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Development, Design, and Testing of PowerSphere Multifunctional Ultraviolet-Rigidizable Inflatable Structures

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The continuing advancement of microsatellites and nanosatellites for space application has identified a need for a simple, low-mass, and low packing volume solar array system for these satellites. The result of decreasing satellite size, thus surface area, and increasing power demand as these satellites become more capable is the inevitable problem of power choke on satellite systems with body-mounted solar cells. The use of traditional, rigid, solar arrays necessitates larger stowage volume and mass, and also requires gimbals for pointing. In previous studies, the PowerSphere solar array system has been identified as one of the solutions to this power choke problem by lowering mass and stowage volume and eliminating pointing mechanisms. Given these requirements, ultraviolet cured composite materials have been identified as the best candidate for this application. The development of PowerSphere multifunctional ultraviolet-rigidizable (UV-rigidizable) inflatable structures is beneficial not only to micro- and nanosatellites it also enables the advancement of gossamer-type structures. In conjunction with UV-rigidizable material, these structures incorporate thin-film flex-circuit to make them multifunctional. Two multifunctional structures in the PowerSphere system use the UV-rigidizable material, namely, the inflatable hinge and the inflatable isogrid center column.

Nomenclature

E	=	Young's modulus
$I(t_h)$	=	section modulus (function of thickness)
M	=	moment induced by angular velocity
P	=	vertical load applied
R	=	radius of the hinge (test specimen)
t_h	=	thickness of the hinge (test specimen)
V	=	shear load induced by angular velocity
δ	=	deflection of the hinge
ν	=	Poisson's ratio

Introduction

THE original charter for the development of PowerSphere is to address the issue of power choke in small satellite systems.[1,2] The requirements of PowerSphere to be low cost, low mass, low packing volume, and low power for deployment dictated the research and development of multifunctional UV-rigidizable inflatable structures as an enabling technology. As the technology advanced, it was realized that the development of this enabling technology would allow the realization of not only PowerSphere in particular, but gossamer-type space structures in general.

In the previous phase of research, configuration trade studies such as system configuration, preliminary mass analysis, hinge configuration, and center deployment column configuration have been completed.[3–5] The effort of the current study is to develop and mature the selected configurations from concept to proof-of-concept engineering prototype. The development of a multifunctional UV-rigidizable inflatable structure requires innovations and advancements in several technologies including materials, structures, ultra-low-mass inflation systems, electrostatic discharge protective coatings, thin-film flex circuits, and associated thin-film applications and fabrication processes. The advancement of each of these technologies needs to be accomplished through systematic analysis and testing. In addition, to bring the PowerSphere system to the engineering prototype level in the near future, the PowerSphere team has begun fabrication trials of various subcomponents. The work presented in this paper focuses on the development, design, analysis, and testing of two PowerSphere subcomponents, namely, the multifunctional UV-rigidizable inflatable hinge and isogrid center column.

System Design

The baseline design of the PowerSphere spherical solar array system consists of two semispherical domes connected to a central spacecraft. Each semispherical dome consists of two different submodules assembled together to form a geodetic sphere of hexagon and pentagon solar panels (Fig. 1). One of the submodules, submodule A (Fig. 2), consists of three hexagon solar panels, one pentagon solar panel, and four inflatable UV-rigidizable hinges integrated with flex circuit blanket to form one multifunctional module. The other submodule, submodule B (Fig. 3), consists of three pentagon solar panels mounted to the instrument deck (or end cap) by three inflatable UV-rigidizable hinges integrated with a flex circuit blanket. In addition, this module consists of an inflatable UV-rigidizable

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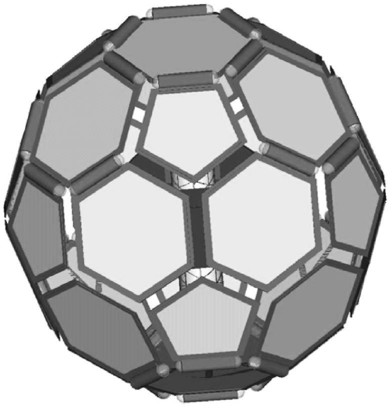

Fig. 1 PowerSphere assembly.

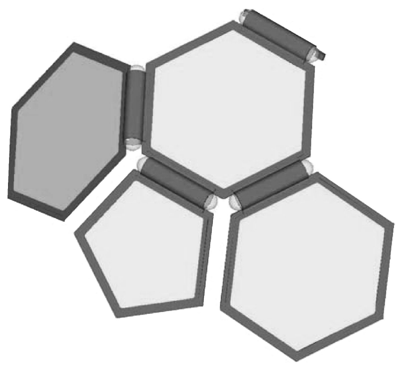

Fig. 2 Submodule A assembly.

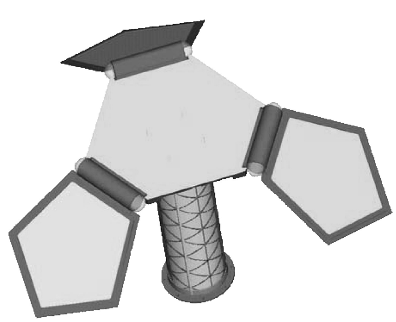

Fig. 3 Submodule B assembly.

isogrid center column with an integrated flex circuit that also mounts to the instrument deck. A single semispherical dome requires three submodule A assemblies and one submodule B assembly.

The use of UV-rigidizable inflatable structures enables the PowerSphere system to have a small packing volume and minimal power required for rigidization. The center column will be z folded for packing. Release ties between the instrument panel and the spacecraft bus will secure the packed center column. The hinged solar panels will fold and stack on top of each other. The solar panels will also be secured to the instrument panel with release ties. (See Fig. 4, and note that release tie and soft cover are not shown.) After launch, the center column release ties are triggered, allowing each center column to inflate and deploy. The UV radiation from the sun or blue or green light emitting diodes will cure the tube into a rigid supporting column. Then the solar panels release ties are triggered allowing the hinges to inflate and deploy the solar panels into the geodetic shape. Likewise, the UV radiation from the sun will cure each hinge into a rigid structural component. A passive inflation method via a material's vapor pressure is used to inflate the center column and the hinges. This is a very simple inflation method that does not require power for initiation.

The integrated flex circuits supply the power from each solar cell to the spacecraft. The flex circuits are on the backside of the

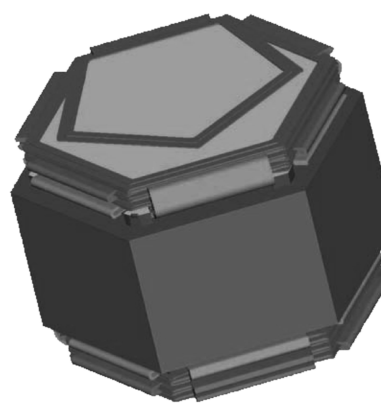

Fig. 4 Packed PowerSphere assembly.

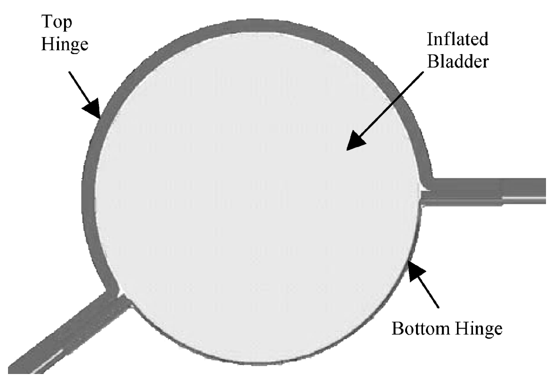

Fig. 5 Hinge cross section.

solar panels. Low-profile connectors will be used to make electrical connections between submodule A, the instrument panel, the center column, and the spacecraft. The interface hinge on submodule A is designed with a quick disconnect feature to aid the manufacturing process and to allow component replacement at the submodule level if the module assembly fails during fabrication or testing. A flex ribbon will be integrated into the inside of the center column. It will be attached to a connector mounted on the instrument panel and a connector on the spacecraft. This concept will provide the required airtight seal of the center column. The PowerSphere Assembly will be coated with indium tin oxide magnesium fluoride (MgF_2) to prevent damage due to electrical arcing.

Multifunctional UV-Rigidizable Inflatable Structures

The PowerSphere system consists of two multifunctional UV-rigidizable inflatable structures: 1) multifunctional UV-rigidizable inflatable hinge, and 2) multifunctional UV-rigidizable inflatable isogrid center column. These two structural/mechanical components use the same rigidization, that is, composite material, system, but employ significantly different structural and mechanical designs to accomplish their requirements.

Multifunctional UV-Rigidizable Inflatable Hinge

The multifunctional UV-rigidizable inflatable hinge for the PowerSphere is a critical element with several design requirements. The hinges must be able to pack the solar panels, unfold the solar panels to the proper angle, and maintain accuracy and rigidity after deployment to the end of the mission.

Hinge Design

To achieve the requirements just mentioned, the base design consists of a tubular bladder, a top UV-rigidizable hinge, and a bottom nonrigidizable hinge (Fig. 5). The hinge is very flexible in the uncured state because it comprises thin films and uncured resin. This flexibility allows a single hinge size to fold and pack multiple layers of varying stack height. After the solar panel release ties are triggered, the hinge bladders will inflate, causing the solar panels to unfold into the geodetic shape. Then the top hinge will cure from UV radiation to become a rigid structural component. The cured hinge stiffness must be great enough to withstand the centripetal force caused by a spinning satellite system such that the deflection of the hinge is within acceptable geodetic shape limits.

In terms of design detail, 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 adhere 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 top hinge length will be longer than the bottom hinge. The difference in the run lengths is such that the proper angle of the panels is obtained on inflation. The diameter of the hinge is dependent on the maximum stack height. The run length of the bottom hinge must be sufficient 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 thin-film solar cell, is incorporated into the hinge layup 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 PowerSphere to be efficiently packed.

Hinge Fabrication

A number of experimental hinges were fabricated for this development effort to define the hinge manufacturing process and to determine how accurately they could be fabricated (Fig. 6). 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 (6.895 kPa). With use of a template, the hinge angle was measured and determined to be 40.5 deg. This meets the requirement of the hinge design angle of 41.8 ± 2 deg. The manufacturing knowledge gained during these experiments will be used to fabricate the hinges that will connect the solar cells for solar modules A and B in the engineering prototype.

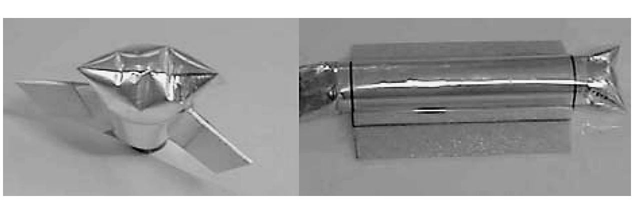

Fig. 6 Inflatable hinge fabrication experiment.

Analysis and Testing

Structural analysis and testing for the hinge is important to optimize the design. From preliminary calculations, it is found that in this application the size of the hinge is not determined or governed by strength but by deflection. In other words, the parameter that governs the design of the hinge is the maximum deflection of the hinge under load. This also indicates that the design will be frequency driven in the final analysis. The primary load that will deflect the hinge comes from the predetermined rotation of the PowerSphere.

In this calculation, the energy method based on Castigliano's theorem was applied to determine the deflection of the submodule A assembly at various points:

$$\delta(P, R, t_h, E) = \frac{\pi \cdot P \cdot R^3}{2 \cdot E \cdot I(t_h)} \left[\frac{t_h^2 \cdot (1+\nu)}{5 \cdot R^2} + \frac{t_h^2}{12 \cdot R^2} + 3 \right] \qquad (1)$$

Figure 7 shows the free-body diagram of submodule A. Based on the assumptions made in the free-body diagram, the results obtained are conservative. The results of the calculation (Fig. 8) indicate that with the composite material given (thus, the material properties defined) the section modulus of the hinge and the frame are the factors determining the deflection under a given rotational speed. Therefore, depending on mission requirement, the design of the hinge and the frame should be optimized according to the rotational requirement. Currently, the rotational requirement is 4–60 rpm. Based on the maximum rotational speed requirement and the maximum deflection of 1.0 cm, the section modulus of the hinge should be greater than 7.6×10^{-10} m^4 and the section modulus for the frame should be greater than 1.0×10^{-10} m^4.

Multifunctional UV-Rigidizable Inflatable Center Column

Center Column Design

The rigidizable inflatable center column must pack into a small volume, must deploy the solar panel assembly, and must be the structural component connecting the solar panels to the spacecraft. The selected design for 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 layup. 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. The length of the center column is sized to the specific geodetic sphere for proper alignment of top and bottom spherical domes. After inflation, UV radiation will cure the center column into a rigid structural component. The strength of the cured center column is designed to withstand the applied moment at the tip of the column due to the rotation of the PowerSphere.

The center column interface design involves integrating the uncured UV-rigidization material to a flange. The UV-rigidization

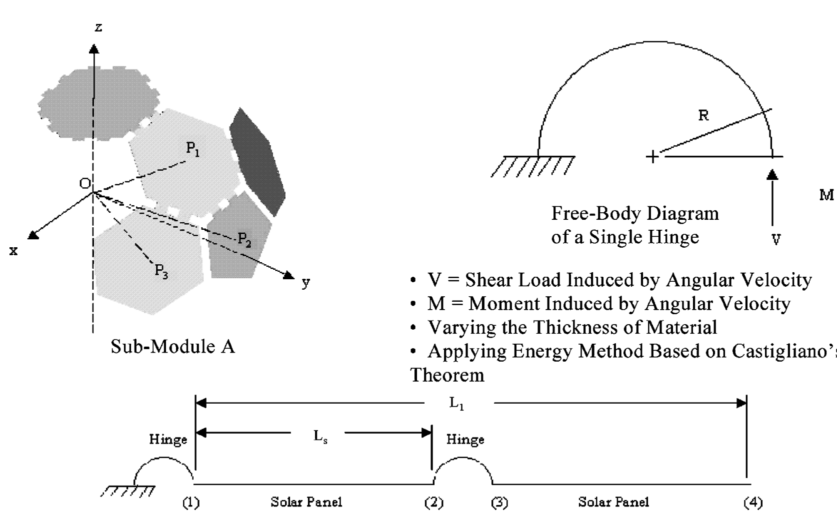

Fig. 7 Hinge deflection calculation assumption and free-bodydiagram.

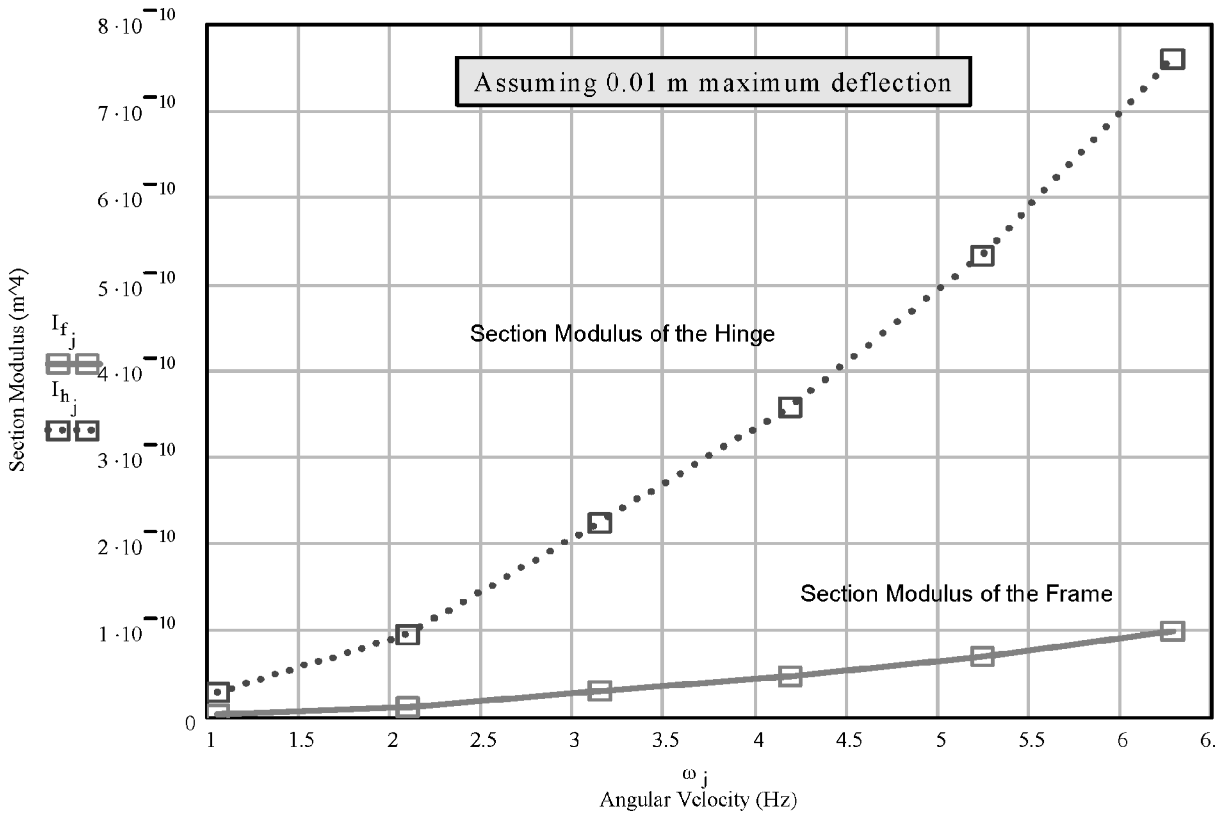

Fig. 8 Section modulus of frame and hinge vs angular velocity.

Fig. 9 Isogrid center column.

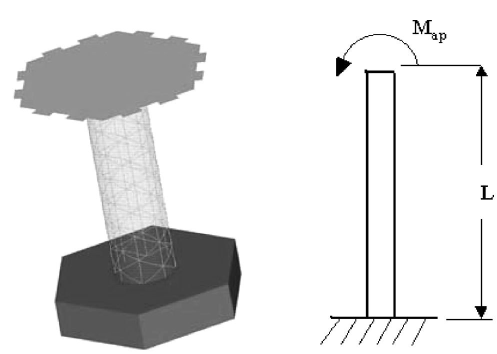

Fig. 10 Isogrid center deployment column and free-body diagram.

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, that is, 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. The flange will allow for circular bolthole attachment to the solar panel container and an O-ring seal for inflation gas retention.

Center Column Fabrication

The center column (Fig. 9) is fabricated using a modified filament winding operation. Patterns were generated to manufacture 3-in.-diam, 12-in., long isogrid booms that will be used as test specimens and engineering models. Both the bladders and antiblocking layers were precision cut and marked on a wheel cutter. The bladders and antiblocking layers are fabricated from 1-mil-thick Mylar®. The tows consist of three rovings of Owens Corning's 449 1250 S-2 glass fiber impregnated with Adherent Technologies' ATI - P600-2 UV-curable epoxy resin.[6] The tubes are bonded onto the flanges, inflated, and then cured using UV energy from the sun.

Center Column Analysis and Testing

The analysis presented in this subsection employs classical theory to analyze the structural performance of the isogrid column.[7] The structural analysis is presented without derivation. The purpose of this calculation is to refine the various parameters (particularly radius of the column, number of axial tows around the circumference, and the diameter of the tow) of an isogrid tube for the PowerSphere application. From the isogrid center deployment column assembly, assumptions were made about the loading and boundary conditions to simplify and to arrive at the free-body diagram as shown in Fig. 10. The center column is assumed to be a cantilever column with fixed–free end conditions. The applied moment at the tip of the column is due to rotation of the PowerSphere during deployment. In the calculation, a lateral acceleration of 0.1 g is also applied to the center column. The cross section of the isogrid tow (Fig. 11) is assumed to be circular.

To optimize the parameters, three modes of failure, namely, global Euler buckling of the column, general instability of the isogrid wall, and local Euler buckling of an individual tow (or rib element), were investigated. The result of the buckling analysis showed that the local Euler buckling of the rib is the limiting case (Fig. 12).

When the predicted loading condition was compared with the local rib buckling limit, an optimized solution was obtained (Fig. 13). (The local buckling limit was calculated with number of axial tows and tow diameter as variables.) The configuration selected for fabrication and testing is as follows: diameter of the column = 7.62 cm

(3.0 in.), number of axial tows = 8, and tow diameter = 1.55 mm (0.061 in.) (This diameter is equal to three roving of S2-glassfiber.) Mechanical properties such as mass, frequency, and deflection have also been calculated for comparison (Figs. 14–16).

Materials Development and Testing

The successful development of inflatable deployable structures relies mainly on the selection of materials to be used. A class of materials called rigidizable materials is usually needed to meet system-level requirements. Rigidizable materials can be defined as materials that are initially flexible to facilitate compact packing/stowage, inflation, or deployment and become rigid when exposed to an external influence.[8] The external influence can be extreme hot or cold temperatures, radiation in the electromagnetic spectrum, or a chemical reaction caused by the inflation gas.

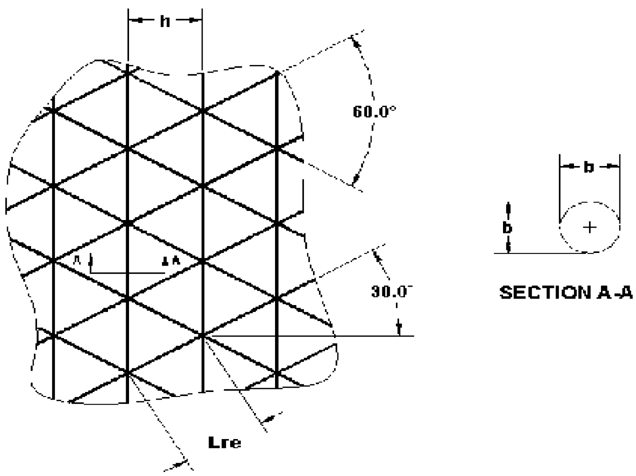

Fig. 11 Isogrid wall of the center deployment column.

The PowerSphere team has identified UV-cured composite materials as the optimal candidate for the PowerSphere program. This decision was based on the available spacecraft energy requirements, packing volume, expected operational temperature regimes, and mass requirements. Before selecting the UV material as the primary resin candidate, other rigidization and deployment mechanisms were identified. These include thermoplastic shape memory composite materials and mechanical solutions.

UV-Rigidizable Material Development

To select the reinforcement fiber for the program, an extensive search of commercially available fibers was performed. Initially, this list included only carbon fibers, but was later expanded to include glass fibers, which could be used with UV-rigidizable resins. Properties that are important to fiber selection are specific stiffness, strain to failure, environmental resistance, thermal conductivity, and coefficient of thermal expansion (CTE). CTE is important in developing a near-zero CTE structure that would not suffer shape changes from variable thermal inputs on the structure. Carbon, Kevlar®, poly(*p*-phenylene-2,6-benzobisoxazole) (PBO), and Vectran all exhibit low or negative CTEs. S-glass also has a fairly low CTE (1.6×10^{-6} ppm/°C). E-glass has a slightly higher CTE (5.4×10^{-6} ppm/°C). Out of these fibers, only carbon, E-glass, and S-glass have the environmental resistance required for the PowerSphere application. The other fibers have various issues with degradation due to tight folding, weaving, or UV exposure.

As the design of the multifunctional inflatable structure matured, it became clear from the results of various trade studies on the different design options that an UV-curable resin is the most attractive

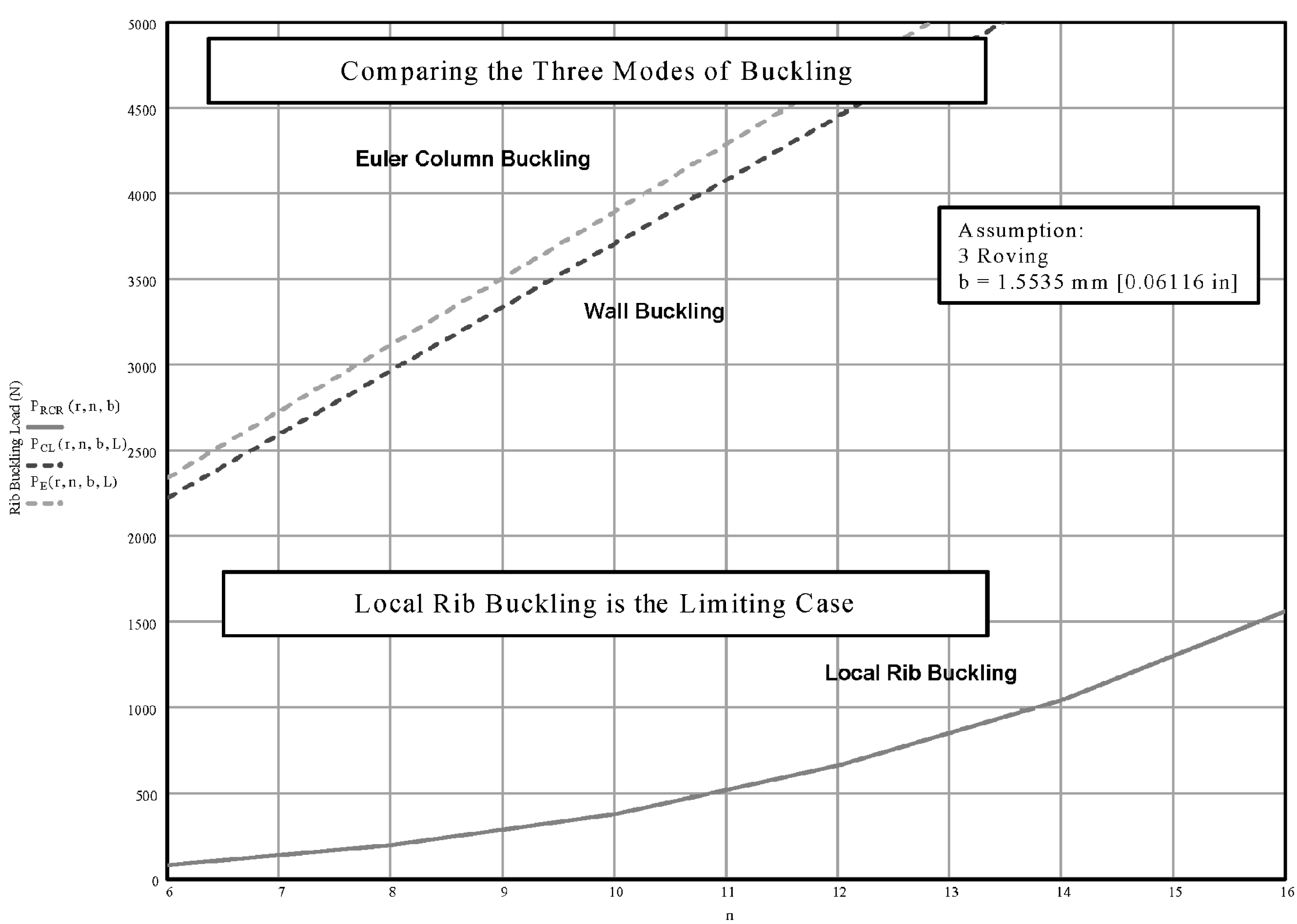

Fig. 12 Three modes of buckling failure.

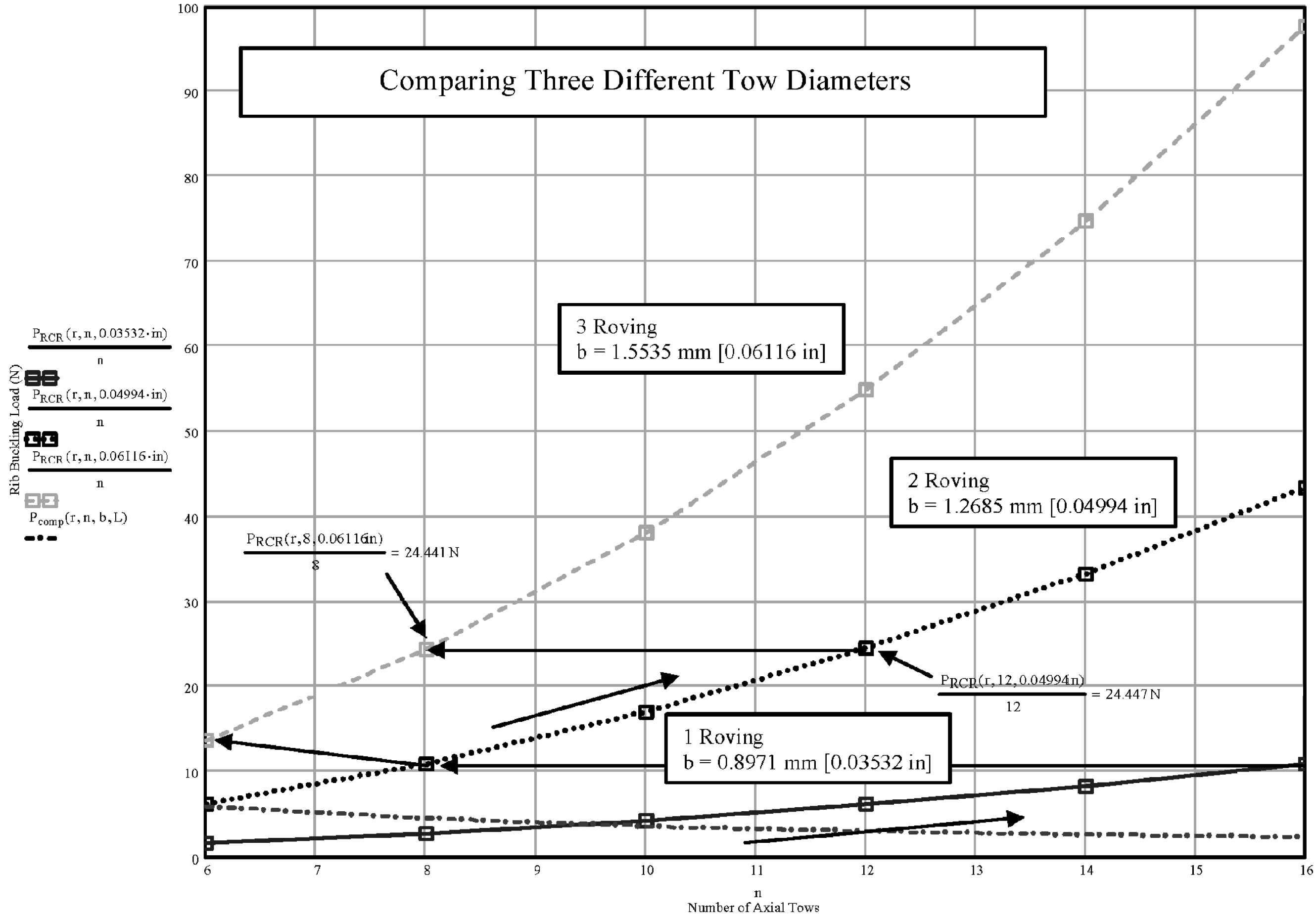

Fig. 13 Rib buckling of three different tow diameters.

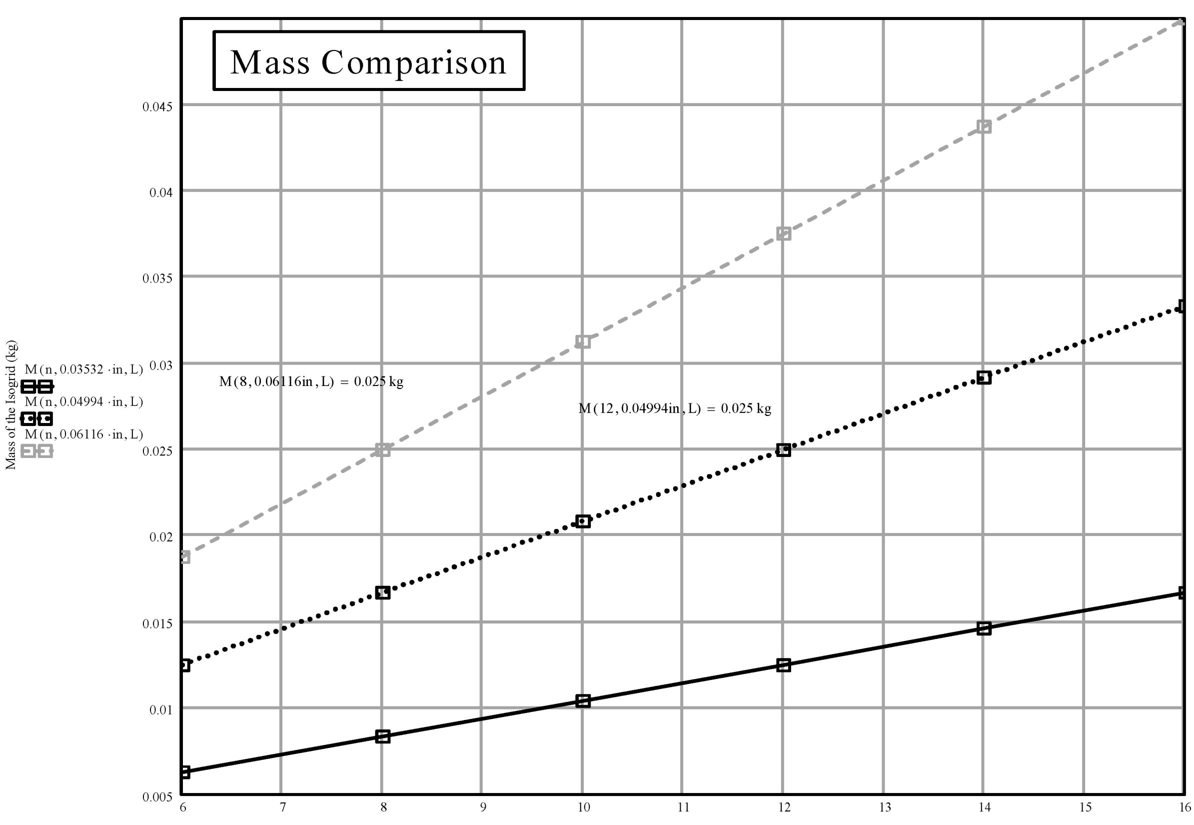

Fig. 14 Isogrid center column mass comparison among three different tow diameters.

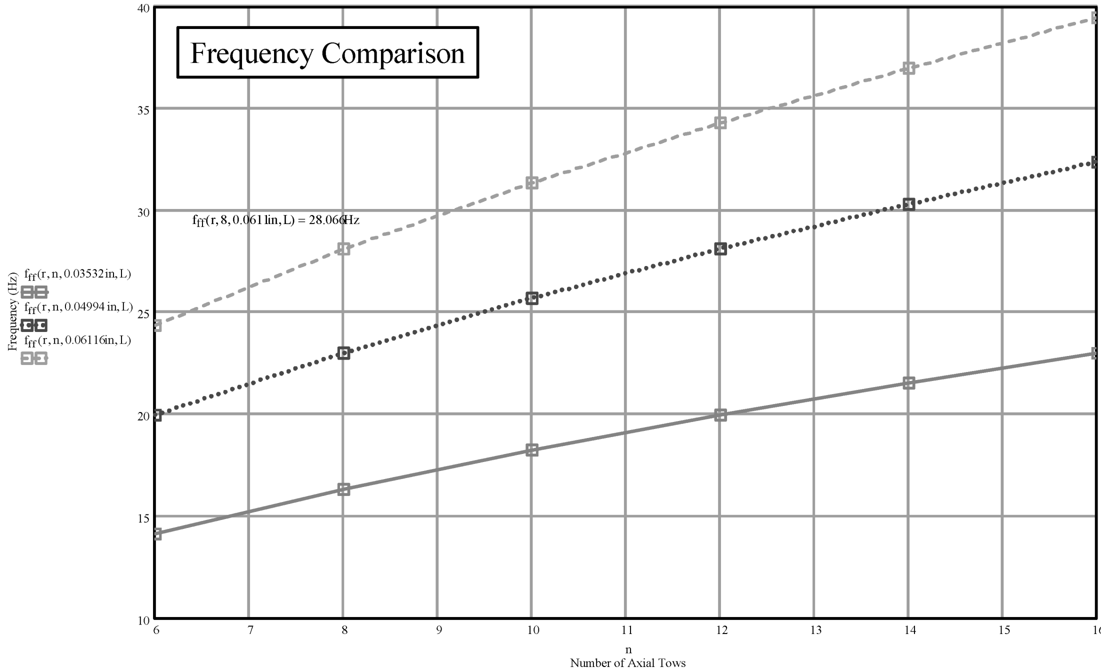

Fig. 15 Isogrid center column frequency comparison among three different tow diameters.

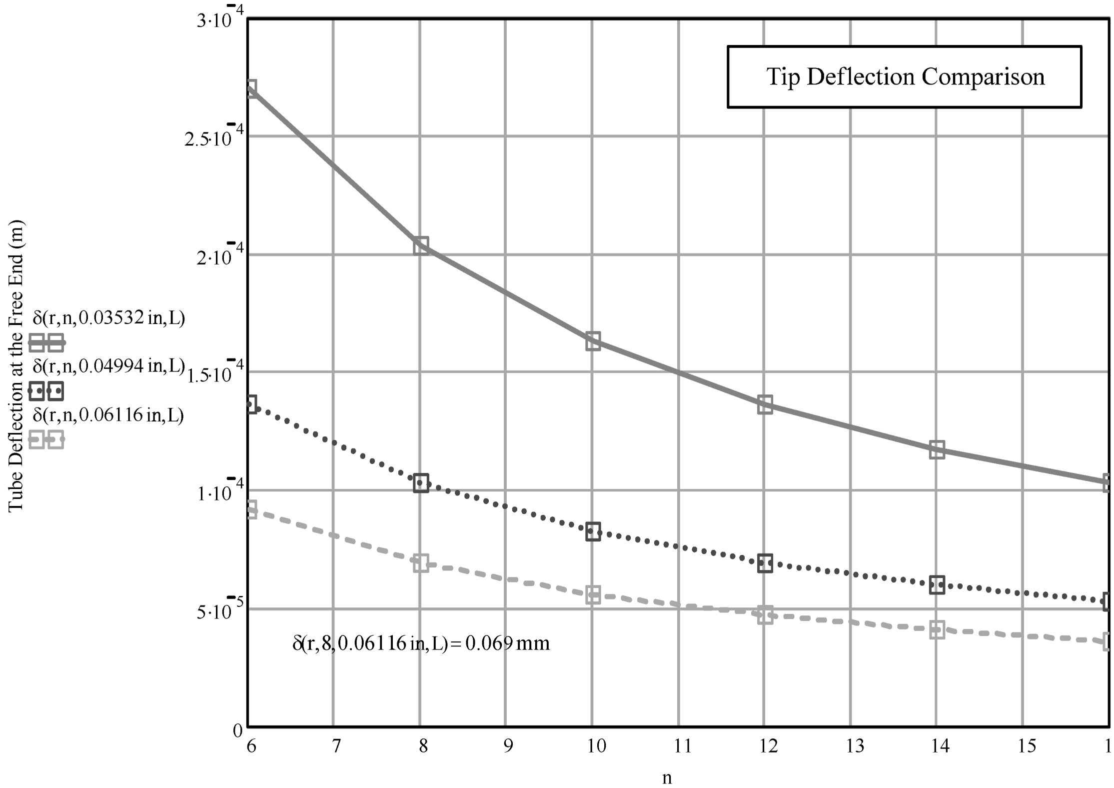

Fig. 16 Isogrid center column tip deflection comparison among three different tow diameters.

choice for the rigidization mechanism. This is because UV-curable resins require little spacecraft energy to cure and may provide the simplest design. The UV-rigidizable resin chosen for further development and testing was AP600-2 UV epoxy resin, recently developed by Adherent Technologies. The resin has a glass transition temperature T_g of 211°C, well above the required operational temperature. It can be cured from UV energy from the sun in approximately 10–45 min, depending on shadowing effects, material thickness, and the UV transparency of the material. The uncured composite fabric (prepreg) coated with the UV epoxy resin must be heated to at least −20°C before deployment and rigidization.

UV-Rigidizable Material Properties Testing

Outgassing Test

Outgassing performance was tested for the AP600-2 UV epoxy resin because of its importance in spacecraft application. Based on the PowerSphere system level requirements, the American Society

Table 1 Tensile properties test results

Resin	Fabric	Plies	Vf, %	Tensile Strength, MPa	Tensile Modulus, GPa	ASTM
AP600-2 UV epoxy	S-Glass 8HS	1	0.45	413.69	17.93	D3039
AP600-2 UV epoxy	S-Glass 8HS	2	0.48	497.80	14.82	D3039
AP600-2 UV epoxy	S-Glass 8HS	3	0.54	437.82	13.35	D3039
TP406 SMP[a] polyurethane	S-Glass 8HS	1	0.56	332.19	15.50	D3039
TP406 SMP polyurethane	S-Glass 8HS	2	0.60	377.83	13.64	D3039

[a]SMP, shape memory polymer.

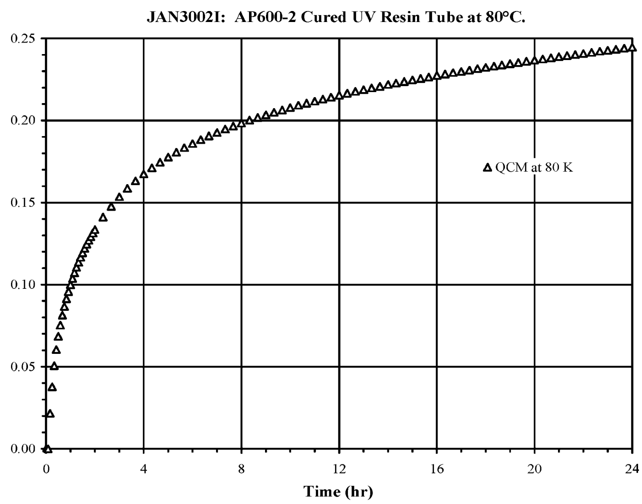

Fig. 17 UV resin percent total mass loss outgassing results.

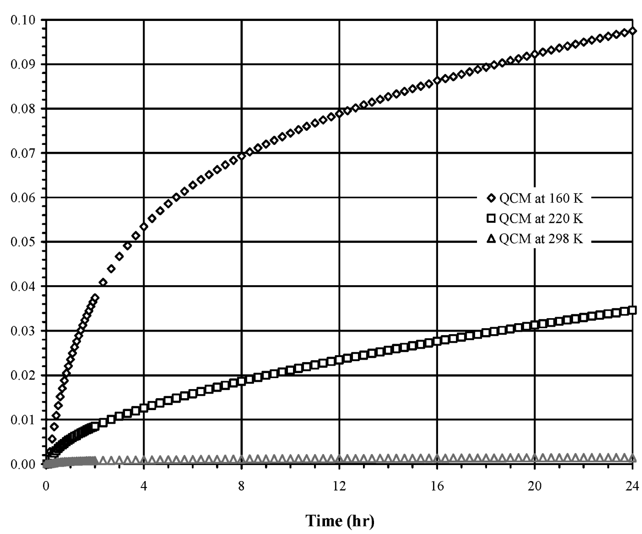

Fig. 18 UV resin percent collected volatile condensable materials outgassing results.

for Testing and Materials (ASTM) E1559 test was performed at 80°C for 24 h under hard vacuum, to simulate worst-case conditions for the material. The sample was fabricated as close as possible to the actual end-use application (an inflatable, rigidizable, deployable, UV/glass hinge). It was a 12.7-mm-diam, 5.1-cm-long composite tube with a $\frac{1}{2}$-mil-thick Mylar bladder and restraint. It was sunlight cured for 4 h, and it also had two 1.27-mm-diam venting holes in the restraint. Normally outgassing samples are baked out at a defined time and temperature to remove volatile materials before test. However, UV-rigidizable resins will not be able to be baked out because the resin would cure during the bake-out process. Because of this, the outgassing test sample was not baked out before the test. Test data from the AP600-2 UV-curable epoxy resin are summarized in Figs. 17 and 18.

Tensile Properties Test

The composite tensile modulus and strength test was performed on a 58 × 54 count, S-glass, 8 harness satin weave fabric impregnated with AP600-2 UV epoxy. The breaking strength of this fabric is 221 and 235 lb/in. in the warp and fill, respectively. Because there is only a 6% difference in the breaking strength between the warp and the fill, this was not considered significant, and therefore, the data presented here are considered an average of both the warp and the fill. The AP600-2 resin was tested in 1-, 2-, and 3-ply composites. Five samples of each were fabricated and tested to obtain statistical significance. All of the samples were cured under vacuum. The UV samples were cured in sunlight for approximately 5 h. Table 1 summarizes the results of the testing with representative materials for comparison.

Thermal Cycle Testing of UV-Rigidizable Material

Composite samples (1, 2, and 3 ply) were also fabricated from the 8HS glass fabric and the AP600-2 UV epoxy resin for thermal cycling tests. The samples were consolidated under pressure and sunlight cured for approximately 5 h. They were then thermal cycled from −138 to +100°C for up to 1000 cycles. After thermal cycling, the samples were cut into 1-in.-wide strips and tensile tested in accordance with ASTM D3039. From Figs. 19 and 20, it is apparent that there is some slight reduction in tensile properties after the thermal cycling. One of the visible effects of the thermal cycling was the yellowing of the composite. To determine the cause of this yellowing, a 3-ply sample was placed in a 100°C oven for 24 h and then examined. It was also tensile tested to determine any strength or stiffness loss. After the elevated temperature exposure, the color of the sample was similar to the color of the thermal-cycled samples. The results show that there is slightly more reduction in properties from elevated temperature exposure alone than from thermal cycling.

Inflation Material Trade Study

Given the objective of PowerSphere to be a small, low-cost, simple spacecraft, the use of a passive inflation method via a material's vapor pressure was researched. All materials have a specific vapor pressure at a given temperature. 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. It also does not require added spacecraft room as with a compressed gas bottle, for example. This can be used for the inflation of both the tubular hinge and the inflatable center column.

The inflation material search 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. Because of the smaller radius of the hinges compared to the center columns, the hinges can withstand greater pressure. Therefore, a different inflation material will be used for the hinge vs the center column. The minimum pressure needed in the hinge and the center column for inflation and

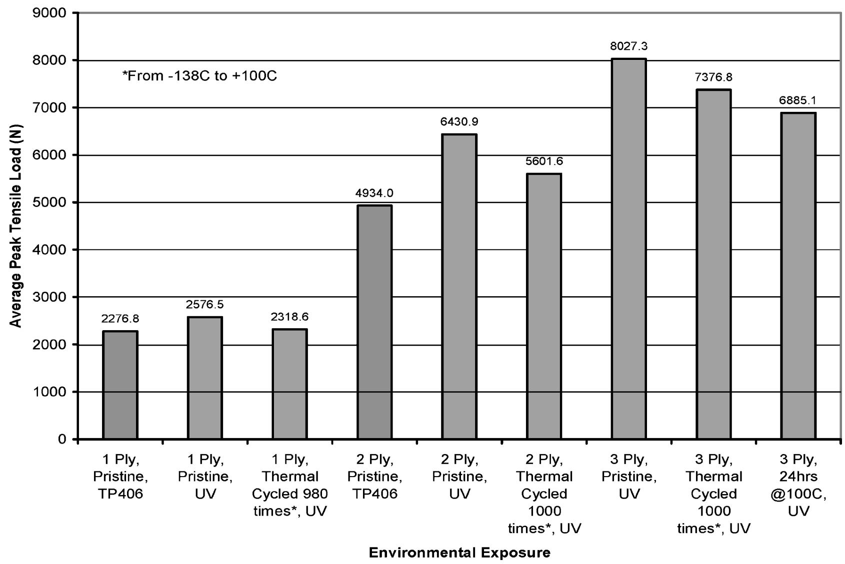

Fig. 19 Peak tensile load results from thermal cycling test.

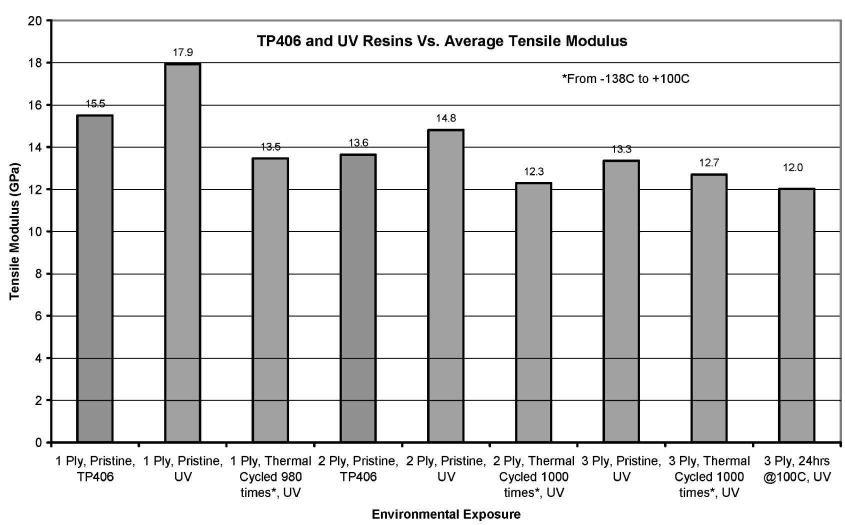

Fig. 20 Tensile modulus results from thermal cycling test.

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 center column 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.

The method of controlled deployment selected is a staged deployment approach that utilizes the passive inflation material to inflate and deploy the inflatable rigidizable center columns and hinges in two controlled stages. The inflation will start to occur as soon as outside pressure is less than the vaporization pressure of the inflation material. Therefore, both the column and the hinges must be restrained until deployment is ready. The center column will be held in the packed state by fuse wire. An electrical signal to the fuse wire will initiate the deployment of the center column. The hinges will be restrained by a fabric cover. The fabric cover will contain carpenters tape that will retract the cover once the cover tie down is released, thus, allowing the full inflation of the hinges and deployment.

Summary

Significant progress has been accomplished through the systematic development, design, analysis, and testing of various technologies that make up the multifunctional UV-rigidizable inflatable structures for the PowerSphere application. Both types of structures investigated have been proven to be feasible. A fully assembled engineering unit for the thermal vacuum chamber deployment test is planned for the next phase.

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