

A00-24831

AIAA 2000-1822

TRANSHAB: NASA's LARGE-SCALE INFLATABLE SPACECRAFT

Horacio de la Fuente¹, Jasen L. Raboin², Gary R. Spexarth³, and Gerard D. Valle¹

¹ NASA Johnson Space Center, Mail Code EX14, Houston TX 77058; ² NASA Johnson Space Center, Mail Code ES5, Houston TX 77058; ³ Lockheed Martin, 2400 NASA Rd 1, Mail Code B14, Houston TX 77058

I. Abstract

TransHab is a, 27-foot diameter by 40-foot, lightweight inflatable habitation module for space applications. TransHab consists of a lightweight graphite-composite core, 11-foot diameter by 23-foot tall, surrounded by a 27-foot diameter inflatable shell. Originally envisioned to be the habitation module of an interplanetary transit vehicle, TransHab is currently being considered as a module for use on the International Space Station (ISS). During the past two years, several tests have been performed at the NASA/Johnson Space Center to demonstrate and prove the technologies required in building a large-scale inflatable habitation module. This paper discusses the results of these tests which including the following: 1) a structural integrity development test article hydrostatically tested to four times ambient pressure, 2) a full-scale development test article manufactured, assembled, folded and deployed at vacuum, and 3) extensive hypervelocity impact testing of the micrometeoroid and orbital debris protection system.

II. INTRODUCTION

TransHab's inflatable shell has the ability to be folded for launch and then deployed on orbit. Therefore, TransHab can provide more than three times the volume, and over twice the storage space, for similar cost and weight than a traditional aluminum structure. The interior configuration (see Figure 1) of the inflatable module consists of three main levels. On level one, there is a fully equipped galley and large table capable of seating a total of 12 crewmembers providing enough room for the primary and replacement crewmembers. There are multiple soft stowage arrays around the perimeter opposite of the wardroom table. On level two, in the central core, there are six individual crew quarters. Each compartment contains a sleeping area with personal stowage and a computer for entertainment or personal use. The crew quarters are surrounded by a 2-inch thick water tank,

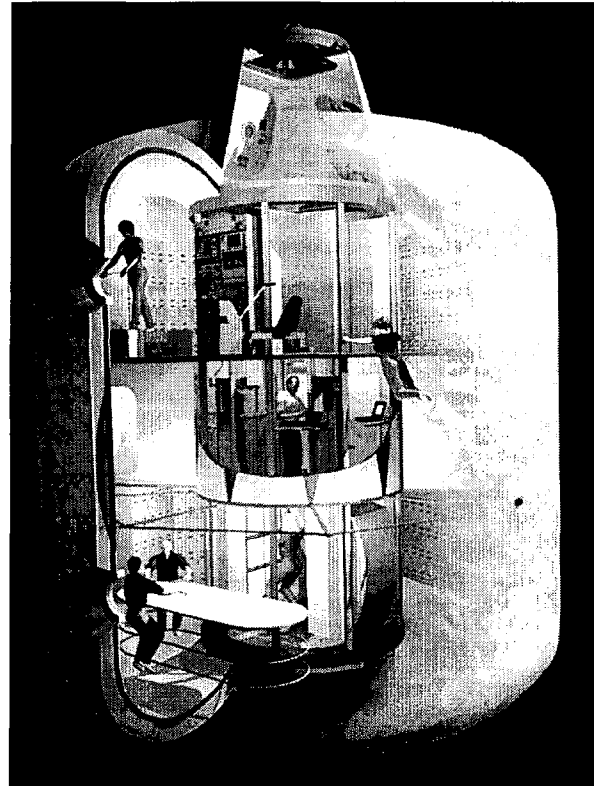


Figure 1: TransHab Outfitted with Crew

referred to as the "storm shelter", that will give the astronauts additional protection in the event of a solar flare. Level 2 also houses the mechanical room and environmental control and life support system (ECLSS). Directly over the, previously mentioned, large table the floor of level 2 is removed to allow additional crew translation and thereby creating a roomy atrium effect. Level three houses exercise equipment required in maintaining a healthy crew on extended missions, a bathing area and additional soft stowage arrays. There is also a health care system, which will help monitor crew health and provides emergency equipment. There are also two, 20-inch diameter, Nadir facing windows viewable from the first and third levels.

TransHab will be launched, fully outfitted, during a single shuttle mission. Then it will be deployed and inflated while on orbit. In addition to the volume and storage benefits, TransHab provides

Release D: "Copyright 2000 by the American Institute of Aeronautics and Astronautics, Inc. No copyright is asserted in the United States under Title 17, U.S. Code. The U.S. Government has a royalty-free license to exercise all rights under the copyright claimed herein for Governmental Purposes. All other rights are reserved by the copyright owner".

Prepared for the 2000 AIAA Space Inflatables Forum; Structures, Structural Dynamics, and Materials Conference,
3-6 April 2000, Atlanta GA.

superior radiation and micrometeoroid protection than conventional aluminum modules.

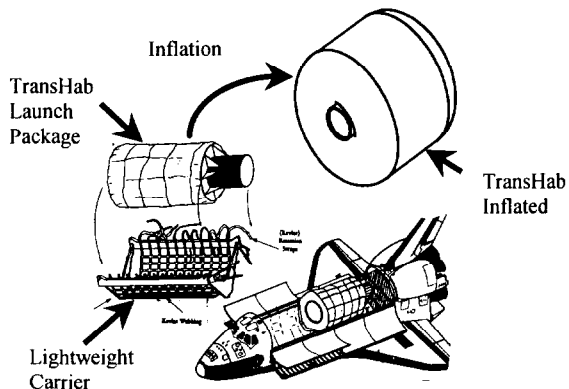


Figure 2: TransHab Launch/Inflation Scenario

The inflatable shell is 16 inches thick and is composed of over 60 layers arranged as five major subassemblies. As shown in Figure 3, the inner liner (1) is the innermost layer and acts as a protective layer for the triply redundant bladder layers (2). A woven restraint layer supports the bladder and is designed to withstand 4 atmospheres of internal pressure (3). The restraint and bladder layers are protected from micrometeoroid impacts by the debris protection system which consist of multiply layers of ceramic fabric separated by open cell foam and a Kevlar fabric debris catcher (4). The outer most layers consist of multi-layer insulation (MLI) and atomic oxygen (AO) protective layers (5).

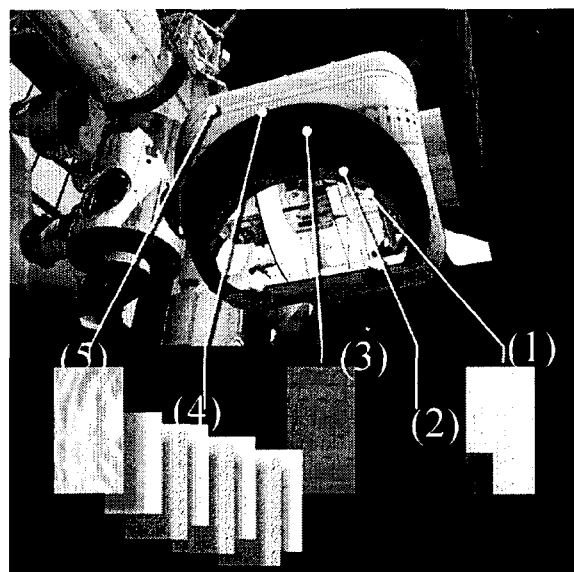


Figure 3: TransHab Shell Layers

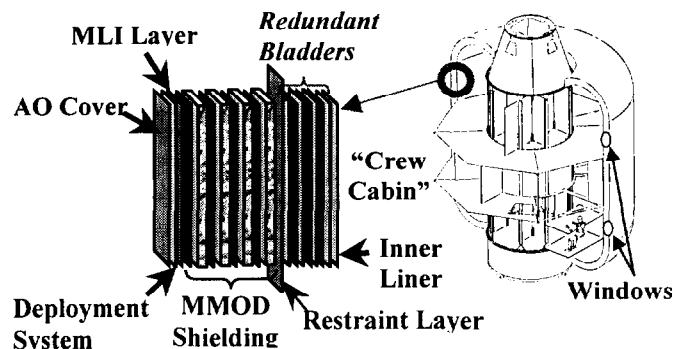


Figure 4: TransHab Shell Layers

III. MATERIAL SELECTION AND DESIGN PROCESS

INNER LINER:

The inner liner is a system of different materials that combine to provide a barrier that is durable, flame and puncture resistant, easy to clean, and has good acoustic properties. Nomex fabric provides a flame resistant surface that is easy to clean and has a significant flight history. Kevlar and Nomex non-woven felts also provide good puncture resistance and acoustic absorption properties. Further testing is being conducted at NASA to determine the optimum sequence of the liner assembly.

BLADDER:

The bladder is a triple redundant system that has a low permeability, and is durable and flexible. Several materials were tested for permeability rate, flexibility using the Bally flex test, and durability using

a severe triple fold test. Some of these results are summarized in Table 1.

Based on these test results, Combitherm was chosen as the initial baseline bladder material. Combitherm is a very low permeability material widely used in the food packaging industry. After being subjected to severe flex testing, Combitherm maintained a much lower permeability when compared to other candidate materials. Combitherm is a laminate consisting of multiple polyethylene, nylon, and EVOH (vinyl alcohol) layers. The polyethylene on the outermost surface makes Combitherm easy to heat seal on one or both sides while the EVOH layer is the primary gas barrier. Additional material characterization testing is being conducted at NASA to verify material properties at various environmental conditions, such as temperature extremes.

Prepared for the 2000 AIAA Space Inflatables Forum; Structures, Structural Dynamics, and Materials Conference,
3-6 April 2000, Atlanta GA.

Kevlar felt bleeder cloth surrounds each bladder to provide additional required puncture resistance. The bladder is oversized with respect to the

restraint layer and is indexed to prevent it from shifting out of position and taking load during deployment.

Table 1: Bladder Testing Results

Material	Perm. O ₂ cc/100in ² /day/atm	Tensile Strength lb/in	Tear Strength lb	Puncture	Toxicity	Flammability	Other Results
Combitherm VPC 140	0.07	42.1	34.8	9.59	OK	In Progress	
Combitherm XX 70	0.09	18.1	9.03	6.91	OK	-	One side sealable
Urethane coated Nylon	16.52	150	22.76	-	OK	-	
Urethane coated Polyester Scrim	25.7	170	88.42	-	-	-	
Urethane/Mylar/Tedlar/ Polyester Scrim	1.65	170	105.8	18.99	OK	-	One side sealable Non-Thermoformable ILC Proprietary
Armor Flex TM	0.32	16.1	12.46	-	retest reqd.	-	ILC Proprietary
Combitherm-Kevlar Laminate - one sided	0.1	291.4	121.5	-		-	One side sealable Non-Thermoformable Experimental De-Lamination
Combitherm-Kevlar Laminate - two sided	0.02	300.2	127.5	-	-	-	Non-Thermoformable Experimental De-Lamination

RESTRAINT LAYER:

The restraint layer is the primary structural member responsible for supporting the large loads incurred from inflating a 25-foot diameter module to 14.7 psi. The

restraint layer must be able to be folded, deployed and inflated on orbit and maintain its structural integrity for over 10 years. Properties of some high performance fibers are summarized below:

Table 2: Comparative Evaluation of Candidate Fibers for the TransHab Restraint

Fiber Type	Tensile Strength (ksi)	Breaking Tenacity (gm/den.)	Tensile Modulus (gm/den.)	Elongation at break (%)	Density (gm/cm ³)	Resistance to Flex Cracking	Low Temp. Brittleness (°F)	Flamm- ability (LOI)	Abrasion Resistance
Kevlar	490	23	555	3.6	1.44	Poor	<-321	27-29	Poor
PBO	820	41	1300	3.5	1.5	Poor	-	>56	Poor
Spectra 1000	435	35	2000	2.7	0.97	Excellent	<-13	18-19	Excellent
Vectran HS (LCP)	412	23	680-840	2.2-2.5	1.41	Good	<-256	28	Good

Data/Testing Provided by Rajib dasGupta, Lockheed Martin

Although the tensile strength of PBO⁹ (p-phenylene benzobisoxazole) is almost twice as high as Kevlar or Vectran, it could not be considered a viable candidate due to high cost, limited availability, difficulty in preparation and limited material database. Spectra has adequate tensile strength, however, the brittleness at low temperature (<-13 °F) eliminated it as a viable candidate. Kevlar was chosen over Vectran

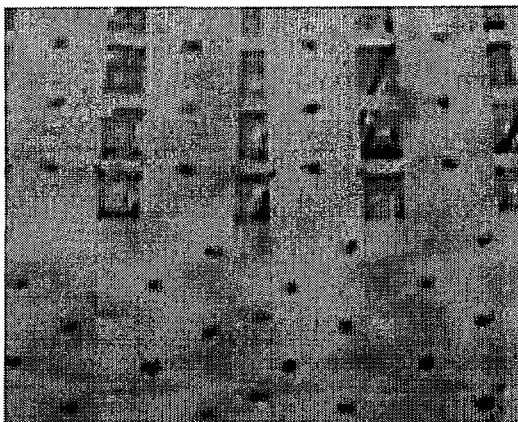
because of its significant flight history, thoroughly well known properties, availability, and low cost. Concerns related to flex cracking or abrasion resistance were eliminated by the large folding radius and low folding cycles. The restraint layer is designed to a Factor of Safety of 4.0 not including D-factors such as life, load sharing, seam efficiency and handling.

Prepared for the 2000 AIAA Space Inflatables Forum; Structures, Structural Dynamics, and Materials Conference, 3-6 April 2000, Atlanta GA.

The first TransHab Shell Development Unit (SDU I) was designed with 1 inch, 6 inch and 12 inch wide indexed webbing. Marking of the index and seam locations was performed while the webbing straps were under load to insure proper placement. The wide custom webbing was chosen to simplify manufacturing and assembly by reducing the number of webbing interfaces. Building a large-scale inflatable with wide webbing created gaps between the horizontal and longitudinal webbings (See Figure 5a). These gaps could be covered using a filler fabric between the bladder and restraint layer. The SDU I test article was tested to failure using hydrostatic internal pressure at NASA's Neutral Buoyancy Laboratory (NBL) in Houston, TX in May 1998. Ultimate structural failure occurred at an internal pressure which exceeded twice ambient sea level pressure (1 atm = 14.7 psi). Because habitable pressure vessels, used in space, are typically designed to ultimate factors of safety ranging from 1.4 to 2.0, this test was a significant milestone in inflatable technology by showing that the large-scale inflatable modules could be designed for space use. The failure of the SDU I test article was initiated by: (1) uneven loading near the restraint gaps, (2) stress concentrations at index stitching, and (3) the non-uniform stress distribution across the width of the wide webbing. Clearly, a more uniform stress distribution throughout the restraint layer could be achieved by eliminating the wide webbing.

In June of 1998, the test article was redesigned using standard 1-inch wide webbing. The new test article was called SDU II. Fabrication of SDU II was completed in less than 1 month. In July 1998, the first inflation of the SDU II test article was performed.

Sewn Multi-Width Kevlar Webbing



(a) SDU I

Woven 1" Width Kevlar Webbing



(b) SDU II

Figure 5: Test Article Restraint Layer Changes

The correct geometrical shape was not achieved during this first inflation (Figure 6). This was caused by shifting of the weave due to inadequate indexing. The SDU II test article was disassembled, and then reassembled with the appropriate indexing (Figure 7). During the disassembly process, the original hoop seams were kept intact since they would see the highest stresses during testing. This ability to quickly and cheaply disassemble and reassemble the restraint layer demonstrated a unique advantage of inflatable modules.

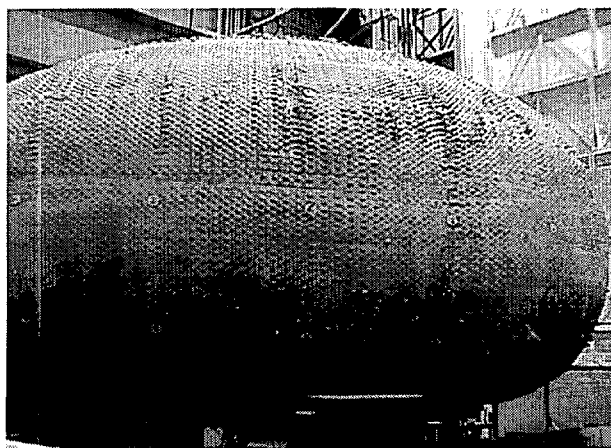


Figure 6: SDU II Inflated Shell w/o Adequate Index Stitches

Prepared for the 2000 AIAA Space Inflatables Forum; Structures, Structural Dynamics, and Materials Conference,
3-6 April 2000, Atlanta GA.

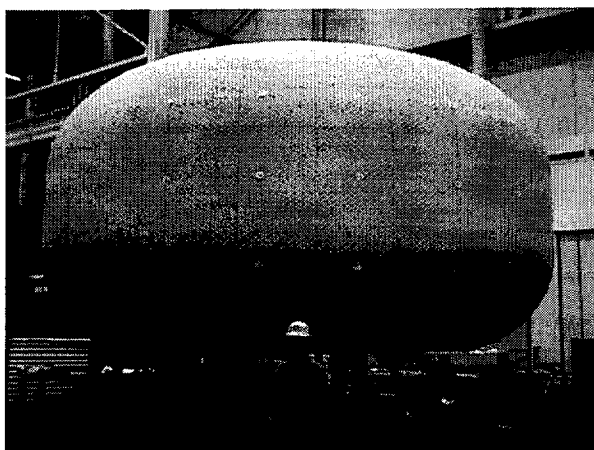


Figure 7: SDU II Inflated Shell w/o Index Stitches and Updated with Index Stitches

In early September 1998, the SDU II test article was hydrostatically tested, to 4.0 times limit load, a significant increase over previously flown space habitation modules. This milestone proved that highly loaded, large diameter inflatables can be manufactured to meet design requirements and demonstrated that they can be manufactured in less time than conventional aluminum structures.

SEAL INTERFACE:

The interface between the inflatable shell and the central core is the most critical area of the module. This is where the bladder must maintain a leak tight seal and the restraint must react the shell load into the core. The bladder interface is made by bonding the bladder to a metallic interface ring using a flexible flight certified adhesive sealant. The metallic ring is then sealed to the core using conventional o-ring face seals. Over sizing the bladder and proper indexing to the restraint are crucial to maintaining a zero stress environment for the bladder seal interface.

The restraint layer interface is made by using individual clevis/roller assemblies to attach the restraint straps to the bulkhead. Large radius rollers are used to prevent creasing of the straps. The rollers also enable load sharing between two adjacent straps by allowing the straps to "self adjust".

MICROMETERIOID/ ORBITAL DEBRIS (M/OD) PROTECTION SYSTEM¹:

TransHab's compressible and deployable, multi-layer, all fabric micrometeoroid and orbital protection (M/OD) protection system represents the state of the art in hypervelocity impact (HVI)

protection. The shield consists of multiple layers of ceramic fabric (NextelTM) bumper layers separated by low-density cored polyurethane foam. The foam is vacuum compressed prior to launch, to minimize volume and allow the shell to be easily folded. On orbit, in the vacuum of space, the foam regains its original standoff thickness due to the resilience of the foam. Behind the multiple layers of Nextel there is a high strength fabric rear wall (KevlarTM). As the hypervelocity particles impact each of the multiple Nextel layers, they are continually shattered into smaller, slower, particles over a larger area. With a properly sized shield, by the time the particles reach the Kevlar rear wall, they are small and slow enough to be stopped.

THERMAL PROTECTION SYSTEM:

TransHab will be thermally protected from the extreme temperatures of the ISS space environment, +150 °F to -250 °F, by a multi-layer insulation (MLI) consisting of multiple layers of Nylon reinforced double aluminized Mylar sandwiched by an inner and outer layer of double aluminized Polyimide film (Kapton). The internal MLI layers are perforated to allow venting. The MLI will be fabricated in gore sections and then assembled onto the shell. Kevlar indexing cords attach the gore-to-gore and layer-to-layer interfaces. The MLI blankets are also oversized with respect to the M/OD layers to prevent them from carrying load. Sub-scale thermal vacuum tests have been performed on the TransHab shell lay-up to verify thermal performance.

DEPLOYMENT SYSTEM:

The deployment system is required to restrain the folded shell layers prior to deployment. The deployment system consists of a series of deployment straps that span every third gore (deployment gores). When the test article is folded, every third gore is pushed in towards the central core (Figure 8). The adjacent gores are folded over so that the ends of the deployment straps on one deployment gore line up with the ends of the deployment straps on the next deployment gore. Deployment cords are then tied to each end of the deployment straps and laced together in a daisy chain manner (Figure 9). The deployment straps form multiple segmented rings that fully contain the folded assembly. Each set of daisy chains can be released from a single "cut" location using redundant pyrotechnic guillotine pencil cutters. Since there are seven deployment gores, there are seven independent "cut" locations.

Prepared for the 2000 AIAA Space Inflatables Forum; Structures, Structural Dynamics, and Materials Conference, 3-6 April 2000, Atlanta GA.

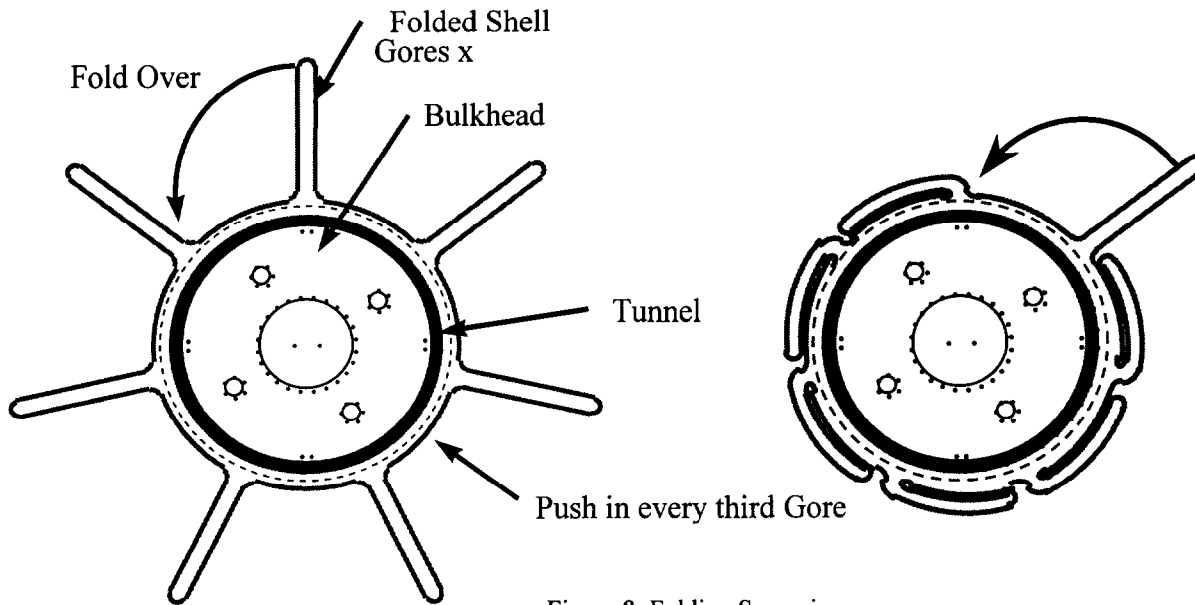


Figure 8: Folding Scenario

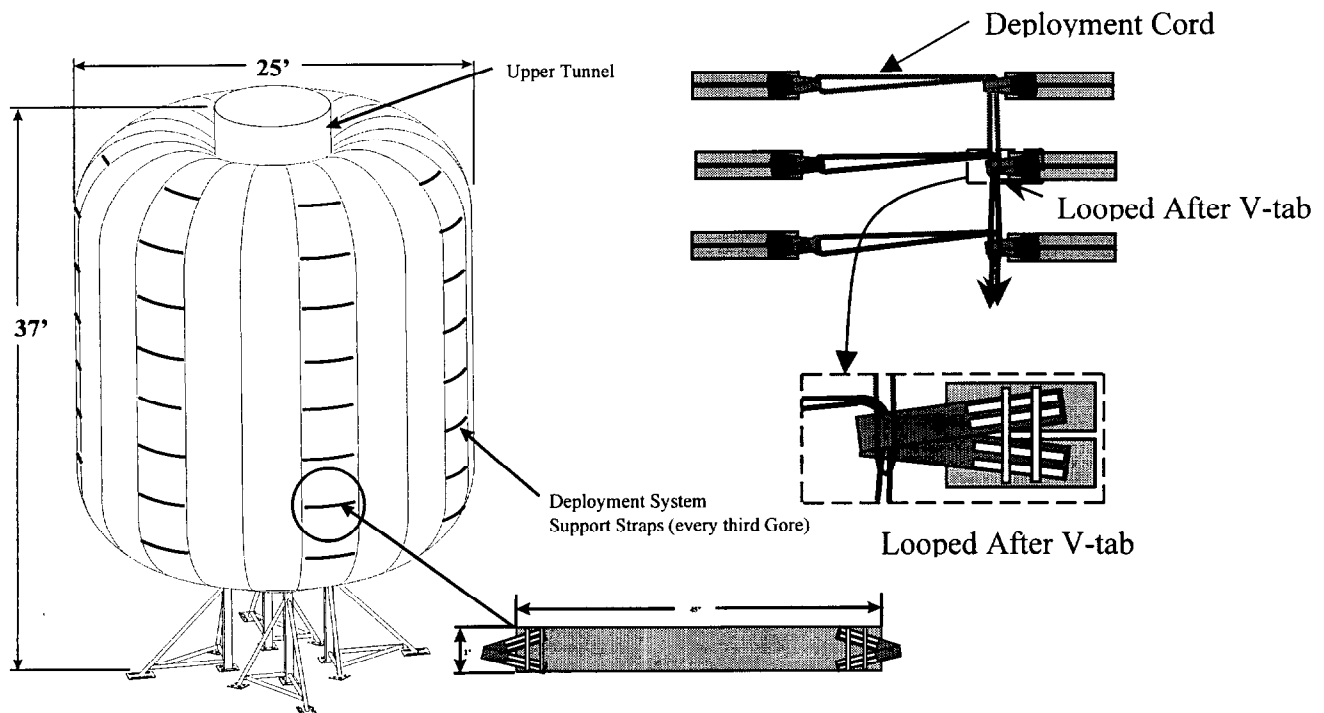


Figure 9: Deployment System

ATOMIC OXYGEN PROTECTIVE LAYER:

TransHab's outermost layer is single-side aluminized Betaglass fabric, which protects all of the shell layers from Atomic Oxygen (AO). Betaglass fabric is used throughout the space program and has been proven to protect against Atomic Oxygen damage. Vent holes and vent covers are also placed on the AO

cover. The AO cover will be fabricated in a series of 21 separate gores. The AO cover is oversized with respect to the adjacent deployment system layer to prevent it from carrying load. Each gore of the MLI and AO layers will be grounded to the aluminum bulkhead and grounding jumpers will be placed between adjacent gores to prevent build-up of electrostatic charge.

Prepared for the 2000 AIAA Space Inflatables Forum; Structures, Structural Dynamics, and Materials Conference,
3-6 April 2000, Atlanta GA.

IV. TESTING

Hypervelocity Impact Testing (M/OD Protection)¹:

A variety of hypervelocity impact tests, using different size particles at speeds ranging between 2.5 through 11 km/s, have verified the TransHab multi-shock shield. Initial ballistic limit equations have been developed from these test for use in shield optimization. As an example, this sub-scale and full-scale testing has demonstrated that the TransHab shield can stop a 1.7-cm diameter aluminum particle traveling at 7 km/s fired at both 0 and 45 degree angles. The results of these tests have verified that the TransHab M/OD shield would exceed the ISS M/OD shield requirement for a habitation module.

Hydrostatic Pressure Testing:

As mentioned before, to verify the structural integrity of the Kevlar restraint layer, a hydrostatic test was performed on a 23-foot diameter development unit. On September 12, 1998, a 23-foot diameter inflatable TransHab Shell Development Unit (SDU II) was lowered into the 6.2 million-gallon water tank at JSC's Neutral Buoyancy Laboratory. To minimize safety hazards, instead of pressurizing the test article pneumatically, the test was conducted hydrostatically and under water. A 10% degradation was taken into account due to the effects of water on Kevlar. The test article was successfully pressurized to four times the ambient pressure at sea level. This high stress condition was maintained for five minutes with no detectable degradation of the test article. This represented a significant milestone in validating large-scale inflatables for potential space applications.

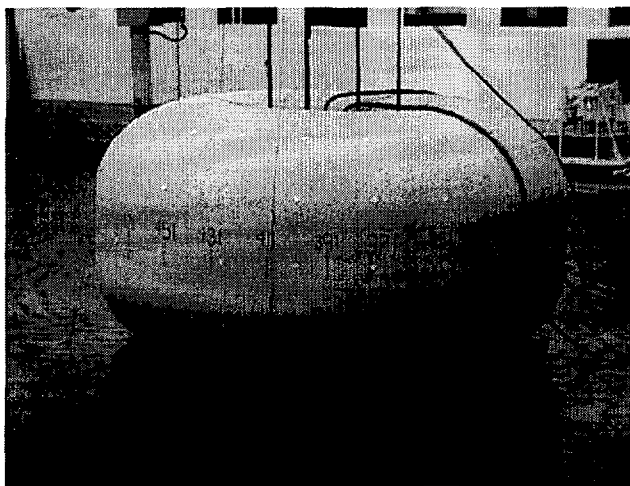


Figure 10: TransHab SDU Hydrostatic Test
(4.0 X ambient)

Folding and Vacuum Deployment:

To demonstrate the ability to assemble, package, and deploy the multi-layer shell, a full-scale test article, called SDU III, was manufactured and assembled. After verifying the structural integrity of the restraint layer, it was safe to pressurize the SDU III pneumatically. The full-scale development unit was folded while in a vertical configuration. In order to accomplish this a series of four cables were attached to each of the 21 gore interfaces. The 84 cables were attached to an overhead support fixture that supported the 10,000 pounds shell weight and allowed each gore to be folded. In order to fold the 21 gores, every third gore was pushed in towards the central core. Each of the seven adjacent gores was folded over (recall figure 8). The SDU III test article was slowly deflated, transferring the shell weight to the overhead support structure, and Kevlar webbing was used to draw in the 14 gore-to-gore seam interfaces. Temporary segmented hoops were created, using some of the deployment straps, and then incrementally tightened to help fold the SDU III into the proper configuration. Finally, the test article deployment system was laced up (daisy chain, See Figure 9) and tied off with pyrotechnic test cords. The SDU III was successfully folded with minimal ground support equipment (Figure 11). The final packaged diameter was small enough to fit in the shuttle cargo bay.

After the SDU III was folded and all pyrotechnic cutters were armed, JSC's seven-story thermal vacuum Chamber A was pumped down to approximately 27 torr (.5 psi.). The deployment system maintained the packaged configuration throughout Chamber A pump down. Next, all pyrotechnic cutters were fired thereby releasing the packaged shell. The SDU III was then re-inflated to 14.7 psi (Figure 12). The inflation system used a prototype heat exchanger to heat the gas during inflation. This test was successfully completed in late December 1998.

Prepared for the 2000 AIAA Space Inflatables Forum; Structures, Structural Dynamics, and Materials Conference,
3-6 April 2000, Atlanta GA.

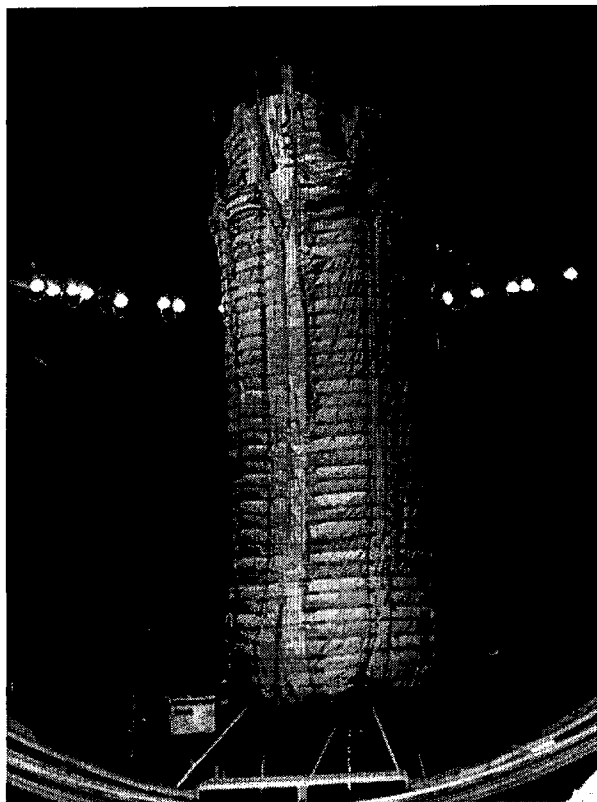


Figure 11: TransHab SDU III Folded

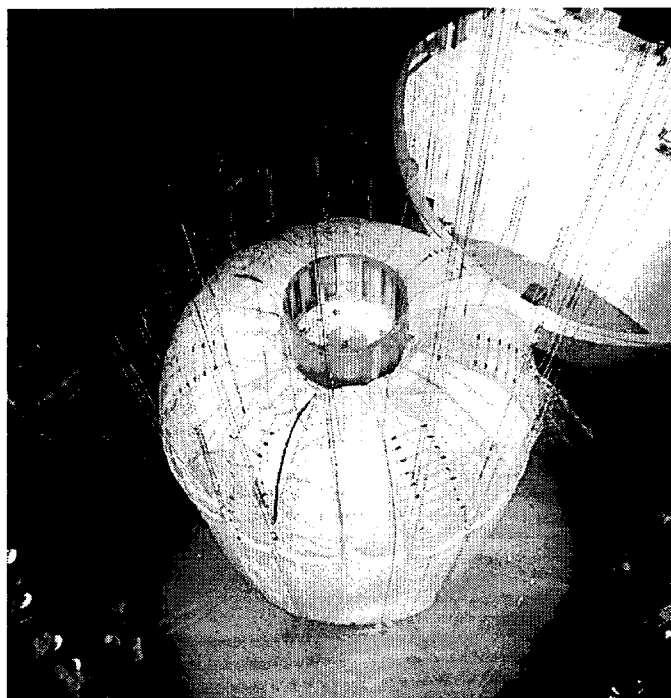


Figure 12: TransHab SDU III Deployed

V. FUTURE TEST PLANS

This impressive body of work has demonstrated the feasibility of inflatable space modules. Additional near term testing includes verification of adequate shell venting during shuttle ascent, verification of the overall leak rate, verifying the thermal performance at vacuum on a full scale test article and verifying our seal interface design during sub and full scale testing. Additional objectives include additional material testing, testing our bladder and M/OD compression system venting design, completing and testing a window design.

VI. CONCLUDING REMARKS

The technologies required to design, fabricate, and utilize an inflatable module for space applications has been demonstrated and proven by the TransHab team during the development phase of the program. Through testing and hands-on development several questions about inflatable space structures have been answered, such as: ease of manufacturing, structural integrity, micrometeorite protection, folding, and vacuum deployment. The TransHab inflatable technology development program has proven that not only are inflatable structures a viable option, but they also offer significant advantages over conventional metallic structures.

Prepared for the 2000 AIAA Space Inflatables Forum; Structures, Structural Dynamics, and Materials
Conference, 3-6 April 2000, Atlanta GA.

VII. REFERENCES

1. E. L. Christiansen, J.H. Kerr, H.M. de la Fuente, and W.C. Schneider, Flexible and Deployable Meteoroid/Debris Shielding for Spacecraft, International Journal of Impact Engineering, Vol. 23, 1999.
2. Advanced Structural and Inflatable Hybrid Spacecraft Module, Patent Application NASA Case # MSC-22900-1, 1996.
3. Advanced, Large Volume, Highly Loaded, Hybrid Inflatable Pressure Vessel, Patent Application NASA Case # MSC-23092, 1999.
4. C. Johnson, TransHab Shell Development Unit (SDU) Hydrostatic Test Report, TH-TR-0001, July 1998.
5. C. Johnson, G.D. Valle, TransHab Shell Development Unit II (SDU II) Hydrostatic Test Report, TH-TR-002, June 1999.
6. G.D. Valle, TransHab Full Scale Development Unit (SDU III) Fabrication, Folding and Vacuum Deployment Post-Test Report, May 1999
7. J. Lester, G.D. Valle, TransHab S-Fold Post-Test Report, December 1999
8. NASA International Space Station TransHab, Web Page,
<http://spaceflight.nasa.gov/station/assembly/elements/transhab/>
9. Evelyne Orndoff, Development and Evaluation of Polybenzoxazole Fibrous Structures, technical Memorandum 104814, September 1995.
10. NASA Fact Sheet, TransHab: An Inflatable Home in Space, FS-1999-08-006-JSC
11. Steven L. Koontz, Ph.D., Progress report and Preliminary Recommendations: TransHab ESD Risk Reduction Assessment, Contract NAS9-19100, Subcontract G962310J76, August 16, 1999