POWER-SCALABLE INFLATION-DEPLOYED SOLAR ARRAYS

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In 1999, DARPA contracted L'Garde, Inc. to develop an ultra low-mass solar array for rapid deployment micro satellites. The results of that effort yielded a high performance design that was tested up to a flight demonstration and outperformed competing designs in power density (65.4 W/kg at 274 W) and stowed volume (0.04 cubic meters). However, this design lacked the ability to scale the power level beyond 1 kW. Recently there have been significant advances in the area of inflatable-rigidizable space structures. The purpose of the most recent investigation was to develop a scalable version of the technology leveraging the previously proven design with revolutionary inflatable technology to produce a solar array that will be adaptable to any micro satellite mission and beyond. The methods of the most recent investigation involved analysis, fabrication, and tests. The result is a design ready to move to the next phase with power density performance better than two times that of the state of the art (115 W/kg at 1250 W) while utilizing existing solar cell technology. This performance level should be attractive to anyone interested in lowering the cost and increasing the reliability of their mission. The new structural technology will lend itself to a wide range of applications. This work is the result of a phase I contract that was performed for Defense Advanced Research Projects Agency (DARPA) under SBIR funding.

I. Introduction

L'Garde has developed the Inflatable Torus Solar Array Technology (ITSAT) to supply power to the growing fleet of small satellites in the 1 kW class making forays into the space market.[1-4] The ITSAT configuration shown in Figure 2 with low mass and stowage volume and the inherent reliability of inflatably deployed structures is an excellent solution for these low power applications. This paper summarizes a study of a power scalable version of the Inflatable Torus Solar Array Technology (ITSAT) developed by L'Garde funded by a Phase I DARPA SBIR. It leverages the previously proven design with our advanced inflatable technology to produce a concept that will be adaptable to wide range of power requirements. To accomplish this the structural components of the solar array system utilize the latest boom technology developed by L'Garde.

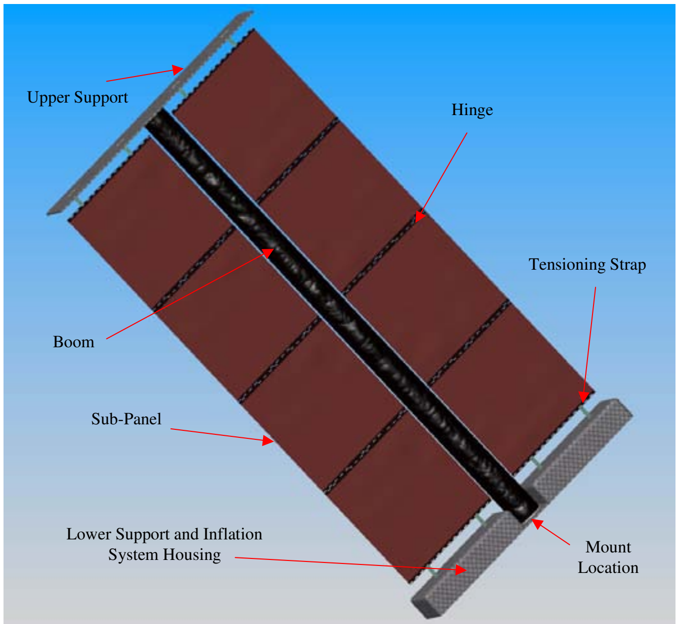

Figure 1: Typical Deployed Configuration

The performance requirements for this effort were open ended with a best power density performance as the target. The structural strength and natural frequency of the design drives the performance parameters when considering any design. From this, the performance and cost factors emerge. These factors include mass of the system and volume of the packaged system.

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The design studied herein centered around Triple Junction GaAs/Ge cells mounted on a flexible Kapton® blanket.[5] Beginning of Life (BOL) data is based on laboratory standard measurement, End of Life (EOL) data is based on typical GEO mission on orbit corrected for radiation and temperature. This cell/blanket choice will provide the best technology that is currently available. By picking a high efficiency solar cell, it is possible to use a smaller structure and benefit from the mass savings since the area required to achieve a design power will be smaller. This design was further exercised to meet the New Millennium Program's, ST-8 requirements. The design for the ST-8 study was a 7 kW array with a power density of >175 W/kg, a very small stowed volume <0.22 m^3, and a deployed natural frequency >0.1 Hz. The typical conceptual configuration is shown in Figure 1 in the deployed configuration.

To analyze this configuration L'Garde developed a software tool to size structural components with given design inputs. The inputs of interest are the orbital maneuvering loads, the desired natural frequency, and the power of the system. The outputs are structural safety factors, system mass, center of gravity, and specific power.

Representative booms have been designed, fabricated, and tested in the laboratory environment for several programs at L'Garde. The conical boom is considered by L'Garde as state of the art technology. A laboratory test deployment is shown in Figure 4. The sequence is shown from fully packaged on the left to deployed on the right.

Figure 2: ITSAT Solar Array

II. Design Evolution

A. Background

The initial ITSAT 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 100 W 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 2.

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 was 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.

Recent advancements allow the design to be more scalable and include the use of sub-T_g rigidizable materials and conical deployment of the booms. These coupled technologies form the basis for the advancements in the ITSAT design.

B. Sub-T_g Rigidization

Sub-Tg or cold rigidization takes advantage of the phase change of certain materials at specific temperatures to achieve structural strength. Instead of a thin sheet of aluminum as used on ITSAT, the material is made up of a specialized composite weave utilizing strong, lightweight fibers impregnated with a specialized L'Garde developed elastomer. Though called cold rigidizables they do not necessarily require cold temperatures. Elastomers can be formulated which rigidize at temperatures tailored to specific mission requirements. Cold rigidized structures can be constructed for a variety of missions, from LEO to deep space applications.

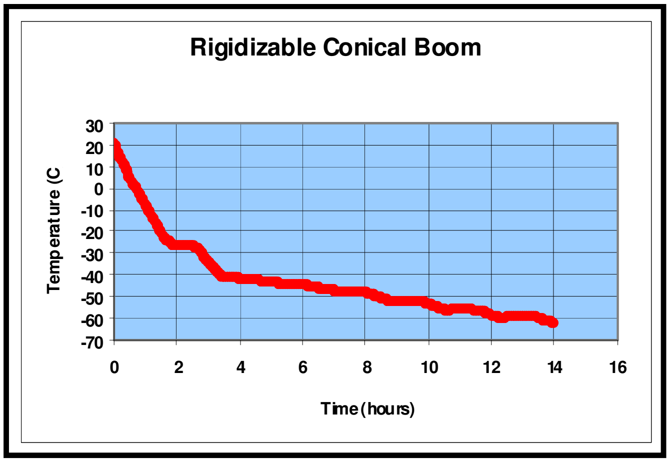

Figure 3: Temperature-time history of orbiting MLI-covered Sub-Tg boom (1000 km orbit).

At the heart of the composite is L'Garde's sub-T_g or cold rigidization matrix. The matrix is a thermoplastic elastomer tailored to be space hazard resistant and become rigid below a designed temperature. Current matrix T_g's include +50C, +20C, 0C, and –20C to meet the peak temperature requirements that would be seen on a variety of missions. The material is completely passive, reversible, and in general requires only moderate heating to soften for deployment if the spacecraft environment is below the composite T_g. This is a low power option to thermosetting plastics. After deployment, outside the spacecraft's thermal environment, the boom cools passively and becomes rigid. Cold rigidizables do not suffer from the scalability issues affecting the aluminum laminate rigidization concept allowing a wide range of thickness and can be deployed and packaged reliably.

In a space application, prior and during deployment, the MLI-covered rigidizable boom is kept above its T_g and hence flexible. Once deployed by inflation it is allowed to passively cool down to its operating temperature, which is well below its Tg. As an example, for a 1000 km orbit altitude- thermal analysis shows that after a few orbits, the temperature will have fallen to about -60°C. The temperature-time history of such an orbiting boom is shown in Figure 3. The thermal loadings were obtained from TRASYS[6] and the temperatures were calculated using SINDA.[7]

The glass-transition temperature can be tailored and the choice depends on the mission thermal environment. Preliminary measurements show that moduli on the order of 28 to 83 GPa are obtainable, depending on the Sub-Tg resin and structural fabric/weave design chosen. These measured values agree with our predictions using micromechanics theory. Commonly used structural fabrics are graphite, Kevlar, PBO, and glass.

C. Conical Deployment

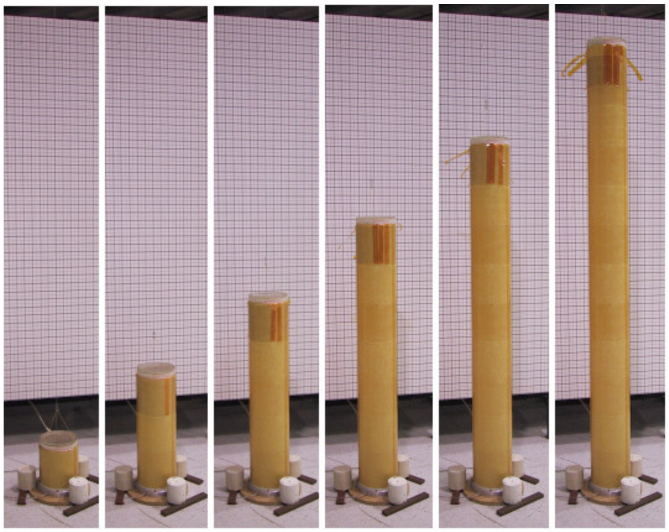

Figure 4: Boom Deployment in Laboratory Environment

Inflatables are robust when it comes to deployment. Properly designed inflatables require minimal parasitic control mass during inflation to reach their final configuration. Mission and spacecraft constraints become the driving requirement for additional control of the inflation and deployment. Figure 4 shows the conical boom deploying in the laboratory environment (US Patent Pending Serial Number 10/234047, "Deployable Inflatable Boom and Methods for Packaging and Deploying a Deployable Inflatable Boom," filed August 29, 2002). It uses a unique concentric packaging arrangement about the boom axis shown in Figure 5 and provides a high degree of deployment control. In this method, a tapered tube is packaged in a manner similar to a telescoping tube. L'Garde conceived this method for applications requiring highly controlled booms and is an offshoot from our decoy work in the

70's. Because there is a very low mass associated with the deployment control method, it scales very well both up and down in size and provides excellent packaging efficiency. To deploy the conical boom, inflation gas is introduced at the base. Pressure is exerted against the walls of the tube, the tip, and base end caps. The inflation pressure squeezes the walls against the outer folds and also unfolds and deploys the leading folds. This provides stability both during and upon completion of deployment.

III. Current Design Description

The structural system changes from the ITSAT design are centered on the use of the conical boom. The system design is comprised of an inflation-deployed boom flanked by two solar array blankets, as shown in Figure 1. The boom is a telescoping, thin-walled, conical tube that when inflated deploys the solar array system. The solar array blanket is a flexible, thin film polyimide curtain populated with solar cells as previously described.

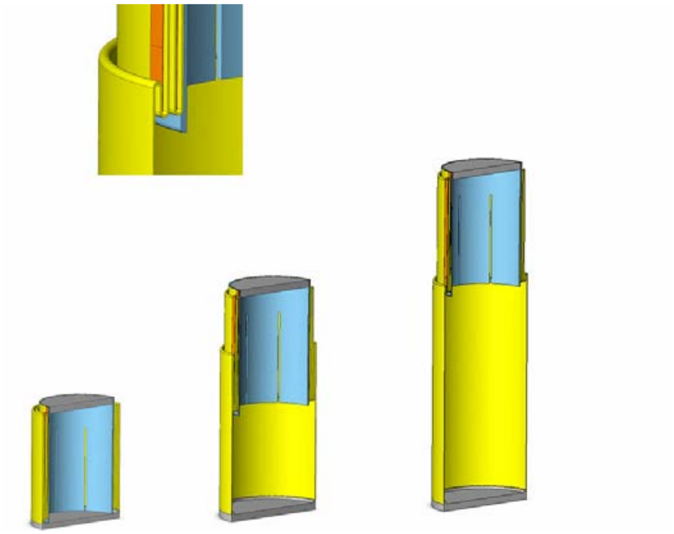

Figure 5: Typical Conical Deployment Unfolding the First Section from Left to Right.

A. The Conical Boom

The material chosen for this boom design can vary but its usual construction is of a Kevlar® fabric impregnated with L'Garde's proprietary sub T_g matrix. Kevlar is used in the composite to achieve the fabric flexibility required to deploy. The reversibility of the Sub-T_g matrix allows the same article to be tested for flight for a ground-based qualification program. The sub-T_g conical boom has a robust capability for dealing with buckling phenomena. Using thicker materials mitigates local buckling effects; using larger diameters mitigates long column buckling effects.[8] This flexibility makes the design fully scalable: other composites and resins tailored for a wide range of glass transition temperatures can be developed to fit the structural needs of a specific mission. Consequently, the free design parameters for the inflatable, rigidizable boom design are not tightly constrained and can be tailored to fit a wide variety of missions.

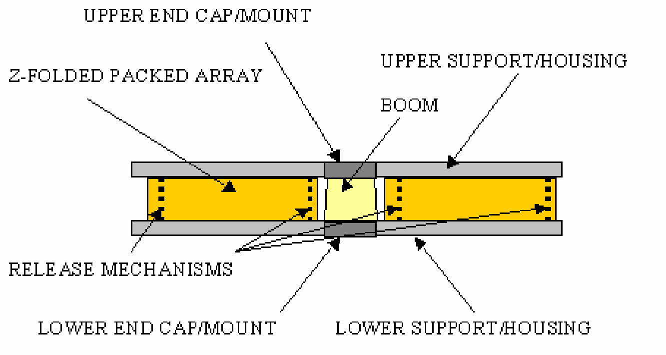

Figure 6: Stowed Configuration

B. Deployment Sequence

The first step of the deployment sequence is to energize a heater to allow the boom material to become pliable. This is required if the spacecraft thermal environment is colder than the T_g of the boom composite. During deployment, the boom is always enclosed in multi-layered insulation (MLI) to reduce the heat needed to make the boom pliable and minimize thermal gradients on orbit during operation. The outer layer of MLI is coated to have optical properties that allow the temperature of the boom to fall below the T_g of the matrix.

During deployment and until the boom is rigidized, the boom remains inflated (pressure-stabilized) and can carry load both in its partially

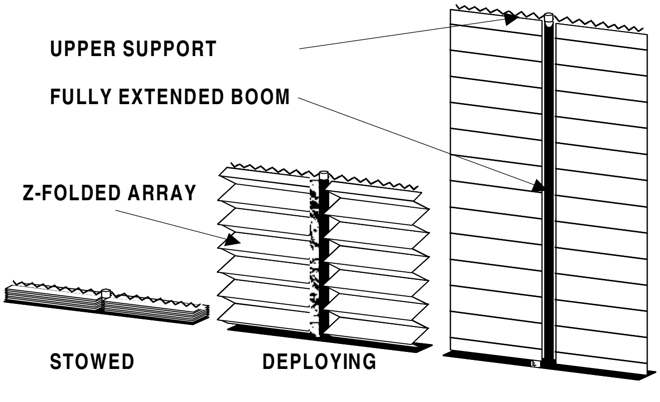

Figure 7: Deployment is simple, stable, and mass efficient.

and fully deployed state, see Figure 7. Finally, once the boom is fully extended the heater is de-energized. The inflation gas remains while the boom passively cools below its Tg to rigidize. Once rigidized, the inflation gas is no longer required for support and is non-propulsively vented.

The folding parameters are governed by the length, diameter, and thickness of the boom. The packaging factor, a parameter determined by the type of material, is used to properly size the boom and subsequently provide a taper ratio output.

IV. Breadboard Test Results

A. Deployment

Deployment tests have been conducted in the laboratory environment. The overall length of the test sample shown in Figure 4 was 2.74 m with a base diameter of 0.165 m. This is shorter than the 1250 W design but has approximately the same diameter and material thickness that would be required to achieve the structural performance. Complete deployment occurs in ~2 minutes and can be slower or faster depending upon inflation rate. Some nodding of the deploying tip occurs when a leading fold finishes unfolding. This occurs at intervals of two times the folding length during deployment and is predicable. Techniques and hardware have been developed to reduce these dynamics and are described in Section C below.

B. Stiffness

To confirm the performance predictions of the laminate, laboratory tests were conducted on a suitable structural composite. The predicted value for the compressive modulus of the material of 27.3 GPa compares quite well to the value of 28.2 GPa achieved during laboratory testing before deployment, and the value of 27.0 GPa achieved after stowage and deployment. This modulus would allow for the desired boom stiffness to be realized for all the point designs studied.

C. Deployment Nodding Reduction

Mission and spacecraft constraints become the driving requirement for additional control of the inflation and deployment. Improvements to the deployment of the conical tube have been ongoing. In some system configurations it may be required to constrain the base and the tip coaxial during deployment thus reducing the nodding previously described. Nodding reduction would come naturally in most system designs where a rigid structure is deployed away from the spacecraft by three or more booms. To accomplish this task when only one or two booms are used without increasing the package volume requires the use of a coaxial stabilization mandrel. The concept is based on providing axial stiffness during the transition period from a fold finishing deployment to the next fold starting deployment. A simple fix would be to extend the mandrel or decrease the fold length. This however would not allow for packaging of the mandrel to the original length. The resulting configuration extends and locks in the extended position in a passive manner. Midpoint stabilizers are used to provide additional support. The concept would be made of lightweight composite material for flight hardware and should result in an additional mass of 0.2 kg for a 0.165 m diameter boom. The mandrel design shown in Figure 8 allows for a passive deployment and full extension locking that occurs when the first fold is half deployed. The nylon bumpers provide support during the transition that occurs at the end of a fold. Deployment occurs with the deployment of the first fold and uses the deploying force of the end cap to extend it. Once in the fully deployed position it locks by using shaft spring locks.

Figure 8: Nodding Reduction Mandrel (shown deployed)

This concept was tested using the boom described above and the nodding was reduced to a minimum. To complete this design it would be lower risk to actively control the deployment of the stabilizer by a latching mechanism.

V. System Study Results

The 1250 W design is completely scalable and can adapt to a variety of mission requirements. As an example, work was proposed on the New Millennium, ST-8 Program to develop a 7 kW array with an overall power density of >175 W/kg and a stowed volume of <0.22 m^3. To achieve the stowage requirement will be less difficult than the power density. The blanket design, as can be surmised from the array data presented, has a maximum power density of ~157 W/kg in its current configuration which does not allow the total design to reach >175 W/kg.

Table 1. Case Study Results

	Case 1	Case 2	Case 3
Power	866 W	1320 W	2667 W
Power Density	102 W/kg	115 W/kg	130 W/kg
Stiffness	0.85 Hz	0.66 Hz	0.34 Hz
Strength	> 0.030 g	> 0.030 g	> 0.030 g
Stowed Volume	0.04 m^3	0.04 m^3	0.05 m^3

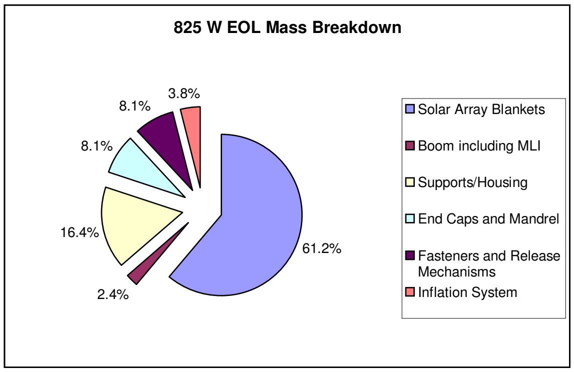

Figure 9: 825 W EOL/866 W BOL Mass Breakdown

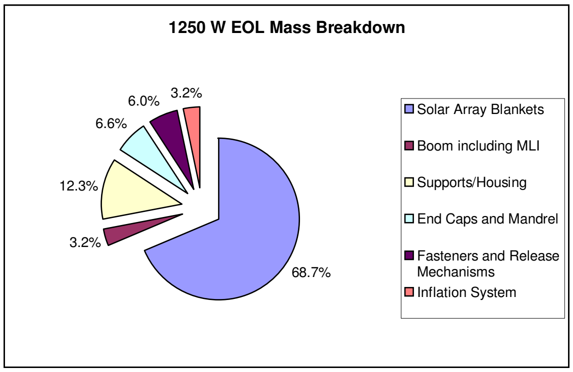

Figure 10: 1250 W EOL/1320 W BOL Mass Breakdown

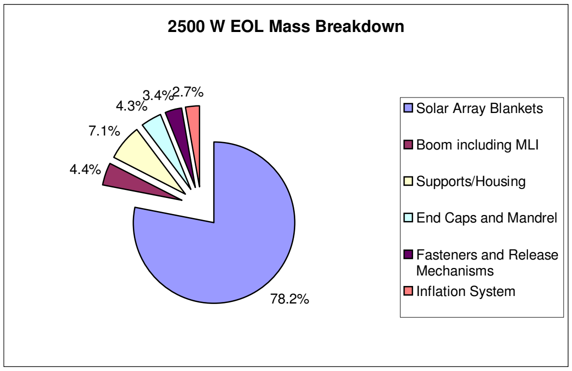

Figure 11: 2500 W EOL/2667 W BOL Mass Breakdown

A. Configuration Design and Develop Baseline Selection

Table 1 summarizes the BOL performance of the SISA design and a system specification is provided for the 1250 W EOL array is summarized in Table 2. The case studies were done by using the same width array and adding sub-panels to arrive at higher powers. GaAs/Ge cells were used for this study without consideration for mass improvement by replacing the cell cover glass technology. This decision is based on the near term availability of the technology and the cost associated with its development. The design was scaled by making it longer. Two very interesting design characteristics result:

1. The stowed volume increases very slowly for increased amounts of power. This is due to the efficient packaging method of the conical boom and the z-folded array adding little volume when folded.
2. By scaling along the length of the boom the first vibration mode goes from torsion to bending as the aspect ratio of the solar array blankets increase. Ultimately a wider array will be required to manage the natural frequency of the system for larger power outputs

Other variations could exist where the array becomes wider and lower masses and/or higher natural frequencies could result. An infinite number of permutations exist and can be tailored to fit a wide variety of solar array missions.

Mass breakdowns are summarized in Figure 9, Figure 10, and Figure 11. From the figures it should be noted that the overhead mass percentage (the mass that is not the blanket) decreases as the array size is increased.

Table 2: System Specifications for 1250 W EOL Array

Specification	Goal	Design
System		
EOL Power	1250 W/wing	1244 W/wing
BOL Power	-	1320 W/wing
BOL Power Density	-	115 W/kg
EOL Power Density	-	108 W/kg
Mass	-	11.5 kg
Packaged Volume	-	0.04 m3
Packaged Dimensions	-	1.37 m x 0.24 m x 0.12 m
Deployed Dimensions	-	1.37 m x 0.24 m x 4.05 m
Natural frequency		
System	> 0.5 Hz	0.66 Hz
Array		
Type	-	Triple Junction GaAs/Ge
Cell Thickness	-	140 um
Cell Size	-	3.716 cm x 7.16 cm
Cover Glass Thickness	None	3 mil
Cell Efficiency	-	27.6%
Aspect Ratio of Blanket	-	6.2:1 (each array)
Deployment Characteristics		
Tube Deployment Temp.	-	~ 20 C
Tube Ridgidization Temp.	-	-20 C
Tube Operating Temp.	-	~ -45 C
Deployment Time	-	2~5 min
Rigidization Time	-	~ 6 hours
Orbital Parameters		
Lifetime	-	5 yr
Altitude	-	600-800 km (750 km nominal)
Inclination	-	28.5 degree
Acceleration	> 0.03 g	> 0.03 g

C. Notes on Technology Readiness Level

The ITSAT design has been tested through TRL 6 during previous programs. That is to say it has been tested in a relevant environment on the ground and met the performance parameters. The proposed boom technology for the new design is at TRL 3~4, the critical function has been demonstrated in the laboratory, and it is the focus of many programs at L'Garde where it is being integrated into systems.

VI. Conclusion

The concept is scalable and can adapt to a variety of mission requirements. From the mass breakdown it is obvious that the overhead mass (the mass that is not the blanket) is approaching a very small fraction of the total mass when an inflatable structure is used. Additionally, significant mass reduction is possible in the solar array design and can be done by reducing the cell mass of the high efficiency cells or by increasing the efficiency of the low mass thin film technologies. Clearly once this design becomes established in the marketplace a stronger effort will be required to reduce the solar array blanket mass especially for larger arrays where the ancillary components are only a small fraction of the total.

Acknowledgments

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References

[1] Lichodziejewski, D., "Inflatable Rigidizable Solar Array for Small Satellites", AIAA-2003-1898, 39th AIAA Aerospace Sciences Meeting, Jan. 1998, Reno, NV

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

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

[4] 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

[5] Kruer, M., Phase I Deliverables SHIEDR Solar Array Study by Northrop Grumman Space Technologies, L'Garde Document 02-003, June 19, 2003.

[6] TRASYS, Thermal Radiation Analysis System, COSMIC, University of Georgia, Athens, Georgia.

[7] SINDA, Systems Improved Numerical Differencing Thermal Analyzer, COSMIC, University of Georgia, Athens, Georgia.

[8] NASA/SP-8007, Seide*, P. and Weingarten*, V. I. and Peterson**, J.P., Buckling of thin-walled circular cylinders, NASA SPACE VEHICLE DESIGN CRITERIA (Structures), NASA (Washington, DC, United States), *University of Southern California, **NASA Langley Research Center., September, 1965.