IAA-98-IAA.13.2.04

INFLATABLE COMPOSITE HABITAT STRUCTURES FOR LUNAR AND MARS EXPLORATION

D. Cadogan, J. Stein, M. Grahne
ILC Dover, Inc.

49th International Astronautical Congress
Sept 28-Oct 2, 1998/Melbourne, Australia

Abstract

Recent advances in materials technology have improved the performance capabilities of inflatable, flexible composite structures, which have increased their potential for use in numerous space applications. Space suits, which are comprised of flexible composite components, are a good example of the successful use inflatable composite structures in space. Space suits employ inflatables technology to provide a stand alone spacecraft for astronauts during extra-vehicular activity. An natural extension of this application of inflatables technology is in orbital or planetary habitat structures. NASA Johnson Space Center (JSC) is currently investigating flexible composite structures deployed via inflation for use as habitats, transfer vehicles and depots for continued exploration of the Moon and Mars.

Inflatable composite structures are being investigated because they offer significant benefits over conventional structures for aerospace applications. Inflatable structures are flexible and can be packaged in smaller and more complex shaped volumes, which result in the selection of smaller launch vehicles which dramatically reduce launch costs. Inflatable composite structures are typically manufactured from materials that have higher strength to weight ratios than conventional systems and are therefore lower in mass. Mass reductions are further realized because of the tailorability of inflatable composite structures, which allow the strength of the system to be concentrated where needed. Flexible composite structures also tend to be more damage tolerant due to their "forgiveness" as compared to rigid mechanical systems. In addition, inflatables have consistently proven to be lower in both development and manufacturing costs.

Several inflatable habitat development programs are discussed with their increasing maturation toward use on a flight mission. Selected development programs being discussed include several NASA Langley Research Center habitat programs that were conducted in the 1960s, the Lawrence Livermore National Laboratory inflatable space station study, the NASA JSC deployable inflatable Lunar habitat study, and the inflatable Mars TransHab study and test program currently ongoing at NASA JSC. Relevant technology developments made by ILC Dover are also presented.

1.0 Introduction

The United States National Aeronautics and Space Administration (NASA), along with a multitude of other countries and space agencies, have set forth a mandate to continue manned exploration of space including eventual journeys back to the Lunar surface and to Mars. Recent economic trends indicate that manned presence in space is highly dependent on the costs of the support equipment for such missions. Therefore, teams around the world are working to develop cost effective, robust systems that can safely facilitate these ventures. One method being considered by several groups to meet these goals is to utilize inflatable composite structures (Figure 1).

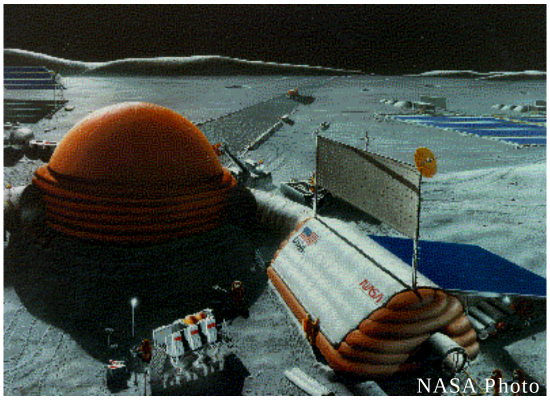

Figure 1. NASA Inflatable Habitat Concept

Inflatable composite structures are compilations of structural materials that are flexible in nature and are combined in such a manner as to provide comparable structure as their rigid metallic counterparts. Flexibility of the materials allows the structure to be packaged into a small volume for launch that is considerably smaller than its deployed volume. This will enable the user of the technology to consider smaller launch vehicles or considerably increased usable launch volume.

Flexible inflatable composite materials are utilized in many applications today but perhaps find their greatest benefit in space structures. The most well known example of a flexible inflatable composite structure is a automobile tire. In this case, the flexible matrix material is reinforced with woven materials such as steel or Kevlar. The reinforcement materials aid in supporting the structural loads due to inflation and also increase the composite material's puncture resistance. Inflatable structures for space use similar principals to achieve the same or better performance as rigid structures. As is the case with automotive tires, space inflatable structures have become more durable and robust with the advent of new materials. Advanced flexible polymers and high strength fibers such as Kevlar, Vectran, and Spectra, have enabled the fabrication of very low mass structures that are deployable from a densely packed state.

2.0 Historical Perspectives & Related Technology

Throughout the 1960s and early 1970s, NASA and industry teams were at work developing inflatable space structures ranging from space suits to habitats. These development programs included the manufacture and test of several large scale prototypes. While space suit development continued at a strong pace from the early days of manned space exploration to today, the development activities in inflatable habitats was not as rigorously pursued. Inflatable habitat structures were included in various studies conducted by NASA and Aerospace prime contractors through the 1980s and 1990s, such as the Space Exploration Initiative (SEI), but it was only recently that development activities which included the fabrication and test of prototype units has recommenced.

Much of the early inflatable habitat development (1960s) was overseen by NASA Langley Research Center (LaRC) with major contributions by Goodyear Aerospace. Several programs were conducted ranging from study efforts to development and test of full scale hardware in a vacuum chamber. Of particular interest were the Lunar Stay Time Extension Module (STEM), the Large Expandable Module, and the expandable airlock programs which were active in the late 1960s. The STEM was an inflatable cylinder with hemispherical endcaps that was 5.3 m long by 2.1 m in diameter and was intended as an expandable shelter for Lunar stay extension. The structure weighed 148 Kg and could be packaged within a 2.3 m^3 canister. The STEM's operational pressure was 34.5 KPa and it had a factor of safety of 3 over ultimate. A prototype STEM was manufactured and tested for packing and deployment feasibility, gas leakage, and habitability. Test results were encouraging for future application.

The Large Expandable Module was developed to be a manned earth orbiting artificial gravity vehicle. The concept was to deploy a 33.5 m long, 3.9 m diameter cylinder in earth orbit and rotate it such that differing fields of gravity were experienced at points along the length of the structure. A 11.4 m long portion of the structure was fabricated and tested. The total weight of the structure was 745 Kg which was divided into 584 Kg of flexible composite structure and 161 Kg of rigid support structure such as support rings, doors and packaging rings. The operational pressure was 34.5 KPa and the structure had a factor of safety of 3 over ultimate. The system was packaged and deployed in LaRC's 16.8 m vacuum chamber to evaluate deployment dynamics. It was also tested extensively for gas leakage and structural integrity at various pressures and dwell times. Again, the results of the tests showed promise and applicability if such systems were required in future missions.

The expandable airlock program was initiated to develop a one-man expandable airlock which decreased launch volume. The expandable airlock was a deployable and retractable inflatable cylinder that was 1.2 m in diameter and 2.1 m in length and had a packing ratio of 4:1. The airlock structure consisted of a gas tight convoluted sleeve that was contained within a series of polyester cords and rigid fiberglass composite rings to carry the longitudinal and circumferencial loads respectively. The end dome was also a rigid fiberglass structure that contained valving and acted as the hatch cover when the airlock was retracted. Deployment took place via inflation and a motor-driven retraction mechanism was used to retract the airlock into the packaged configuration. The airlock, designed to have an operational pressure of 69 KPa and a factor of safety of 5 over ultimate, weighed 97 Kg, 28 Kg of which was in the retraction mechanism. Test results showed that the liner material was substandard and that the retraction mechanism did not work properly during retraction in some cases. The program was discontinued due to a shift in research emphasis. It is worth noting that the first spacewalk by Alexi Leonov in 1965 was from an inflatable airlock such as this.

During these developments the evolution of the space suit was underway at ILC Dover. While facing the same challenges as the habitat structures noted above, such as structural integrity and gas containment, the space suit faced a whole new set of challenges that would improve the state-of-the-art for inflatable structure technology. Principal among these were the need for flexible mobility joints in the design, high cycle life materials, and low mass assemblies. Space suits are in essence small, short-term inflatable space habitats. They protect the inhabitant from the harsh extremes of space while providing a safe, comfortable environment. The evolution of the space suit from the Apollo Lunar surface suits to today's Space Shuttle suits have included many technological developments that have, and will continue, to benefit terrestrial inflatable structures and space inflatable structures (Figure 2). Since the development of space suits is well documented, the reader is urged to refer to these sources for additional information in the development of space inflatable systems.

Figure 2. NASA Shuttle Space Suit

Another area of interest worth mentioning due to its relevance to space inflatable structures are high technology terrestrial inflatables. These include inflatable components manufactured from flexible structural composites such as torpedo recovery floats, collapsible hyperbaric chambers, munitions decelerators, etc. Components such as these have not only a visual resemblance to habitat structures, but also a similarity in the sense that they are high specific strength, deployable structures.

The MK50 Torpedo Recovery System, designed and manufactured by ILC Dover, is a high strength reusable inflatable system that is packaged into a very small volume on a torpedo and remotely triggered to inflate to bring the torpedo to the surface for recovery. This component is 0.8 m in diameter by 0.6 m long, inflates to 172 KPa, and has a packing efficiency of 60% (Figure 3). The inflatable portion of the assembly consists of a Urethane coated Kevlar fabric that is bound externally by a series of Kevlar webbings that support the longitudinal and circumferencial stresses in the assembly. The MK50 recovery systems have been successfully used in thousands of training exercises by the U.S. Navy.

Figure 3. MK 50 Torpedo Recovery System

Another example of a high technology inflatable that has structural similarities to inflatable space habitats is the ILC Dover Collapsible Hyperbaric Chamber (Figure 4). This 0.8 m diameter by 2.1 m long cylindrical structure is used as a portable chamber to use in hyperbaric treatment of flying personnel who experience the bends. This structure consists of a bladder layer that provides pressure retention, and a restraint layer that supports structural loads. The bladder is a urethane coated polyester and the restraint is made up of a series of polyester webbings stitched to a polyester fabric substrate. The system operational pressure is 203 KPa with a factor of safety of 3 over ultimate.

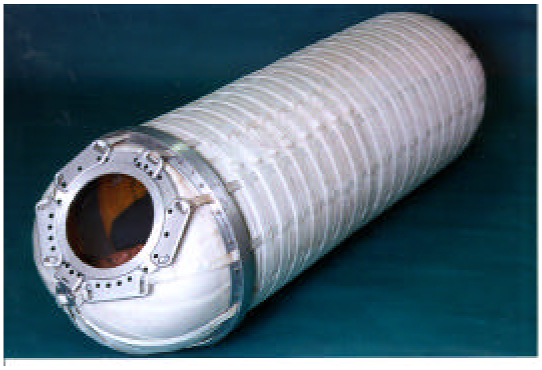

Figure 4. Collapsible Hyperbaric Chamber

Both of the examples discussed above were developed during the 1980s and they advanced inflatable systems technology in the materials and seam areas. Technological advances such as these, in conjunction with the enhancements continuously being made to the space suit, and the previous work performed on space habitats, are all being combined in efforts that have been underway in the last 10 years in the reemergence of space habitat design, prototyping, and testing.

3.0 Lawrence Livermore Inflatable Habitat

In 1989 the Lawrence Livermore National Laboratory, located in Berkeley California, began to study the feasibility of inflatable structures for use in construction of a low cost space station. This work was lead by Dr. Lowell Wood who presented his findings to NASA at the conclusion of the project. At that time NASA reviewed the findings and determined that further study would be necessary in order to implement the plan. NASA has continued the investigation of this technology at Johnson Space Center since that time.

ILC Dover was funded to perform a configuration analysis and design study by Livermore under this project. Aspects of the system that were analyzed in the study included structural analysis, materials evaluation, producibility, redundant pressure containment systems, safety and reliability, mass analysis, consumables, reparability, and cost. The study yielded two configuration options that were different in nature and both we carried until the conclusion of the study. The study focused on the development of standardized modules that could be combined to create larger stations, similar to the current International Space Station design (Figure 5).

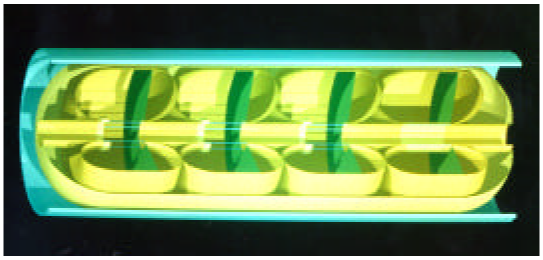

Figure 5. Livermore Habitat Module

It was decided early in the study that the module was to be compartmentalized to increase safety margin. In the event of loss of one compartment, the whole module would not be lost and operations could continue until a repair could be effected. Therefore, both designs had a central core with doors to each compartment that could be closed in the event of an emergency. The module was also to have a redundant pressure containment system that would be pressure retentive in the event of the loss of a sub element. The habitation space would be pressurized to 51.7 KPa, and the secondary containment envelope would be continuously pressurized to 17.2 KPa to maintain module geometry.

The first design option (Figure 6) was to build a system with rigid composite end plates that separated compartments within a module. The second option (Figure 7) was to fabricate an all flexible composite system that consisted of stacked toroidal elements within each module. Both systems were 5 meters in diameter and approximately 17 meters long with a 1 meter diameter central corridor. The flexible portion of both module concepts consisted of a laminate bladder and a restraint assembly (in two areas because of the dual hull). The bladder would be manufactured from a scrim reinforced film laminate. The films in the laminate would be a low permeation film such as Tedlar coated on both sides with Urethane to allow simple manufacture. The scrim would be a Kevlar or other high strength reinforcement to act as a rip stop in the event of a penetration in the bladder. The bladder would be sized to be larger than the restraint to keep a zero-stress condition in the bladder wall. The zero-stress wall will negate the effects of creep in the material and minimize tear propagation loads, thus increasing bladder reliability.

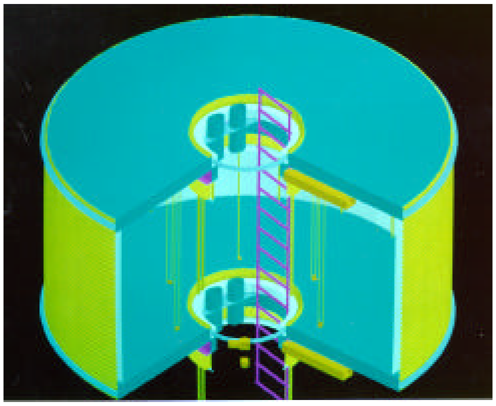

Figure 6. Inflatable Compartment

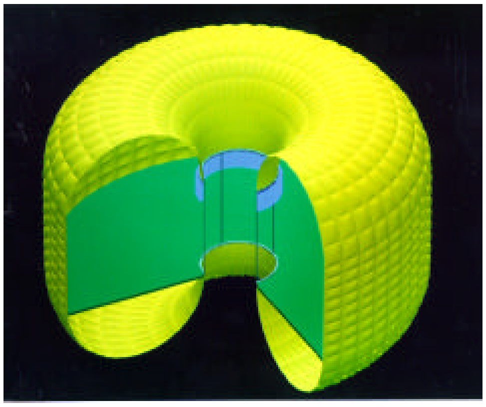

Figure 7. Rigid Wall Compartment

The restraint would be a sewn Kevlar fabric with Kevlar webbings mounted to its exterior in the hoop and longitudinal directions. The webbings were sized to carry all the load in the system in the event of loss of a single webbing with a factor of safety of 4 over ultimate. A stress analysis was performed using ANSYS on both systems under operational pressure to determine the stresses in the flexible composite and loads at the interfaces. The maximum stress location for both systems was in the cylindrical section of the external wall. The resultant stress was 128 Kg/cm in the hoop direction and 41 Kg/cm in the longitudinal direction. The stress in the longitudinal direction was less than half the hoop direction because the center column supported axial load in the module. In the case of the all-flexible composite concept, the stresses decreased as the geometry transitioned from the cylindrical section to the toroidal section. This allowed the restraint to be sized to support only the required load where it was required to conserve system mass.

The outer pressure containment envelope that was pressurized to only 17.2 KPa, witnessed a maximum hoop stress of 44.8 Kg/cm and a maximum longitudinal stress of 22.5 Kg/cm. In all areas the system was designed to have a factor of safety of 4 over ultimate over the loads noted here.

A liner was included in both designs to act as a puncture resistant material to withstand puncture threats from within the structure. All external penetration threats, such as micrometeoroids, were to be repelled through the application of a Thermal/Micrometeoroid Layer (TML). The exterior of this assembly would consist of a multi-layered insulation of metallized films, and the interior of the TML would consist of fabrics such as Nextel and Spectra sandwiched in foam layers to create a multi-layered Whipple Bumper.

System masses, packed volumes and deployed internal volumes were calculated for both concepts. System masses included all components discussed above but did not include Life Support Systems (LSS). Deployed internal volumes calculated excluded the center corridor.

	All-Flexible Composite	Rigid End Plates
Total System Mass (Kg)	1523	1344
Total Usable Volume (m^3)	232	196
Total Packed Volume (m^3)	29	32

Each of the concepts has potential benefits and drawbacks. Some of the benefits of the rigid end plate concept include :

- Lower mass
- Simplified attachment of equipment to floor
- Flexible assemblies are simplified (cylindrical)
- Pressure compartmentalization is simplified with rigid endpoints
- Lower permeation rates with less flexible material area

Some of the benefits of the all-flexible module included:

- Greater usable volume
- Lower leakage - less hardware/softgoods transition length
- Lower cost
- Better impact tolerance
- Simplified packing and deployment

Based on the system requirements of the proposed station at the time, the all-flexible concept was selected as the most promising candidate for further study. Further study of this concept as a stand alone system did not occur because of a change in the direction of the program and this work was shelved until it could be used to support the Deployable Lunar Habitat Study and Mars Transhab prototype fabrication.

JSC Expandable Lunar Lander & Habitat

In 1996, NASA Johnson Space Center (JSC) began to study a return mission to the Lunar surface. It was determined that a habitat craft would make the trip and check-out prior to launching the manned craft. The habitat craft was envisioned to be an inflatable, deployable, cylindrical structure with rigid endcaps that would sit atop a landing craft and expand to full volume when on the surface (Figure 8). The deployed habitat measured 2.3 m in diameter and 3.7 m in length.

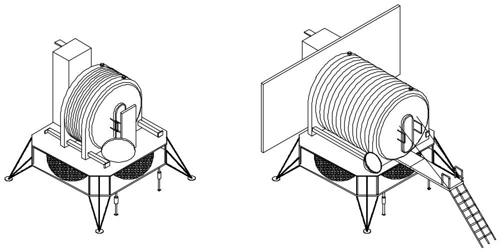

Figure 8. Stowed & Deployed Lunar Habitat

ILC Dover was contracted to study various configuration options and design the inflatable portion of the habitat. As with the Livermore habitat, the expandable Lunar habitat was compiled of separate subassemblies including the bladder, restraint, and Thermal & Micrometeoroid Cover (TMC). Numerous concepts were developed for the bladder and restraint subassemblies. Among the concepts studied for the bladder were dual walled, self-sealing, coated fabric, and film laminates. The coated fabric bladder, made from silicone coated Vectran, was chosen for its simplicity, cold temperature deployment properties, and robust nature. Numerous concepts were also developed for the restraint layer (Figure 9), with the final selected concept being a webbing restraint with an underlying structural fabric layer. The webbing system was anticipated to be manufactured from a Kevlar 4082 Kg webbing and the structural fabric layer was to be a 710 polyester fabric with a 440 denier, 45 x 45 count plain weave. The structural fabric layer was to be slightly oversized to create a "quilted" effect that would reduce the load transmitted through the fabric by reducing its local radius.

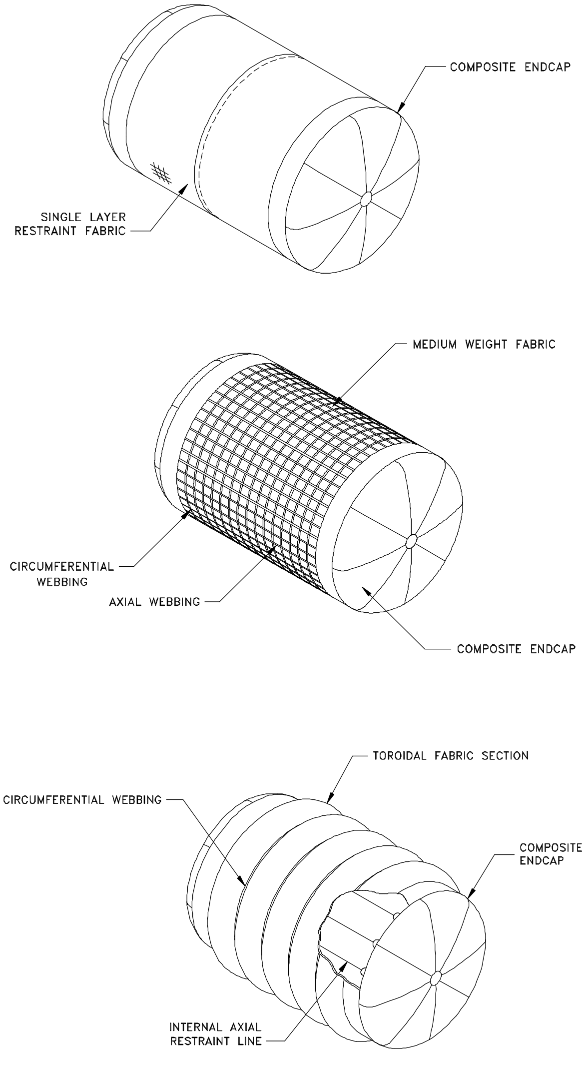

Figure 9. Restraint Concepts (Fabric, Webbing & Cable)

The final assembly is shown in Figure 10. Here each of the layers of material can be seen along with the structural endcaps.

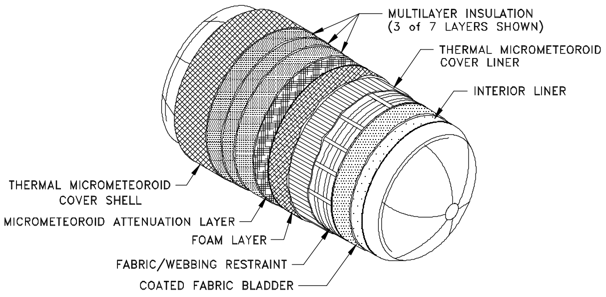

Figure 10. Lunar Habitat Layers

An interesting aspect of the study was to determine how to maintain structural geometry once the habitat was depressurized for ingress/egress. One option developed to address this was to "rigidize" the structural restraint portion of the habitat. Rigidizable structures are being studied for use in many space applications such as radar and communication antennas, solar arrays, sunshields, and solar sails. These structures are flexible when packed and deployed, then rigidized when in their final configuration. The rigidization process can be thermally or chemically induced by several methods. Once rigidization is complete, the structure acts as a rigid composite structure. Although this was investigated for the Lunar habitat, it was not recommended because of the short stay times.

4.0 JSC Mars TransHab

NASA JSC is currently working on a program to develop an inflatable habitat structure to be used as a transfer vehicle to Mars, or possibly as the habitation module on the International Space Station. The design is compiled of a metallic central core with a flexible composite outer shell that is cylindrical and has toroidal ends. The inflatable structure is packaged around the central core to decrease its volume for launch, then inflated, on-orbit, to its approximate 7.6 m diameter by 9.1 m length (Figure 11). The high packing efficiency of the system will allow the entire module to be launched on a single Shuttle launch as compared to two launches for a equivalent volume rigid structure. The inflatable structure is a series of material layers that perform numerous functions including:

- Gas retention
- Structural Restraint
- Micrometeoroid/Orbital Debris (MMOD) Impact Protection
- Thermal Protection
- Radiation Protection

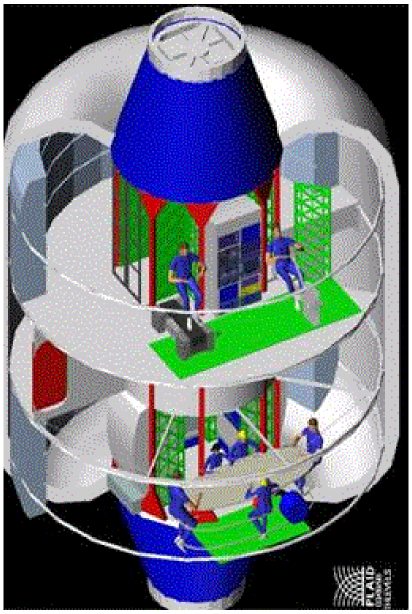

Figure 11. Mars Transhab

Gas retention is achieved by a double redundant bladder assembly (discussed later). Structural restraint is achieved by a series of Kevlar webbings that are interwoven and indexed to one another to form a shell. The webbings are terminated to pins which are mounted to the ends of the metallic core structure. The webbings are sized to withstand the 101 KPa internal pressure (Space Station variant) loads with a factor of safety of 4 over ultimate. This yields a structure that must withstand approximately 2232 Kg/cm maximum stress in the hoop direction and 893 Kg/cm stress in the longitudinal direction. Other materials, such as Vectran, are also being considered for the webbings in the later configurations.

MMOD impact protection is being accomplished by a series of woven 1.5 mm thick Nextel layers separated by foam spacers to create a multi-hull structure. This structure was tested for hypervelocity particle impact by JSC and found to provide greater protection than the current Space Station design. Testing revealed that 1.8 cm particles traveling at 7 km/sec would not penetrate the structure. This provided margin over the current limit of 1.3 cm particles at 7 km/sec for the Space Station in a roughly equivalent mass system. The Nextel layers were coated with polyethylene to enhance their stability. The polyethylene also provides a significant amount of radiation protection. Thermal protection is accomplished by a series of metallized films on the exterior of the assembly that reflect radiation.

Prototype manufacture and testing is currently in progress at JSC on full scale diameter (reduced length) units that are being hydrostatically tested in the JSC Neutral Buoyancy Facility. The first unit (Figure 12) was inflated to twice the operational load without failure. Design modifications were made and a second unit will be hydrostatically tested to a full 4 times safety factor in September of 1998. Vacuum chamber testing will be conducted later in the year at JSC on a third prototype unit. The chamber test will be used to evaluate leakage, structural rigidity, and deployment.

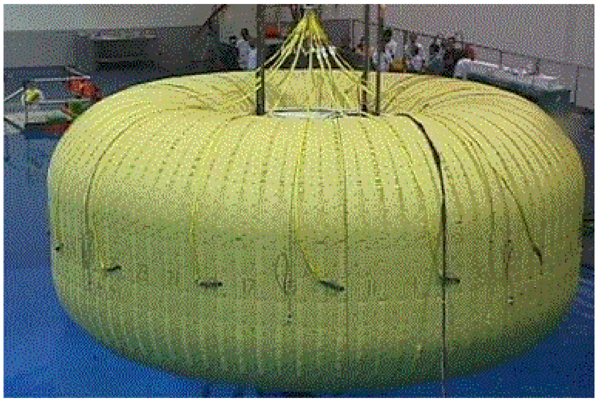

Figure 12. 30 ft Diameter Transhab Test Unit

ILC Dover is part of the Integrated Product Team (IPT) working on the system design and testing. ILC Dover is currently in fabrication of the bladder that will be used in the first vacuum chamber test of the TransHab in late 1998. The bladder is manufactured from a lay-up of various materials to provide a double redundant bladder. Each individual bladder layer is a laminate of polyethylene, nylon, ethylene vinyl alcohol (EVOH), and polyethylene film. The resultant laminate is an ultra-low permeable film. Polyethylene is placed on both sides to facilitate thermal sealing of the structure. Three layers of the bladder laminate are separated by a 148 g/m^2 nonwoven polyester to allow flow paths for pressure monitoring between each layer which is used to sense leaks in the individual bladder layers.

5.0 Conclusions

Flexible composite inflatable structures offer many advantages over conventional structures for space applications. Principal among the advantages is the ability to package inflatable structures into small volumes for launch. This allows for smaller launch systems to be used, which reduces program costs dramatically, and yields greater deployed volume on site. Mass reductions are also realized in the structural and hypervelocity impact shield portions of the assembly. The introduction of rigidization technologies which give the structural layer the ability to deploy in a flexible state, then become a rigid structural composite once deployed, will also enhance structural capability of these systems.

Many other space structures are being studied for application of this technology such as communications and radar antennas, solar arrays, and habitat structures. The design, manufacture, and test of manned inflatable space habitats has been ongoing for decades. Design maturation and the development of advanced materials and fabrication processes have made the concept of an inflatable habitat achievable in the near future. Uses of inflatable habitats currently being investigated include the habitation module for the International Space Station, a deployable Lunar surface habitat, and the Mars transfer or surface habitat (TransHab). The most recent effort (currently ongoing at NASA Johnson Space Center) is the design, fabrication and test of sections of size representative elements of the Transhab. Inflatable structures tested in this effort will prove the viability of the technology and pave the way for their application in an upcoming mission.

6.0 Acknowledgments

The authors thank the members of the NASA JSC inflatable habitat teams (TransHab and Lunar Habitat) for their support of the advancement of this technology. Specifically, Donna Fender, Horacio De La Fuente, and Gerard Valle of the JSC TransHab team, and Kriss Kennedy of the habitat team. The authors also acknowledge the support and technical advice from Phil Spampinato and Steve Lloyd of ILC Dover.

Bibliography

1. Cadogan, David and Graziosi, David. (ILC Dover) “Recent Advances in the Development of Spacesuit Gloves.” Proceedings of the 26th International Conference on Environmental Systems. Monterey, CA: SAE, July 8-11, 1996.

2. Cadogan, David and Grahne, Mark (ILC Dover) and Mikulas, M. (University of Colorado). “Inflatable Space Structures: A New Paradigm For Space Structure Design.” Proceedings of 49th International Astronautical Congress. Melbourne, Australia. September 28 - October 2, 1998.

3. Crimmins, Rob. “Final Report For Conceptual Design Study For Modular Inflatable Space Structure.” ILC Dover. December 4, 1989.

4. Boyle, Alan. MSNBC. Mars Affects Plans for Space Station. http://www.msnbc.com/news/128835.asp. August 24, 1998.

5. Kosmo, Joseph J., Spenny, William E. (NASA Lyndon B. Johnson Space Center) and Gray, Rob and Spampinato, Phil (ILC Dover). “Development of the NASA ZPS Mark III 57.2-kN/m^2 (8.3 psi) Space Suit.” Proceedings of 18th Intersociety Conference on Environmental Systems. San Francisco, CA: SAE, July 11-13, 1988.

6. Balinskas, Robert (Hamilton Standard), James W. McBarron II (NASA Johnson Space Center), and Spampinato, Philip M. (ILC Dover). “Shuttle Extravehicular Mobility Unit (EMU) Operational Enhancements.” Proceedings of 20th Intersociety Conference on Environmental Systems. Williamsburg, VA: SAE, July 9-12, 1990.

7. Shortliffe, Glen (GB Tech) and Christiansen, Eric (NASA). “Mars Trans Hab Meteoroid and Orbital Debris Shield Performance Assessment.” Prepared for the JSC Engineering Directorate (EA). June, 1997.

8. Morgenthaler, George W. “Some Realistic Barriers to International Mars Human Exploration Now: Work to be Done - New Approaches.” Proceedings of 1996 AIAA Space Programs and Technologies Conference. Huntsville, AL: September 24-26, 1996.

9. Tynan Jr., C.I., Williams, J.G., and Osborne, R.S. “Expandable Structures Technology For Manned Space Applications.” Proceedings of AAS/AIAA Variable Geometry and Expandable Structures Conference. Anaheim, CA: April 21-23, 1971.

10. Stein, Jim, Cadogan, Dave, Fredrickson, Thad, and Sharpe, George. “Deployable Lunar Habitat Design and Materials Study, Phase I Study Program Results.” ILC Dover. January 29, 1997.

11. Stimler, Frederick J. “System Definition Study of Deployable, Non-Metallic Space Structures.” Prepared for NASA Marshall Space Flight Center. Huntsville, AL. June 1984.