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# Spiral Wrapped Aluminum Laminate Ridgidization Technology

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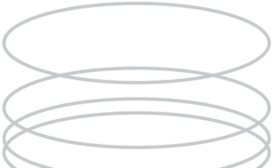

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# SPIRAL WRAPPED ALUMINUM LAMINATE RIGIDIZATION TECHNOLOGY

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## Abstract

Aluminum Laminate is the most mature space inflatable / rigidization technology; it has been flow on the early echo balloons in the 1960s and most recently on L'Garde's Orbital Calibration Sphere in 2000, all with very successful results. Several recent programs at L'Garde have further developed and enhanced the technology, the enhanced ITSAT solar array, and the Techsat 21 deployable boom (Figure 1). The structural performance of the design has been significantly improved with the addition of an external helically wound filament to absorb the hoop stress during rigidization. A new sheath deployment technique, developed for Techsat 21 program, offers a unique and mass efficient way to controllably deploy a structure incorporating this technology. Though limited in thickness, this rigidization technique has many uses for small to medium sized structures. L'Garde has designed, fabricated, and tested many tubes incorporating this new design. This paper will review the history of aluminum laminates at L'Garde, discuss the design of the new tubes, and finally review the mechanical test data gathered during its development. Using empirical techniques, a method will be outlined to predict the structural performance of these new spiral wrapped aluminum laminate tubes.

Figure 1. Inflatable Solar Array and Sheath Deployment

## Introduction

The system consists of a laminate of "0" condition aluminum (normally 0.003 in thick) "sandwiched" between two layers of a thin plastic film (0.001 in thick Kapton). The laminate is used to fabricate tubes that can be packaged for volume efficient stowage. The tubes are deployed by inflation and rigidized by over-pressurizing to yield the aluminum. The over-pressurizing permanently strains the aluminum removing packaging wrinkles and work-hardens the aluminum. The rigidized tube becomes a thin-walled monocoque structure.

The Aluminum Laminate system was flown most recently in 2000 on L'Garde's Optical Calibration Sphere, Figure 2. This structure was flown in LEO for a year and utilized by the Air Force to calibrate optical tracking systems. The 4.6m sphere was deployed and rigidized on orbit and provided a highly specular optical reflection for the life of the mission thus space validating the material and rigidization concept.

Figure 2. L'Garde's Optical Calibration Sphere

During L'Garde's ITSAT inflatable solar array program (left side of Figure 1) the aluminum laminate concept was further validated by deployment and testing in a thermal vacuum chamber. The complete structure was deployed,

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rigidized, and thermally cycled to simulate the space environment. Additionally, dynamic testing was conducted to validate predictions and mission goals. The system passed these and other post-flight qualification and acceptance tests with complete success.

The aluminum laminate rigidization system has distinct advantages over other resin/composite rigidization techniques. The system requires no specific thermal environment for deployment and can be deployed and rigidized in extreme hot or cold conditions. The system requires no additional power for deployment; it requires only the internal pressure for rigidization. Further, the system requires no MLI (Multi Layer Insulation) for thermal control. When properly designed, with emissive internal surfaces, incident energy is quickly distributed throughout the structure keeping thermal gradients and associated geometric distortions to a minimum. This rigidization system has no out-gassing and is highly resistant to the space environment hazards such as atomic oxygen and radiation.

The improvements of this new design are illustrated in structural test results shown in Figure 3. On the Y-axis are the loads at which the tubes buckled, on the X-axis are the lengths of the tubes. The solid horizontal line represents the load at which a 5" tube fails in local buckling, this load is unaffected by the tube length and remains constant. The curve on the right represents the Euler buckling failure load, as the tube becomes longer it will fail at a lower load due to imperfections in the tube causing the tube to bend. The performance of several L'Garde tubes are shown on the chart, however, it is clear our new spiral wrap design tube is superior and demonstrates load carrying capabilities significantly higher than our previous tubes.

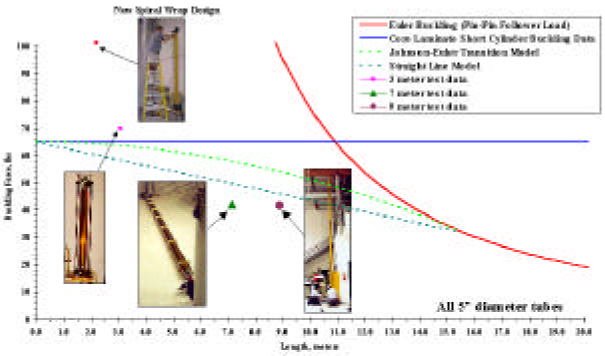

Figure 3. Aluminum Laminate Tube Development

Strengths not withstanding, the system has some limitations. The aluminum core of the laminate is limited to 3mils in cross section; in greater thicknesses, packaging damage can occur to the laminate resulting in surface distortions and inflatant leaks. While highly applicable to small and medium sized structures the system is not scalable to very large structures requiring individual element compressive loads in excess of 100 lbs. This scaling limitation can be extended through the use of multi-element truss structures.

While the thickness limitation is constraining for highly loaded structures, the ability to fabricate very thin aluminum laminate films is a great advantage. Composite fabrics are made up of fiber toes, which are typically about 3 mils in diameter. Thus, lightly loaded structures, not requiring thick wall structures, can benefit from the thin aluminum laminate and achieve high strength for less mass than the thicker walled composite fabric structures. An example of both an ultra-thin walled structure, and a multi element truss configuration is shown in Figure 4. This aluminum laminate truss configuration, designed to support large solar sails, can support a 30.0 lb. compressive load while achieving a lineal mass of only 114gms/m. This particular laminate contains only 1.2mils of aluminum, a thickness difficult to achieve with a continuous composite fabric weave.

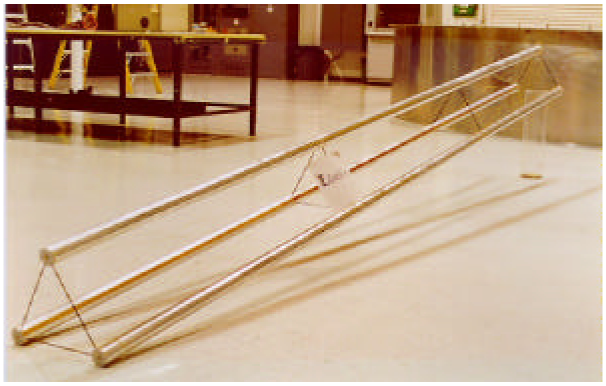

Figure 4. Aluminum Laminte Truss

The high relative stiffness of the aluminum complicates controlled deployment, however reliable techniques are available. ‘Z’ Fold packaging of aluminum laminate tubes has been demonstrated many times at L’Garde, both in ambient conditions and space chamber tests, and is the preferred deployment method for aluminum laminate booms. The structure is simply folded back and forth resulting in high packaging efficiencies and reliable deployment. Inflation of the Z-folded package results in reliable deployment however the passively constrained structure exhibits a large deployment envelope. A new hybrid deployment technique has been developed at L’Garde to supplement the deployment techniques to include a highly controlled sheath deployment method. This system utilizes a low mass Mylar sheath around the Z-folded tube to constrain and control deployment of the aluminum laminate structure. An example of this technique is shown in Figure 5.

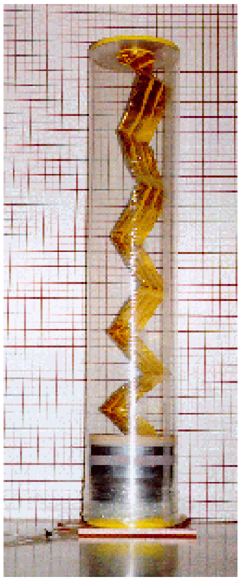

Figure 5. Sheath Deployment

Other deployment techniques have been researched and evaluated. A direct mandrel deployment technique has been tried with limited success. Deployment around the mandrel causes high localized stress points in the laminate resulting in damage to the film. Additionally a roll-up packaging and deployment of the laminate has been tried. The roll-up technique creates longitudinal deformations in the laminate that cause residual bowing in the deployed structure impacting the geometric straightness of the final configuration. It should be noted that alternating the roll direction of subsequent deployments has been shown to reduce this effect by an order of magnitude over multiple roll deployments in the same orientation. However, even small straightness distortions in the final deployed structure can severely limit the Euler buckling characteristics limiting the applicability of this deployment technique to shorter tubes only.

## Spiral Wrapped Tube Design

The most notable of the recent developments is the incorporation of a high modulus helically wound reinforcement filament around the external surface of the structure. This filament reinforces the hoop direction of the tube improving the rigidization process, structural efficiency, and greatly increases the burst margin.

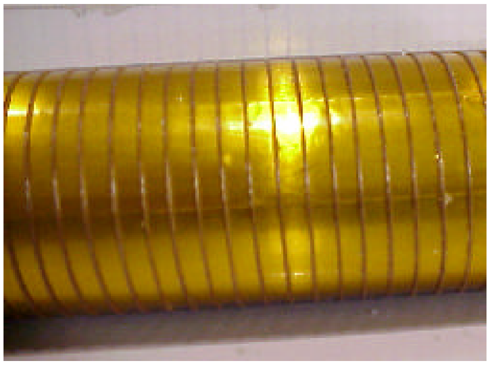

Figure 6. Reinforceing PBO Filament

Due to the mechanical characteristics of an inflated tube, the hoop stress is double the longitudinal stress in the tube. Thus during the rigidization process the limiting stress was dictated by the hoop stress in the material, the aluminum was yielded in the hoop direction but the corresponding stress in the longitudinal direction was not enough to fully yield the aluminum. Wrinkles created during packaging were not fully removed in the longitudinal direction and the tube was not as geometrically precise as possible. By incorporating the spiral wrapped filament around the outside of the tube the hoop stress is absorbed by the filament allowing higher rigidization pressures in the tube and fully yielding the material in the longitudinal direction. The result is a tube with a smoother surface and improved geometric precision.

An intriguing by-product of the rigidization process of the spiral wrapped aluminum laminate tubes is the so-called "Michelin Man effect". This phenomenon occurs as the aluminum layer between the spiral reinforcements yields slightly in the hoop direction and leaves doubly curved bulges between the filaments, Figure 7. Initially it was thought that these bulges would negatively effect the compressive local buckling of the structure, and cause premature buckling. Tests have shown this not to be the case and in fact the tubes are now more capable of handling compressive load than the non-reinforced tubes.

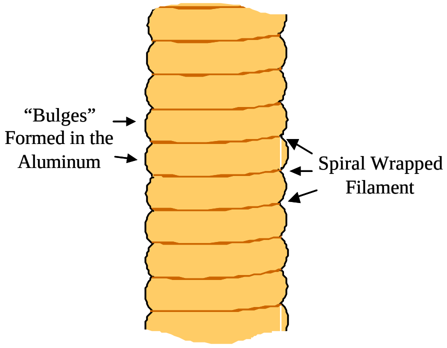

Figure 7. "Michelin Man" Effect (Greatly Exagerated)

The complex mechanical interactions between the filament reinforcement and the aluminum laminate are not researched in this paper. For further information please review reference 1.

## Geometric Stability

It is very important for a structural tube in compression to maintain it's circular cross-section. Any distortion in this cross-section reduces the load carrying capacity of the wall. Previous aluminum laminate designs have exhibited a cross-sectional distortion by flattening and becoming elliptic. This phenomenon is caused by several factors but has been eliminated in the new reinforced design.

The flattening of the cross section in the non-reinforced laminate was greatly contributed to by the seam configuration. Since the hoop stress of the un-reinforced tubes was born by the seams in the laminate, it was important to include a layer of aluminum. Since the yielding aluminum absorbs some of the stress in the laminate during rigidization, it was required to include a layer in the seam to help support the Kapton. This thick seam resulted in a significant thickness and stiffness discontinuity in the perimeter of the tube wall and was a natural place for any geometric distortions caused by internal stresses to manifest themselves. Often after rigidization, the seams would flatten and cause the tube cross-section to become "oval". As the reinforcing filament in the spiral wrapped absorbs the hoop stress, the aluminum layer in the seam is no longer required. The new seams consist of a thin layer of Kapton on the inside to provide a pressure barrier, and a similar seam on the outside to support the edge of the laminate and maintain continuity.

A second feature of the new design that provides cross-sectional stability is an interesting by-product of the "Michelin Man Effect". The bulges created by this effect create a doubly curved surface around the perimeter of the tube acting like ribs supporting the circular cross-section. Additionally the added stiffness of the adhesive coated filaments adds to this effect. Long-term test samples at L'Garde have maintained their cross-section circularity to within a few percent.

Another advantage of the spiral wrapping is increased burst margin or the ratio of burst pressure to rigidization pressure. Previous tubes had a burst margin of only 1.5 and could fail catastrophically when over pressurized. The new spiral wrapping brings the burst margin to more than 3.0, and, equally as important, fails gently by leaking at the endcaps and not bursting catastrophically.

## Fabrication

A 2.5" diameter aluminum laminate spiral wrap tube is shown during construction in Figure 8. The external wrapping is visible on the outside. The tube is fabricated from a 0.5 mil Kapton, 3.0 mil aluminum, 0.5 mil Kapton laminate. The laminate material is wrapped around a mandrel with 0.5" wide, 0.5 mil Kapton seams mounted at 180 degrees apart bonded on the inside and outside of the tube. Around the outside a PBO cord is helically wrapped. The fixture used to provide the precise wrapping pitch is also visible in Figure 8, a lead screw on the right of the tube is geared to provide the proper carriage travel for the wrapping as the mandrel is rotated. Adhesive is applied to the cord as it is wrapped around the mandrel to bond it to the outside of the laminate.

Figure 8. 2.5" Diameter Spiral Wrap Tube

## Structural Tests and Analysis

A series of tubes of varying geometries utilizing the new spiral wrap technology have been mechanically tested at L'Garde. Shorter tubes have been tested to characterize the local buckling characteristics and longer tubes have been tested to characterize the Euler or long-column buckling characteristics. Two of the test setups are shown in Figure 9. L'Garde's tensiometer is used to test the shorter tubes as shown on the left, and a larger apparatus is used to test the longer tubes as shown on the right.

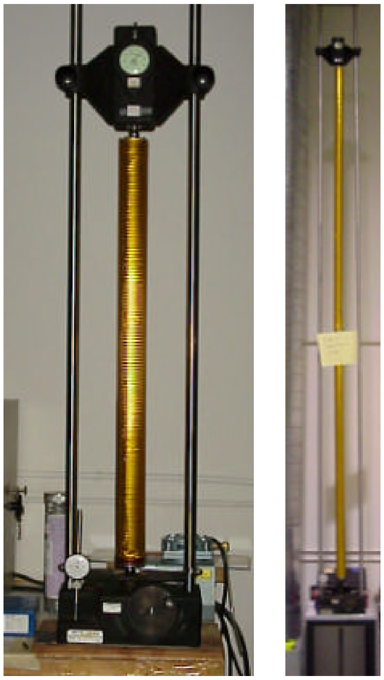

Figure 9. Compression Test Setups

A matrix of the spiral wrapped aluminum laminate tubes tested to date at L'Garde is shown in Table 1. Numerous geometries have been tested in support of several programs. Also shown in the table are the measured buckling compression loads measured during the tests.

Table 1. Compression Buckling Test Results

| Diameter (in.) | Length (in.) | Buckling (lbs.) | Std. Dev |
|---|---|---|---|
| 2.5 | 32 | 50* | 5 |
| 5.0 | 32 | 105 | - |
| 5.0 | 72 | 105 | - |
| 5.0 | 81 | 112 | - |
| 2.5 | 86 | 50* | 5 |
| 4.0 | 93 | 72 | - |
| 2.5 | 139 | 39.5* | 0.71 |

* Denotes average of multiple tests, standard deviation noted

The tubes were folded to simulate stowage for launch before testing. An example of a packaged tube is shown in Figure 10.

Figure 10. Packaged Tube

Using the compression setup shown, the tubes were compressed until buckling occurred. During Euler buckling tests the tubes failed toward the middle of the tubes with the classic diamond shape distortions, see Figure 11. Interesting to note that generally the major axis of the buckling diamond corresponded to the location of a reinforcement filament wrap.

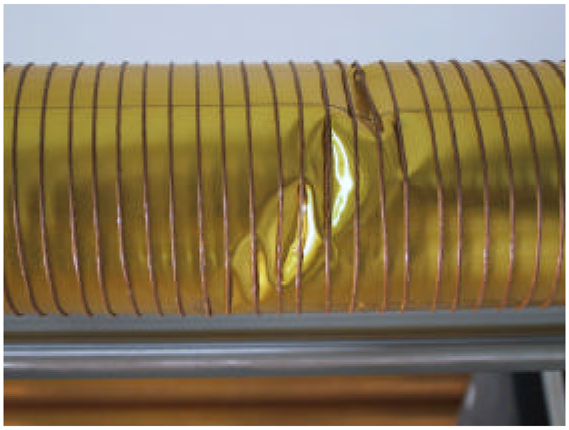

Figure 11. Euler Buckling

### Compression Data Analysis

In predicting the compressive strength of the stretched aluminum tubes, we use three curves. The Euler Buckling Curve (for a following load) is defined by the equation [Ref 2]:

$$P_E = \frac{p^3 E t r^3}{L^2}$$

E = Young's Modulus (For Al = 10 mpsi)
t = thickness = .003 in.
r = radius

L = length

The local buckling curve is defined by the NASA equation for thin walled tubes [Ref. 2] and is:

$$P_L = g_C g_n g_L 2pEt^2$$

where

$$g_C = 1 - 0.901(1 - e^{-q}) \approx 0.3$$

$$q = \frac{\sqrt{\frac{r}{t}}}{16}$$

$$g_n = \frac{1}{\sqrt{3(1-n^2)}} \approx 0.6$$

$g_L = 0.326r$ (L'Garde correction, see text)

with ν = Poisson's ratio

The NASA report predicting the buckling load of thin walled tubes was based on a large test database of extruded thin walled tubes. While of similar thicknesses to the inflatable aluminum laminate tubes they do not include the Kapton sandwich or spiral wrapping, and they were not packaged and deployed. Because our tubes are not made from homogenous thin aluminum, we do not expect to have the same results as predicted by the NASA data. We have incorporated a L'Garde correlation factor into the NASA equation. This factor, which we have taken as 0.434r, was determined empirically using our in-house test data.

The third curve, the Johnson-Euler Transition [Ref. 3] curve takes into account the transition area between the short column local buckling failure mode and the long column Euler buckling load. These failure modes are not independent of one another and structurally interact in this region. This curve is defined by:

$$J.E. = P_L - \frac{(\frac{P_L}{2})^2}{P_E}$$

These three curves, when developed for the length of interest, define the expected compressive load carrying capability as a function of tube diameter (Figure 12). This provides a very useful tool for implementing designs that incorporate inflatably deployed and rigidized stretched aluminum boom system. The curves define the expected failure point so an appropriate safety should be used with these curves when designing the boom system.

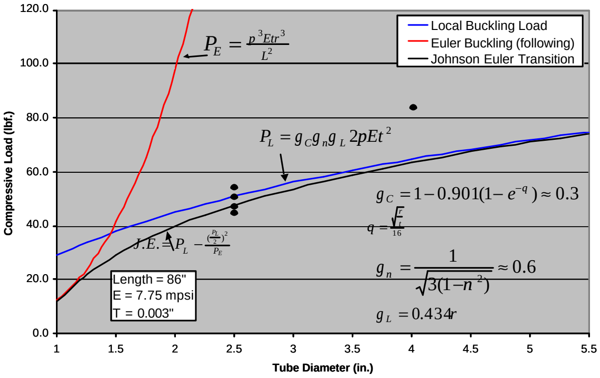

Figure 12. Buckling Pedictions

By utilizing the L'Garde correlation factor the predicted data more closely matches the test data. The match is very good for tubes of the 2.5" diameter and wanders significantly for larger diameters but remains conservative. These correlation factors and design curves are meant to aid a potential user in utilizing these tubes given a set of loading requirements. Once a tube diameter is selected, further testing on the specific configuration should be conducted to validate predictions.

## Bending Tests

Many tubes were subject to a bending test to validate predictions. The bending tests utilized L'Garde's tensiometer as shown in Figure 13. The tube was firmly mounted to the wall with a large plate to ensure proper fixity at the base. The tensiometer applied a known deflection and load through the fixture attached to the end of the tube in the foreground. The tensiometer measured and recorded the load and deflection at the end of the tube during the test.

Figure 13. Bending Test Setup

The results of the bending buckling test are shown in Table 2.

Table 2. Bending Test Results

| Diameter (in.) | Length (in.) | Buckling (in*lbs.) | Std. Dev |
|---|---|---|---|
| 2.5 | 32 | 50* | 5 |
| 5.0 | 32 | 437 | - |

* Denotes average of multiple tests, standard deviation noted

Bending Data Analysis

In predicting the bending strength of the stretched aluminum tubes, we again based our analysis on the NASA report [Ref 2]. The tubes we tested were consistent but were not as strong in bending as the extruded thin walled tubes compiled in the NASA tests. To aid a user in predicting the bending strength of the aluminum laminate tubes L'Garde developed an empirical correction factor based on our test data. The equation used, including the L'Garde correlation factor is:

$$M_B = \frac{l_{LB} s_Y r}{I_Z}$$

where:

$l_{LB} = 0.7\sqrt{r}$ (Bending correction factor)

$s_Y = Yield\ Stress$ (6000psi Aluminum)

A comparison of the above prediction technique and limited bending test data are shown in Figure 14. Again, the comparison is quite good at the smaller diameters and wanders for larger diameters, though remains conservative.

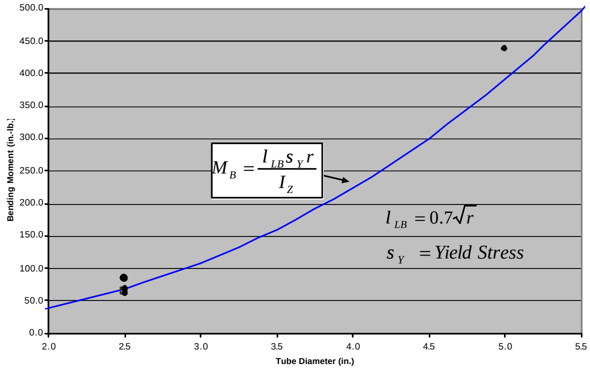

Figure 14. Bending Test Results vs. Predictions

Multiple Rigidization Cycles

A major concern of all spacecraft Program Managers is the ability to "test what you fly, and fly what you test." L'Garde subscribes fully to this test of flight hardware philosophy and, as such, has pursued reversible or at least testable rigidization concepts almost exclusively. In the case of the aluminum laminate tube concept, the process is not truly reversible, however, it is testable. The aluminum laminate tube can be packaged, deployed, rigidized, and buckled several times without significant degradation in its compressive strength. To demonstrate this, we performed axial compression tests on two 4-in diameter samples after repeated packaging, deployment, and rigidization cycles. The results are shown in Figure 15. In each case, we experienced only a 25% drop after repeated cycles.

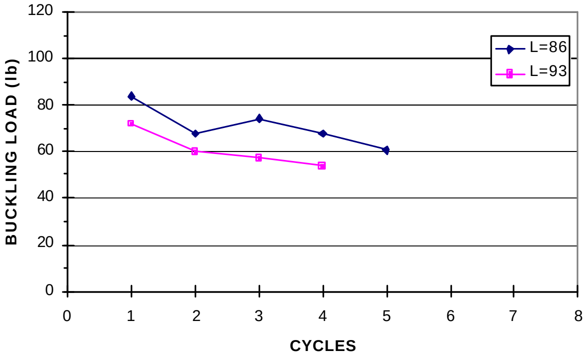

Figure 15. Rigidization Tests

It should be noted that in each case of the above tests the tube was compressed to buckling failure, in subsequent rigidization / buckling cycles the tube would generally fail in the same location. For a flight system it would not be necessary to fully buckle the structure during pre-flight testing, it would only have to demonstrate the ability to support the flight loads with some appropriate safety factor. Though not specifically tested, it is intuitive that the structural degradation of subsequent cycles would be greatly reduced.

Mass Predictions

The Aluminum Laminate with 0.2" pitch filament winding weighs 0.1 oz / in2, an appropriate endcap to complete the pressure seal and transfer loads to the laminate shell weighs about 0.05 oz / in2. Once the tube geometry is selected, the mass of the deployable tube can be calculated from the above areal densities.

## SUMMARY AND CONCLUSIONS

The aluminum laminate rigidization system is the most mature of the rigidization technologies. It was utilized as far back as the early 1960's on the early Echo balloon experiments, and was flown as recently as 2000 in L'Garde's OCS mission.

The technology has been significantly enhanced recently with the incorporation of a helically wrapped filament to absorb the hoop stress during rigidization. The new tube design allows a higher rigidization pressure to improve removal of packaging deformation resulting in a more geometrically precise and robust structure. The rigidized tube is stronger and more precise than previous designs and withstands higher compression loads of up to 100 lbs for a single element. The burst margin has been increased significantly, additionally; the burst failure mode is no longer catastrophic but a predictable release of pressure near the endcaps. The unique "Michelin Man" bulges present after rigidization stiffen the cross section and exhibit greater geometric stability.

A new hybrid mandrel deployment method has been developed allowing a highly controlled and predictable deployment envelope. However, the passively constrained Z-folded deployment remains the simplest and most mass efficient technique.

Results of mechanical testing at L'Garde of a number of tube geometries have been compiled and presented. An empirical technique for predicting the compressive and bending performance of the new spiral wrapped tubes has been developed and outlined. This technique will aid the prospective user in designing struts for mission specific applications with some confidence.

The aluminum laminate rigidization technique is the most mature of the rigidization technique and has been validated both in space and on the ground. It requires no specific thermal environment for deployment and for most applications doesn't require MLI for thermal and geometric stability. It requires no additional power for rigidization but utilizes only the inflation pressure needed to yield the thin aluminum shell. While limited to small and medium sized structures, it is one of the simplest and most elegant solutions to the requirements of space rigidization of ultra-lightweight deployable structures.

## ACKNOWLEDGEMENTS

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