Abstract—Increases in satellite launches over the next few decades will emphasize reduction of hardware mass, stowage volume and costs. Inflatable space structures offer benefits over current mechanical technologies and are principally attractive because they provide reduced mass and can be packaged into small volumes, thereby reducing launch vehicle needs. Reduced costs are realized in development and production as well as in enabling smaller launch vehicle size.

One program that may benefit from this technology is the Next Generation Space Telescope (NGST) planned for launch in 2007. The NGST is a NASA Origins program whose goal is to observe the first stars and galaxies in the Universe. The NGST will detect 0.6 to 20 micron wavelength radiation, seeing objects 400 times fainter than those currently studied with ground or space-based infrared telescopes, all with a spatial resolution comparable to the Hubble Space Telescope.

The Next Generation Space Telescope will be constructed using deployable structures since the maximum size of the rocket shrouds likely to be available will not accommodate the full mirror or sunshield. Current designs of NGST have a large deployable sunshield (on the order of 200 m²) thermally insulating a large telescope, keeping vital detector temperatures to below 60 K.

As a precursor to the flight telescope, NASA has begun a technology validation program to prove the merits of a large deployable structure. The Inflatable Sunshield In Space (ISIS) Experiment is currently under development and planned to be flown on a Space Shuttle Mission in mid-year 2001. ISIS will demonstrate a controlled deployment of a large sunshield enabling it to stay out of NGST’s "zone of exclusion" which guarantees that the sunshield will not disturb the optics or systems of NGST. In addition, ISIS will demonstrate in-situ rigidization of a thermoset composite structural frame utilizing a resistive heating circuit. This paper will describe the status of the ISIS sunshield development. Objectives for the flight experiment are discussed in detail and developments in in-situ rigidization methods and controlled deployment in relation to the telescope are also presented.

1. INTRODUCTION

The ISIS experiment will demonstrate the feasibility of using inflatable technology to provide a spectral light cover and passively cool optical systems for the NGST. The experiment will also develop test data for correlation of analytical models. It is a scaled model of a proposed NGST sunshield that will demonstrate the controlled deployment and subsequent rigidization of an inflatable structure in space. Figure 1 depicts the ISIS experiment as it will deploy the subscale sunshield off of a mast that will extend from the Shuttle Cargo Bay. The telescoping mast provides a separation distance between the sunshield experiment and the orbiter.

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Figure 1 ISIS Deployed from Shuttle Cargo Bay

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1 0-7803-5846-5/00/$10.00 © 2000 IEEE
2. SUNSHIELD SYSTEM

The sunshield configuration, established by Goddard Space Flight Center (GSFC), is shown in Figure 2. It consists of four diamond-shaped membrane layers mounted to a central rectangular rigid container. The layers are 0.013 mm thick aluminized polyimide film. They are not parallel to each other, but fan out at a slight angle relative to each other. This geometry is selected for its ability to laterally emit radiation that passes through the successive layers.

Four cylindrical booms cantilevered from the central container support the assembly in a cruciform arrangement. These support booms are the heart of the new technology being demonstrated by the ISIS experiment. Before deployment, they are flexible tubes made of an uncured thermoset composite laminate. After deployment, they are rigidized so that they do not require continued pressurization to support the sunshield.

In the stowed configuration, the sunshield's membranes are folded “accordion style” in two sets of two membranes that are packed against two shelves mounted to the central container. They are secured during launch by lightweight compression plates and polyimide foam that are released upon initiation of deployment. The booms, rolled up and mounted to the central container, are likewise secured for launch and are released prior to inflation by a paraffin-actuated mechanism. Figure 3 depicts the stowed ISIS configuration. The central container and all launch tie and release systems are being designed and fabricated by GSFC.

Inflation gas at 25.5 kPa is introduced into the base of the two lateral booms first. These booms then unroll in much the same way as the familiar party favor. A device mounted on the tip of each boom provides the roll-out resistance necessary for controlled deployment and beam stiffness of the inflating tube. As the booms deploy in a slow, controlled fashion, they pull the stowed membranes from stowage clips that ensure their orderly release. This prevents excess membrane material from becoming entangled with other spacecraft components. A lightweight spreader assembly on the end of each boom tensions and separates the membrane layers at their corners. Constant force springs in the spreaders apply approximately 69.0 kPa longitudinal and 34.5 kPa lateral stress in the membranes across their widest sections. Following the complete deployment of the lateral booms, the longitudinal booms are deployed in the same fashion.

After the sunshield is completely deployed, rigidization is accomplished by applying power to flexible resistive heaters that are integral with the composite laminate in the booms. Based on thermal vacuum testing with an effective $\varepsilon^*$ of 0.7 of the Multi-Layer Insulation (MLI) surrounding each boom, the heaters, applying 35 W/m$^2$, will require about 25 minutes to bring the booms to the cure temperature of +125°C to +149°C. They will be held at this temperature by active control for 45 minutes while the booms fully cure. Power required to maintain cure temperature, verified by test, is 20 W/m$^2$. The total energy required for warm-up and cure of all four booms is <<1 kW-hr. After the 45 minute cure, power is removed and the booms are allowed to cool to less than +90°C before the inflation gas is vented. This ensures full composite strength and stiffness in the booms before they are required to support load as unpressurized beams.

Following deployment, cure, cool-down, and venting, the ISIS experiment will conduct dynamic testing of the sunshield. Inertial loads will be applied to the sunshield by the orbiter’s Primary Reaction Control System (PRCS). The response of the sunshield will be monitored by accelerometers on the boom tips and video recording.
When dynamic testing of the sunshield is complete, it will be released from the orbiter at the base of the mast and the orbiter will be maneuvered away from it. The sunshield will then deorbit, concluding the ISIS experiment.

3. Sunshield Membranes

The design of the four sunshield membranes is straightforward, as their geometry is relatively simple. While almost flat, they are in fact very shallow eight-faceted surfaces. They are made of .013 mm Kapton® VN polyimide film and are spaced 2.54 cm apart at the container interface and 15.24 cm apart at their tips. The same spacing is maintained between the inner membranes and the booms. The outer two membranes are Vapor Deposited Aluminum (VDA) coated on one side only. The VDA side faces inward, toward the boom. The bare sides face outward, toward space and the orbiter cargo bay. The inner two membranes are VDA coated on both sides.

GSFC thermal analysis of this configuration was performed for a variety of possible beta angles and orbiter attitudes. It is believed that beta angle = 0 and bay-to-wake attitude are the most likely conditions for ISIS. Under these conditions, a maximum membrane temperature of +223°C is predicted to occur on the third membrane and a minimum membrane temperature of -88°C is predicted to occur on the second membrane. Membrane seams are designed to carry the specified membrane loads at these temperatures, with safety margin. Thermal analysis of the membranes was also performed by the Technical Alliance Group (TAG) of La Canada, CA under subcontract to ILC Dover, Inc. The results (Figure 4) were in good agreement with thermal analysis performed by GSFC.

Membrane Patterns

The membrane patterning locates seams along the edges of the faceted surfaces. Membrane pattern layout is shown in Figure 5. This arrangement distributes seams symmetrically about the membranes, minimizing uneven membrane tensioning due to uneven distribution of the higher modulus seam areas. Some additional seams are required to accommodate material width limitations. The membrane tips terminate with cords that are attached to it in a circular arc as shown, uniformly distributing load into the membrane. These areas have a higher concentration of membrane load and are therefore reinforced with ripstop tapes.

Membrane Seams

The minimum membrane tensioning requirement of 69.0 and 34.5 kPa in the longitudinal and lateral directions respectively, is derived from a study performed by Dr. Martin Mikulas of the University of Colorado. This study defined an optimum compromise between membrane tension needed to flatten wrinkles due to folding while avoiding excessive loading of the support booms. In a 0.013 mm thick film, this represents a skin load of 0.876 N/m longitudinally and 0.438 N/m laterally. The membranes are loaded to achieve these minimum values at the widest sections of the sunshield. Maximum skin stress
occurs at one longitudinal tip where the width is narrowest. Here skin stress becomes as high as 12 N/m.

The membrane panels are joined with butt & taped seams using 25.4 mm wide x 0.013 mm thick polyimide tapes on both sides held with silicone pressure sensitive adhesive (PSA). All membrane seams have demonstrated strengths of at least 175 N/m at 220°C in elevated temperature dead load testing. While the two sided seam tape provides much more than the required strength at temperature, it is selected over single sided taping for its resistance to peel initiation during folding.

Membrane Tips

A Vectran® cord, captured in a concave circular arc, forms two loops for cord attachments to the constant force springs in the boom tip spreaders. A circular arc is selected over a true parabolic catenary because it is desired to distribute load into the membrane biaxially. The arc is sized and positioned such that forces balance at the attachment points without any tendency for the membrane to spread apart or to collapse inward.

All membrane panels are required to be electrically grounded to the central container, not only to eliminate arcing potential, but to minimize static attraction between membranes. Electrically conductive adhesive tapes cross the membrane seams at various locations, electrically connecting panels to each other and to the aluminum frame that joins them to the central container.

The membranes and booms are sized to accommodate the thermal expansion and contraction that will occur in the membranes over the expected -88°C to +223°C temperature range. The Coefficient of Thermal Expansion (CTE) of polyimide is not uniform over this range and had to be taken into account in this sizing. The longest container-to-tip distance will contract 1.27 cm and will expand 5.33 cm. The nominal membrane/spreader offset of 7.62 cm and corresponding stroke of the constant force springs that tension Vectran® cords from the spreader to the membrane tips more than compensate for the membrane CTE.

A requirement to prevent tears greater than 30.5 cm long is met by the tear resistance of the polyimide film. Tear tests on this material indicated that a skin load of 45.5 N/m is required to propagate a pre-existing 15.24 cm tear positioned normal to the load. Since the actual maximum skin load is 12 N/m, applied load would have to exceed the expected maximum by 3.7 times in order to propagate such a tear. Nevertheless, a ripstop tape was added to one side of the material in the tip areas to provide additional tear protection in these highest loaded areas.

Membrane Folding

Membranes are folded in paired sets as shown in Figure 7. Membranes are accordion folded with 22.9 cm wide segments in the reverse order in which they are deployed. The projected thickness of the resulting stack of folded membranes varies from 0.20 mm to 4.25 mm, depending on location. These variations are compensated for in the thickness of the polyimide foam on the compression plates that secure the stowed membranes during launch.

Figure 6 Membrane Folding

Membrane Mass

Projected mass of each membrane layer is 645 grams for a system total of 2.58 kg for all four layers. Approximately 70% of this is the 0.013 mm VDA coated polyimide panels themselves. The remaining 30% is the mass of the seam tapes, ripstop tapes, electrical jumpers, reinforcements, and attachment cords.

4. Sunshield Booms

Boom Requirements

Performance requirements and goals for the four booms that will support the ISIS sunshield include:

* Inflation deployed
* Capable of deploying stowed membranes
* Rigidizable
* 4.0 safety factor over applied inertial loads after venting
* Controlled deployment within a line from edge of container +/- 6°
* 1.29 Hz first mode for longest boom
* Low mass
* >1.5 year latency @ RT prior to cure
* Rigidized geometry. Straightness +/- 16 mm for boom tip location. Maximum twist 2°.

Boom sizing is based on analysis of inertial loads that will be applied by 1/3 PRCS. This analysis assumed that the ISIS experiment would be mounted in Bay 9 and it used preliminary mass estimates of the sunshield components. The 1/3 PRCS translational and rotational accelerations about the orbiter CG and the geometry of the mast-mounted ISIS experiment were used to determine maximum moments and compressive loads in the ISIS booms. A maximum moment of 16.61 Nm is applied to the longest boom and the maximum inertially applied compressive load
is 3.169 N. In addition, there is the constant force spring load of 17.79 N for a total compressive load of 20.96 N.

Applying the 4.0 safety factor, the cured boom structural requirement becomes 66.44 Nm bending moment and a simultaneous 83.85 N compressive load.

The structural requirement for the inflated unrigidized booms is that they be capable of supporting the membrane tensioning load of 17.79 N and also any inertial loads that may be applied by the orbiter’s Vernier Reaction Control System (VRCS) if station-keeping firings are required before rigidization is completed. VRSC loads are a fraction of the 1/3 PRCS loads.

**Boom Components**

Each boom consists of a composite laminate cylinder, base and tip end caps, and an MLI assembly. The two lateral booms have the same length of 1.94 m. The shorter of the longitudinal booms is 4.21 m and the longer of them is 5.54 m long. The composite laminate cylinder sized to meet the above structural requirements has an outside diameter of 130.18 mm. A sectional view is shown in Figure 7 and a wall section including MLI is shown in Figure 8.

*Figure 7* Composite Laminate Sectional View

The composite laminate consists of three elements: the bladder, the composite prepreg, and the heater/restraint assembly. The bladder retains internal gas pressure and pushes the prepreg out against the heater/restraint. The composite prepreg is packaged soft and uncured, then is cured in situ to become the main structural element after cure is complete. The heater/restraint provides resistive heat to cure the composite prepreg. It also supports loads during deployment before rigidization. It is the element in the composite laminate that controls the final size and shape of the boom.

**Bladder**—The bladder is a layer of 0.025 mm Kapton® VN film. It is intended only as a gas barrier and not as a load-carrying element. For this reason, it is slightly oversized so that pressure loads are assumed by the outer layers. It is fabricated with two axial seams. One of them is used to close the tube; the other is placed 180° opposite from it to balance material thickness, mass and modulus in the assembly. The bladder accounts for 30.3 grams/meter of boom length.

**Composite Prepreg**—The composite prepreg layer is a 0.305 mm thick 12 x 12 square weave AS4 carbon fiber fabric impregnated with a high latency epoxy resin. The material has a 45% to 55% fiber volume fraction. Its low CTE of 1.8 x 10⁻⁶/ °C is excellent for thermal deflection minimization. Typical cured physical properties, measured by ASTM methods are:

<table>
<thead>
<tr>
<th>Property</th>
<th>Warp</th>
<th>Fill</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile Strength, Pa</td>
<td>6.83 x 10⁷</td>
<td>6.34 x 10⁷</td>
</tr>
<tr>
<td>Tensile Modulus, Pa</td>
<td>5.45 x 10¹⁰</td>
<td>5.45 x 10¹⁰</td>
</tr>
<tr>
<td>Compression Strength, Pa</td>
<td>2.21 x 10⁷</td>
<td>2.83 x 10⁷</td>
</tr>
<tr>
<td>Compressive Modulus, Pa</td>
<td>5.45 x 10¹⁰</td>
<td>5.45 x 10¹⁰</td>
</tr>
</tbody>
</table>

*Table 1* Cured Composite Physical Properties
The epoxy resin has a latency > 2 years at room temperature, but can be greatly extended with cold storage. Latency, or the useful life of the material prior to cure, is characterized by $\Delta h$ (enthalpy) energy released during the cure reaction. It is a measure of cross linking potential lost over time. Latency studies, currently in progress, are tracking $\Delta h$ of the uncured composite when stored at +20°C, +40°C, and +60°C. These studies have already confirmed useful life of more than 2 years when stored at +20°C.

The modulus of the cured composite drops off rapidly at temperatures above +90°C. For this reason, the booms will not be vented until after they have cooled below this value. Thermal analysis of the boom/MLI system indicates that the maximum post cure temperature reached as it cycles in and out of eclipse will be below this value. The prepreg accounts for 169.2 grams/meter of boom length.

**Heater/Restraint** — The heater/restraint layer is 0.051 mm Kapton® VN film. It carries the hoop load in the inflated boom. The inflation pressure, determined by the structural requirements of the inflated boom was determined to be 25.51 +/- 3.45 kPa. The tolerance on this pressure was based on the performance of space-qualified inflation system components. With a maximum inflation pressure of 28.96 kPa and a boom radius of 65.1 mm, the maximum hoop load is 1885 N/m. The 0.051 mm Kapton® VN film and the structural seam developed by ILC Dover have demonstrated strengths of 5254 N/m in +149°C dead load testing, or 2.8 times the maximum hoop load.

Integral with the restraint is a resistance alloy wire heater for prepreg curing. This type of heater was selected over a number of alternatives based on technical maturity, availability, and robustness. In order to bring the booms to cure temperature in a reasonable time and to have adequate power margin for the active control during cure, a heater capacity of 155 W/m² was baselined. Also baselined was an element layout where power is applied in parallel to elements over 180° of the boom circumference at the base end. All wires are connected at the tip end, and the circuit is completed at the base end on the remaining 180°. This arrangement was selected because it minimized the number of locations where any potential existed between adjacent heater wires (i.e., two) while only requiring power leads at the base of the boom.

To maximize heater design commonality, the two lateral boom heaters are wired in series so that they perform similarly to the heater in the shorter longitudinal boom, which is close to twice the length of the lateral booms. Based on this approach, heater wire alloy, wire diameter, and spacing were varied to achieve the required power density. Selection of wire spacing also involved the thermal conduction of the prepreg. This resulted in three heater assemblies (lateral 1&2, and 2 longitudinal) with approximately the same total resistance. The heater/restraint accounts for 91 grams/meter of boom length.

**Composite Laminate** — The composite laminate that comprises the boom includes the bladder, prepreg and heater restraint elements described above. The composite laminate mass totals 290.5 grams/meter of boom length.

It is very important to note that the composite laminate developed for use in the ISIS flight experiment was selected based on previously testing conducted on prototype boom assemblies. ILC is currently developing boom assemblies that will reduce the overall mass per unit length of the ISIS booms by 30 to 50% (including the insulation blanked).

**End Caps** — The boom end caps close the boom ends for gas retention, provide the structural connections at the base and tip, provide electrical connections, and provide the gas interface for inflation gas and pressure sensing. These parts are machined ULTEM® polyetherimide (PEI). PEI was selected primarily for its low thermal conductivity, which minimizes the rate at which heat will be lost through conduction at the boom ends. Its maximum operating temperature, tensile strength and low mass also led to its selection. See Table 2.

<table>
<thead>
<tr>
<th><strong>Density</strong></th>
<th>1.28 g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tensile Strength</strong></td>
<td>113,763 kPa</td>
</tr>
<tr>
<td><strong>Max Temperature</strong></td>
<td>+171°C</td>
</tr>
<tr>
<td><strong>Thermal Conductivity</strong></td>
<td>3.10 x 10⁴ cal-sec-°C</td>
</tr>
</tbody>
</table>

**Table 2** PEI Physical Properties

The base and tip end caps are the same, except that the tip does not include gas ports. The mechanical design is a three-piece construction. The end cap body is a machined ring that is bonded and clamped (via cord winding) to the composite laminate cylinder. The bus plate is a thin ring attached to the access plate that houses the bus wires that distribute power to the heater wires at both ends. The end cap assemblies, including all seals, fasteners and fittings are 171.3 grams and 159.9 grams for the base and tip ends respectively. The base end cap assembly is shown in Figure 9.
Multi-layer Insulation (MLI) — The MLI that surrounds each boom serves two purposes: 1) reduce heat loss during cure to minimize power required, and 2) reduce the high and low temperature extremes of the boom after cure as it progresses in and out of eclipse. The current baseline MLI design includes seven reflector layers. Thermal analysis performed on the system to date has assumed that an effective emittance of 0.7 will be realized by the MLI.

The MLI wall section is comprised of many layers. Its inner and outer layers are 0.051 mm Kapton® film, VDA coated on the internal side only. This thickness is required to meet Orbiter flammability requirements. Between these are five layers of 0.0076 mm Kapton® film, VDA coated both sides. Each of these layers are separated from each other by a thin Dacron® spacer fabric. All Kapton® layers are perforated for adequate venting during ascent.

The Boom MLI is assembled with Kapton/PSA film tapes as concentric cylinders of film and spacer fabric. Its mass is 120.7 grams/meter of boom length.

Boom Assembly — The distributed mass of each boom is the sum of its composite laminate and MLI distributed masses, which totals 411.2 grams/meter of boom length. This value is important to the structural analysis of the booms. The mass associated with the base end cap, while part of the ISIS sunshield mass, is closely supported by the central container and is neglected in the boom analysis. The mass associated with the tip end cap is added to the other tip components as part of the boom tip mass.

Boom Structural Analysis

The boom diameter was established by an iterative process of analyzing different sizes, calculating the resulting structural performance, and comparing it to requirements. The analysis that resulted in the selected diameter of 130.18 mm is presented here.

Each boom is considered as a fixed-free cantilever. Worst case loading (bending and Euler) occurs in the longest boom (length = 5.54m). Distributed load on the boom is from the inertia of the distributed masses of the composite laminate and the boom MLI. Concentrated loads on the boom are from 1) the inertia of the tip hardware, 2) the inertia of that portion of the membrane mass that is supported by the longest boom, and 3) the membrane tensioning load.

\[ m_{boom} = \text{Distributed Mass of Boom} \]
\[ = 411.2 \text{ grams/meter x 5.54 m} = 2.28 \text{ kg} \]
\[ m_{mem} = \text{Membrane Mass Carried by Longest Boom} \]
\[ = 2.34 \text{ kg} \]
\[ F = \text{Axial Compressive Load} = 17.79 \text{ N} \]
\[ m_{tip} = \text{Tip Mass} = 1.92 \text{ kg} \]

(calculated from design of tip hardware)

\[ A_z = \text{Acceleration in z-direction} = 0.052 \text{ g (0.03 g RSS)} \]
\[ L = \text{Boom Length} = 5.54 \text{ m} \]
\[ R = \text{Outside Radius of Boom} = 65.09 \text{ mm} \]
\[ t = \text{Thickness of Composite Wall} = 0.305 \text{ mm} \]
\[ A = \text{Cross Sectional Area of Boom} = \pi [R^2 - (R - t)^2] \]
\[ R_{avg} = \text{Average Radius of Boom} = R - 0.5t \]
\[ I_o = \text{Boom Moment of Inertia} = \pi R_{avg}^3 t \]

Critical Buckling Load

\[ k_c = \text{Boom Length Factor Based on End Conditions} \]
\[ = 2 \text{ (Fixed-Free)} \]
\[ E_c = \text{Compressive Modulus of Elasticity of cured composite} \]
\[ = 3.45 \times 10^{10} \text{ Pa} \]
\[ P_{cr} = \frac{\pi^2 E_c I_o}{(k_c L)^2} = 748N \]

Local Buckling Load

\[ \gamma_r = \text{rigidization factor} = 0.6 \]
\[ \gamma_c = \text{NASA correlation factor} \]

\[ P_{local} = \gamma_r \gamma_c 1.2 \pi E_c t^2 = 3.437 \times 10^3 N \] [1]

Maximum Compressive Stress Due to Euler Buckling

Assume that boom is manufactured with an initial deviation of up to 25.4 mm from straight (required straightness is much better than this). Assume no eccentricity of applied axial load.

\[ \delta_0 = 25.4 \text{ mm} \]
\[ Z = \text{Section Modulus} \]
\[ e = \text{Eccentricity} = 0 \]
\[ c = \text{Distance from centroid to extreme fibers} \]

\[ \sigma_{\text{max Euler}} = 1.573 \times 10^6 \text{ Pa} \]

Maximum Compressive Stress Due to Local Buckling

\[ \sigma_{\text{max local}} = 1.571 \times 10^6 \text{ Pa} \]
Maximum Compressive Stress Due to Bending

\[ \sigma_{\text{max bend}} = \frac{P}{A} + \left[ \frac{0.5m_d a_z L_c}{I_o} \right] + \left[ \frac{(m_i + 0.5m_m)a_z L_c}{I_o} \right] + \frac{P_{\text{PEC}}}{I_o} \]

\[ \sigma_{\text{max bend}} = 3.239 \times 10^6 \text{ Pa} \]

Maximum Allowable Compressive Stress

Compressive yield stress of cured composite

\[ \sigma_{\text{yield}} = 2.206 \times 10^7 \text{ Pa} \]

Safety Factor = \[ \frac{\sigma_{\text{max bend}}}{\sigma_{\text{yield}}} = 6.81 \]

Frequency Calculation (deflection method)

Assume parabolic deflected shape; centroid at \( x = 3L/4 \)

\[ \rho_b = 480.3 \text{ g/m} = \text{distributed mass of boom (composite laminate and MLI)} \]

\[ m_b = \rho_b L \]

\[ \omega = \frac{m_b g}{I_c} = \text{Weight per unit length of boom, + MLI} \]

\[ \delta = \text{deflection taking compressive end load into account} \]

\[ \delta = \frac{m_i x^4}{24EI_c} (x^2 - 4Lx + 6L^2) + \left( \frac{m_i}{6EI_c} \right) (3Lx^2 - x^3) \left( 1 - \frac{1}{4} \right) \]

\[ f_n = \frac{1}{2\pi \sqrt{\delta}} = 1.25 \text{ Hz} \]

Inflation Pressure Calculation

Max predicted elevated seam strength = 5254 N/m \times 90\% = 4728 N/m

Design skin load = 4728 N/m/2.5 (FS) = 1891 N/m

\[ \sigma_{\text{skin}} = p r = 1891 \text{ N/m} \]

\[ p = \frac{\sigma_{\text{skin}}}{r} = \frac{1891 \text{ N/m}}{0.065087 \text{ m}} = 29053 \text{ Pa} \]

Inflation system delivery pressure tolerance = +/-3447 Pa

Inflation system must deliver gas at 25,606 +/- 3447 Pa

Minimum pressure = 25,606 - 3,447 = 22159 Pa

Bending strength of inflated boom at minimum pressure

Boom will fail at root when axial compressive stresses from bending and compression equals the axial tensile stress from internal inflation.

Axial tensile stress due to inflation = \( \sigma_{\text{tension}} = p_{\text{min}} \left( \frac{K}{27} \right) \)

\[ \sigma_{\text{tension}} = 2355727 \text{ Pa} \]

\[ \sigma_{\text{max root}} = p \left[ \frac{0.5m_d a_z L_c}{I_o} \right] + \left[ \frac{(m_i + 0.5m_m)a_z L_c}{I_o} \right] + \frac{P_{\text{PEC}}}{I_o} \]

setting this expression equal to 2356 Pa and iteratively solving for acceleration yields

\[ a_z = 0.364 \text{ m/s}^2 = 0.0371 \text{ g} \]

This is the RSS of 0.0214 g simultaneous in all 3 axes. This is the predicted 3-axis acceleration that the longest inflated unrigidized boom could support, without safety factor. This value is reported to be significantly less than the accelerations that would be imposed by VRCS station-keeping, which are the only loads applied before rigidization.

The assumption that an inflated beam, can only support compressive stress equal to axial tension from pressurization is conservative. Literature indicates [2] actual test results typically 1.6 times higher than this value due to local rigidity, depending on the beam material. The maximum sustainable moment predicted by pressurization alone is

\[ M_{\text{max}} = \frac{\sigma_{\text{max}} L_c}{c} = 9.48 \text{ Nm} \]

where \( \sigma_{\text{max}} = 2355727 \text{ Pa} \), the tensile stress due to pressurization. ILC's testing of an unrigidized booms inflated to the minimum pressure of 22159 Pa supported a maximum bending moment of 29.13 Nm, over three times the predicted value.

**Boo Thermal Analysis**

Thermal modeling of the booms in their deployed condition was performed by the Technical Alliance group (TAG). Assumed Beta angle was 0, Shuttle attitude was bay-to-wake, and orbit period was 1.53 hours with 25 minute eclipse. Detailed physical and thermal properties of the uncured and cured composite laminate were incorporated. The composite laminate wall was examined as it varied in thickness around its circumference due to the seams and overlaps of its layers. An area-weighted average wall thickness of 0.56 mm was established, and thermal properties were determined using gravimetric and rule of mixture analyses. A selected value of 155 W/m² was used for the applied heat for ramp-up, based on heater design. The required time and temperature for cure (+125°C to +149°C for 45 minutes) were also incorporated.
A significant issue for the thermal modeling was the expected performance of the boom MLI. Since the MLI would undergo rolling and rolled storage, it was thought that it might exhibit some permanent set compression. As a result, it might not achieve the same $\varepsilon^*$ (effective emittance) that the same number of reflective layers otherwise would. An MLI design with 7 reflective layers (5 internal) achieving an $\varepsilon^*$ of 0.07 was baselined pending the results of thermal vacuum chamber testing. Recently completed thermal/vac testing confirmed the $\varepsilon^*$ with predicted power required to ramp-up and to cure the booms in the cold chamber.

Figure 10 presents a typical predicted temperature gradient circumferentially around the tube, as it is situated between the membranes in the orbital environment. This indicates a maximum circumferential temperature gradient of only about 1°C.

### Figure 10 Boom Circumferential Temperature Gradient

Similarly, the longitudinal temperature gradient is much less than 1°C (Figure 11). The small gradient is due to the boom placement between membranes with a small view to cold space and low solar heating.

### Figure 11 Boom Longitudinal Temperature Gradient

Key results of the boom temperature vs time analysis are presented in Figure 12. The predicted warmup rate is 7.9 °C/minute for a warmup time of 25 minutes. The predicted power required to maintain cure temperature is 88 W/m². The predicted time to cool down to 90°C is 12 minutes. Again, some of the power values were found to be conservative when compared to thermal vacuum test results.

![Figure 12 Boom Temperature/Time During Cure](image)

Based on these results, the expected total energy required for warm-up and cure of all four booms is 0.73 kW-hr. See Table 3.

### Table 3 Predicted Boom Power Requirements

<table>
<thead>
<tr>
<th>Boom Testing</th>
<th>Warm-Up</th>
<th>Cure</th>
<th>Cool-Down</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (Watts)</td>
<td>Time (Min)</td>
<td>Power (Watts)</td>
<td>Time (Min)</td>
</tr>
<tr>
<td>Lateral Together</td>
<td>246</td>
<td>25</td>
<td>140</td>
</tr>
<tr>
<td>Longitudinal #1</td>
<td>351</td>
<td>25</td>
<td>200</td>
</tr>
<tr>
<td>Longitudinal #2</td>
<td>267</td>
<td>25</td>
<td>152</td>
</tr>
</tbody>
</table>

**Burst Test**

Two 0.81 m heater/restraint assemblies (the structural element of the composite laminate prior to rigidization) were burst tested at +149°C. This was considered a conservative evaluation because by testing the heater/restraint alone, any (unintended) structural contribution or load sharing by other layers is treated as zero. One test article burst at 76531 Pa and the other at 72395 Pa. The failure mode in both cases was tensile failure of the 0.051 mm Kapton® VN film rather than the axial seam. Separate testing of the structural seam indicated that the seam would be capable of supporting about an additional 11% load before it would have become the failure mode.

**Leak Test**
Leak testing of numerous boom test articles have resulted in a baseline leakage requirement of \(< 20\) standard \(\text{cm}^3/\text{min}\) (any boom) at the maximum inflated gage pressure of \(29053\) Pa, tested at \(1\) atm ambient. All booms have demonstrated leakage of less than this value at this pressure. The boom leak rate in a vacuum can be expected to be about an order of magnitude less than this due to choked flow. This leak rate value is used in sizing the inflation system stored gas.

**Boom Structural Testing**

Prototype booms were fabricated and tested to characterize their structural behavior in both the inflated/unrigidized and the rigidized/vented conditions. Booms were rigidized at ambient pressure using their integral heaters for the heat source. Since the rigidization was not performed in a vacuum, convective insulation had to be wrapped around the booms during cure to minimize heat losses.

Booms were tested as horizontal cantilevered beams, rigidly supported at the base and periodically supported along their length by air bearings to enable their free response to side load. See Figure 13.

**Figure 13** Boom Structural Testing

Membrane tensioning load was accurately represented by tension cords applying axial load on the boom tip. Measured values included tip side load vs tip side deflection of cantilevered boom with \(83.85\) N constant axial load, maximum sustained bending moment, Euler buckling load, torque vs rotational deflection. In the case of the inflated/unrigidized booms, the bending and compression tests were performed over a range of inflation pressures. All bending tests were performed on the boom in four rotational orientations. Calculated values include bending stiffness, \(EI\), and torsional stiffness, \(GJ\).

**Inflated/Unrigidized Boom Test Results** – A \(2.24\) m boom was tested in combined cantilever bending with \(83.83\) N constant axial load over inflation pressures of \(15168\) Pa, \(22159\) Pa, and \(29053\) Pa. Typical load/deflection behavior is shown in Figure 14 and the resulting stiffness values are shown in Table 4.

**Figure 14** Inflated Boom Load vs Deflection

<table>
<thead>
<tr>
<th>Pressure (Pa)</th>
<th>(EI) (Nm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>15168</td>
<td>966</td>
</tr>
<tr>
<td>22159</td>
<td>1144</td>
</tr>
<tr>
<td>29053</td>
<td>1239</td>
</tr>
</tbody>
</table>

**Table 4** Inflated Boom (2.24m) Stiffness

While still under axial load of \(83.85\) N, the inflated boom was side loaded until further deflection resulted in no further increase in reaction load. This value was recorded as the maximum sustained bending moment for the inflated boom and it was measured for the three inflation pressure conditions (Table 5).

<table>
<thead>
<tr>
<th>Pressure (Pa)</th>
<th>Maximum Sustained Moment (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15168</td>
<td>23.15</td>
</tr>
<tr>
<td>22159</td>
<td>29.13</td>
</tr>
<tr>
<td>29053</td>
<td>36.35</td>
</tr>
</tbody>
</table>

**Table 5** Inflated Boom (2.24m)

Maximum Sustained Moment

While a predicted applied moment from VRCS loading was not quantified, the bending moment capability of the inflated beam can be compared with the moment that will be applied to the longest boom by \(1/3\) PRCS after rigidization. This value was determined by GSFC to be \(16.61\) Nm. The unrigidized boom was able to support a moment that is \(1.75\) times this value when inflated to its minimum pressure of \(22159\) Pa.

Axial load on the inflated boom was increased until it began first mode buckling (Table 6).
<table>
<thead>
<tr>
<th>Pressure (Pa)</th>
<th>Maximum Sustained Axial Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15168</td>
<td>359</td>
</tr>
<tr>
<td>22159</td>
<td>436</td>
</tr>
<tr>
<td>29053</td>
<td>548</td>
</tr>
</tbody>
</table>

Table 6  Inflated Boom(2.24m) Maximum Sustained Axial Load

The axial load supported at the minimum boom pressure of 22159 Pa was 436 N. This is 20.8 times the maximum compressive load of 20.96 N on the cured boom during 1/3 PRCS, so the margin will be even greater during VRCS loading of the inflated unrigidized boom.

Torsional loading and stiffness requirements have not been established for the ISIS booms. Torsional stiffness of the inflated unrigidized 2.24 m boom was measured and are shown in Table 7.

<table>
<thead>
<tr>
<th>Pressure (Pa)</th>
<th>Torsional Stiffness (Nm²/rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15168</td>
<td>280</td>
</tr>
<tr>
<td>22159</td>
<td>289</td>
</tr>
<tr>
<td>29053</td>
<td>298</td>
</tr>
</tbody>
</table>

Table 7  Inflated Boom(2.24m) Torsional Stiffness

Rigidized Boom Test Results — A 5.54 m boom was manufactured and cured under 25606 Pa (gage) internal pressure using its own heaters. Boom cure was performed at 1 atmosphere ambient pressure and the booms were wrapped in convective insulation to minimize heat loss. Meaningful data, therefore, on heater and MLI performance could not be generated by this test article, but were acquired on other test articles in later thermal vacuum chamber tests.

This test article was cured, however, with the same time/temperature profile under the same internal gage pressure as planned for the flight experiment.

When the cured boom was tested in cantilever bending only, the average bending stiffness across four rotational orientations was:

$$EI_{\text{average}} = 9304 \text{ Nm}^2$$

The boom was then tested in combined cantilever bending with 49 N constant axial load (based on an earlier flight experiment location in the cargo bay). The average bending stiffness across four rotation orientations was:

$$EI_{\text{average}} = 8256 \text{ Nm}^2$$

The torsional stiffness of the cured boom was measured at

$$GJ = 239 \text{ Nm}^2/\text{rad}$$

The maximum sustainable bending moment of this cured tube was determined at a later date when the axial load requirement had been updated. Under a constant axial compressive load of 83.85N, the 5.54 m cured boom was side loaded until further deflection resulted in no further increase in reaction load. This value was recorded as the maximum sustained bending moment for the cured boom and it was measured for four rotational orientations. The average maximum sustained moment was

$$\text{Maximum Moment}_{\text{average}} = 69.77 \text{ Nm}$$

This exceeded the requirement of 66.43 Nm.

Thermal Vacuum Chamber Testing - The above summarizes the analysis and data on the inflated and cured booms as of the ISIS Preliminary Design Review in June, 1999. Three 3.35 m booms were subsequently fabricated and tested in a thermal vacuum chamber at Goddard Space Flight Center in November, 1999. Two of the deployed and inflated booms were cured in the cold wall chamber using their integral heaters and MLI. These tests were used to establish the effective emittance of the MLI after rolling and deployment, to confirm the proper sizing and design of the heaters, and to confirm the proper cure of the prepreg under cold full vacuum conditions. The third boom was left in its stowed position in the chamber and was used to determine the heater power required to maintain a boom redeployment temperature of 20°C. Boom leakage in vacuum was less than 0.20 standard cm³/min. As of this writing, the cured booms have been examined but no structural testing on them has been completed. They appear to have cured properly, with shape and rigidity comparable to earlier booms cured at ambient pressure. Planned non-destructive testing includes determination of bending stiffness, torsional stiffness, first mode natural frequency, and verification of required axial load capability. Destructive tests will include determination of maximum bending moment, maximum axial load, and differential scanning calorimeter (DSC) testing of cut out composite samples from the boom to verify completeness of cure.

5. Controlled Deployment

The booms must be controlled during their deployment such that the deploying sunshield remains within its...
specified deployment envelope (+/- 6° from container). During deployment, the booms must have adequate beam stiffness to pull the membranes out from their retainers. When deployed, the tip hardware must support the membranes in the correct position and spacing. The tip hardware applies the 0.5 lb/tip point and transfers this load into compression through the boom.

**Boom Controlled Deployment Design** - The hardware assembly on the end of each boom is shown in Figure 15. The assembly enables the unrolling boom to function as a linear actuation device. It allows the moving end of the boom to rotate while it is guided out in a linear motion by a sliding collar that bears on the inflated portion of the boom immediately behind it. The main components include:

1) A ladder assembly, which is a lightweight aluminum frame that supports, tensions, and spaces the membrane tip points. Its crossbars house four 227g constant force springs that connect via cords to the membrane tips. Two reaction arms extend back from the ladder verticals and connect to the collar at a pivot joint.

2) A spool on which the boom is originally rolled up. The spool rotates relative to the ladder.

3) A collar that slides along the inflated boom and orients the ladder relative to the boom axis. It is a thin aluminum tube with an angled lead-in and clearance for the boom and its MLI.

4) A belt tensioning device that prevents inflation gas from pressurizing the portion of the boom that is still rolled up on the spool. This device is a torsion-spring biased roller that winds a Teflon-coated fabric belt that extends from its roller, around the rolled up boom, and anchors to a crossbar on the ladder structure. The roller rotates on a clutch bearing that only allows rotation in one direction. This feature guarantees that, in the event of a membrane snag and subsequent increase in axial load, continued pressurization will not be able to begin inflating the rolled boom on the spool. (Inflating the boom on the spool can result in uncontrolled boom deployment.) With the belt tensioning device, a membrane snag results in increasing axial load until either the snag is dislodged or the axial motion simply stalls.

5) A brake inside the spool that provides torsional resistance to spool rotation. Controlled and predictable deployment requires that the booms behave as inflated beams while they unroll. The rolled up portion of the boom must offer some resistance to unrolling, therefore, in order for the deployed portion to have some internal pressure during deployment. This resistance is provided by a braking device inside the spool. The brake device design does not depend on friction, which can vary significantly across large temperature ranges and between atmospheric pressure and vacuum environments. The brake in the ISIS spool provides a nominal 7 Nm torque resistance by pulling two 4.8 mm diameter 1100-T0 aluminum wires off of storage shafts and winding them onto a central shaft. The work required to bend and yield the aluminum wires provides the torsional resistance. Testing indicates that it is relatively insensitive to the expected ISIS temperature range.
Controlled Deployment Hardware Mass – The mass of major components of the boom controlled deployment hardware is summarized in Table 8.

<table>
<thead>
<tr>
<th>Boom Controlled Deployment Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ladder Assembly</td>
<td>0.96</td>
</tr>
<tr>
<td>Spool Assy &amp; Wire Brake</td>
<td>0.91</td>
</tr>
<tr>
<td>Belt Tensioning Device</td>
<td>0.79</td>
</tr>
<tr>
<td>Collar Assembly</td>
<td>0.16</td>
</tr>
<tr>
<td>Other Small Parts &amp; Fasteners</td>
<td>0.15</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.97</strong></td>
</tr>
</tbody>
</table>

Table 8 Boom Controlled Deployment Hardware Mass

The mass of this hardware plus the 160 grams mass of the tip end cap results in a total tip mass of 3.13 kg. This is 1.21 kg higher than the estimated tip mass used in the original boom sizing structural calculations. This will be partially offset by a lower membrane mass than originally estimated because full coverage with ripstop tapes was determined to be unnecessary. The resulting projected first mode frequency is 1.18 Hz, which is 91.5% of the 1.29 Hz goal. Maximum bending moment will also increase as a result, decreasing the margin to some extent.

Controlled Deployment Testing – Testing of boom controlled deployment is shown in Figure 16. Pictured is an earlier configuration prior to the adoption of the belt tensioning device. The assembly is supported in a fixture for horizontal deployment. An overhead track with suspended cords provides g negation. Cords attached to the ladder assembly simulate the axial load that will be exerted by the deploying membranes and the membrane tensioning load that is applied by the constant force springs at the end of deployment.

Regulated gas from a preset regulator is introduced into the base of the boom. Flow rate is controlled by a needle valve, simulating the fixed orifice control that the actual inflation system will use. This testing was used to determine the required torsional resistance of the brake under nominal deployment conditions. Membrane snagging was simulated by increasing the axial load until forward deployment was stopped. It was this testing that determined the need for the belt tensioning device to preclude uncontrolled boom growth in the event of a membrane snag.

Figure 19 Boom Deployment Evaluations
The nominal load per boom required to pull the membranes out of their retainers is 0.225 N. The membrane retainers apply this load intermittently as each fold is released. The load increases to 0.90 N at the end of the deployment when the constant force springs tension the membranes. Under these conditions, a brake torsional resistance of 7 Nm resulted in smooth, slow, controlled and repeatable deployments. In simulated membrane snag tests, a total axial load of 3.60 N was developed by the device before stalling. This is 16 times the required force to deploy the membranes. In the event of a snag that is not dislodged by a force of this magnitude, the axial deployment simply stops.

Membrane Controlled Deployment

The dispensing of the folded membranes in an ordered sequence is accomplished with membrane retainer assemblies. Retainers are mounted in the center of each container face above the membrane stowage shelves. Each retainer includes several slip-sheets of Teflon-coated fabric that are interleaved with the membrane folds. The slip sheets are anchored on one edge to the container wall. When the first membrane fold is pulled off the top of the stack, the slip sheets isolate the friction of the sliding membrane from the membrane folds beneath, guaranteeing that they pull out in order from the top to the bottom. Figure 17 shows the arrangement of the membrane folds in the retainer.

Figure 17 Membrane Retainer (not to scale)

Configuration of the major elements of the ISIS sunshield system has been determined. Engineering development of the key technologies, rigidizable thermoset inflatable booms and their controlled deployment, is substantially complete. All components have demonstrated capability of meeting structural margins required for each phase of the flight experiment.

The thermoset laminate composite booms have demonstrated at least 4 times safety factor in bending and compression in both 1) the inflated condition when max loads are applied by VRCS and 2) the rigidized and vented condition when loads are applied by 1/3 PRCS. Projected first mode natural frequency of the boom/membrane system is 91.5% of the 1.29 Hz goal. Curing of the laminate composite boom with integral heaters in a cold wall vacuum chamber has been successfully demonstrated. The boom MLI has exceeded predicted performance expectations, resulting in lower required power to cure (about 20 W/m²).

It should be noted that structural advances in inflatable boom design continue in parallel with the ISIS program. These include investigations into inflatable space frames, iso-grid reinforced inflatable booms, and other concepts to improve structural efficiency. Mass reductions of 30 – 50% over the ISIS style boom are projected while maintaining the same stiffness and structural performance. These advances are expected to be ready for application on NGST.

Controlled deployment of the booms via inflation driven roll-out has been demonstrated. A lightweight hardware assembly on each boom tip supports the membranes and controls the boom deployment. Deployment tests have demonstrated controlled, repeatable boom deployment with axial load capability of 16 times the nominal load required to deploy the membranes. Orderly pay-out of the folded membranes is achieved with a spring clip device that isolates friction between folds and guarantees sequential top-down membrane stack deployment.

When deployed, the resulting assembly will apply the specified 69 kPa to the widest membrane section longitudinally and 34.5 kPa to the widest membrane section laterally.

Launch tie and release systems for both membranes and stowed booms are attached to the central container and are being designed and fabricated by GSFC. Description of these mechanical systems is beyond the scope of this paper, but their function will be verified in the Engineering Model (EM) test program that will also verify the sunshield booms and membranes as a system.

Key remaining ISIS program elements to verify include:

1. Structural characterization of booms recently cured in a thermal vacuum chamber.
2. Final selection of number of MLI layers and specification of heater power based on thermal vacuum chamber performance and flight experiment operational constraints (available power, flight experiment timeline).
3. Completion of engineering development evaluations of boom controlled deployment hardware.
4. Fabrication of full flight-like ISIS Engineering Model.
5. Engineering Model (EM) testing, including:
   - Stowed system mass and dimensional properties
   - Stowed system launch environment testing
   - EM deployment (1 g, 1 atm) with g-negation fixturing
   - Deployed system dimensional and mechanical properties
   - Post-deployment cure of booms
   - Cured boom mechanical properties.
6. Fabrication & integration of flight system

Current plans are for the ISIS flight experiment to be flown on a Space Shuttle Mission. The information, experience and flight heritage gained will be instrumental in advancing space inflatable/rigidizable structure technology for the Next Generation Space Telescope as well as future space applications.

Acknowledgements

The author would like to thank the members of the ISIS Integrated Product Team (IPT) for their efforts in making the program a success. Special thanks go to Art Chmielewski and Dr. Mike Lou of JPL, Linda Pacini and Mike Adams (and many others) of NASA GSFC, Dr. Chris Moore of LaRC, Dr. Martin Mikulas of the University of Colorado, and Dr. Paul McElroy and Dr. Robert Wise of TAG.

REFERENCES


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