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Lessons from TransHab

AN ARCHITECT'S EXPERIENCE

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ABSTRACT

TransHab was designed to be a space-inflatable habitation module. This multipurpose designed habitat was planned for use as: a) a Transit Habitat (TransHab) element of an interplanetary vehicle that transports humans to Mars and back and b) a proposed alternate habitation module for the International Space Station (ISS). In addition, TransHab proved the building technologies for a predeployed Mars' surface habitat. TransHab has a unique hybrid structure that incorporates an inflatable shell and a central hard structural core. The shell comprises four functional layers: the internal barrier and bladder, the structural restraint layer, the micrometeoroid/orbital debris shield, and the external thermal protection blanket. The structural core comprises longerons, repositionable isogrid shelves, and a bulkhead and tunnel at each end.

This paper gives a high-level overview of the habitat design and discusses the author's lessons learned as an Architect and Systems Engineering & Integration Lead for this project. The technical lessons of most interest pertain to the internal design, the structural testing of the inflatable shell, and the development and testing of the orbital debris shield. Cultural lessons about teamwork and leadership were also learned from the team approach taken by this project.

INTRODUCTION

As old as architecture itself, fabric structures have been interwoven throughout humankind's history—and will be in its future. The cave dwellers created portable housing as they became nomadic, following herds of animals in search of food. They used animal skins stretched over bones and tree limbs to create shelters. Subsequently, this type of habitat gave way to sewn-together hides combined with erectable structures for easier deployment and breakdown. Over hundreds of years, yarns and fabrics were developed, further enhancing the fabric structures known as tents. Tensile fabric structures have always been at the revolutionary forefront of architecture with their dynamic shapes, sweeping boldness, and technological robustness. So it is not too surprising that a team of architects and engineers at NASA's Johnson Space Center designed and tested this ancient architecture as a way to create habitats in space and on other planets.

NASA has considered tensile fabric structures in the past. In the late 1960's, several inflatable structures were designed and tested for space applications. Langley Research Center led efforts to develop and test a 24-ft diameter torus space station, a lunar stay-time extension module prototype, and a large space station module nicknamed Moby Dick. All were successfully tested. It took many years of persistence, and a few failures, before the textile industry turned the technological corner with fibers like Kevlar, Vectran, and Polybenzoxazole (PBO). *

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* Trade names are used in this paper for identification only, not to indicate NASA endorsement.

Over the years, the idea of inflatable structures as space habitats began to catch on. Several important NASA reports, such as the Synthesis Group Report, identified inflatable structures as an enabling technology that would allow NASA to accomplish lighter weight structures at a lower cost. NASA continued to refine ideas and concepts, preparing for an opportunity to prove that the inflatable structure would live up to being an enabling technology for advanced missions. The day came when a NASA-led tiger team was given a challenge: design an interplanetary vehicle habitat in which a crew of six can travel to and from Mars. However, there was one major catch: deliver this habitat to space using existing launch vehicles. To meet the amount of volume required per crew member for food, spares, and other provisions, the logical choice was an inflatable structure. Mars mission studies had already defined types of habitats as transit (for interplanetary travel) and surface (other planetary) habitats. So when the team began design work on this transit habitat, the author coined the name "TransHab" for Transit Habitat. The nickname caught on quickly and soon took on a life of its own.

TransHab pushed the technological envelope beyond the author's previous design work on inflatables. The innovative engineers soon shaped a revolutionary concept that provided an alternative to hard aluminum shell architecture. Since that early concept in 1997, TransHab has been through numerous design iterations. The last design was a proposed habitat module for the International Space Station (ISS). It evolved from the Mars TransHab. A team of architects and engineers at the Johnson Space Center had been working, designing, and testing this concept to in anticipation of the technical challenges that critics were bound to present. The TransHab Project team met every challenge with vigor and determination.

TransHab is a hybrid space structure that synthesizes a hard central core with an inflatable exterior shell. It is thus differentiated from all previously developed space vehicles, which have traditionally used a hard external shell as both main structure and pressure vessel. Therefore, the TransHab vehicle's technology, revolutionary both in overall concept and in the development of each of its primary parts, represents a leap from the exoskeletal type into a new generation of endoskeletal, complex spacecraft.

Beyond the straight technological innovation of this vehicle—and in no small part because of it—TransHab is also breaking new ground in its support of the human system. The process by which the structure involved human engineering from its early conceptual stage and throughout its development has allowed TransHab to achieve a unique level of efficiency as a human-rated spacecraft. Its dimensioning and layout are optimized for flexibility and long-term use by a diverse crew. Because TransHab can be packaged into a smaller volume for launch and be deployed on orbit to provide a much larger, more usable volume, this vehicle offers both great architectural opportunities and tremendous technical and design challenges.

Due to Congressional action on Space Station activities, all ISS TransHab development was canceled. The systems integration and detailing of the interior elements was stopped, along with an aggressive testing program at JSC in which the technology had been consistently proven to meet and exceed existing requirements. All of the successes of the program—its unique technology, its high level of habitability, and its outstanding testing record—are attributable to the working of a strongly integrated project team. The team of test engineers, structure and subsystem engineers, architects, and human factors experts collaborated intensively from the project's outset.

TRANSHAB ARCHITECTURE

The TransHab module proposed for the ISS is 23 ft of open interior length from inside bulkhead to inside bulkhead, and approximately 40 ft (12.19 m) long overall by 25 ft (7.28 m) internal diameter that provides 12,077 ft^3 (342 m^3) of pressurized volume (fig. 1). Levels 1 and 3 are 8 ft tall at the central core and level 2 is 7 ft tall at the core. The 8-ft ceiling height of level 3 was derived from human engineering analysis showing the height requirements of crew members using the treadmill. The 7-ft level 2 was derived from a minimum head height for crew while sleeping, with room to lock in the equipment shelves between floor struts.

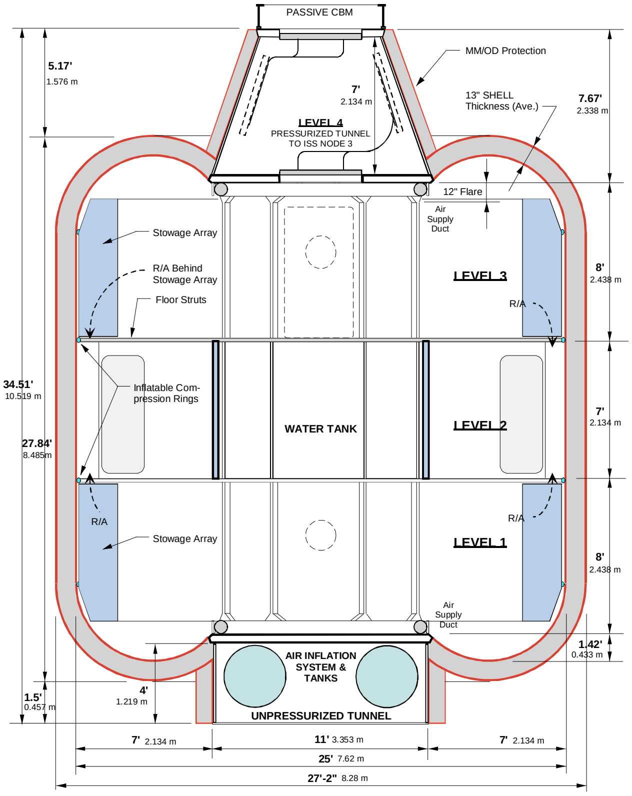

Figure 1. ISS TransHab Section

The TransHab module was to be packaged and folded on the ground and launched in the Space Shuttle Orbiter for delivery to the space station. After the Orbiter docked with ISS, the TransHab would be removed from the Orbiter payload bay and berthed with station using the space station remote manipulator system (SSRMS). Once captured on station, the TransHab would be deployed and then inflated to its internal operating pressure of 14.7 psia; during the inflation period, the air system is activated for conditioning the environment prior to crew entry and outfitting. Several days are required for the assembly crew to activate all the systems and complete preliminary outfitting of the habitat. To the extent possible, all systems, utilities, and internal structure are preintegrated into the central core.

Space architects took advantage of the added height in the first and third levels of the vehicle for easier integration of the air ducts and local-area utility distribution. Soffits attached to the core structures both there and in the crew quarters in level 2 combine the air-supply system with an enclosed chaseway for all power, data, and coolant runs so that each area is easily served with minimal exposure to utility connectors within the cabin. This system also saves valuable time in on-orbit assembly and in preflight checkout by allowing these structures to remain fixed within the core and operate in both vehicle configurations.

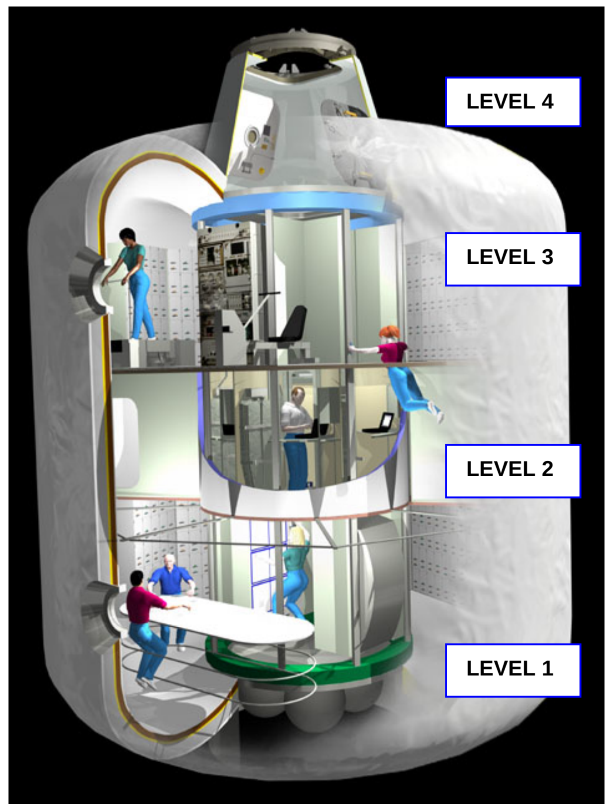

Figure 2. ISS TransHab Internal View

Another example of integrated systems architecture within the TransHab interior volume is the design of the stowage array to serve also as a plenum for return air flow. A subsidiary structure, which attaches to the floor struts after deployment, the stowage array accommodates ISS-standard stowed items in a highly usable inventory system, while at the same time forming a gap between outfitting and the shell walls through which return air is channeled. Thus, this system serves an operational function at the same time that it helps TransHab to “breathe.”

The architecture of TransHab provides an integrated habitable environment that creates private and social spaces. This feature is very important for crew social and interpersonal relationships. This is especially true for the long-duration confinements of a space station or an interplanetary vehicle. A functional and physical separation of the crew health care area, crew quarters, and galley/wardroom area creates a home-like design for the crew living in space, while allowing each functional area to remain permanently deployed for regular use.

Figure 2 shows an overview of the ISS TransHab architecture. With a larger volume than a station hard module, TransHab has the ability to provide more storage volume, two means of unobstructed movement within the vehicle, and permanently deployed equipment in the primary activity centers. Important design objectives of TransHab are to maintain a local vertical configuration, to separate the exercise area from the dining area, and to provide larger crew quarters. A central passageway in the core and a side passage large enough to translate an ISS rack on the forward side achieves crew circulation in TransHab.

The ISS TransHab’s interior pressurized volume is divided into four functional levels: the first, second, and third are for living space, and the fourth is the connecting tunnel. Providing a consistent local vertical orientation in keeping with operational requirements established in all programs since Skylab, TransHab’s architecture offers the opportunity to separate conflicting functions while enhancing the usability of each area. Level 1 is the galley/wardroom and soft stowage area. Level 2 houses the crew quarters between the core’s water tanks, and an enclosed mechanical room in a half-toroid of the outer area. Level 3 is the crew health care and soft stowage area.

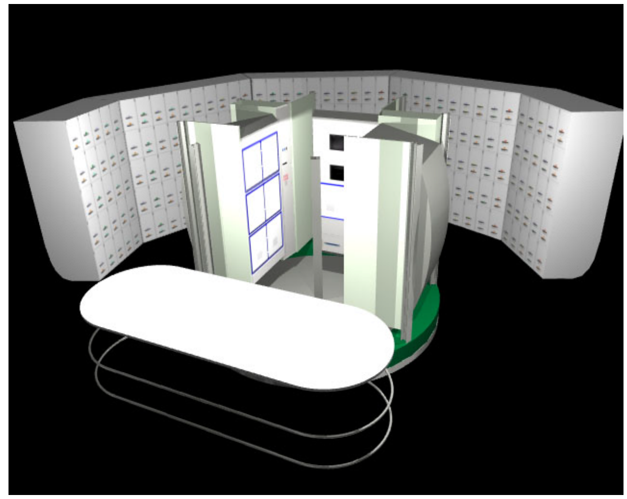

Figure 3. TransHab Level 1 Galley/Wardroom Area (CAD image)

Level 1 is the main social and professional meeting place within TransHab (fig. 3). It incorporates the galley, wardroom, and one portion of the stowage array described earlier, along with three ISS galley racks, a large wardroom table, and an Earth-viewing window. The galley area incorporates a rack-based ISS galley and two rack-based ISS refrigerator/freezers (R/F), which are installed in TransHab once the module is activated. Designed to accommodate all 12 crew members during a crew changeover, the wardroom is a double-height room that features an Earth-viewing window. It is used for meals, meetings, conferences, daily planning, public relations gatherings, and socializing. Having one large common area in which to gather all the crew members for important crew debriefings and photo opportunities is an outstanding design feature of TransHab, as is the psychological benefit of the large open space provided here. Skylab and Shuttle-Mir experiences have confirmed that the availability of an open, communal area is very important for crew morale and productivity during long-duration isolation and confinement in space. A wardroom or conference area is an important contribution to the challenge of both working and living in space.

Level 2 houses the mechanical room and crew quarters (CQ). The CQ cluster houses six living quarters and a central passageway located in the second level central core structure within the safe-haven of the water tanks (fig. 4). The mechanical room external to the core structure uses only half the area of an available floor, leaving the other half open to the wardroom area. The crew quarters are surrounded by a 2.5-in. water jacket for radiation protection during solar flares. Access to this area is only from level 1 (below) or level 3 (above), via the 42-in. central passageway. The shown configuration will be assembled and outfitted after TransHab's inflation.

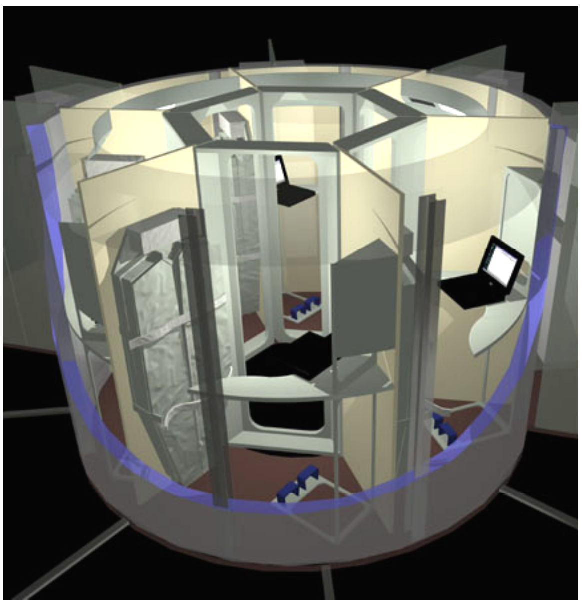

Figure 4. TransHab Crew Quarters (CAD Image)

Equipment shelves are used as CQ partitions. CQ door panels and doors are installed on orbit. Sized at over 81 ft^3 of volume (CQs five and six are a little less), with a full height of 7 ft, each of the crew quarters will have personal stowage, a personal workstation, sleep restraints, and integrated air, light, data, and power in a volume that is 27% larger than the original ISS rack-based CQ.

Level 3 is the crew health care and soft stowage area. The health care area incorporates two ISS crew health care system (CHeCS) racks, a full body cleansing compartment (FBCC), a changing area, exercise equipment (treadmill and ergometer), a partitionable area for private medical exams and conferencing, and an Earth-viewing window (fig. 5). Four movable partitions provide visual screening of crew members during all activities associated with full body cleansing or with private medical exams. The soft stowage area on this level is identical to that on level 1 Circulation passages are included because this level is the primary entry into TransHab.

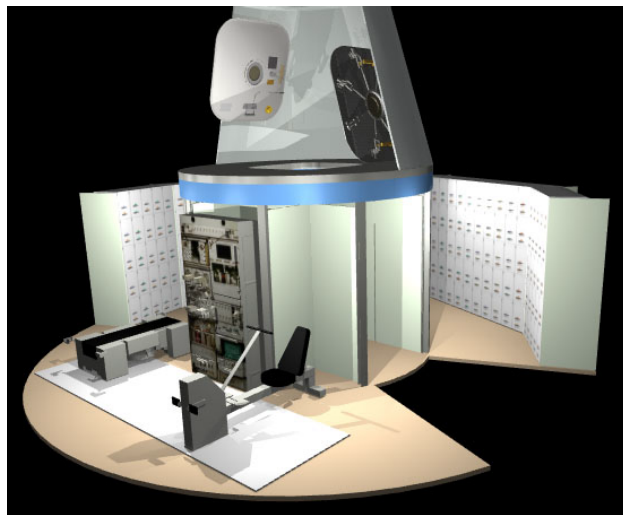

Figure 5. TransHab Level 3 CAD Image

During assembly, the exercise equipment items are permanently mounted in their deployed position, saving crew time by removing the daily hassle of deployment and stowage of exercise equipment. The equipment, positioned near the window to allow the crew Earth viewing during exercise, is stabilized by two launch shelves placed on the floor struts to serve as mounting platforms and structural integration.

Level 4 is the pressurized tunnel, a transition space or vestibule between station (work) and the living space (home). It has two ISS-standard hatches, avionics, and power equipment. The main utilities are brought in at the Node 3 bulkhead and transferred into the TransHab utility chaseways. The tunnel's functions are to provide a transition area between Node 3 and TransHab, to house critical equipment required during inflation, and to provide structural connection to space station. It is the only pressurized volume in TransHab during launch. The packaged central core will vent during launch to a vacuum state until TransHab is inflated. Once TransHab is berthed and bolted to Node 3, level 4 provides immediate access to the vestibule area between Node 3 and TransHab for power and data jumper connection installation. This will provide the critical power and data vestibule connections that will enable initiation of the deployment and inflation operations. A detailed functional operations concept and a crew timeline have been completed for the launch to activation of TransHab.

TRANSHAB TECHNOLOGIES

The TransHab spacecraft represents breakthroughs in the development of flexible, high-load composite structures, in the development of an optimized, independent pressure shell (using breakthroughs in inflatable and shielding technologies), and in the application of both systems in a single, reconfigurable habitat. This hybrid structure combines the packaging and mass efficiencies of an inflatable structure and the advantages of a load-carrying hard structure.

First among these is the hard core. Essentially a multicomponent spindle element which bears the principal shear loading in launch configuration, the core can be reduced to its role as a tensile stabilizer during on-orbit assembly by removal of its internal truss work and reuse of the truss subcomponents as interior framing and outfitting elements. To make this possible, the core's trusswork is made up of modularized "shelf" units with a universal system for attachment to one another and to other core elements. Thus, the hard structures of the vehicle are part of a modular system, which allows them to respond efficiently to two very different loading conditions.

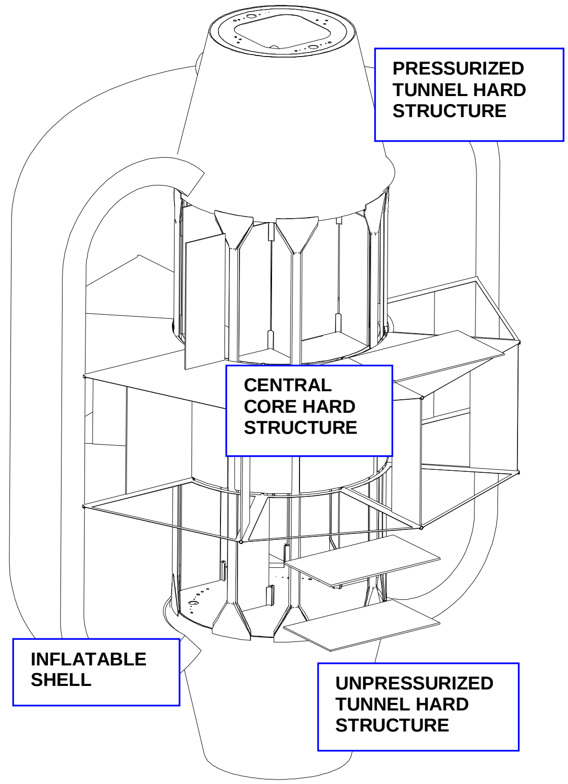

Figure 6. TransHab Assembled Core within the Inflated Shell

The only static elements of the core are the longerons, the central toroid shear panels, and the two end tunnels. Whereas the lower tunnel is an unpressurized ring designed to contain the inflation system, the upper tunnel (level 4) remains pressurized during the entire launch-to-activation sequence. This allows it to serve as an internal airlock during the preliminary docking, inflation, and activation period. Critical electrical switching units are mounted within this cone so that the crew can access them once docking to the ISS is completed. Once assembly is complete, the level 4 tunnel will serve as the connection point to ISS.

Longerons provide the primary load path through the core, reacting to both pressure loads and launch loads. They are 23 ft long with flares at each end to stabilize their attachment to the bulkheads. The shear panel visible around the level 2 central core also incorporates annular water tanks, which provide the vehicle with the dual function of potable water storage and a safe haven in the event of a solar flare.

The movable elements of the core system are the core shelves. Many of them bearing life support and systems equipment, the shelves are placed into the central core for launch (fig. 6). There are 36 shelves in two different sizes: 30 x 84 in., and 50 x 84 in. About half of the shelves are repositioned once on orbit; the others remain in place. For ground operations and launch, these shelves provide structural support and lightweight equipment mounting for preintegration. Once TransHab is deployed, approximately one half of the shelves are relocated into the habitat volume to support floor beams and equipment, thus serving the dual use of primary and secondary structures.

Because all of these elements are made of a standard set of graphite-composite forms, the structure is remarkably low in weight relative to the capability that it gives the vehicle. In fact, some 50% of the vehicle's total weight is contributed by the pressure shell, a combination of robust inflatable restraints and high-performance debris and thermal shielding.

Figure seven shows the TransHab shell. To the far left is the multilayered insulation, followed by four layers of bullet-proof materials separated by open-pore foam; to the right of this we see the webbing of the main restraint layer. Inside (to the right of) the restraint layer are the redundant bladder layers and, on the far right, the interior "wall" or scuff barrier.

The inflatable shell is a separate system from the TransHab's primary structure, and thus can be optimized in its function as a pressure shell. Folded and compressed around the core at launch, it is inflated and deployed on orbit. The shell contains the crew's living space and provides orbital debris protection and thermal insulation. It is composed of four functional layers: the internal scuff barrier and pressure bladder, the structural restraint layer, the micrometeoroid/orbital debris shield, and the external thermal protection blanket. Particles hitting at hypervelocity expend energy and disintegrate on successive Nextel layers, spaced by open-cell foam. Backing layers of Kevlar add an additional degree of protection. An inner liner of Nomex provides fire retardant and abrasion protection. Three Combitherm bladders form redundant air seals. Four layers of felt provide evacuation between bladder layers (necessary for launch packaging).

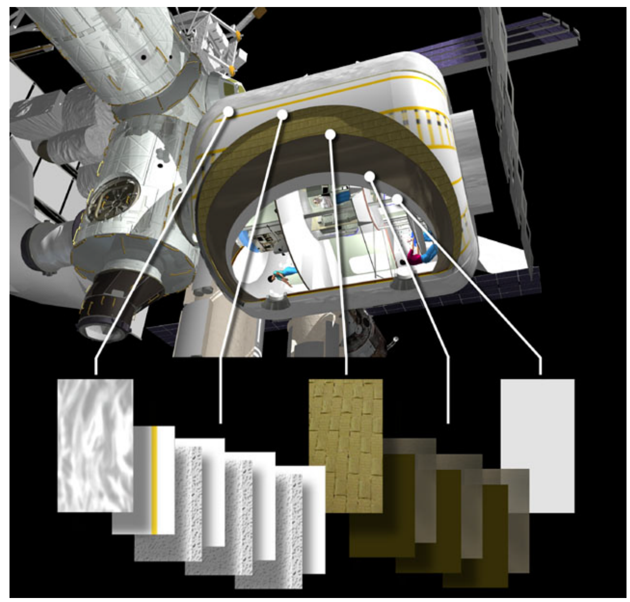

Figure 7. TransHab Demonstrates Large Diameter Inflatable Structure

TRANSHAB TESTING: DEMONSTRATION OF AN INFLATABLE SHELL

TransHab's design concept is based on a relatively unproven space inflatable structural technology. To prove that this technology would work in space—and is safe—the team set three important goals:

1. Determine how to protect an inflatable structure from being ruptured by micrometeoroid and orbital debris impacts.

2. Prove that a large-diameter fabric inflatable structure can hold one atmosphere pressure in the vacuum of space.

3. Prove that TransHab can be folded, packaged, and then deployed in the vacuum of space.

To achieve the first goal, the team built a typical shell lay-up and performed hypervelocity impact testing at JSC and the White Sands Test Facility. This series of tests proved to be very important. If the debris shield could not stop the particle, then TransHab had no chance of surviving. The 1-ft-thick orbital debris shield took shot after shot and kept passing—exceeding all expectations (fig. 7). The test engineers who set up the shot like to blow stuff up with their hypervelocity guns. At first they were disappointed that they were not causing failure in the target, but they got excited when they realized the breakthrough they were now a part of. The tests turned out to be so important that Scientific American Frontiers, with Alan Alda, included these shots as part of a television series on Mars mission technology. In continued testing, TransHab's shell survived a 1.7-cm aluminum sphere at hypervelocity of 7 km/s.

The configuration in figure 8 has withstood impacts of up to a 1.7-cm diameter aluminum projectile fired at 7 km/s (15,600 mph). Woven from 1-in. wide Kevlar straps, the restraint layer is designed to contain four atmospheres of air pressure. Each shell restraint area is structurally optimized for that area's load. To accomplish this, strap seams were developed that achieved more than 90% seam efficiency.

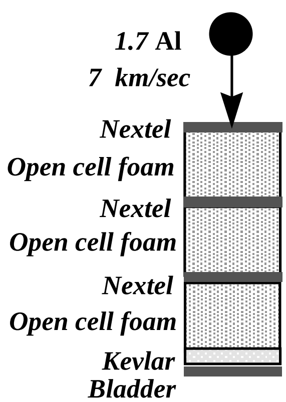

Figure 8. TransHab Orbital Debris Shield

Two shell development test units were built and tested at JSC to prove the second and third goals. The first unit was built to prove the inflatable restraint design would hold the 14.7 psia operating environment for the crew to live in. This unit was 23 ft in diameter by 10 ft tall. Because the testing was for the hoop stress, the unit did not have to be full height. NASA used the aviation-recommended safety of factor of four for tensile fabric structures used in airships and blimps as a basis for this test, which soon became known as the 4.0 test. The structural engineers used a safety factor of four in the design work. This meant the restraint layer had to withstand the equivalent stress of four atmospheres. The only safe way and place to perform such a potentially dangerous test was by a hydrostatic test in the Neutral Buoyancy Lab at JSC. This test was completed in September 1998, marking yet another historical milestone for inflatable habitat structures. Figure 9 shows the test article being lowered into the NASA Neutral Buoyancy pool.

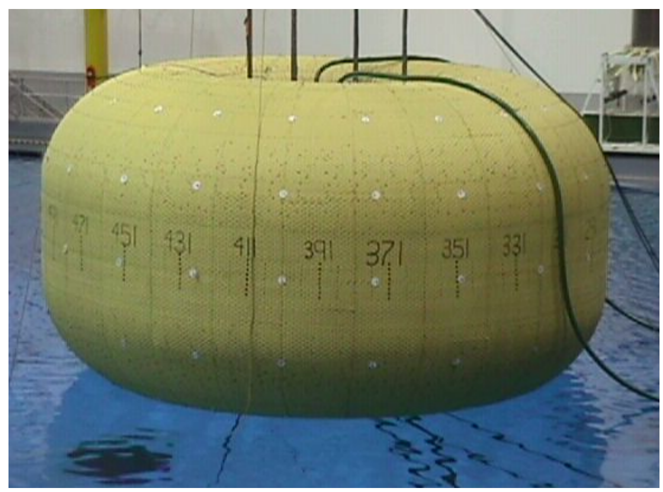

Figure 9. TransHab Hydrostatic Test

The second test unit was to prove the inflatable shell design could be folded and deployed in a vacuum environment. This test unit reused the hydrostatic test article bulkheads and rebuilt a full height restraint layer. Also included in this test was the orbital debris shield that was proven in the first goal. The 1-ft thick debris shield is vacuum packed to reduce its folded thickness, thus enabling the module to fit into the Orbiter payload bay. Once on orbit, TransHab is deployed and the debris shield is released to its desired thickness. Figure 10 shows two technicians performing a final inspection of the test unit before folding it. TransHab was successfully folded and deployed in the vacuum environment of Chamber A in December 1998, proving the second goal.

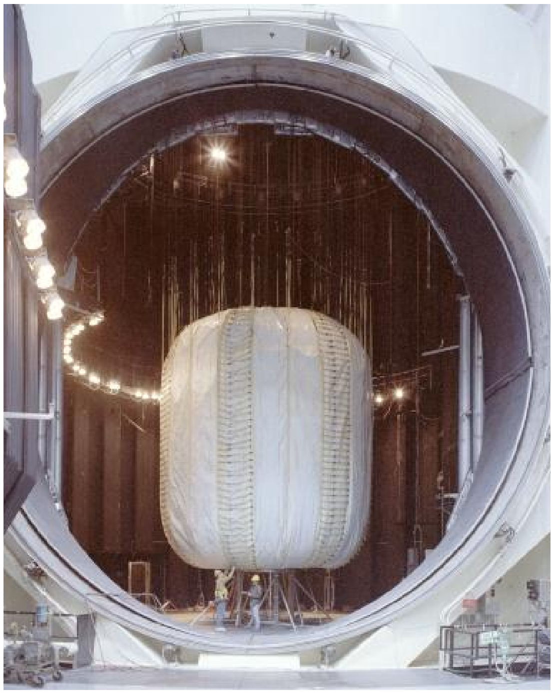

Figure 10: TransHab Vacuum Deployment Test

With the successful completion of the hypervelocity impact testing and inflatable shell development tests, TransHab has proven that the inflatable structure technology is ready for the space age. TransHab demonstrates the great strides made to prove inflatable structures technology is ready to be applied as habitats for space applications. ISS TransHab's design meets or exceeds habitation requirements for space station. If TransHab's development had not been stopped, it would have been an excellent replacement of the hard aluminum habitat for the ISS. It would have been launched as the last station element in late 2004 (fig. 11).

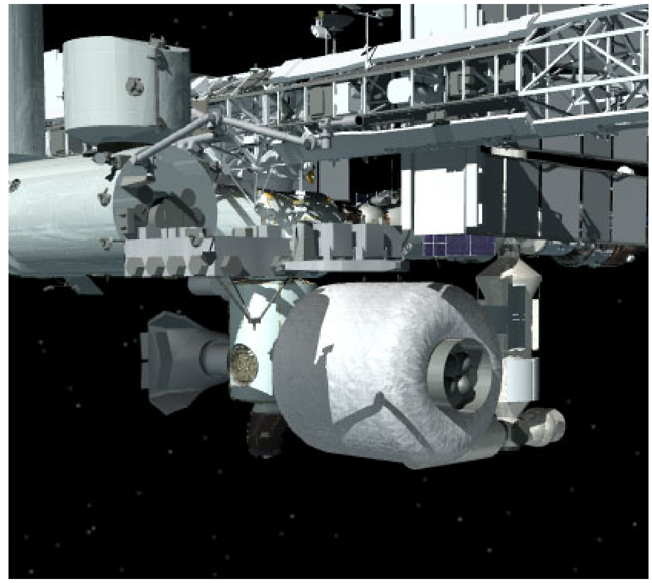

Figure 11. Proposed ISS TransHab on Space Station

LESSONS LEARNED

Of the many lessons during the TransHab experience, one of the most important is to keep the project focused on the technology development. TransHab moved too quickly out of pure technology development to becoming a replacement for the ISS aluminum habitat. This allowed for Congressional scrutiny and subsequent cancellation. A similar fate has occurred with the X-38 crew return vehicle. From a technical perspective, the approach of "build a little and then test, evaluate, and learn" was of great value technically and managerially. It allowed us to incorporate what we learned as the design matured. It is often referred to as the spiral approach to engineering. Below is a summation of the lessons learned from the author's perspective.

Technical Lessons:

- Build a little and then test, evaluate, and learn. Incorporate what you learn as the design matures. (Spiral approach to engineering).

- Technology development needs a real focus—hard requirements and schedule.

- Tiger team technical leads need to sit together. Improve performance and communication.

- Trust the other leads. Let their teams do their jobs and believe in them.

- Be technically honest. If you can't do something—say so. Don't hide or skew the results.

- Build test articles early and often. Build on small successes.

- Build a mockup early.

- Build a constituency of supporters—team, supervisors, crew, management, Congress.

- Keep the team focused. Shield from politics.

- Remember that form follows function. Design drives the systems required; the systems don't drive the design. Delicate balance of what's possible and what's convenient. Comfort zone.

Management Lessons:

- Leadership: Only one person in control. Don't allow multiple chiefs.

- Trust your leads—technical and management.

- Build a four-dimensional team with balance of personalities and skills.

- Perform independent assessments; get outside peer review.

- Know your competition. Don't underestimate political agendas. Don't let the fox into the hen house.

- Co-locate your matrixed personnel. A mix of skills and experience levels enhances team's success.

- Have a weekly status. However, do not try to solve technical issues there (3-minute rule).

- Share the glory in TV, magazine, and newspaper interviews. It's about the project and team.

- Give awards, celebrate accomplishments, have get-togethers outside of work. Blow off steam.

CONCLUSIONS

With the successful completion of the hypervelocity impact testing and inflatable shell development tests, TransHab has proven that the inflatable structure technology is real. TransHab developers had made great strides to prove inflatable structures technology are ready to be applied as habitats for space applications. TransHab's design meets or exceeds habitation requirements for space. It has put the "living" into "living and working in space." TransHab provides facilities for sleeping, eating, cooking, personal hygiene, exercise, entertainment, storage, and a radiation storm shelter. TransHab has also contributed to development, test, and proving of technologies necessary for long-duration interplanetary missions.

TransHab has already contributed many technical and management lessons to the aerospace field. It has broken the volumetric barrier of the exoskeleton spacecraft type by innovating an entirely new, endoskeletal typology; it has demonstrated the advantages of combining human engineering with aggressive structural innovation and testing at the conceptual stage. The integrated effort by which this spacecraft was conceived and developed has proven its virtue in meeting tremendous challenges by combining innovative design with cutting-edge technologies that are appropriate for space and planetary surface habitats, with multiple applications for both Earth and beyond.

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