Review of Habitable Softgoods Inflatable Design, Analysis, Testing, and Potential Space Applications

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Inflatable space structures have the potential to significantly reduce the required launch volume of large crewed pressure vessels for space exploration missions. Mass savings can also be achieved via the use of high specific strength softgoods materials, and the reduced design penalty from launching the structure in a densely packaged state. Inflatable softgoods structures have been investigated since the late 1950's, and several major development programs at NASA and in industry have helped advance the state-of-the-art in this technology area. This paper discusses the design, analysis, structural testing, and potential applications for inflatable softgoods structures. In particular, this paper will discuss the design of the multi-layer softgoods shell (inner layer, bladder, structural restraint layer, micrometeoroid orbital debris protection layers, thermal insulation layers, and atomic oxygen layer (for low earth orbit) and the results of material and module-level testing that has been conducted over the past two decades at NASA. Finally, the current utilization of expandable spacecraft structures is discussed, as well as potential future applications including airlocks and habitats on the Lunar Orbital Platform-Gateway, and the surface of the Moon and Mars.

Nomenclature and Acronyms

AO	=	atomic oxygen
DTT	=	damage tolerance test
EDU	=	engineering development unit
FEA	=	finite element analysis
JSC	=	Johnson Space Center
LaRC	=	Langley Research Center
LBB	=	leak before burst
LSC	=	linear shaped charge
MASH	=	minimalistic advanced softgoods hatch
MMOD	=	micro-meteoroid and orbital debris
MLI	=	multi-layer insulation
NAIPS	=	non-axisymmetric inflatable pressure structure
P	=	pressure
TPS	=	thermal protection system
TTF	=	time to failure
UTS	=	ultimate tensile strength
WSTF	=	White Sands Test Facility

I. Introduction

THE primary advantage of inflatable space structures is in their ability to be compactly stowed for launch and then subsequently deployed to a much larger operational volume. This packaging enables the use of smaller launch vehicles or the ability to package multiple inflatable structures on a larger launch vehicle. These structures also have the potential for mass savings due to the use of high-specific strength materials, such as Vectran or Kevlar, and the reduced impact of launch loads on the design due to the initial packaged state. Habitable inflatable space structures have been designed and tested for over five decades for application to, and enhancement of, human space exploration, with applications including space stations, habitats, airlocks and deployable tunnels for missions, both in space and

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on planetary surfaces. This paper will detail and summarize the research that has been performed at NASA over the last two decades on the material components that make up the multi-layer inflatable shell, and testing that has been performed at the component and module level on these softgoods structures. A discussion of current and future applications for habitable inflatables is also presented and correlated with current NASA plans for cis-lunar, lunar, and Mars exploration missions.

Concepts for habitable inflatable space structures are older than NASA itself, going back to Wernher von Braun's rotating-wheel space station[1] in 1952. This 250-ft diameter, three level, rotating toroid, consisted of 20 inflatable sections that would be connected and deployed on-orbit (Figure 1-1). The primary motivator for using inflatables then still holds today: to provide a large deployed habitable volume that could be compactly packaged for launch.

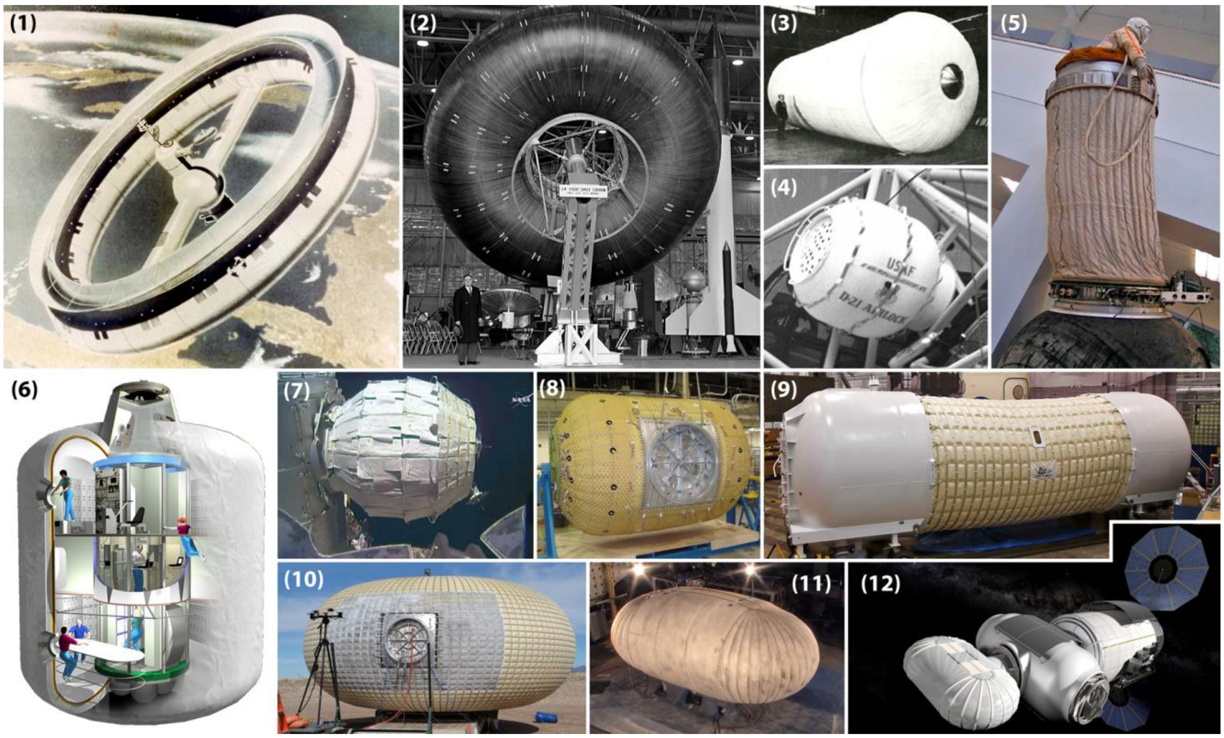

Figure 1. Inflatable Structures: (1) Von Braun's Space Station, (2~4) Goodyear Aerospace's toroidal space station, 'Moby Dick' habitat module, and D021 airlock, (5) Volga airlock, (6) TransHab, (7) BEAM, (8) JSC module with integrated hatch, (9~10) ILC/NASA expandable and toroidal habitats, (11) NASA's MASH inflatable airlock, (12) NextSTEP-2 cis-lunar habitat and airlock concept.

Throughout the 1960's, Goodyear Aerospace, in coordination with NASA, performed the first in-depth study of expandable inflatable space structures intended for human spaceflight[2,3] producing several full-scale test articles that included a toroidal space station concept, two lunar surface habitat concepts and an airlock (Figure 1, images 2,3,4). This program was one of the first to address the challenges of designing and fabricating a multi-layered, human-rated softgoods inflatable that was robust against micrometeoroid and orbital debris, radiation and the thermal environment of space. Sadly none of these concepts were taken to flight as NASA turned its focus on the Apollo missions. During this same period, the Soviet space program also manufactured an inflatable airlock, called Volga[4] (Figure 1-5), and launched it in 1965 on the Voskhod-2, enabling the first spacewalk in history and becoming the only crewed inflatable to go to space until 2016.

The next major human-rated inflatable research program didn't occur until 1997 with the instigation of the Transit Habitat (TransHab) program[5,6] at NASA's Johnson Space Center (JSC). The TransHab (Figure 1-6) was a 3-level, 36 ft. long by 27 ft. diameter inflatable habitat with a rigid core structure, designed as a multi-use living space for a mission to Mars, and as a possible replacement for the habitation module on the ISS that would have provided the first in-space, long-duration test of an inflatable habitat. Although the TransHab was not flown, there was extensive and pioneering development of fabrication processes and the multi-layer fabric shell including the bladders, restraint layer, thermal insulation and micro-meteoroid and orbital debris (MMOD) shielding[7,8]. Sub-scale and full-scale tests were also performed to verify the design and strength of the structure and its packaging and deployment. The patented technologies from TransHab were licensed to Bigelow Aerospace who continued development of inflatable structures, most recently culminating in the launch and deployment of their BEAM module (Figure 1-7) on the ISS in April 2016, where it currently is still in operation.

Since the conclusion of the TransHab program in 1999, inflatables technology development and testing has continued on a smaller scale at NASA. Research has focused on investigating and characterizing areas of primary concern including: the long-duration behavior of high-strength restraint layer materials[9-11], the integration of hard structure such as windows and hatches into the fabric shell, internal and secondary structures, instrumentation and measurement of strains and loads, and efficient folding and packaging of the multi-layer shell. NASA has also tested many different inflatable geometries and architectures (Figure 1, images 8 to 11) at sub- and full-scale, fabricated both at NASA and with its industry partners[12-14]. Currently, several private companies are involved in NASA's NextSTEP-2 program[15] studying inflatable concepts for deep-space habitats and airlocks (Figure 1-12), with the potential that an inflatable component or module will be selected to proceed toward a flight article in the 2020's.

II. Requirements and Design of Softgoods Layers

The softgoods shell of an inflatable structure is made of over 60 layers of fabric materials, totaling 12-20 inches once fully deployed. A combination of materials in sub-assembly layers are stacked up to provide the structural capability and environmental protection required for a space habitat. The shell assembly is composed of five primary layer including 1) liner layer, 2) bladder layer, 3) restraint layer, 4) micrometeoroid/orbital debris (MMOD) protection layer, and 5) thermal protection layer as shown in Figure 2 below.

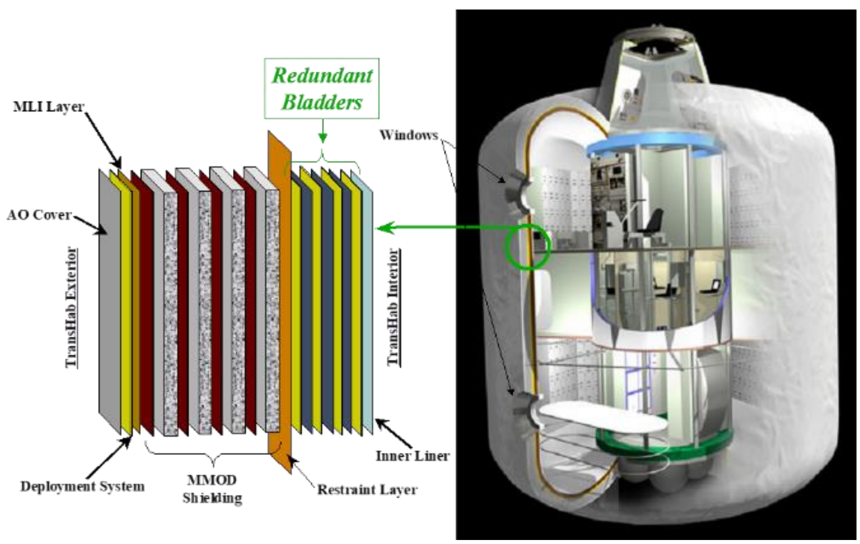

Figure 2 – TransHab Shell Layers[6]

The inner-most layer, facing the crew, is called the liner. It is required to protect the bladder from damage by the crew and to provide a durable and easy-to-clean surface for human contact. It is both flame and puncture resistant, and provides acoustic dampening. In TransHab, the liner was made of Nomex fabric and Kevlar felt[6,17].

The second layer is the gas barrier of the habitat, known as the bladder. Its primary purpose it to contain the internal atmosphere, so it must be flexible, durable, and have low permeability at both high and low temperature ranges. It is a critical layer, and is stacked as three layers to provide redundancy, with each layer sandwiched between Kevlar felt. Unlike the restraint layer, the bladder layer in the TransHab design does not carry load and therefore does not require high tensile strength. The bladder is oversized by design to ensure the pressure force is solely carried by the restraint layer. The bladder is made from polymeric materials and must meet permeability requirements in both cold and hot temperature extremes. It should also be able to be folded, packed, and flexed without detrimental damage. Materials including Combitherm and Urethane coated Nylon have been used in inflatable habitats[6], and Cepac® HD-200 was identified as the preferred embodiment of a gas barrier in a Bigelow Aerospace patent[18].

The third layer is the restraint layer, known as the primary structural layer of the inflatable. This layer carries the hoop and axial loads and must have high tensile strength capabilities. It should also be flexible and foldable for packaging and deployment. In TransHab, this layer was made of Kevlar and Vectran webbing that is woven together in a tight basket weave to form a biaxial membrane[17]. Alternately, a patent from Bigelow Aerospace shows a restraint layer sewn lengthwise, end-to-end in the hoop direction instead of a weave[18]. Since the restraint layer is the load carrying component of the shell, it must meet the NASA structural design standard NASA-STD-5001 requirements. For softgoods structures, the restraint layer must be designed to a factor of safety of 4.0 on both operating pressure and lifetime. Stitching, load sharing, seaming, handling, and creep knockdowns should be considered in determining the safety and life requirements of the restraint layer.

The bladder and restraint layers are attached together at indexing points spread across the surface area of the shell. These connection points allow the layers to move together and prevent the bladder from being loaded during deployment and inflation. There should be enough indexing points to keep the layers together, while not inflicting damage to any individual layer. Another important consideration is the interfaces between the bladder and the bulkhead. TransHab utilized a central core with metallic bulkheads on each end. The bladder is sealed to the bulkhead using O-rings, to prevent any leaks. Gaskets and adhesive type seals can also be used, along with redundant seals to maintain reliability. The bladder should be attached in a way that prevents tension on the bladder and does not allow for tearing at the seam. The restraint layer is also attached to the bulkhead and transfers load from one webbing to the next. The webbing on TransHab is attached is a clevis and roller system that allows for stretch and rotation of the straps.

The MMOD layer is sized for the mission and has the primary job of protecting the restraint and bladder layers from hypervelocity impact damage from MMOD. This fabric layer is a multi-material layup that is made of ceramic fabric bumper layers, separated by low-density foam, and a high strength fabric rear wall. The TransHab bumper is made of Nextel with open cell polyurethane foam and a Kevlar fabric rear wall. This layup is vacuum packed for launch, creating a very thin stack. Then in orbit, the layer expands and a very thick shield is deployed with the shell. This MMOD shield is very efficient with the bumper layers positioned at high standoff distances, allowing the particles to breakup upon impact and disperse through the layers. The total density and number of layers required for the shield is dependent on the mission and MMOD threat to that location.

The thermal protection system (TPS) is the outer layer of the shell and is used to passively maintain the temperature of the habitat. The TPS is a fabric layup, similar to that of an extra-vehicular activity (EVA) space suit, utilizing multi-layer insulation (MLI). This insulation is made of thin sheets of Nylon reinforced, double aluminized Mylar that is sandwiched by an inner and outer layer of double aluminized polymide (Kapton) film. The inner layers are perforated, allowing for venting. The total number of layers is dependent on the thermal environment of the mission.

Atomic oxygen (AO) protection is used in low Earth orbit (LEO), where AO levels are very high and have been shown to damage spacecraft materials. In TransHab, the AO protection was a layer of Betaglass fabric, which is also commonly used on space suits[1]. In deep space, the AO levels are decreased, compared to LEO, but the levels are prevalent in Mars' atmosphere and should be a consideration for future missions.

To assist in a controlled expansion and inflation of an inflatable habitat, a deployment system should be used. The system is required to deploy the habitat in a controlled and predictable madder that is simulated and verified on the ground, before operation in space. In TransHab, the deployment system was integrated with the shell layers and used as both a launch restraint and deployment release layer.

III. Softgoods Component Testing

3.1 – Micro-meteoroid and Orbital Debris (MMOD) Restraint Layer Testing

Hypervelocity impact testing was conducted in 2012 to evaluate MMOD shields for two sizes of inflatable habitats: small, LEO modules, and large, deep space modules. The test series compared 18 shield configurations with varying bumper materials and gap distances with aluminum projectiles at varying angles[19]. There was also a woven restraint layer and bladder layer in the stack up behind the rear wall. The typical pass/fail criteria for an impact test is the amount of damage on the rear wall of the shield. For an inflatable shield, however, the real pass/fail test is the amount of damage to the restraint layer from a hyper-velocity impact. For this test series, there were three failure modes identified including 1) damage to the restraint layer with no damage to the bladder, 2) damage to the restraint layer and the bladder, 3) no damage to the restraint layer or bladder. After the tests, the restraint layer was removed from the specimen and evaluated for damage and strength degradation.

For deep space missions, an in-space inspection capability could be developed to allow the crew to examine the restraint layer to determine the remaining life of the structure and if there has been detrimental damage. In order to conduct this inspection, however, a correlation needs to be made between visual damage and strength degradation of the straps. For this test series, a visual inspection and a strength test was conducted to determine the amount of damage to the restraint layer. Out of 18 specimens, only 4 had no damage to the restraint layer or bladder after a visual inspection. The remaining specimens received close-up visual inspection and were qualitatively scored for the level of damage to the straps. Figure 3 shows a specimen with a lot of visual damage and subsequently a lot of degradation to the webbing strength. Figure 4, however, shows a specimen with less surface damage, but multiple straps with detrimental damage. This varying level of damage was apparent in all tested specimens and it was difficult to correlate visual damage to actual damage. A relation between the amount of visual damage to the webbings and the actual strength degradation was not conclusively found. Further work needs to be done to determine if visual inspections can be used in-space to determine the damage, and associated strength reduction, to a webbing restraint layer[20]. Based on these preliminary results, NASA currently considers any damage to the structural restraint layer an MMOD test failure.

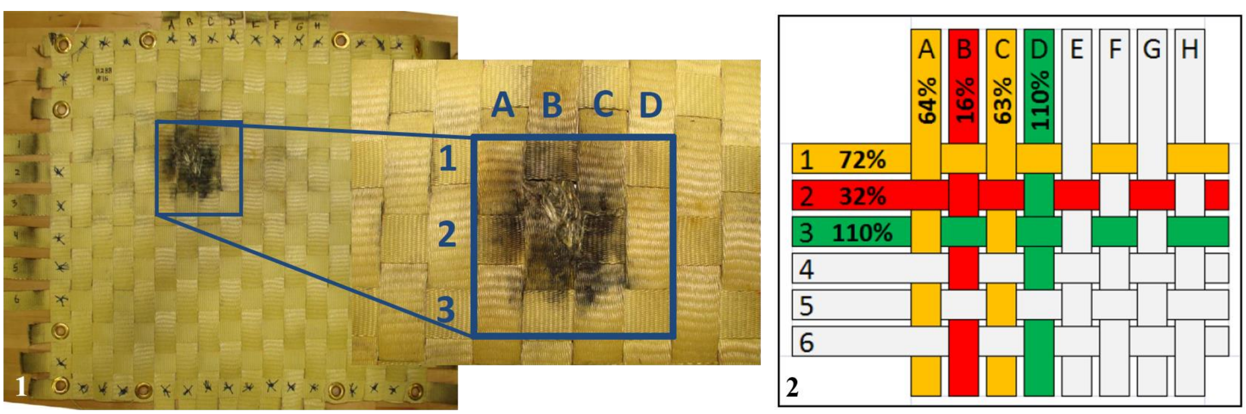

Figure 3. (1) Webbing restraint layer section of HVI test specimen showing visual damage and critical straps, (2) Webbing strap strength as a percentage of rated strength for critical straps.

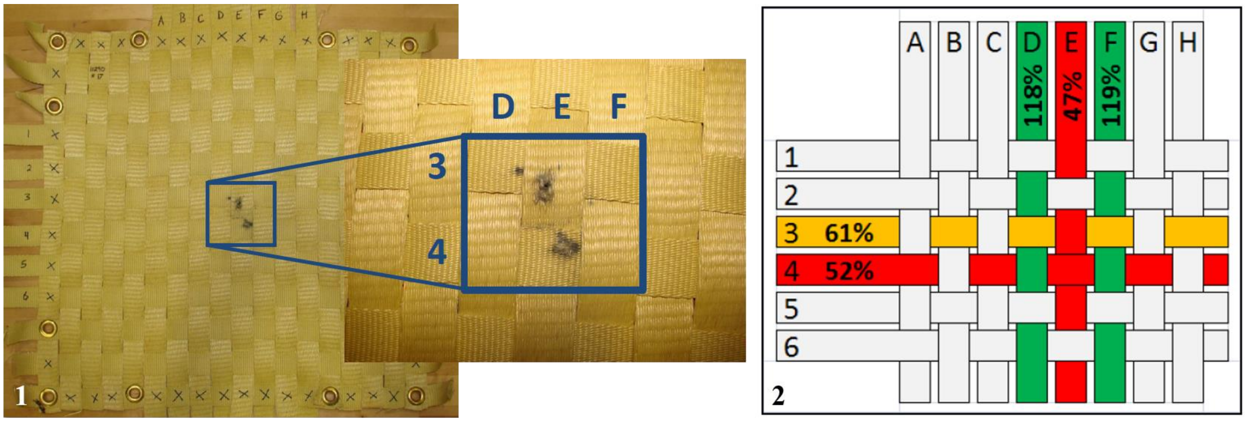

Figure 4. (1) Webbing restraint layer section of HVI test specimen showing visual damage and critical straps, (2) Webbing strap strength as a percentage of rated strength for critical straps.

3.2 – Creep Testing

The long term structural behavior of habitable inflatables is a critical area that must be characterized for successful use of inflatables as primary structures for long duration human exploration missions. Creep, the permanent deformation of a material under a sustained load, is the primary concern for long-term damage to the restraint layer, as the polymeric softgoods used demonstrate viscoelastic creep behavior (Figure 5). Understanding this behavior was identified as one of the highest priority research areas at the end of the TransHab program, and has been a focus area for testing at NASA over the last decade[9-11].

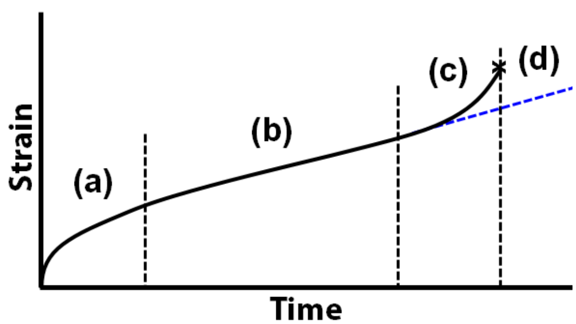

Figure 5. Viscoelastic creep behavior. (a) Primary transient creep, (b) secondary steady-state creep, (c) tertiary unstable creep, (d) creep failure.

Several factors affect the creep behavior of the restraint layer in addition to the principal load and temperature influences. The high-strength softgoods components used for habitat structures, such as webbings and cordage, are built-up, hierarchical structures, made up of polymer fibers and yarns, and integrated into an even higher level structural configuration in the inflatable module. Influence factors are present at each level, including the manufacturing process and sizings used at the fiber and yarn level, weave/twist type and resin selection at the component level, and layout, friction, and stitch properties at the inflatable module level. These parameters combine to produce nonlinear, time and load-path dependent mechanical behavior in the components and full-scale article. This feeds into two other related factors that strongly impact the creep life.

The first factor is variability in the ultimate tensile strength (UTS) of the softgoods components, which has been shown in testing at NASA, to be up to ±6% about an average breaking load for 6,000 lbs-rated (6K) Vectran webbing, and ±10% for 12,500 lbs-rated (12K) Vectran webbing. The second factor is non-uniform load distribution in the restraint layer, where due to the architecture, fabrication, and small changes between the spacing and load-up of the restraint layer during inflation, some softgoods components see a higher or lower load than the ideal uniformly distributed design loading. Both of these factors affect the load level seen by each strap in an inflatable article and have a significant impact on the resultant creep time to failure (TTF). Figure 6 presents a plot of the results from a multi-year creep test program at NASA LaRC studying specimens of 6K and 12K Vectran webbing. Multiple samples were tested at different percentages of the UTS of each type of webbing to characterize and bound the times to failure at different load levels and predict the TTF for lower %UTS levels. It can be observed that at the same %UTS, the 6K specimens have tighter TTF bounds than the 12K specimens reflecting their lower variance in UTS. The wider range of TTF is due to the load at a chosen % UTS being based on the tested average, so an individual specimen may have a higher or lower actual UTS within the tested variance for that roll. As TTF is related exponentially to the load level, even a small percentage change in the load can lead to a dramatic change in the TTF as shown. This bounding of the TTF would be expanded again for an inflatable article if there is a non-uniform load distribution as the individual component load levels would be varying over the inflatable's surface at a given pressure. In addition it should be noted that current inflatables are designed to operate at 25% UTS (a safety factor of 4), where there is also a significantly wider spread in TTF predicted. These factors illustrate the necessity for reducing variability in the restraint layer, via rigorous manufacturing techniques and preconditioning of the softgoods components, and using stringent fabrication processes and architectures that minimize or eliminate non-uniform load distributions.

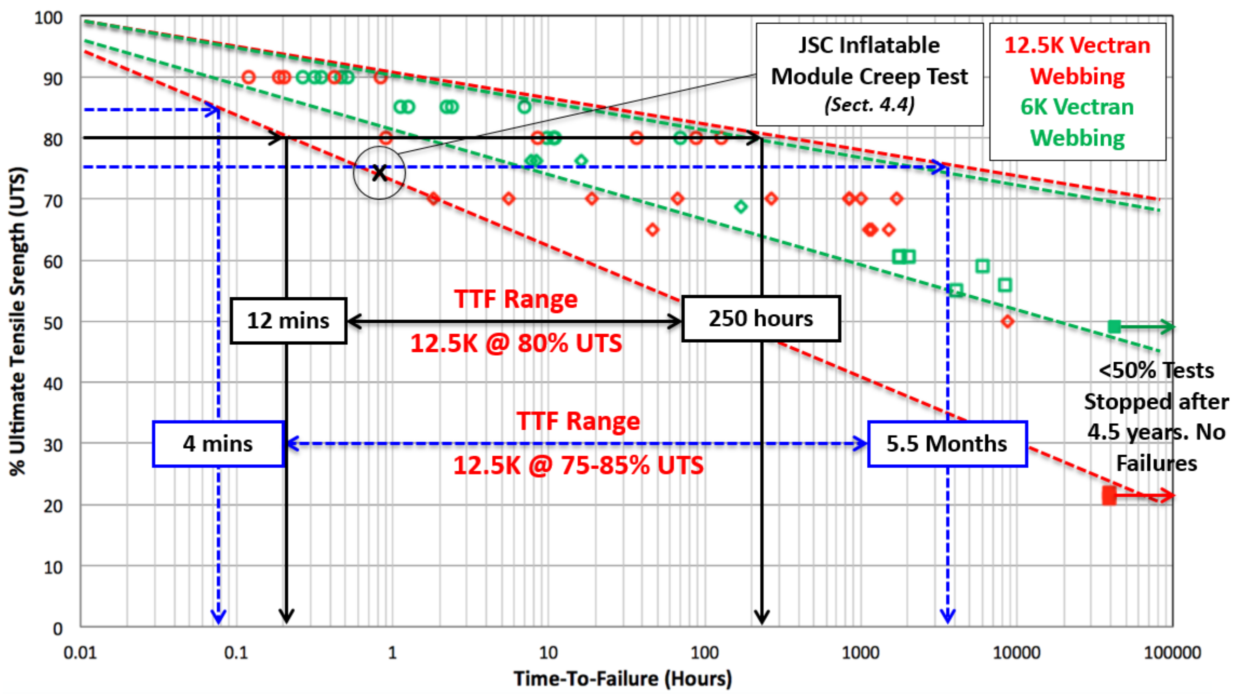

Figure 6. Real-time creep data for 6,000 lbs (green) and 12,500 lbs (red) Vectran webbing. Variance in times to failure strongly correlates with UTS variance and load variance in the structure.

Real-time creep testing of high-strength softgoods is costly and requires a large, environmentally controlled test facility that can house a large number of specimens for multiple years. Due to the high load capacity of the webbings and cordage used in these structures, large weights are typically required to perform the tests. NASA is currently researching more efficient approaches to performing real-time creep testing on high-strength softgoods based on lessons learned from a 5-year creep test program[9-11]. Accelerated creep testing methodology for these materials has also been pursued, to reduce the cost and time required, but initial correlations with real time creep tests resulted in non-conservative TTF estimates. There are a number of factors that may have attributed to these differences, including differences in specimen size and setup, thermal effects on the oils and sizings used in the construction of the softgoods and their impact on the mechanical behavior, and even the core methodology and post-processing of the data required in the accelerated tests. NASA LaRC is currently studying these issues, with the goal of formulating a successful and verified accelerated creep approach for high-strength softgoods components. Creep is one of the most significant factors that could drive the design of future long-duration human-rated inflatables, thus continued research on both accelerated and real time creep methodology is a critical and ongoing area of research.

IV. Assembled Module Testing

4.1 – Pressurization and Burst Testing

In 1998, a 23-ft diameter TransHab inflatable development test article was pressure tested to 60 psig without failure. The test article was manufactured out of Kevlar woven from hoop and longitudinal webbings. The longitudinal webbings attached to top and bottom steel bulkheads using clevis at the interface. Steel longerons attach the top and bottom bulkheads. The bladder was manufactured from nylon coated with urethane to contain the air and water during pressurization. The article was pressure tested hydrostatically to control the stored energy during pressurization. For political reasons, at the time, NASA management decided not to take the test article to burst. At the time, this was the highest loaded inflatable structure based on surface load. The surface load in the hoop direction was 8,300 lb/in.

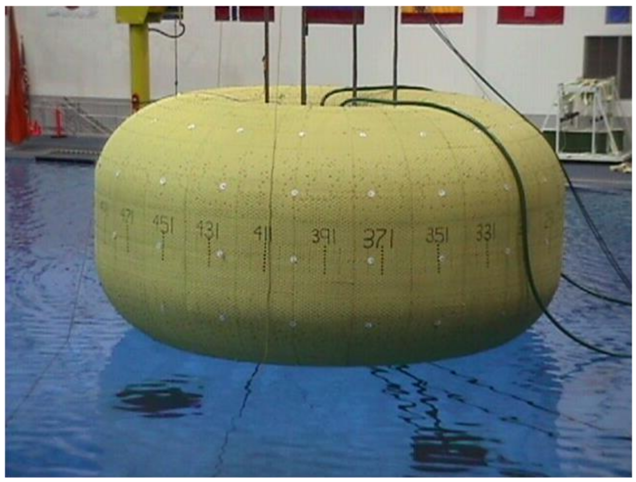

Figure 7- TransHab 23-ft Diameter Development Unit Hydrostatic Pressurization Test Article

Two sub-scale burst articles were fabricated per the NASA woven design. This time the articles were taken to burst pressures and they each failed at 196 psig which had 4% higher surface loading that the TransHab article taken to 60-psig but not taken to burst. The first 88-inch diameter article did not have a window penetration in the belly of the fabric but the second test article did. Calculated surface loading is 8,700 lb/in. This demonstration has shown a high load carrying capability with high repeatability with and without a window penetration. Details of the NASA structural restraint design and window penetrations are described in the patents[23, 24, 25, 26] listed the reference section.

4.2 – Damage Tolerance Testing (DTT)- Leak Before Burst (LBB) Demonstration

Damage Tolerance Test 1 (DTT1)

Another important requirement for human rated spacecraft structures is showing them to leak before bursting. In order to do this for the TransHab woven design, a scaled article was pressurized to 49-psig, representing 25% of the ultimate burst pressure, at White Sands Test Facility (WSTF), and a vertical structural webbings was severed using a linear shaped charge (Figure 8- images 2,3,4). The test article was 88-inches in diameter x 10-ft in length (Figure 8-1). The structural test article was woven from Kevlar webbings left over from the TransHab program.

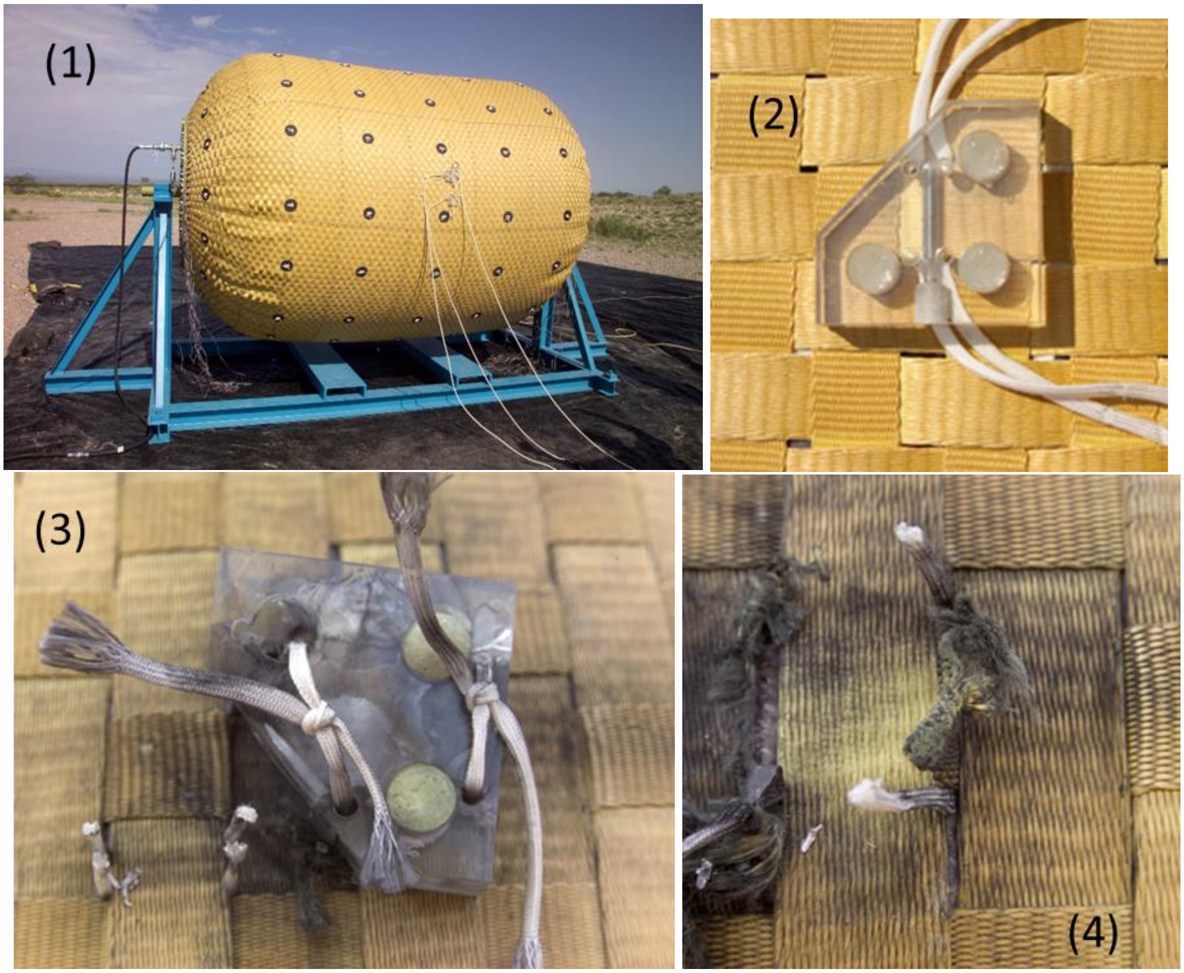

Figure 8- Damage Tolerance Test 1 (DTT1): (1) Test Article, (2) Linear Shaped Charge, (3) Cut Linear Shaped Charge, (4) Kevlar Webbing post cut

Strain gages were attached to the clevises that interface with the structural restraint layer longitudinal members and the bulkheads at both ends of the test article. A very interesting result was that through real-time monitoring strain gages at the top clevis to bulkhead interface there was no indication of load redistribution before and after cutting the two structural webbings[27]. This showed that with the TransHab woven design, the load distributes completely near the cut origin of the fabric and there is minimal to no effect further away.

Damage Tolerance Test 2 (DTT2)

At White Sands Test Facility (WSTF) in 2012, NASA conducted a second test Damage Tolerance Test (DTT-2). The test article was 88-inches in diameter x 10-ft in length and of the same construction as DTT1 (Figure 9-1). The article was pressurized to 49 psig representing 25% of the ultimate burst capability. This time the linear shaped charges (LSC) cut four structural webbings (two horizontal and two longitudinal) sequentially (Figure 9-2) on one side of the test article followed by four straps simultaneously (Figure 9-3) on the other side of the test article. Based on the first DTT, there was no concern with the first test influencing the second test since the load distribution would be local. Photogrammetry measured local load redistribution. As steel plate and Kevlar felt was placed under the Kevlar structural webbings to protect the bladder. The purpose of the test was to demonstrate that the structural restrain layer would not burst. Clearly the bladder will leak if cut.

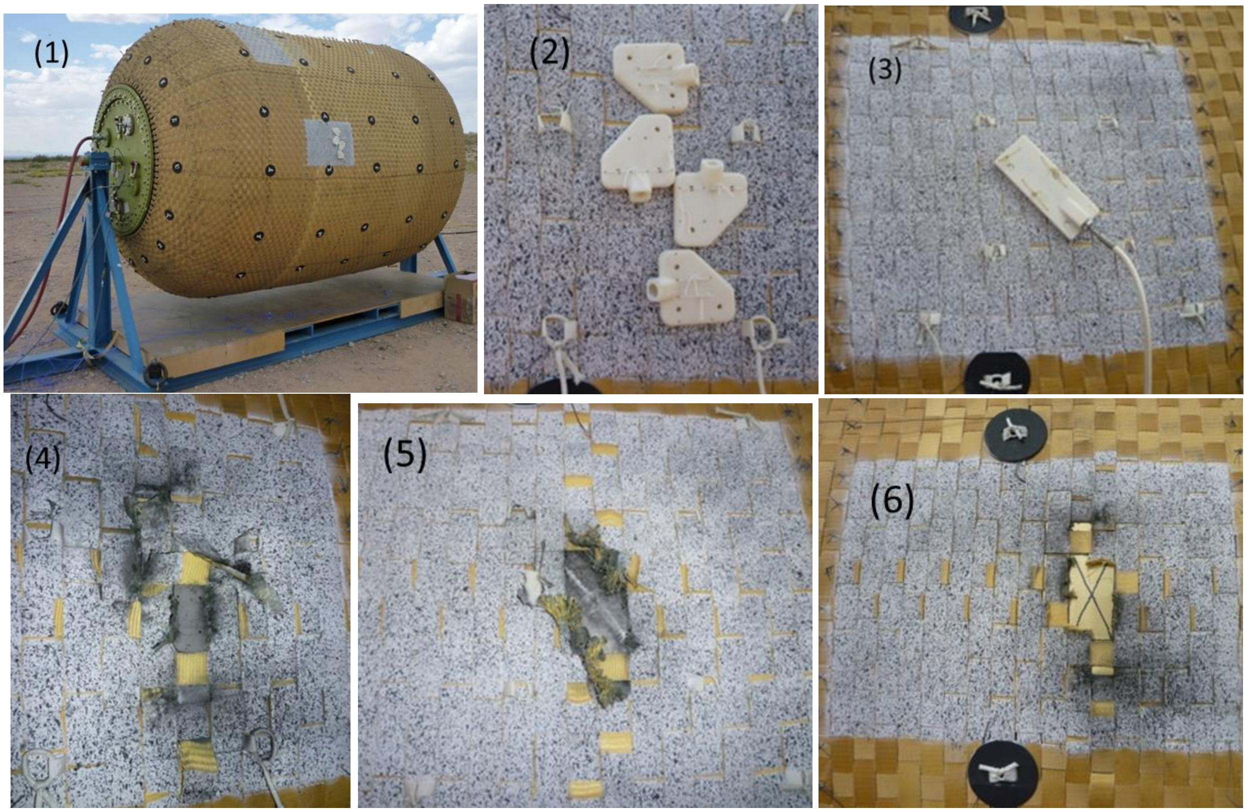

Figure 9- Damage Tolerance Test 2 (DTT2): (1) Test Article, (2) Linear Shaped Charge Sequential Cut Set-up, (3) Linear Shaped Charge Simultaneous Cuts Set-up, (4) Post Sequential Cut, (5) Post Simultaneous Cuts, (6) Post Simultaneous Cuts with Debris removed

Photogrammetry produced mixed results and indicated that refinement is necessary. As better measured proved to be ultra-violet (UV) discoloration of the Kevlar webbing. The exposed webbing had changed color due to UV exposure and the delta displacements was clearly noticed near the cut locations with no movement further out (Figure 9- images 4, 5, 6). The test demonstrated that by cutting a 2 inch x 3.5 inch hole into the structural restraint layer loaded at 25% of burst pressure, the load redistributes locally without ultimate failure of the structural restraint layer (Figure 9-6). Clearly, the woven fabric structure has demonstrated leak-before-burst (LBB) capability.

4.3 – Full-Scale Assembly, Folding, and Deployment at Vacuum

Another important demonstration for inflatable spacecraft structures is to demonstrate assembly, folding, and deployment at vacuum. Due to the large area and weight of the fabric, assembly, folding and deployment can be challenging in a 1-g environment. In 1998, a team of NASA engineers and technicians fabricated, assembled, folded, and deployed at vacuum a full-scale TransHab test article in NASA JSC's Apollo-era Chamber A. The test article was 36 feet tall and 10.2 to 11-foot diameter when folded. When deployed it measured 26 feet in diameter. All of the fabric layers were represented although some layers were simulated since the flight layers were more expensive and not needed to support the assembly and deployment test. The multi-layered insulation (MLI) layers were not included since this was a deployment at vacuum and not a thermal test. An overhead support structure supported the weight of the fabric. The overhead structure had rotating arms that could offset the weight of the fabric and could rotate during deployment at vacuum (see Figure 10-1 and 10-2). During assembly, the bladder and restraint layer were inflated and the other fabric layers were installed gore by gore (see Figure 10-3). The full-scale assembled article is shown in Figure 10-4. For this demonstration all of the fabric shell layers were folded in an s-pattern (see Figure 10-5). During the folding process some of the fabric bunched up at the fold regions as shown in the first image of Figure 10-5. There was also fabric bunching up at the top of the test article as shown in the folded configuration (Figure 10-6). The final folded configuration is shown in Figure 10-6.

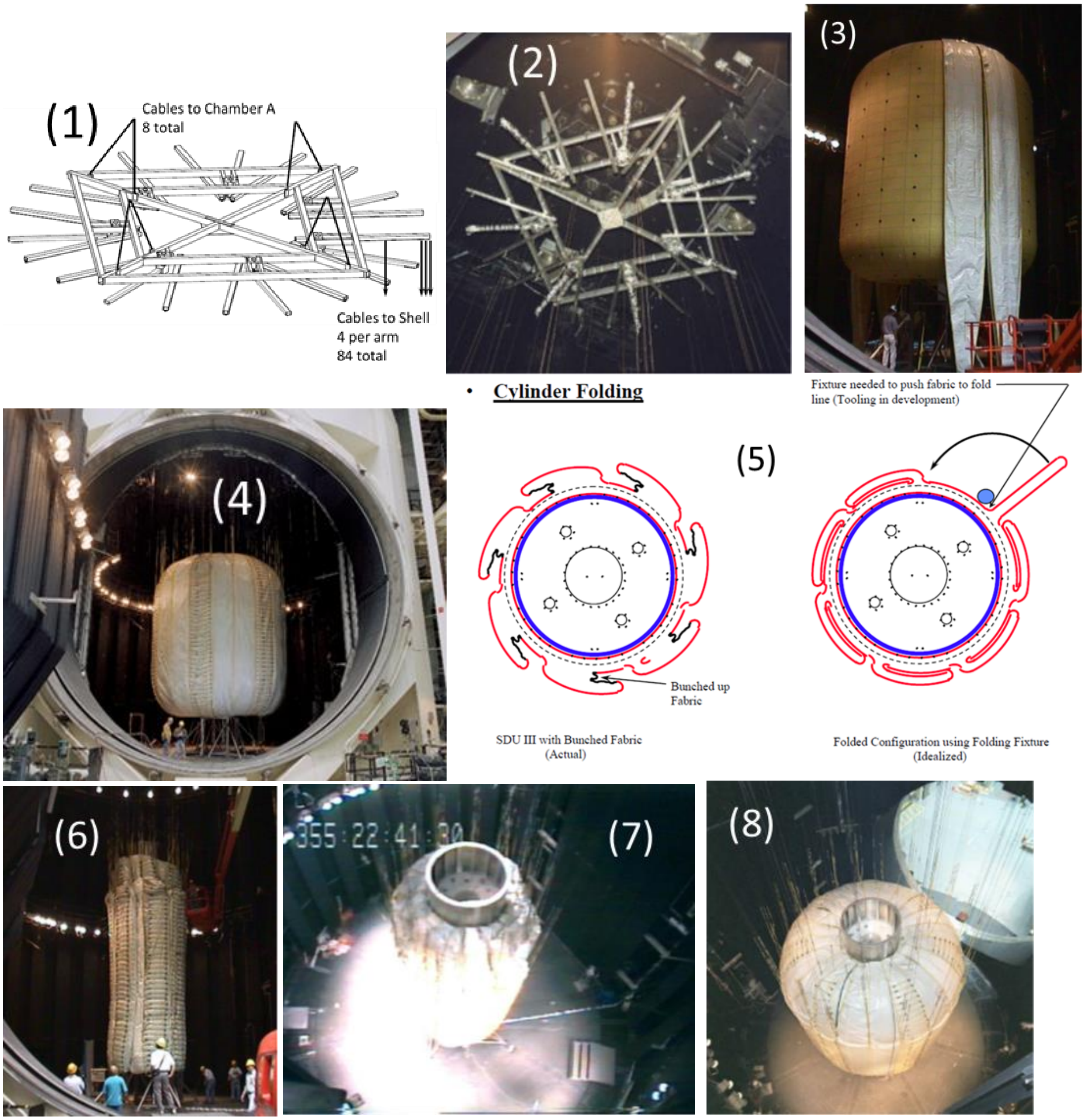

Figure 10- TransHab Assembly, Folding and Deployment at Vacuum: (1) and (2) Overhead Shell Support Structure (3) Shell Assembly, (4) Test Article Assembled, (5) Shell Folding Pattern, (6)Test Article Folded, (7) Folded Test Article at Vacuum, (8) Deployed Test Article Post Vacuum Deployment

During the vacuum test, a prototype heat exchanger was utilized to control the temperature. The folded test article at vacuum is shown in Figure 10-7. The post vacuum deployed image is shown in Figure 10-8. The article was successfully assembled, folded, and deployed at vacuum. Years later, major improvements to the folding method were developed by NASA where the inner liner, bladder, and restraint layer are folded around the core and the subsequent layers (MMOD, MLI, and atomic Oxygen protection layer) are folded as gore patterns and individually attached to the folded bladder/restraint layer and adjacent folded gore members. The process is documented in the patents[28, 29] mentioned in the reference section.

4.4 – Creep Burst Testing

Creep performance is a critical parameter for an inflatable module, as described in Section 3.2. While extensive testing has been completed to measure creep life on webbing straps, little testing has been conducted on creep life for an assembled module. Influence factors at the module level, including stitching and weaving, affect the creep performance and cause variation from the webbing level data to the module level data. In 2014, NASA-JSC conducted a module level creep-burst test to evaluate the performance on an assembled level[21]. The module was a 1/3rd scale TransHab design, made of a Vectran restraint layer using one-inch wide straps woven in a basket weave pattern. The hoop straps in the cylindrical region were 12,500 lb/in rated, while the axial straps were 6,000 lb/in rated. The test article was 88 inches in diameter and 10 feet long with a metallic core and metallic bulkheads on both axial ends. A urethane coated nylon bladder was used on the inside of the test article to maintain the internal air. Figure 11 below shows the test article in the test chamber.

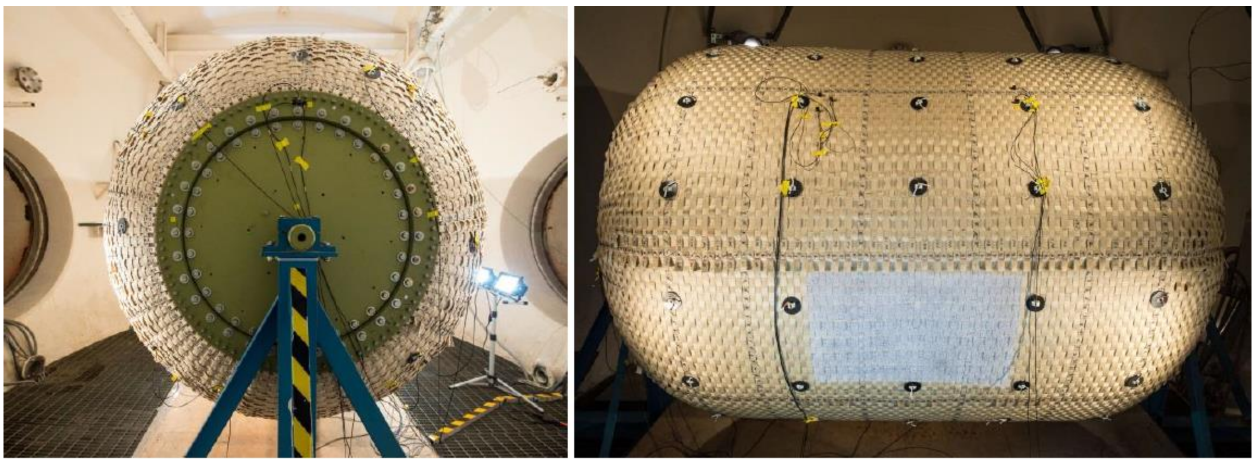

Figure 11. Creep burst test article inside the test chamber at NASA-JSC.

Since this was the first module level creep test, it was designed with the understanding that a successful test could be as short as several minutes, or as long as several months. It was conducted in a spherical containment chamber to mitigate any damage to the surrounding facility and test personnel. To establish the test pressure, the strap level creep data (as shown in Section 3.2, Figure 6) was used as a baseline to predict a module level burst event. The axial straps, rated at 6,000 lb/in had the lowest stress margins and were predicted to fail first, so the creep performance of these straps were used. At 74% of the rated load, the 6,000 lb/in straps had a creep life from several hours to several months, which was acceptable, considering the unknowns of the test. Extrapolating the strap level to the module level, previous burst testing of a similar module failed at 196 psig, so a test pressure of 74% of that burst level was used (145 psig).

The test article was pneumatically pressurized to 145 psig using Nitrogen to prevent humidity issues, and held at constant pressure until burst failure of the restraint layer. The failure occurred after 49 minutes of holding at the test pressure. Standard frame rate video was used to capture the burst, which can be seen in Figure 12.

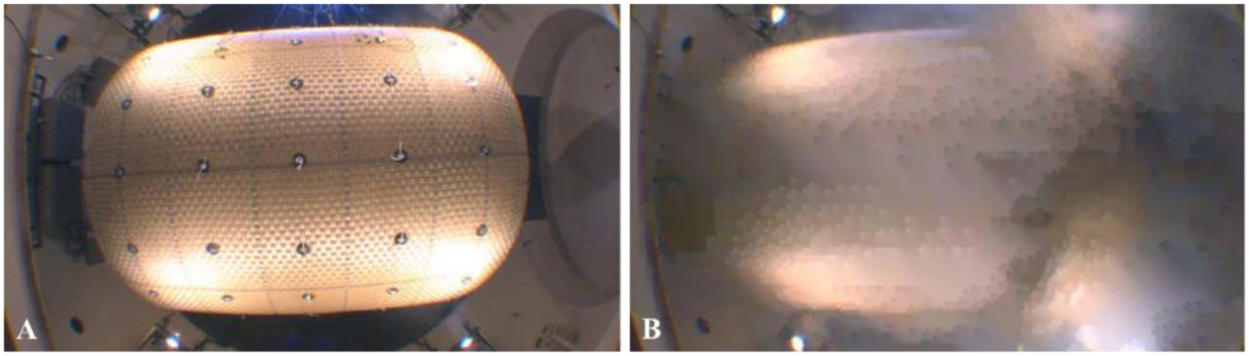

Figure 12. Creep burst event captured in frame (A) and frame (B).

Post-test analysis was also conducted to determine the failure location, which showed that all the axial straps failed, while none of the hoop straps were broken. Photogrammetry was also used to measure the strain in a set of straps, along with accelerometers used to measure the dynamic motion of the straps. The photogrammetry measurements fall below the predicted strain levels, and further work is needed to perfect the photogrammetry technique on softgoods. Further details on the strain measurements can be found in the reference paper[21], along with a companion paper that discusses the dynamic measurements of the accelerometers[22].

The module level creep results are shown as a black cross with the strap level results in Section 3.2, Figure 6. The vertical axis shows the percentage of ultimate strength, while the horizontal axis shows the time to failure on a log scale. The predicted axial failure in the 6,000 lb/in straps are bound by two dashed green lines and have a large failure range at the 74% load. It is shown, however, that the module level assembly has a creep life knockdown compared to the strap level data at the same load level. While this is a revealing data point, it is only a single point, based on a NASA designed restraint layer. Further work needs to be completed at different load levels and with alternate restraint layer designs. Additional module level creep testing is currently underway as part of the NextSTEP-2 program[15] to evaluate several private company's inflatable habitat designs and will provide valuable data for future inflatable habitat certification.

V. Habitable Inflatable Applications and Future Utilization

NASA is currently working with industry partners under the NextSTEP-2 program to develop habitat and airlock systems for the Lunar Orbital Platform –Gateway (LOP-G), as part of the exploration architectures for future cis-lunar, lunar surface and Mars missions. Several industry partners are considering inflatable elements as part of their architectures, and NASA is baselining inflatable structures in several mission architectures for future moon and Mars surface outposts. For Mars missions the ability to stow a habitat compactly behind a heat shield is a significant advantage for atmospheric entry and may allow multiple elements of the outpost to be landed from a single launch. Another primary structure that lends itself well to using an inflatable architecture is an airlock[16]. Many packaging options exist for an inflatable airlock as it is typically connected to a larger vessel at an external hatch and can be packaged around the hatch interface, or around, or alongside the primary vessel. This reduces its impact on both the overall launch volume and dynamic loads. An inflatable airlock may be the primary EVA airlock or it could act as a contingency airlock due to its packaged size. It could also be used on a surface rover, where the capability to package and deploy it multiple times during its mission life could be useful, providing additional livable volume while the rover is stopped. A secondary support structure close to the inner shell is required in an inflatable airlock to maintain its shape when depressurized, but would also provide reaction points for crew mobility and could aid in deployment and retraction of the softgoods.

An inflatable tunnel used to connect two pressurized vessels together is another prospective application for habitable inflatable technology. Inflatable tunnels could be used between habitat elements of an outpost or space station, between a habitat and rover or other spacecraft, or as a connection between two spacecraft or rovers. One interesting variant of a tunnel would be a hybrid that combined articulation with a retraction/deployment capability and a hatch on the free end. This could be used on a rover as both an airlock for EVA and a tunnel to connect to the habitable elements of an outpost or another rover. A final application is an inflatable space hangar that is in essence a much larger airlock, many times bigger than a typical habitat structure. It would be designed to provide a large in-space, shirt-sleeve environment for assembly, maintenance and upgrade of spacecraft and space systems. Inflatable structures provide one of the few approaches to creating such a large, contiguous habitable volume in space, but the fabrication, packaging and testing of a single shell of that size on the ground, protecting it from damage, especially in low earth orbit from MMOD given its surface area, and integrating a hatch structure large enough to allow the passage of a spacecraft would be challenging.

Habitable softgoods structures have many applications for NASA and commercial missions in space and on the surface of other planetary bodies. The applications presented here represent use cases where inflatables would provide a significant benefit based on their ability to be compactly packaged and deployed. It is expected with the continued development of inflatable shell architectures, the ongoing test programs at NASA and in industry, and future employment of these structures, that additional applications will be conceived of and integrated into future missions.

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