Rigidizable Structural Concepts for Space Power", AIAA-98-1089, 39th AIAA Aerospace Sciences Meeting, Jan. 1998, Reno, NV

5) D. Lichodziejewski, G. Veal, ”Spiral Wrapped Aluminum Laminate Rigidization Technology”, AIAA-2002-1701, 43rd AIAA Aerospace Sciences Meeting and Exhibit, Apr. 25, 2002, Denver, CO

6) G. Greschik, D. Lichodziejewski, ”Wrap Reinforcement of Aluminum Rigidized Struts Study with Some Counter Intuitive Conclusions”, AIAA-2002-1262, 43rd AIAA Aerospace Sciences Meeting and Exhibit, Apr. 25, 2002, Denver, CO

7) H. S. Rauscenbach, et al, “FEP Teflon Covered Solar Cell Array Advancements”, Proceedings of the 10th Photovoltaic Specialists Conference, 1973

8) R. A. Meese, et al, “Solar Array System for the Solar Maximum Mission”, Proceedings of the 16th Photovoltaic Specialists Conference, 1982

9) Communication with M. Kruer, Northrop Grumman, to be published at a later date.

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