System Integration Comparison Between Inflatable and Metallic Spacecraft Structures

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Abstract—**Inflatable spacecraft structures are an alternative to traditional pressurized metallic structures that provide significant launch volume savings. A flexible primary structure, however, has a number of design and construction details that must be considered when moving from a metallic architecture to one based on softgoods. It is not only necessary to compare the structural mass and volume differences, but also examine the overall system integration changes that are required to implement a large-scale inflatable spacecraft. This paper compares inflatables with traditional metallic spacecraft by reviewing the integration of sub-systems in each vehicle and identifying the key differences. Additionally ground integration and prelaunch considerations are detailed, along with differences in requirements for environmental and human factors. The paper concludes with a discussion of future in-space and surface applications for inflatable structures.**

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1. Introduction

Inflatable structures for use as crewed space modules (Figure 1) predate the establishment of NASA and were recognized early on for their potential benefits in providing both a compact launch package and a large deployed living volume versus rigid pressure vessels. In 1952, the famed German rocket scientist Werner Von Braun proposed a concept for the first space station[1] that used inflatable modules attached to a rotating central core. A space station was seen as the logical first step for the newly formed NASA in 1958, and NASA Langley Research Center (LaRC) quickly down-selected to an inflatable toroidal design, similar in principle to Von Braun's station. Throughout the 1960's LaRC worked with Goodyear Aerospace[2,3], researching, developing and testing inflatable technologies for a number of applications in addition to the station, including several long-duration habitat modules and an inflatable airlock. Unfortunately, none of these designs were ever flown, as the space program's focus turned to the Apollo missions, and the extended missions that the habitats may have been used for were curtailed due to programmatic budget cuts. In 1964~65, the Russians developed, flew and successfully operated an inflatable airlock on the Voskhod-2 mission to perform the first ever Extravehicular Activity (EVA). They had been constrained by the need to fit an airlock within the confines of the Voskhod launch shroud, and the air-beam deployed Volga[4] airlock was their solution, providing the first demonstration of a manned inflatable in space and the potential of inflatables for future missions.

Research and development of crewed inflatables then lay dormant for two and a half decades, as the world's space agencies directed their resources towards efforts in Low-Earth Orbit (LEO), including the launch of MIR and Skylab, the construction of the International Space Station (ISS), and the Space Shuttle program. In the late 90's, as NASA once again set its sights beyond LEO to Mars, a major effort in inflatables was once again pursued with the Transit Habitat

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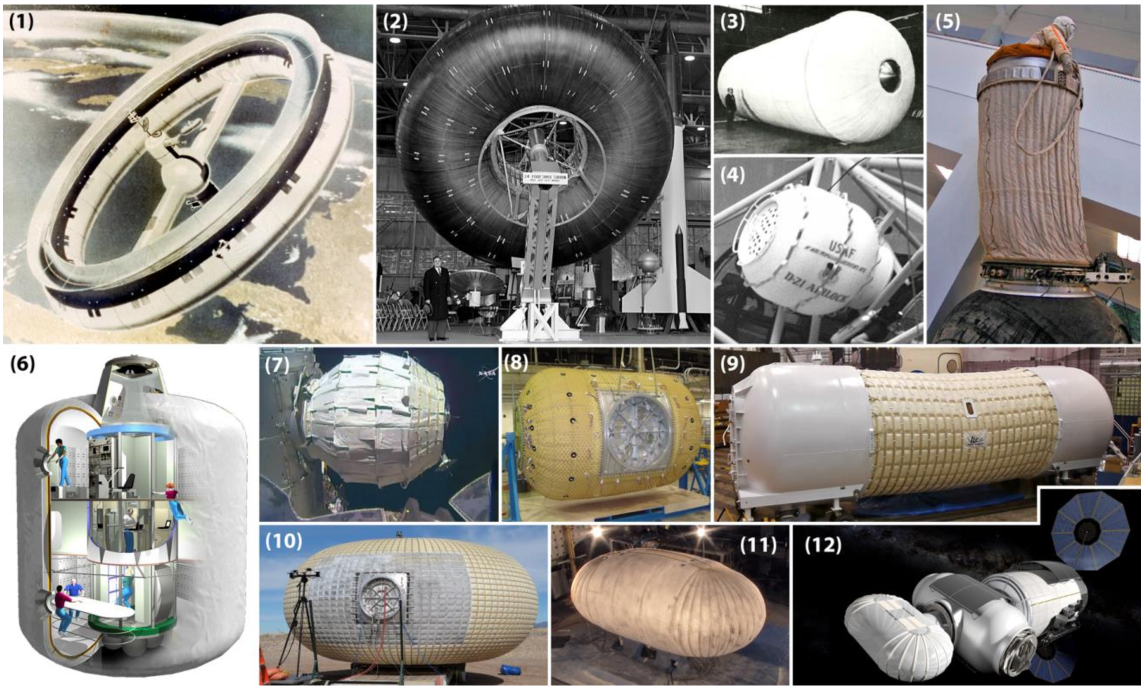

Figure 1. Inflatable Structures: (1) Von Braun's Space Station, (2~4) Goodyear Aerospace's toroidal space station, 'Moby Dick' habitat module and D021 airlock, (5) Volga airlock, (6) TransHab, (7) BEAM, (8) JSC module with integrated hatch, (9~10) ILC/NASA expandable and toroidal habitats, (11) NASA's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

or 'TransHab' program[5] at the Johnson Space Center (JSC). The TransHab was a 3-level inflatable habitat with a rigid core structure that was intended as a multi-use living space for a mission to Mars, and was considered to replace 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[6,7]. 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 these structures most recently culminating in the launch and deployment of their Bigelow Expandable Activities Module (BEAM) on the ISS in 2016.

Since the conclusion of TransHab 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[8-10], the integration of hard structure such as windows and hatches into the fabric shell, 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 at sub- and full-scale, fabricated both internally and with its industry partners[11-14]. Currently, several private companies are involved in NASA's NextSTEP-2 program[15] studying inflatable concepts for deep-space habitats and airlocks, with the potential that an inflatable component or module will be selected to proceed towards a flight article demonstration.

2. Inflatable Structure Design

Unlike metallic space structures, inflatable modules are made up of high-strength fabrics that are stacked together to form the outer shell and pressure hull of a habitat. A large scale inflatable habitat module uses a shell that is made up of over 60 layers, totaling 12-20 inches thick when fully deployed. The stack-up of material layers provides the required structural and environmental protection for the habitat. The complete assembly is broken into five primary sub-assemblies including 1) inner liner layer, 2) bladder layer, 3) restraint layer, 4) micrometeoroid/orbital debris (MMOD) protection layer, and a 5) thermal protection (MLI) layer. Figure 2 shows the shell layup for the TransHab module design[5].

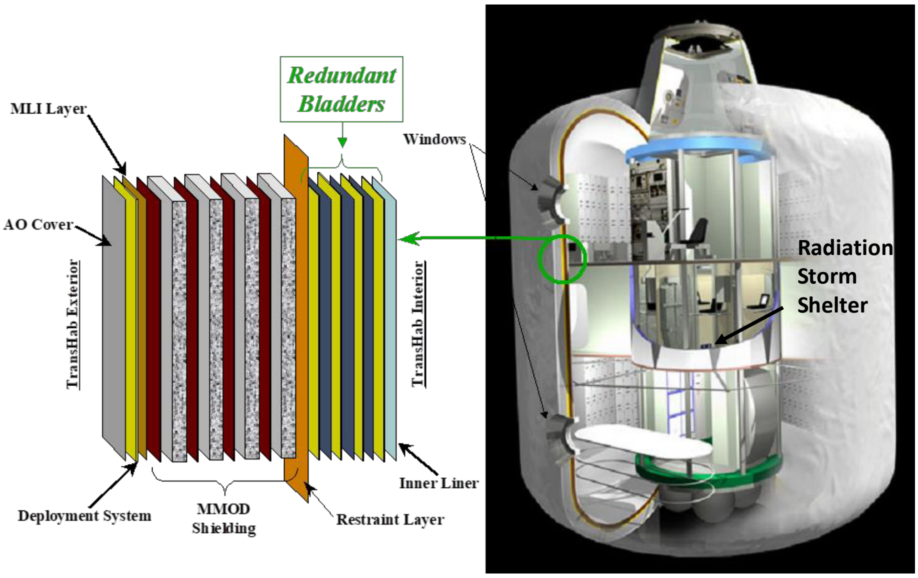

Figure 2. TransHab Shell Layers

Inner Liner Layer—The inner liner layer is the crew-facing layer on the inner-most wall of the structure. This layer is known as a scuff layer and acts as a barrier for the crew. This layer is flame-resistant, easy to clean, durable, puncture resistant, and provides acoustic dampening.

Bladder Layer—The bladder layer is the gas (air) barrier of the module. It is considered the most critical layer. During TransHab the bladder consisted of multiple layers to provide redundancy and increased safety. The bladder should be durable, flexible and have low permeability at both high and low temperatures. The bladder is designed to be oversized, when compared to the restraint layer, in order to ensure the pressure force is fully transferred to the restraint layer and the bladder does not carry any load. Bladder materials are typically polymeric and must go through a variety of testing including permeability, cold temperature flexure, durability, and manufacturability. During TransHab, individual bladder layers were separated by a felt cloth to act as a bleeder layer and to protect the layers from damage[5].

Restraint Layer—The restraint layer is the structural layer of the inflatable. It carries the high membrane loads and stresses imparted by the internal pressure of the module. The restraint layer materials must be strong, stiff, but also flexible, foldable, and able to be packed on the ground and deployed in orbit without degradation. Depending on the operating pressure of the fabric structure, there are a number of different restraint layer design options. Figure 4 shows a plot with multiple design options that vary with expected membrane loads. Starting on the left side of the plot is a single bladder design, like a balloon or beach ball. Slightly higher pressures require a broadcloth restraint layer that is coated or contains a separate bladder to act as a combined restraint and bladder layer, like a blimp or basketball. Even higher loads require a separate bladder and restraint layer with additional loose webbing or cordage to strengthen the restraint layer, (e.g., an inflatable radome or lightweight airlock). Very high loads, like that of a full-scale space module, require a bladder and restraint layer with tight webbing, like the TransHab module. Lastly, with even higher loads, new materials and restraint layer designs must be developed to carry the loads over a large habitat or vehicle.

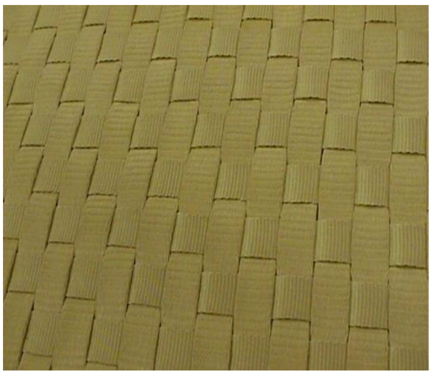

Figure 3. NASA-designed tight woven restraint layer

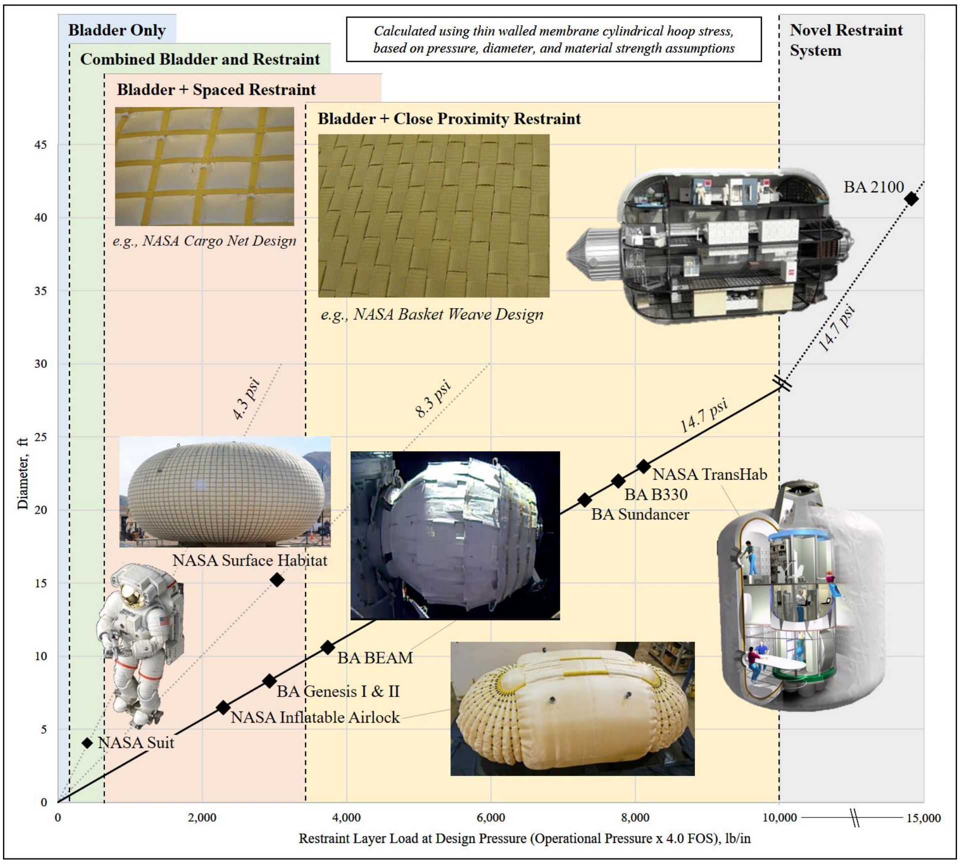

Figure 4. Inflatable structure restraint layer loading versus diameter for various design configurations

A typical NASA JSC design fits into the tight webbing category and is composed of high-strength webbings that are woven together in a tight basket weave pattern in the axial and hoop directions of the module, as shown in Figure 3. Alternately, a Bigelow Aerospace patent[32] shows a restraint layer made of hoop webbings that are abutting and sewn end-to-end lengthwise, which reduces the potential stress points on a strap weave. With this design, there are also fewer longitudinal, or axial, straps, which reduces the overall weight of the module.

While there are a variety of design options, every restraint layer design must meet requirements for flight certification. NASA structural design standard NASA-STD-5001 dictates that safety critical 1 or 2 (possible loss of life or vehicle) softgoods structures must be designed to a factor of safety of 4.0 at operating pressure and over its operating lifetime[16]. This means that a habitat operating at 14.7 psig must be designed to a pressure greater than 58.8 psig. The module should also be shown to survive at operating pressure (14.7 psig) for four times the expected life of the mission. If it's a 15-year mission, then the module should be shown to survive 60 years at 14.7 psig. As a fabric structure, there are additional knockdown factors for the assembled structure that should be considered including creep behavior, load sharing, seam efficiency, and handling.

Indexes and Seal Interfaces—The bladder layer and the restraint layer must work in tandem to carry the pressure load and contain the internal atmosphere of the module. As mentioned, the bladder layer is oversized with respect to the restraint layer so that it never carries load, but transfers it all to the restraint layer. In order for the stack-up to be packed, folded, and deployed as designed, the bladder and restraint layers must be aligned together. Indexing is used throughout the acreage of the shell to hold the layers together. The indexing points should tie the liner, bladder, and restraint layers together while not reducing the strength of any individual layer. Not enough indexing points can lead to uneven distribution of the bladder, potentially resulting in a failure and leak, while too much indexing can add manufacturing time and add unnecessary weight to the shell assembly.

Most common inflatable modules include rigid bulkheads on both ends of the softgoods shell. These bulkheads contain hatches and docking/berthing rings for attachment to larger habitats or space stations. The interface between the rigid bulkhead and the softgoods shell is another vital component of the inflatable habitat design. The bladder layer must be sealed to the bulkhead to prevent any leaks from occurring and should be attached in a way to prevent the bladder from taking any tension or stress once internal pressure is applied. This can be done with o-rings, gaskets, or adhesive-type seals and should include redundant seals for increased reliability. The restraint layer is structurally attached to the bulkhead to transfer loads from the webbings. A clevis and roller system is used in the NASA design that allows the webbing to stretch and rotate around the attachment point while maintaining a stiff connection under load[5].

MMOD Protection Layer— Micrometeoroids and orbital debris (MMOD) are present in space and are an active damage threat for all space vehicles. Micrometeoroids occur both in low Earth orbit (LEO) and in deep space, while orbital debris is currently only a threat in LEO. The MMOD layer protects the restraint and bladder layers from hyper-velocity impact damage from these threats. The layer is a fully fabric, multi-material layup typically composed of ceramic fabric bumper layers that are separated by low-density foam with a high strength rear wall layer. At launch, the foam layers are vacuum packed and the overall stack-up of the MMOD layer is very thin. Once in orbit, however, the vacuum of space equalizes with the bags and the foam layers expand, creating a very thick MMOD layer when fully deployed. This creates a very efficient MMOD shield with bumper layers positioned at a high standoff distance due to the foam separation. As MMOD impacts the ceramic layers, it breaks apart into small pieces with each layer and disperses into a larger area so that by the time it reaches the rear wall layers, it is only dust or molten droplets and does not penetrate the rear MMOD wall. The number of layers and the overall density of the MMOD shield depends on the mission and the MMOD threat to that location and module orientation.

Designing a mass efficient micrometeoroid shield is critical for any deep space mission. During the TransHab on ISS study, the Micrometeoroid/orbital debris (MMOD) shield made up the bulk of the fabric shell weight (~68%). This was primarily due to the more severe low Earth orbit (LEO) MMOD environment, the on-orbit duration, and large exposed surface area of TransHab. Looking at a deep space or Lunar orbit environment, the micrometeoroid shield can be much lighter since there is currently no orbital debris field. Preliminary studies indicate that for a similar sized TransHab vehicle in deep space, the micrometeoroid shield will only take up approximately 14% of the shell mass. When designing an MMOD shield for an inflatable, NASA assumes that zero penetration through the rear wall of the shield can be tolerated and no contact with the restraint layer. Challenging this requirement requires additional testing that proves that damage to the restraint layer does not drastically reduce the structural performance of the restraint layer over the remaining life of the module or penetrate the gas barrier. When designing a mass efficient meteoroid shield, studies have shown that a Whipple shield with a larger standoff can be more mass efficient than a Whipple shield with a closer standoff (Figure 5). For a metallic module the rear wall of the meteoroid shield is partially composed of the metallic pressure shell and the thickness is fixed by minimum gauge (due to pressure and durability requirements). Since the rear wall mass of the metallic module is fixed, there is less flexibility in optimizing the mass towards the outer bumper layers.

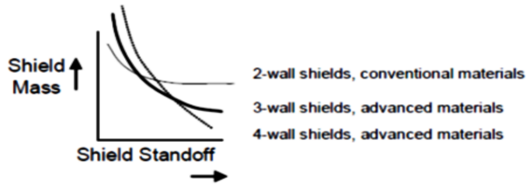

Figure 5 - Effect of shield standoff on shield mass[30]

Passive Thermal Protection Layer—The outermost major layer of the module is the passive thermal protection system (TPS) that is used to help maintain proper thermal control of the module's shell and internal atmosphere. The TPS for a fabric structure is similar to that of an extra-vehicular activity (EVA) space suit which uses a NASA-designed multi-layer insulation (MLI). MLI is composed of very thin sheets of reinforced, double aluminized material that is sandwiched by an inner and outer layer of double aluminized polyimide film. The inner layers are perforated, which allows for venting, and separated by a scrim layer. The number of layers depends on the thermal environment of the mission. The total MLI stack-up is very thin, compared to the MMOD shield and extremely flexible. The TPS layer, along with the MMOD shield, are both oversized with respect to the restraint layers and are indexed to the adjacent layer to ensure proper coverage and alignment.

Atomic Oxygen Protection—Atomic oxygen (AO), or single atoms of Oxygen, are very reactive and can damage exposed spacecraft materials. In LEO, AO is very prevalent and a danger to orbiting vehicles. In deep space, the AO level significantly decreases and is no longer a threat, but AO has been discovered in the atmosphere of Mars and is a concern for future exploration[17]. For inflatable habitats, the outer most layer of the shell is made of Betaglass fabric to protect against AO. This material has been used historically since the Apollo program to protect vehicles and space suits against AO.

Deployment System Layer—Because of the expandable nature of an inflatable habitat, a deployment system must be used to constrain the prepackaged shell prior to deployment. The system should execute a controlled and predictable deployment that is simulated and verified on the ground prior to utilization in space. The deployment system of a large inflatable module is integrated with the shell layers and is used to restrain the shell during launch/ascent and then release the layers for expansion once in orbit. The assembled shell should be folded and packed on the ground using a series of deployment cords and straps to keep it taut and then released at the start of inflation, in orbit. Once the layers are released, air is filled into the internal cavity of the module and the internal pressure begins to increase. The loose shell is filled with air and the layers begin to unfold and expand into their proper position. Once fully inflated, the softgoods shell of the module becomes very stiff and should maintain its shape for its operational lifetime.

3. Launch to Activation

Figure 6 shows a high level Launch-to-Activation scenario for an inflatable module launched on a deep space mission along with some of the high level requirements specific to an inflatable module. Since an inflatable module can have a high expansion ratio it is desirable to be able to pre-integrate critical integrated utilities (power system, ECLSS system, avionics systems, and substructure) into a central core. The module will have to be folded and packaged prior to launch and the packed configuration will have to remain within the dynamic volume of the launch shroud during ascent. Launch support structure will have to be included within the inflatable module. For TransHab, the launch support structure was integrated into the ends of the central core and loads were transmitted from the central core into the launch vehicle attach structure. Vent valves will have to be integrated into the inflatable core structure to allow air to vent during ascent. The vent valves will have to be closed prior to inflation. Environmental conditioning (heaters or humidity control) may have to be integrated into the launch vehicle cargo bay. After launch, the inflatable module will have to be attached to the deep space station via a docking or berthing mechanism. If the inflatable module has to be extracted from the launch vehicle payload bay, a grapple fixture will be required to be placed on the metallic core. After docking/berthing, verification of vent valve closure is required. At that point the vestibule can be pressurized and an atmosphere check can be performed. After this step, the redundant pyros can fire, thereby releasing the deployment system. Next, the pressurization system can inflate the module. After performing leak checks, the heaters and fans can be activated. Once air samples have been taken and positively verified, the crew can ingress the inflatable module and on-orbit operations can begin.

4. Mass / Volume Comparisons

The clearest advantage of inflatable spacecraft structures is the lower launch/ascent volume. Lower launch/ascent volume offers reduced fairing size, drag, and mass atop the launch vehicle or additional cargo inside a similar sized fairing. A comparison of an inflatable versus a metallic module is highly dependent upon the respective mission (requirements, internal outfitting, environment, duration, size, materials, launch vehicle requirements etc.) therefore, comparing existing spacecraft structures is difficult to support an apples-to-apples comparison. Any general comparison should emphasize the potential mass savings with inflatable spacecraft structures due to the greater specific tensile strengths especially for much larger, higher volume, spacecraft structures. High strength fabrics such as

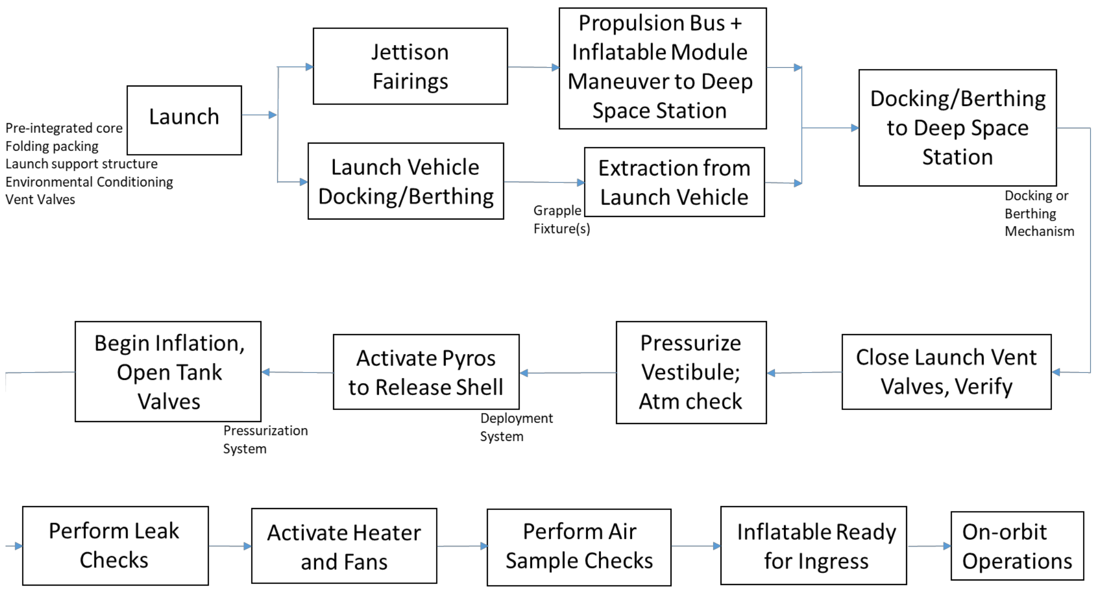

Figure 6 - Simplified Launch-to-Activation Scenario- Inflatable Module Deep Space Station

Kevlar, Vectran, and PBO (as mentioned in the TransHab patent[31]) provide an order of magnitude higher specific strength than aluminum and titanium alloys (Table 1).

Table 1. Specific strength comparison of high strength fabrics versus traditional spacecraft metals

Material	Density (g/cm^3)	Ultimate Tensile Strength (Mpa)	Specific Strength (kNm/kg)
Vectran HT	1.4	3200	2330
Kevlar 49	1.44	3600	2500
PBO	1.5	5800	3840
Titanium Alloy Ti-6 Al-4V	4.4	950	220
Aluminum Alloy 7075-T6	2.81	572	204

Fabric weaves or webbings have mass advantages over metals although not as high as the individual fibers. For example, an aluminum 7075 bar (1-inch wide x 0.17-inch thick) has nearly four times the mass of a 1-inch wide Kevlar webbing with the same load capability.

Some of the mass advantages can be reduced due to a variety of reasons. Safety critical fabric structures need to be designed to a factor of safety of 4.0 as compared to 1.4 (tested) for metallic structures. The micrometeoroid/orbital debris protection shield can make up the majority of the shell mass especially for a low Earth orbit (LEO) mission. Efficiently-designed micrometeoroid protection shields are also essential for deep space missions where the mass fraction (fuel multiplier to get to deep space) is much higher than that for LEO.

Table 2 provides a summary comparison of inflatable and metallic modules. As was mentioned before, this is simply a high-level comparison, as the missions for each of these spacecraft are different. Mass is intended to be dry launch mass although some masses may include outfitting/payload. Data sources are listed in the reference section[18-26]. As shown in Table 2, the mass advantage for inflatable structures is greater for larger volume inflatable spacecraft structures due to the higher percentage of higher specific strength fabric relative to a metallic core structure. This, of course, still needs to be proven as of this writing a B330 class vehicle has not flown.

Table 2. Comparison of metallic and inflatable spacecraft

	Module	Launch Mass (Kg)	Pressurized Volume (m^3)	M/V (Kg/m^3)
Inflatable	TransHab (not flown)	13200	340	39
	BA330 (not flown)	18500	330	56
	BEAM	1415	16	88
Metallic	PMM (ASI Leonardo MPLM)	4428	77	58
	Cygnus PCM (enhanced)	2000	27	74
	Cygnus PCM (standard)	1700	19	90
	Columbus (ESA Lab)	10275	75	137
	Harmony (Node 2)	14288	76	189
	Tranquility (Node 3)	15500	76	205
	Skylab Orbital Workshop	28300	302	94

5. SE&I CONSIDERATIONS

ECLSS—The environmental control and life support system (ECLSS) of a spacecraft provides a safe and comfortable environment for the equipment and the crew to work and live. An inflatable habitat will have a similar ECLSS to a metallic module, with some additional considerations. The air system is the primary component of the overall ECLSS and is responsible for maintaining the air quality, air flow, temperature, humidity, and pressure. Air temperature control helps maintain crew comfort and maintains hardware within operating limits, while humidity control prevents the growth of mold and mildew on surfaces. Ventilation helps prevent the buildup of stagnant pockets of CO_2 and other gases while mixing fresh air and ambient air.

The ventilation approach for a large inflatable habitat would be different than a small ISS module, for example. Those modules use a localized approach with a cross-flow design. In general, they utilize long air ducts along the length of the module that blows air through the module. This flow is generally laminar and slow-moving and stagnant air pockets are easily formed. For a large habitat, like the TransHab module, a global flow approach could be used. This type of flow moves a large amount of air through the entire volume and does not require long runs of ductwork. The shape and size of the TransHab module itself serves as a large, open duct. The air flow is along the length of the module instead of across the diameter using fans, with low head pressure at the top and bottom of the module. The common cabin air assembly is used to heat the air and remove humidity to the air as needed. This device should be located in the middle of the module to allow for efficient use. For this global flow concept to work, however, it requires open air paths along the sides of the module walls and through the central volume. Floor panels or rigid hardware will be incorporated into the module and should be designed to allow for open air flow. Additional booster fans may be used at those rigid interfaces to encourage air flow where needed.

For inflatable modules, specifically, there is concern about humidity and condensation on the liner and bladder layers. These layers will likely be exposed and not hidden behind hardware, but are very susceptible to condensation because of the drastic temperature change through the thickness of the softgoods shell. One concept developed during TransHab, was to prevent bladder condensation using an inner shell annulus. This volume could be formed between the inner liner and bladder, creating an air channel where warm air can flow. The inner liner could be made with a smaller diameter than the bladder and tied to each other with indexing. This annulus would provide a dedicated layer of warm air along the interior of the shell bladder and be independent of the internal hardware layout.

To maintain pressure in the module, a positive pressure relief valve should be used to prevent over-pressurization. A manual pressure equalization valve can also be provided to equalize pressure with any docked modules and allow for an emergency evacuation capability in the event of a fire or toxic atmosphere. Launch vent valves are also used to expel internal atmosphere during launch, ascent and contingency return venting of the inflatable module.

Power—For an inflatable module, like any other kind of module, the electrical power system distributes power through the module from the power generation source (normally solar arrays). This voltage arrives at 120V[33]. The module will have its portion of the Power Management and Distribution (PMAD) system as required by the internal systems. While lower voltages (e.g. 28V) for primary power have been studied in the past, it has been found that for elements of a space station, the length of power lines, the harshness of the environment and the needed reliability over a long period time drives a 120V architecture for primary power to individual modules.

Similar to ISS, the module will likely receive its primary power from a Primary Main Bus Switching Unit (PMBSU). A Secondary DC-to-DC-Converter Unit (SDDCU) isolates the primary power feed from the secondary power distribution system to provide fault isolation and current limiting. A Secondary MBSU (SMBSU) provides switching to the Power Distribution Units (PDUs) which provide power to the various module systems.

Bi-directional DDCU's (BDDCUs) will be needed to pass power between modules, if required. Portable Utility Panels (PUPs) can be located throughout the module to carry portable loads (e.g., laptops). If batteries are required inside the module to supplement main power (e.g., during eclipse periods), a separate Battery Charge/Discharge Unit (BCDU) will be required. Cut-off switches to terminate power (i.e. a breaker box) can be located within the module to terminate power in case of a fire or other emergency.

The failure tolerance in the module's electrical power system will be driven by program requirements. It's expected that the power system will be at least single-failure tolerant for providing power (redundant buses or power feeds) and two failure tolerant against catastrophic hazards. Power distribution lines should have dedicated returns to prevent unwanted current flow through structure. Internally derived isolated power (i.e., 5V, 28V, etc.) can be locally referenced to chassis or isolated.

No differences in the electrical power architecture or power distribution systems are foreseen when using an inflatable module vs. a metallic module.

Avionics—Similar to the electrical system, the avionics architecture is driven by Program requirements rather than the module construction. So, no unique differences are expected for an inflatable structure.

The avionics architecture must be capable of supporting crewed missions beyond LEO, but also provide for long-term autonomous operation and remote commanding from Earth. The habitable module is expected to include Flight Computer Modules (FCMs) and Remote Interface Units (RIUs) which interface with the Redundant Flight Busses to provide single string redundancy. Connecting all the FCMs and RIUs to the Redundant Flight Critical Busses plus the use of Core Flight Software gives the system design the capability of dynamically reconfiguring the system architecture for different phases of the mission. Data storage onboard the inflatable module along with Wireless Access Points to minimize masses of cable runs will be an evolution from the ISS avionics architecture.

Redundant high data rate Ethernet is the backbone between FCMs, RIUs along with a hardline interface between the inflatable module and any other interfacing elements. A number of options exist for Voting/Fault Tolerance depending on system requirements. COTS hardware and open source software should be used to the maximum extent practical while remaining in compliance with reliability requirements. Scarring with remote terminals to provide both power (120Vac) and wired data (Ethernet IEEE 802.3) interfaces are desirable. The software architecture will be determined by mission requirements and is not driven by the inflatable construction.

Secondary Structures—An inflatable module is packed in a small volume for launch and then expanded to a much larger volume once fully deployed in orbit. This increase in volume drives the need for secondary structure that is deployable and installed by the crew in orbit. Secondary structure is required to create handrails and foot restraints for crew members. It is also used to mount hardware and equipment for daily operations.

A number of internal configurations can be used for an inflatable habitat, but they all require basic secondary structure. These structures may be floors or walls to divide the volume into smaller segments. Deployable racks could be used to mount experiments and equipment. Expandable ductwork may be required for proper airflow between the segments. Rigid foot restraints and handrails should be used for the crew to stabilize themselves when working at a particular station. Most of the secondary equipment will be cantilevered off the central core of the module and should be deployable or collapsible for launch. Mounting equipment to the inner liner will be difficult as the liner is not designed to carry load. Additionally, loading on the liner could cause unwanted damage to the bladder and a premature failure.

Secondary structure could be designed to provide a framework on the shell layer and a mounting system for additional attachment points. This framework would act similar to studs in a wall and could be placed behind the liner layer and made of inflatable tubes. Inflatable tubes are a compact option that could be inflated by the crew in orbit. Besides an outer framework, these tubes could serve as racks, shelves, and even handrail structures that are rigidized by low pressure inflation.

Similarly, fabric walls and curtains can be used to divide segments and provide acoustic dampening. Cargo transfer bags that are commonly used on the ISS are fabric-based bags and could be reused as fabric walls for deep space missions. As the mission changes, the storage requirements could also change. The need for more or less science would be adjusted as well for a transit mission to Mars versus a surface exploration mission to the Moon. The combination of inflatable tubes and fabric walls can be used to provide a building block capability for a modular and reconfigurable cabin configuration.

6. Habitat Environmental Factors

Radiation— Space radiation exposure is one of the highest risk items for long-term deep space habitation. Outside the Earth's magnetic fields there are continuous high-energy galactic cosmic rays (GCR) and intermittent short-lived solar storms known as solar particle events (SPE). Although predicting the timing of solar storms (SPE) is difficult, a storm shelter can be provided that the crew can retreat into until the storm surge passes. For a full-scale inflatable habitat, the crew quarters are typically designed to be located in the central core surrounded by a water wall. This concept was originally described in the TransHab design[27, 28] and is shown in Figure 2 and 7. Alternate water wall configurations and radiation protection materials can be utilized.

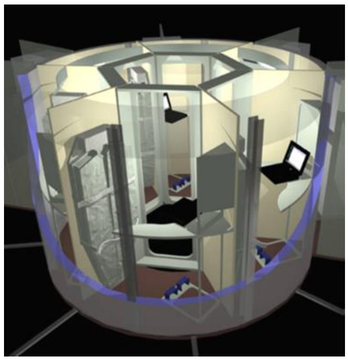

Figure 7. TransHab Crew Quarters with water wall for radiation protection

GCR is continuous and contains much higher kinetic energies than the intermittent SPE and, therefore, requires much better radiation protection. For extended exposures (3-years or greater), GCR limits are exceeded without some form of radiation protection. Active magnetic shielding systems, biomedical mitigation methods, and digging lunar or MARS tunnels all currently have a low Technical Readiness Level (TRL) but may prove effective if consistent and long-term funding is provided. The current high TRL solution is to add mass, preferably low-Z, high Hydrogen content materials.

Allowable risk can be defined as the allowable Blood Forming Organ (BFO) dose. Depending on the level of risks acceptance, for a three-year mission (assuming worst case solar minimum GCR environment and 3 high SPE events), the amount of shielding could range from 25 cm (9.8-in) to 400 cm (157-in). See Figure 8 (1 cm of water = 1 gm/cm^2 of shielding). Results for longer and shorter mission (1, 2, 3 and 4-year) are provided in reference 29. Inflatable structures can provide the large volume required to support augmentable shielding, consumables and waste, on the outermost wall of the spacecraft.

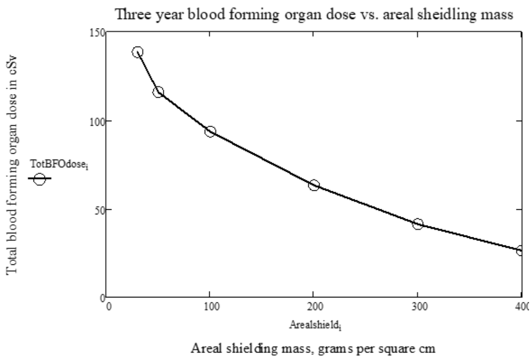

Figure 8. Blood Forming Organ (BFO) Dose as a Function of Areal Shielding Mass[27]

Thermal Insulation—An inflatable module presents many unique thermal design challenges, the first of which is keeping the layers of fabric that make up the pressure bladder within the allowable temperature range prior to deployment and through the operational life of the module.

The materials which make up the inflatable bladder are most susceptible to cold temperatures. The thermal performance of the Multi-layer Insulation (MLI) that is used must be understood by rigorous testing and analysis. If the bladder loses its elastic properties because of low-temperature exposure, the deployment and long-term structural integrity of the inflatable can be adversely affected.

As the module is pressurized, internal thermal and humidity conditions must be kept stable to preclude condensation from forming inside the element. This process will require internal fans and heaters to maintain the dew point within limits and to protect seal-to-bladder interfaces. Preliminary analysis of a TransHab configuration indicated that heater power up to 4kW may be needed and it may be up to 24 hours after inflation before the module may be entered.

For NASA's TransHab concept, thermal protection from the extreme temperatures of the ISS space environment, +150 to -250 degrees F, was provided by MLI consisting of multiple layers of double aluminized Mylar sandwiched by an inner and outer layer of double aluminized Polyimide film (Kapton). The purpose of this hardware is to provide insulation to minimize heat loss or gain in a vacuum environment. A cross-section of the blanket is shown in Figure 9. The internal MLI layers are perforated to allow venting. The MLI will be fabricated in gore sections and then assembled onto the shell. Kevlar indexing cords attach the gore-to-gore and layer-to-layer interfaces. The MLI blankets are also oversized with respect to the MM/OD layers to prevent them from carrying load. Sub-scale thermal vacuum tests have been performed on the TransHab shell lay-up to verify thermal performance.

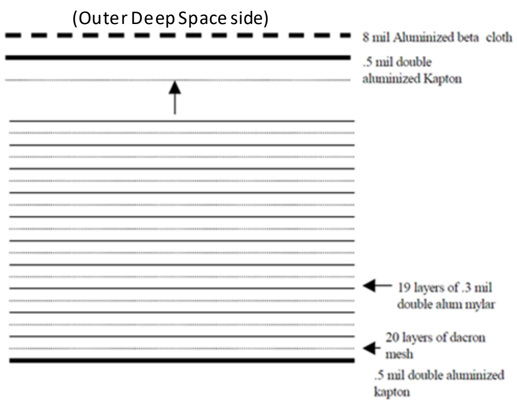

Figure 9. Cross-section of TransHab MLI

The aluminized beta cloth protects the blanket from atomic oxygen degradation. It also prevents light transmission to the internal blanket area. The layers of double aluminized Mylar minimize radiation heat transfer through the blanket. The aluminized sides of the Mylar are poor emitters of infrared radiation. The Dacron mesh layers minimize heat transfer through conduction by preventing direct contact of the Mylar layers. A conduction path through the blanket would result in a heat short. The Kapton layers prevent damage due to punctures or tears. Dedicated full-scale test articles of the MLI lay-up inside thermal vacuum chambers are needed to test the robustness of the thermal design. Rigorous thermal analysis supported by a full-scale thermal vacuum test of an outfitted module thermal test article is needed for math-model validation.

The Active Thermal Control System of an inflatable module can draw off existing design solutions for the International Space Station. An internal water loop that is plumbed to an ammonia-water external heat exchanger and central thermal control system radiator separate from the inflatable module is recommended. The internal loop would be launched dry with the assumption that active cooling of internal systems is not required until the inflatable module is attached to other elements. Integrating a dedicated body-mounted radiator external to the inflatable module would be a significant design challenge.

EMI—Electronic hardware is typically designed and tested to NASA and Industry standards to mitigate any risk due to electromagnetic interference and to ensure electromagnetic compatibility. MIL-STD-461, MIL-STD-464, MIL-STD-981 and NASA-STD 4003 are the typical requirements documents that human spacecraft must comply with.

For inflatable structures, there are not any new requirements levied for EMI/EMC because the pressure-bearing structure is a fabric design. The fabric will not be subject to significant static charging or induce any electromagnetic effects on hardware contained inside it. So, the standard methods of design, construction and verification to mitigate these effects can be employed.

Crew Accommodations—Flight Crew System hardware includes the restraints and mobility aids, Crew Health Care System (CHeCS) and exercise equipment, the crew quarters outfitting, hygiene systems, galley, refrigerator/freezer(s), stowage system, and other miscellaneous items such as portable fans, portable lights, portable power strips, laptops and wireless devices for personal use. Sleep stations dedicated to each crew member have been found to be beneficial based on ISS experience. These sleep stations can be outfitted with supplemental radiation protection.

The restraints and mobility aids can be as simple as fabric straps located internally and externally to the module or rigid handholds could be required. Any inflatable module will have some kind of internal structure, be it a central core with bulkheads or an internal skeleton, to maintain its shape in the event of a depressurization event. Restraints or mobility aids, whether human or robotic, that require significant stiffness or load-carrying capability will be attached to this rigid structure.

The Crew Health Care System (CHeCS) will depend greatly on the level of care that is determined to be required for an ill or injured crewmember. For a long duration, deep space mission, an inflatable module may have to be equipped with a critical care monitoring system, Intravenous (IV) fluid system, Crew Contamination Protection Kit (CCPK), Volatile Organic Analyzer (VOA) & kit, defibrillator kit, a spectrophotometer, Tissue Equivalent Proportional Counter (TEPC) Cable, Heart Rate Monitor (HRM), active personal dosimeters, Total Organic Carbon Analyzer (TOCA) & supply kit, Ion Selective Electrode Assembly (ISEA), Water Sampler & Archiver (WS&A) and support such as power, thermal and avionics. CHeCS stowed equipment would include the Grab Sample Containers (GSCs), Blood Pressure/Electrocardiogram (BP/ECG), Formaldehyde Monitoring Kit (FMK), Solid Sorbent Air Sampler (SSAS), CO2 Monitoring Kit (CDMK), Compound Specific Analyzer – Combustion Products (CSA-CP) and Portable gas analyzer. These functions may not all be resident in the inflatable module, but a portion of this functionality will certainly be required inside the habitation module.

Due to design provisions in the inflatable (i.e. ducted air and integrated light), a derivative of the ISS Temporary Sleep Station (Figure 10) is planned to be used to provide each crewmember a dedicated sleeping area. While this concept will not be exactly duplicated for an inflatable module, it does include many of the features required for a crew quarters.

Figure 10. ISS sleep station concept

The hygiene hardware includes the full body cleansing compartment, a waste and hygiene compartment and a handwash. Provisions for biohazard waste disposal would be incorporated if the inflatable module was required to house this capability.

The galley includes a food warmer, water dispenser, trash compactor, food preparation surface, some stowage for food items, utensils and condiments, and a task specific lighting. The Refrigerator/Freezer stows both refrigerated and frozen foods. Portable Breathing Apparatus (PBA) and Portable Fire Extinguisher (PFE) hardware will be located as required throughout the module.

While windows may not be required for technical reasons, they may be provided for psychological reasons. Integration of windows and hatches have been performed in inflatables, so this is not an insurmountable challenge.

Resistive exercise such a treadmill with a vibration isolation system and a cycle ergometer may be included in an inflatable module. Centrifugal Artificial Gravity as an Adaptive Countermeasure may also be needed for long-duration space flight. Inflatables can provide a large radius so that a centrifuge or large radius bicycle track could be included. The major advantage of an inflatable structure is the large in-space volume that can be provided for the same upmass and launch vehicle shroud volume that a rigid module requires. This gives an inflatable module an enormous range of possibilities when it comes to crew equipment outfitting.

7. Future Applications

Spacecraft launched to deep space will be limited by the launch vehicle shroud volume. Figure 11 depicts the co-manifested payload volume available on the Space Launch System when it launches an Orion Spacecraft. The cylinder represented in the volume is roughly the largest rigid structure that could be launched without violating payload envelope constraints.

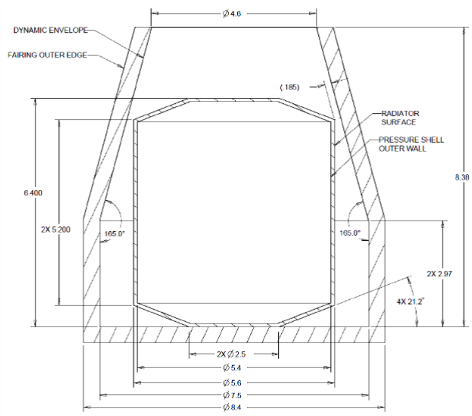

Figure 11. Largest rigid module that will fit as an SLS co-manifested payload

An enormous amount of pressurized volume will be needed for the provisions, systems and living space required for extended duration missions beyond low Earth orbit (LEO). Heavy Lift Vehicle launch opportunities will be infrequent, so an inflatable structure gives the opportunity to provide large in-space volumes for similar launch mass of a rigid pressurized cylinder.

These large volumes can be outfitted in any number of ways; one example is shown in Figure 2. A cutaway view of TransHab is shown where interior decks are deployed from a central core that provides the backbone of the module as well as the mounting structure for the major subsystems.

An inflatable can also be used to house a large radius centrifuge module (Figure 12) to provide 1-g of artificial gravity as an adaptive countermeasure. Artificial gravity may be required to counteract the deleterious effects of prolonged exposure to microgravity on deep space missions. Inflatable structures technology provides the large volume pressurized structure to house such a system.

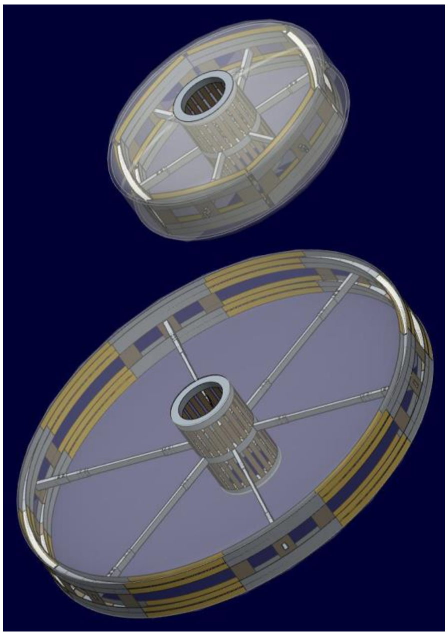

Figure 12. Inflatable artificial gravity centrifuge - stowed and deployed

The full potential of inflatable structures in human spaceflight has just begun to be realized. These types of structures will provide an indispensable role in future crewed deep space missions because of their adaptability to different applications and their volumetric efficiency. As we continue to understand these structures more, elements of deep space vehicles and surface habitats will use inflatable structures to meet the enormous challenges in front of future explorers of the solar system.

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