Deep Space Habitat Primary Structure - A Comparison between Metallic, Inflatable, and Composite Materials

Matthew T. Ziglar[1] and Michael Elsperman[2]
Boeing Exploration Systems, Boeing Defense and Space, 3700 Bay Area Blvd., Pasadena, Texas, USA 77058

This paper presents a comprehensive trade study comparing metallic, inflatable, and composite primary structure materials for a Mars Transit Habitat module. The study evaluates the impact of these materials on the overall mass, outfitting, and mission complexity of the habitat. The results show that the composite module outperforms the other options in terms of minimum mass, being 33% lighter than the metallic configurations and 41% lighter than the inflatable option. The study highlights the potential of composite habitats for future space missions and emphasizes the need for further development and testing to increase the Technology Readiness Level.

I. Introduction

To contribute to sending humans deeper into space, the challenge of developing mass efficient habitation systems must be solved. The configuration and material system of a deep space habitat's primary structure has a significant impact on the overall vehicle's mass, outfitting, cost, and mission complexity. This paper compares the use of metallic, inflatable, and composite primary structure materials implemented on the same reference mission and Ground Rules and Assumptions (GR&A) so that a true comparison of the system level mass could be evaluated. The Boeing Company conducted the comprehensive trade of the three primary structure types for a Mars Transit Habitat (TH) module. The trade was conducted over multiple phases: Phase 1 evaluated two different diameter metallic modules and an inflatable module, Phase 2 further refined the down selected option from Phase 1, and the Phase 3 introduced a composite module with a direct comparison back to the refined selection from Phase 2.

A total of four different vehicle configurations (Fig. 1) were traded using a fixed volume constraint and the same GR&As developed by NASA [1]. The configurations were 1) 5.5 m diameter metallic habitat, 2) 7.0 m diameter metallic habitat 3) 7.63 m diameter inflatable habitat, and 4) 5.5 m diameter composite habitat.

---

[1] Habitation Technical Integrator, Boeing Exploration Systems

[2] Exploration Director, Boeing Exploration Systems

5.5m TH: Description
- Safe Haven Airlock Compartment on aft port
- Structure: Al 2050vSLS-type barrels, efficient dome shape, FSW
- Delivery Bus: custom 5.5 m disposed axially
- Subsystem: body mounted radiators
- Internal: 4 floors, wall mounted equipment

7.0m TH: Description
- Safe Haven Airlock Compartment on aft port
- Structure: Al 2050vSLS-type barrels, efficient dome shape, FSW
- Delivery Bus: custom 7.0 m disposed axially
- Subsystem: body mounted + deployable radiators
- Interior: 3 Floors, wall mounted equipment

Inflatable TH: Description
- Enhanced Safe Haven Airlock Compartment
- Structure: metallic SHAC, central core and ports; softgoods Hab. Toroidal endcap
- Delivery Bus: custom 3.0 m disposed axially
- Subsystem: Deployable radiators
- Interior: 2 Floors, Wall-ventilation, core mnt equip

5.5m Composite TH: Description
- Safe Haven Airlock Compartment on aft port
- Structures: continuous layup Hab and SHAC
- Delivery Bus: same as 5.5m metallic
- Subsystem: body mounted radiators, modified MMOD
- Internal: 4 floors, comp. longerons for equipment

Fig. 1 Four Mars Transit Habitat Configurations Traded

Because the volume was constant among the different concepts the length of each configuration varied. Phase 1 resulted in configuration 1) being the most favorable [2] and was refined in Phase 2 to quantify mass reduction opportunities and implement them into the design. Building upon the refined 5.5m metallic configuration, a composite structure of 5.5 m diameter was traded to further expand the scope of a comparison across three very different structure types. During Phase 3, in order to have a direct comparison between configuration 1) and 4), as many design variables as possible were held constant to focus the changes to those items driven by the material system change.

In order to complete the trade, each configuration was analyzed and sized for the loading environments and a system level approach was taken to ensure other aspects and subsystem changes besides the structure were captured. The different configurations were allowed to optimize the layout and subsystems to minimize mass while meeting all GR&As. The primary functions of softgoods (i.e. restraint layer, bladder, multilayer insulation [MLI], micro-meteoroid orbital debris [MMOD]) and strength advantages are understood and have been studied, but other system level impacts were discovered or addressed that are unique to softgoods. For the metallic structure, the mass efficient aluminum lithium material and advanced SLS based manufacturing process were applied to a longer length 5.5 m diameter and a shorter length 7 m diameter structure. The composite configuration largely followed the 5.5 m diameter metallic configuration but was optimized to enable a continuous Automated Fiber Placement (AFP) end to end layup with no structural joints in the pressure shell. The composite configuration, like the inflatable, had unique subsystem impacts due to the material characteristics such as poor thermal and electrical conductivity and less damage tolerance then aluminum.

A. Background of Habitation Modules

Metallic modules have a long history of providing reliable habitation environments for crew. Since the inception of human spaceflight, all crewed space modules have been made of metallic materials. Metallic modules are well suited for containing pressure, handling various loading environments that can include both tension and compression inducing loads, and having predictable life usage. The module's size is fixed and is constrained by the launch vehicles fairing and the strength to weight ratio of metallics is limited. Examples of built and flown metallic modules include the International Space Station's three common Nodes, Laboratories, and Service Module, the first of which to launch have been on-orbit and crewed for over 20 years. A conceptual metallic Mars TH was previously studied by NASA [3]. This represents one design for a Mars TH and option for structural materials, and the Space Launch System (SLS) rocket, which uses large metallic pressurized fuel tanks of similar construction and usage, has been built and successfully flown.

Inflatable habitats on the other hand are still early in the maturation process, although studied for space applications going back to the 1960's. Inflatable modules split functions into separate layers or components (see Figure 2). Pressure loads, which for habitats requiring a large volume and high pressure are very high, are handled by a restraint layer (which can vary from webbing straps to cordage and/or fabric) and are tensile only structure. The pressure is contained via an internal bladder layer. Additional layers for thermal control and MMOD shielding are external to the restraint layer and must also fold up in the stowed state. To handle compressive launch in in-space vehicle loads, a rigid core is typically implemented to hold the softgoods and other need equipment prior to inflation in-space.

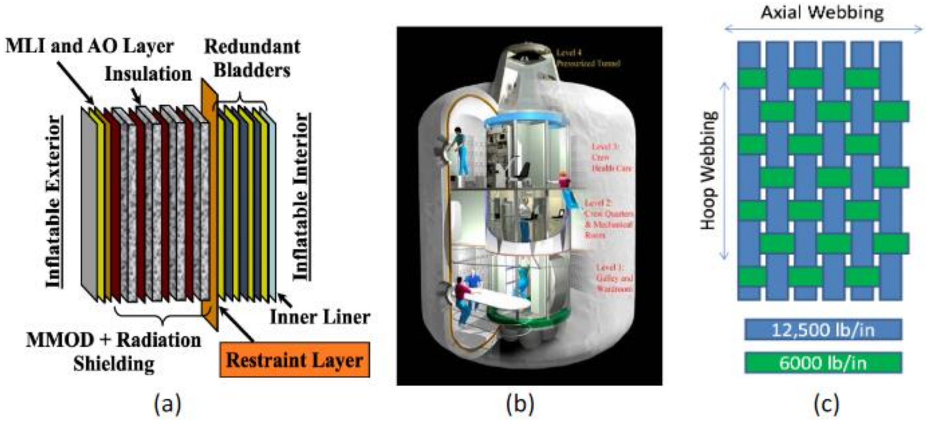


Fig. 2. TransHab Inflatable Shell Layers [4]

The size of an inflatable module is not constrained to a launch vehicle fairing because the softgoods are folded and packed and can inflate to a much larger volume once in space. The restraint layer strength to weight ratio can also far exceed that of any aerospace metallics (by nearly 10 times) because of the fibrous strap designs. The first major development of an inflatable habitat was NASA's TransHab [4] that went through design and development testing before being cancelled. The LIFE module is another in development [5]. Built and flown examples include the Bigelow Expandable Activity Module (BEAM) that has flown to ISS, Genesis I, and Genesis II which are solo uncrewed space habitats placed into LEO.

The use of composite structures in space applications has gained significant attention and interest in recent years. Composites offer several advantages over traditional metallic structures, including their high strength-to-weight ratio, excellent fatigue resistance, and low thermal and electrical conductivity properties. These materials, typically made of carbon fibers embedded in a polymer matrix, provide enhanced structural performance while reducing overall weight, which is crucial for space missions where every kilogram matters. Composite structures also offer design flexibility, allowing for complex shapes and configurations that can be tailored to specific mission requirements. The composite structure is configuration is fixed and constrained by launch vehicle fairings in the same way as metallic modules. However, the use of composites in crewed space applications presents unique challenges, such as ensuring long-term survivability in the harsh space environment and addressing concerns related to induced damage from micrometeoroid impacts or ground and crew induced impact damage. Composite materials have been utilized for space applications on NASA's Space Shuttle and in commercial and government satellites. Boeing developed and is still producing the 787 Dreamliner, an all composite structure commercial aircraft. This has produced a significant experience base in designing and producing large scale structure that must meet rigid regulatory safety requirements. Ongoing research and development efforts are focused on advancing composite materials, manufacturing techniques, and testing applications to fully exploit their potential in space exploration and habitation.

System level comparisons between metallic and inflatable spacecraft structures have been attempted in the past [6]. However, as stated in Ref. [6] the comparisons are "highly dependent on 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". Therefore, comparing the mass to volume ratio of inflatable and metallic spacecraft designed for different missions is very limited. This study performed a specific trade of metallic, inflatable, and composite habitats designed for the same reference mission so a true comparison can be performed.

II. Mars Transit Habitat System

The objective of the Mars Transit Habitat is to provide in-space transit and habitation supporting crew for approximately 1100-day missions to Mars/Mars vicinity. The Mars Transit Habitat also expands habitat capability while attached to Gateway prior to Mars Propulsion Element arrival for Mars transit. The increased Gateway habitable volume allows for extended crewed Gateway stays and attached operation simulations of Mars missions.

A. Ground Rules and Assumptions

In this study, the Mars Transit Habitat design, regardless of the configuration, needed to meet the Ground Rules and Assumptions developed by NASA [1]. The key GR&As relative to this study include:

- ☐ Mass: The TH allowable dry mass at Mars trajectory Earth Departure burn will be 26.4 metric tons
- ☐ 4 Crew
- ☐ 1200 days crewed mission duration
- ☐ 15-year life
- ☐ Launch on Commercial Launch Vehicle with optional SLS
- ☐ Contingency airlock and contingency safe haven
- ☐ Docking ports on two axial and one radial locations
- ☐ Accommodate logistics storage (~19 mT of solid logistics and 0.67 mT of water/gas)

B. Concept of Operations

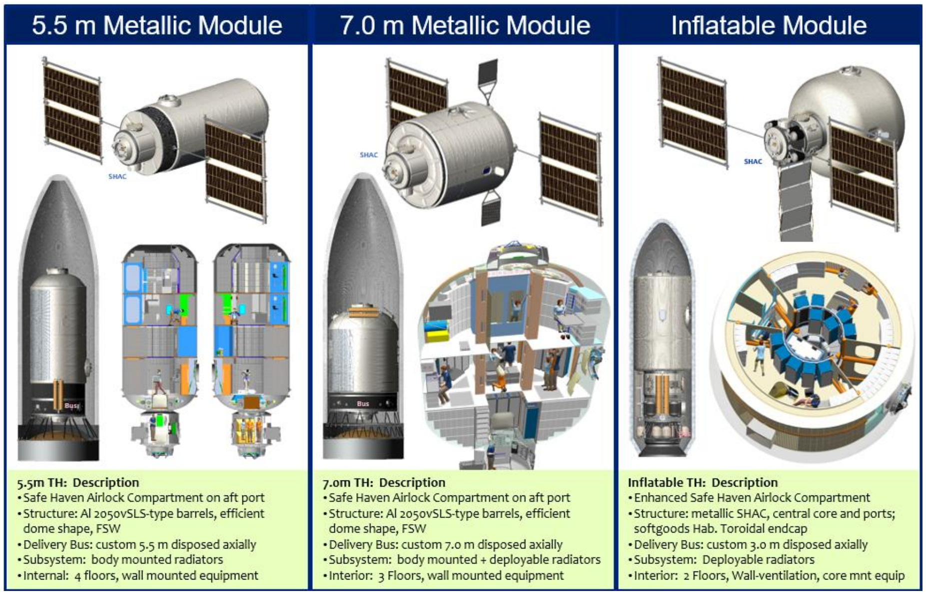
A Transfer and Attitude Control (TAC) Bus is launched and delivered to a Cis-Lunar parking orbit prior to the Transit Habitat launch. The Transit Habitat and its disposable Delivery Bus are launched and attached to Gateway in Cis-Lunar orbit. The crew arrives at Gateway with Orion and a logistics module. The TAC Bus can move from its parking orbit and docks to the Transit Habitat on Gateway. The TAC Bus can provide attitude control support to Gateway while in this configuration.

For the 1100-day mission to Mars, the Mars Propulsion Bus is assumed to be in a High Earth Orbit (HEO) prior to launch of Orion/crew for Mars Mission. The TAC Bus transfers the Transit Habitat from Gateway in Cis-Lunar to the Mars Propulsion Element in HEO. The crew arrives at HEO to the Transit Habitat/Mars Propulsion Element stack with Orion and the logistics module. Crew transfers logistics to the Transit Habitat prior to Orion and Logistic Module departure. The Transit Habitat/Mars Propulsion Element stack with crew transits to Mars Orbit. Mars surface missions or sorties are performed with crew transporting to and from Mars and Transit Habitat with a human-rated crew vehicle. Once the Mars Mission is completed, the Mars Propulsion Element transfers the Transit Habitat from Mars Orbit to HEO. Orion and Logistic Module meet the Transit Habitat in HEO. Crew transfer from Transit Habitat to Orion and return to Earth direct from HEO. The Transit Habitat can transfer from HEO to Gateway with a TAC Bus or be disposed.

III. Trade Study Configurations

A. Phase 1 Trades

Boeing conducted the Transit Habitat Phase 1 Design Analysis Cycle with an emphasis on a primary structure configuration trade study to determine a minimum mass configuration for use as the point of departure for further refinement. Boeing developed three candidate configurations: 5.5m and a 7.0m diameter rigid structure configurations that incorporated aluminum lithium alloys and friction stir welding manufacturing techniques and a 7.6 m diameter inflatable soft goods configuration. An important consideration was that all configurations provided the same pressurized cabin volume which enable an unbiased mass comparison. The constant volume constraint also set the cylinder length. Each concept has a Safe Haven Airlock Compartment (SHAC) and a disposable delivery bus on the vehicle’s aft end. Other deviations to the design or configuration are specific attributes of that vehicle’s configuration, whether a pro or con. Figure 3 shows the three structures configurations that were assessed for the Mars Transit Habitat Phase 1.



5.5 m Metallic Module

5.5m TH: Description
- Safe Haven Airlock Compartment on aft port
- Structure: Al 2050vSLS-type barrels, efficient dome shape, FSW
- Delivery Bus: custom 5.5 m disposed axially
- Subsystem: body mounted radiators
- Internal: 4 floors, wall mounted equipment

7.0 m Metallic Module

7.0m TH: Description
- Safe Haven Airlock Compartment on aft port
- Structure: Al 2050vSLS-type barrels, efficient dome shape, FSW
- Delivery Bus: custom 7.0 m disposed axially
- Subsystem: body mounted + deployable radiators
- Interior: 3 Floors, wall mounted equipment

Inflatable Module

Inflatable TH: Description
- Enhanced Safe Haven Airlock Compartment
- Structure: metallic SHAC, central core and ports; softgoods Hab. Toroidal endcap
- Delivery Bus: custom 3.0 m disposed axially
- Subsystem: Deployable radiators
- Interior: 2 Floors, Wall-ventilation, core mnt equip

Fig. 3 Phase 1 Configurations

Both the 5.5 m and 7.0 m diameter habitats share a similar configuration and manufacturing methods that were advanced in this study to provide a mass optimized solution. The dome shapes were optimized to handle the various combined loading and the cylinder section length was set to achieve the fixed volume constraint. The 7.0 m diameter was selected as the largest diameter that could meet the launch fairing constraints. The 5.5 m diameter was selected based on heritage with the diameter, manufacturing constraints, and layout considerations.

Because of the unique ability of the inflatable module to stow for launch and then inflate in space, a dissimilar configuration was established and its own layout and layers were optimized. An Enhanced aluminum SHAC was implemented to house critical systems required prior to inflation, and the configuration has the SHAC in the launch load path. A fixed length rigid central core was also designed that stretches from the forward bulkhead to the aft bulkhead. The stowed softgoods are constrained against the core pre-deployment. The inflatable diameter was traded and an optimized solution of 7.6 m was settled upon after considering variables such as restraint layer load, core height, internal outfitting, and end dome shape.

B. Phase 2 Refinement to 5.5m Metallic

Within the same period of performance as the Phase 1 study, a second Design Analysis Cycle was conducted with the down selected 5.5 m metallic configuration to further refine the design, eliminate mass threats, and capture mass opportunities. The overall configuration did not change in this phase, but the internal outfitting arrangements were updated and refined, the structural sizing was refined along with other subsystem updates.

C. Phase 3 Trades

In the Phase 3 Design Analysis Cycle, a composite primary structure module was added to the trade space and compared directly to the refined 5.5 m metallic module (Fig. 4). In order to have a direct comparison of the benefits and challenges of a composite primary structure versus metallic, the Composite Habitat DAC is using the preferred 5.5 m diameter configuration. As much as possible, the design of the 5.5m metallic TH is carried forward for this DAC with the same GR&As, Con Ops, design constraints, etc. Subsystems and specialty engineering disciplines that are impacted by the incorporation of the composite primary structure are assessed and the impacts are reported and incorporated into the Master Equipment List (MEL).

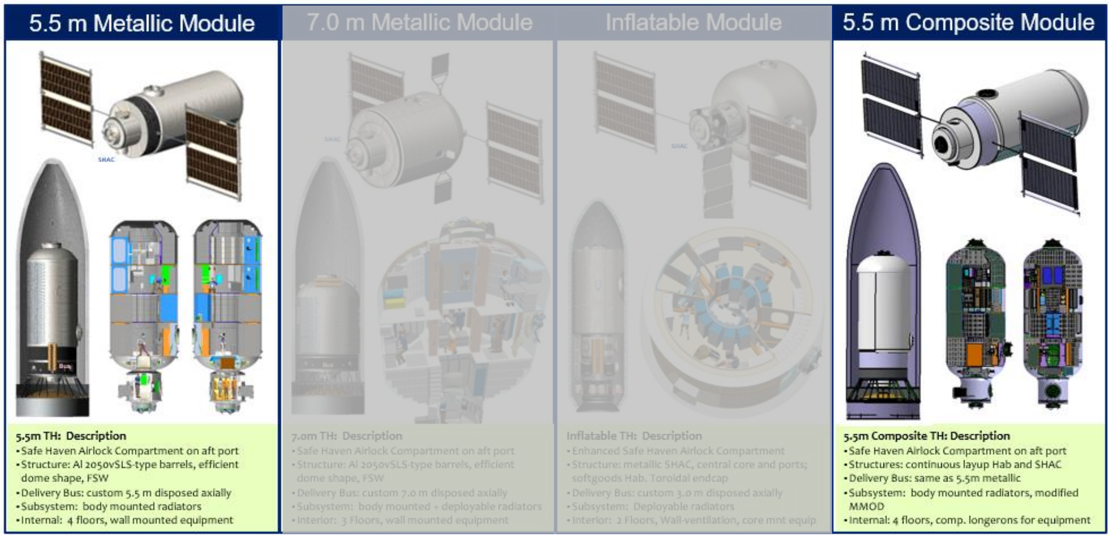


Fig. 4 Phase 3 Configuration – 5.5 m Composite

IV. Analysis Methods

The intent of the trade was to quantify the impacts on overall system mass of each of the four primary structure material options and to better understand the manufacturing, launch, and outfitting challenges associated with each configuration. Each configuration was brought to a similar level of design fidelity to ensure consistency among the comparisons. In order to have a valid trade between the four configurations, the trade criteria were defined so the analysis could be tailored to output the proper results. The dominating criteria was minimizing mass, followed by a host of secondary factors. Therefore, the analysis was orchestrated to be able to properly size the primary structure and output the various subsystem's mass.

A. Structural Analysis

The structural analysis methodology and tools varied between the metallic, inflatable, and composite configuration due to the different material behavior of the structure. For the metallic modules, a Finite Element Method (FEM) loads model was developed to obtain element loads that were then feed to a structure sizing tool. The inflatable restraint layer did not necessitate a dedicated FEM model since the hoop and longitudinal loads are only pressure dependent and calculated analytically. Webbings were sized based on the calculated loads. A FEM model was employed to trade and size the metallic center core. For the composite module, a similar method to the metallic module was performed where a FEM model was created and stress/strain was extracted and margins of safety were generated based on the composite material allowables.

Loads and boundary conditions are common across all of the configurations. The primary loading events are from launch, on-orbit pressure, NASA Docking System (NDS) interface loads, and the fully outfitted module's Trans Mars Injection (TMI) burn. Other loading scenarios such as thermal loads, crew loads, or other propulsive burns were determined to not be the critical load cases for the primary structure and were not included.

Launch load factors were enveloped from both the SLS and the SpaceX Starship to ensure that either launch vehicle (or a similar class vehicle) could be used. The Maximum Design Pressure (MDP) was set to 15.2 psi and applied to the pressure shell. NDS interface loads were applied to all of the ports (2 axial, 1 radial). An envelope of the International Docking System Standards cases 1-3 was used and the in-plane shear and moments were clocked every 30°. The final case considered was the TMI burn case with the vehicle fully outfitted with all necessary equipment and logistics for the 1100 day mission. A 0.3 g load was applied to the fully outfitted module.

The boundary conditions for the Transit Habitat vary between the launch and on-orbit configuration. During launch, the module is constrained at the aft end where the module would interface to the delivery bus (which then attaches to the launch vehicle). On-orbit, the module is constrained at the forward NDS interface representing the Transit Habitat docked to the Gateway. Additionally, when representing free-flying or NDS interface loads applied to the forward NDS an inertial relief condition was applied. Figure 5 below shows the boundary condition locations on three FEM model configurations. The 5.5 m TH has identical boundary conditions between the metallic and composite configuration so only one is displayed. The inflatable habitat FEM model only represents the metallic core.

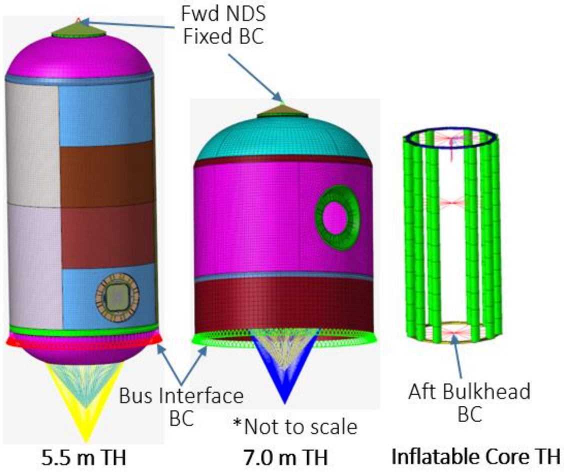


Fig. 5. Boundary Conditions on the Models

Factors of Safety (FS) were applied to the load cases within the sizing analysis. Per NASA-STD-5001B the factors of safety for metallic, inflatable softgoods, and composites were set to the following in Table 1.

Table 1. Factors of Safety

Hardware	Load Case	FS_{yld}	FS_{ult}
Metallic	All	1.0	1.4
Habitable Module	Internal Pressure Only	1.65	2
Softgoods	All	N/A	4
Composites	All	N/A	1.4

The softgoods have a much more significant Factor of Safety in part because of the lower Technology Readiness Level (TRL) of the technology. The other reason for the large FS is due to the complex nature of the material and its susceptibility to creep, which is a complex phenomenon that is difficult to characterize and requires long testing durations. When operating at a high percentage of the restraint layer’s ultimate strength, creep can significantly reduce the ultimate strength over time. The large factor of safety ensures the operating load stays low enough that creep should not be a concern. If a full scale inflatable module undergoes long term testing in space, there would be rationale to lower the FS.

1. *Metallic Modules Analysis*

The metallic modules utilize a NASTRAN loads model to develop element loads for the given load cases. These loads and the NASTRAN model file were then input to a commercial structure sizing tool called HyperSizer. HyperSizer uses the loads from the FEM model and inputs like material, structural concept, and multiple other parameters, then sizes the structure by performing closed-form calculations of the applicable failure criteria and selects minimize mass solution that maintain positive margins of safety.

A FEM model was constructed to adequately represent the 5.5 m and 7.0 m diameter modules’ primary structure. For each model, the pressure shell was modeled with 2D plate element and the rings or thick plate flanges were modelled with 1D bar elements. The axial and radial bulkhead detailed FEM (ISS heritage) was included in the model to have proper stiffness at these interfaces, but the bulkheads themselves were not sized in this exercise. Figure 6 shows the whole 5.5 m and 7.0 m diameter habitat models.

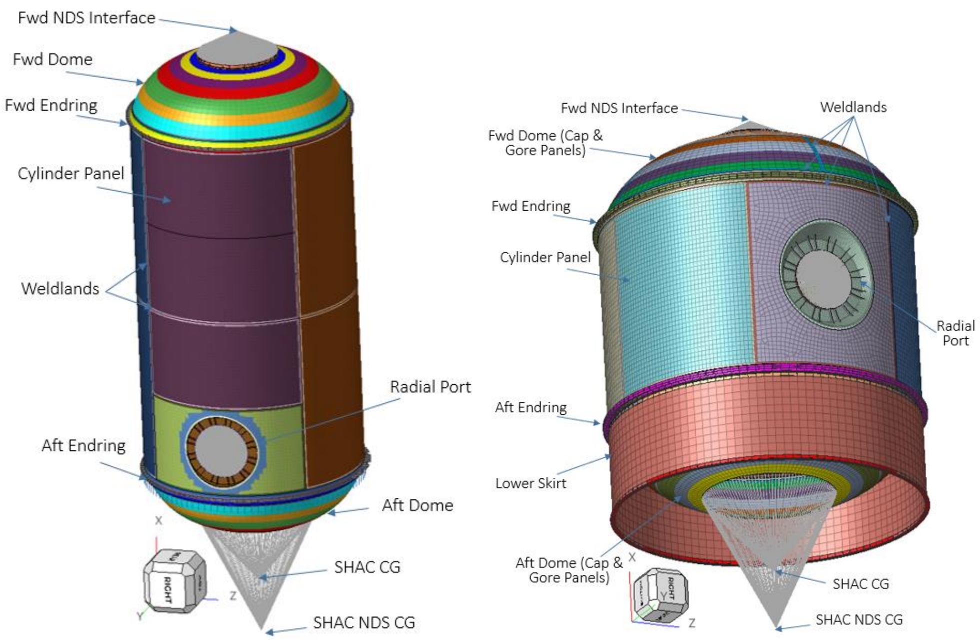


Fig. 6 FEM Model of Metallic 5.5 m and 7.0 m Module

Getting the total mass of the model is important for running the inertial loads during launch and for the inertial relief conditions on-orbit. The non-structural mass was applied to the model to reach the full launch mass (run with the cases that cover launch loads) and the full Mars outfitted mass target (run for the TMI burn case). Mass was applied as a lump (or point) mass for large mass items with a known location in the vehicle. The remaining mass was smeared over the pressure shell via non-structural mass.

HyperSizer was used to size the metallic structure. For the domes and cylinder sections, grid stiffened concepts of orthogrid and isogrid structure were applied. Each weldland was configured as a plate structural concept and given a minimum thickness of 0.25" since that is the minimum thickness of the material data available.
Manufacturing constraints were implemented to ensure the structure remained feasible and manufacturable.

2. *Inflatable Module Analysis*

The structural portions of the inflatable module analyzed for this study were the restraint layer that takes pressure loads, and the rigid core structure that takes launch and on-orbit NDS interface loads. The remaining layers (as seen in Figure 7) were traded and the mass optimum solutions were adopted, but are not the focus of this paper.

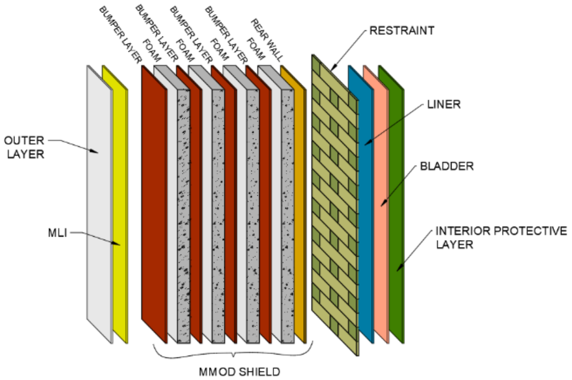


Fig. 7 Inflatable Softgood Layers

The restraint layer supports the bladder and carries the very high internal pressure loads. These pressure loads are calculated from thin-walled pressure vessel theory. Loads per unit area are calculated analytically for the cylinder section hoop and longitudinal directions and the toroid end cap hoop and longitudinal directions. Due to the high magnitude of the restraint layer loads, a plane weave webbing approach was used. Since the hoop load is twice that of the longitudinal load, two different rated webbings are used and woven perpendicular to each other. Figure 8 below shows the woven webbing terminating into a window panel.

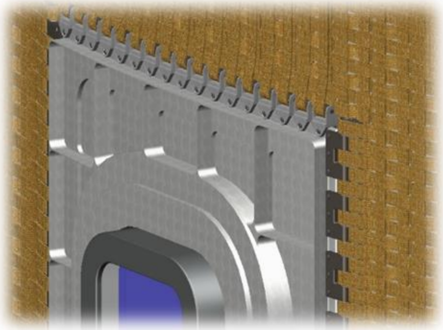


Fig. 8. Restraint Layer Webbing

Determining the webbing capability must take into account multiple factors and considerations. The webbing must incorporate the FS=4 (see Table 1), material strength knockdowns from handling, seam efficiency, seam strength testing standard deviation, and stress risers due to port and window discontinuities, axial stiffness variance, and manufacturing tolerances. With the aggregation of the above mentioned factors, a mean value webbing strength and B-basis seam strength allowable was calculated and the webbing was properly sized. The sized webbing has a known areal density and therefore a mass was calculated. This was done for the cylinder hoop and longitudinal webbing and the endcap hoop webbing.

Trade studies were also performed for each of the other discrete layers which included the inner protective layer, bladder layer, liner layer, MMOD layer, and outer/MLI layer. Various parameters were assessed and the mass optimized solution that meets requirements was selected in order to have a full system mass estimate.

The inflatable habitat core is stiff structure that spans from the aft bulkhead to the forward bulkhead and is comprised of 12 struts. During launch it must support the weight of the folded softgoods layers and the equipment mounted on the internal side of the Core. A FEM model was constructed of the Core to accurately capture the loading from all applicable load cases and to be able to properly size the struts. The 12 struts were constructed of 1D bar elements. The bulkheads were modeled as a ring of bar elements with a rigid element connecting them. The restraint layer loads into the bulkhead were not considered for this phase. Loads were applied to the upper bulkhead while the lower bulkhead center was fixed. NDS interface loads along with the calculated core pressure load from the inflated internal pressure (i.e. plug load) were applied simultaneously. Launch inertial load cases were also applied. The Core FEM model was run and the struts sized in HyperSizer.

3. *Composite Module Analysis*

Composite module analysis was conducted in a similar manner as the metallic module. A FEM model, shown in Fig. 9 below, was developed utilizing 2D elements of the thin laminate that includes the pressure shell and internal and external longerons.

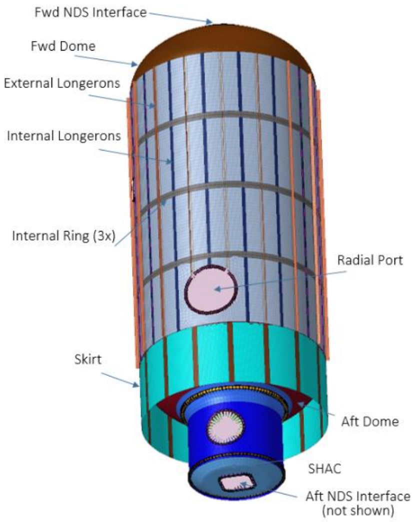


Fig. 9 FEM Model of Composite Module

Mass distribution and application method, loads, and boundary conditions were identical to the metallic module for consistency. The laminate thickness (number of plies) was sized based on the FEM stress/strain results to ensure the predicted stress/strain remained within the material allowables after factoring in the Factors of Safety. Buckling modal frequency checks were also performed and ensured the final design provided adequate stiffness to support launch requirements.

3.6 Other Sub-Systems

Each other major sub-system of the Transit Habitat was also evaluated for the four configurations. Where possible, the same solutions were used across all configurations to minimize the variables affecting the mass output. Sub-systems that were common among all configurations as far as total mass are: Connection and Separation Systems, Command and Data Handling, Guidance Navigation & Control, Communications & Tracking, Crew/Habitation Systems, EVA, and Payload Provisions. Sub-systems that noted differences between the four concepts included MMOD, Power, Thermal Control Systems (TCS), and Environmental Control Systems. The inflatable and composite habitat had unique considerations that required different design solutions than the metallic options due to the low conductivity or lower threshold of damage tolerance. The inflatable MMOD sub-system required to be more robust due to a requirement for no damage to the restraint layers whereas the metallic and composite pressure shell can have some allowable damage. The Thermal Control System was constrained to a deployable radiator solution on the SHAC rather than body mounted radiators used on the metallic modules. Additionally, preventing condensation on the internal layer of the inflatable and on the interior of the composite module required additional ventilation and thermal control solutions.

V. Results

A. Phase 1 Trade Results

Phase 1 traded the two metallic diameter options and the inflatable. The focus of the study was on identifying the minimum mass candidate. Subsystems with mass impacts due to the primary structure material type or configuration are compared in Figure 10.

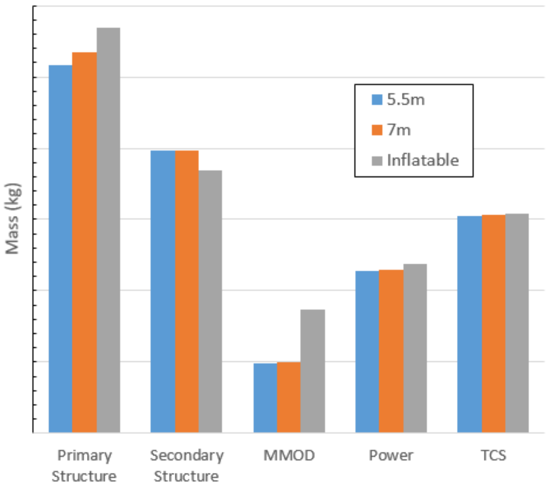


Fig. 10 Phase 1 Subsystem Mass Comparison

Both of the metallic primary structures were similar in mass with the 7.0 m habitat being slightly heavier due to the larger diameter skirt. As seen in Figure 10, the mass of these specific subsystems was generally slightly higher for the inflatable configuration as compared to either of the metallic options. Rationale for these differences include:

☐ Heavier primary structure for inflatable configuration due to the enhanced SHAC required to accommodate launch loads (metallic module's SHAC is not in the launch load path, it is support from the Aft Dome) and additional support structure for the radial port (launch restraints, deployment aids, deployed support structure)

☐ Difficulty to use inflatable primary structure to mount internal subsystem hardware presents larger uncertainties for inflatable configuration secondary structures

☐ Use of deployable radiators for the inflatable configuration which are more complex and lack the multi-functional ability to also provide MMOD protection that the body mounted radiator/MMOD panels as used on the metallic concepts

☐ Inflatable configuration had a heavier MMOD shielding mass due to the inability to use the primary structure as part of the overall protection strategy as allowed with metallics. Inflatable restraint layer are not allowed to be damaged per NASA requirements.

☐ Larger power requirements to address environmental control issues (condensation, increased heat loss, heater power to support pre-deployment thermal considerations)

Overall system mass values were calculated for each configuration and a common approach to mass margin management was applied to all three options to arrive at the final mass values. All are very close to meeting the NASA mass target of 26.4 mT. Even with the differences described above, each option is very close in overall mass, with the inflatable being over 1000 kg (4.3%) heavier than the 5.5m metallic version. A list of mass threats and opportunities was developed to help gauge the risk of meeting the mass target. Figure 11 below shows the total system mass comparison of each configuration relative to the target mass and the error band represents the mass threats and opportunities.

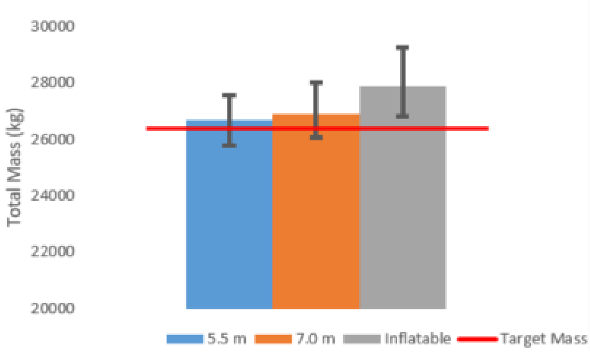


Fig. 11 Phase 1 Total System Mass Comparison

The 5.5 m habitat is slightly over the target but the opportunity band extends down below the target and is also the only configuration whose mass opportunities exceed the threats. The 7.0 m habitat is slightly heavier than the 5.5 m (1% heavier) and the threats exceed the opportunities, but the opportunity band still dips below the mass target. The inflatable habitat's mass threats also exceed the opportunities and it is the only configuration whose opportunities, if all realized, do not bring the total mass down to within the mass target.

It was concluded that, based on the current level of understanding, there are no combination of identifiable mass opportunities for the inflatable configuration that could close this ~1000 kg gap. Many inflatable mass opportunities would require significant material testing and are not easily captured. The inflatable configuration also has more uncertainties and threats due to unique design challenges such as secondary structure integration/installation, condensation control, and interior routing and attachment of wiring/plumbing.

The 5.5 m module was selected as the preferred minimum mass configuration. It was determined that the 5.5 m design would realize more mass/technical opportunities and avoid the threats over the 7.0m module. Additional the 5.5 m module was rated higher for architecture habitability and adaptability.

B. Phase 2 Results

The Phase 2 study took the winning module from Phase 1, the 5.5 m metallic module, and performed a refining Design Analysis Cycle to capture the mass opportunities, retire the mass threats, and mature the design where applicable. Internal outfitting of all the equipment and logistics was refined and matured. Updates were incorporated into the TCS, Crew/Habitation Systems, Extra-Vehicular Activity, Environmental Control Systems, Command and Data Handling, and Structures resulting in over 700 kg of mass reduction. The mass reductions and associated adjustments to the Mass Growth Allowable (MGA) via matured design and analysis allowed the total TH to come in more than nearly 800 kg under the mass target. With a viable 5.5 m metallic module below the mass target, the next phase of the project was initiated.

C. Phase 3 Study Results

In Phase 3, the refined 5.5 m metallic module from Phase 2 was used as a template for designing the same module out of carbon fiber composite. As many variables as possible were held constant while still allowing the design to be optimized for the use of composites while maintaining the direct comparison. The unique capability of The Boeing Company enables continuous dome to dome Automated Fiber Placement (AFP) layout that can be performed using existing manufacturing facilities, robotic equipment and autoclaves. This eliminates the need for major structural joints along the pressure shell that add complexity and mass. The dome shape was modified to allow for AFP head clearance and gradual geometry changes from the dome to the SHAC. Internal and external longerons are used to help stiffen the module and provide internal and external attach points that don't require any pressure shell penetrations.

Subsystems impacted by the use of composites included Secondary Structure, MMOD, Power, and TCS. The secondary structure was able to reduce mass over the metallic module by incorporating detailed external outfitting attachments that bond to the Skirt or other equipment mounting directly to the internal and external longerons. For MMOD, a more efficient multi-shock shield with larger standoff distance was introduced than what was used in the Phase 2 study. The multi-shock shielding was more efficient, but because metallic modules have better understood and tested hyper-velocity impact failure modes the updated design would be lighter on a metallic module. The use of composites and the need to be conservative on ballistic limits for a composite panel due to limited data or literature on the matter resulted in the composite multi-shock MMOD system being heavier than a metallic module multi-shock module, but still lighter than a metallic double walled MMOD system. Power system mass increased for the composite driven by the composite's lack of electrical conductivity requiring a Current Return Network. The Thermal Control System mass also increased for the composite system due to the lack of thermal conductivity precluding traditional patch heaters on the shell to maintain temperatures above due point. The solution was a ventilation based design to keep the shell above the dew point. This increased the mass, but also allowed for a reduction in total power consumption.

A comparison of the composite vs metallic subsystems affected by the introduction of composite primary structure is presented below in Fig. 12.

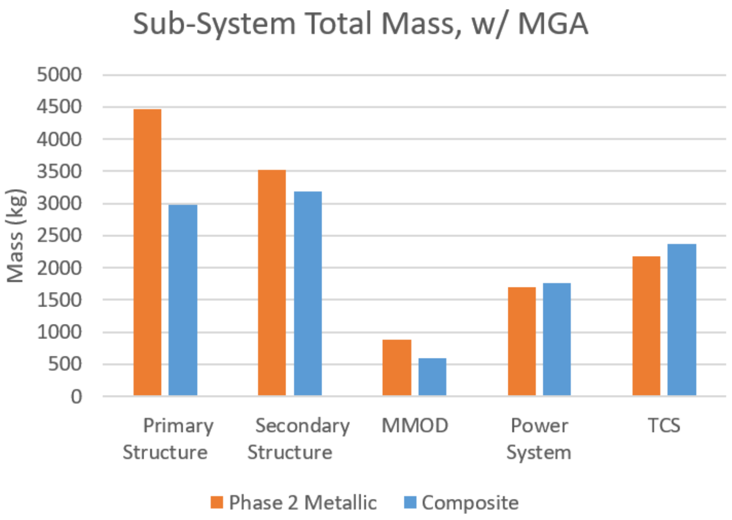


Fig. 12 Phase 3 Subsystem Comparison of Composite vs Metallic

The composite design results in a 33% reduction of primary structure and an overall net reduction of nearly 1900 kg. This mass efficient structure is just 14% of the total vehicle dry mass, a significant improvement.

VI. Comparisons of Metallic, Inflatable, Composite

A comparison can be made between the two configurations of metallic modules, the inflatable module, and the composite module as they were all designed to the same reference mission, GR&As, and derived constraints such as constant volume. It should be noted that the 7.0 m metallic and the inflatable configurations were not afforded the opportunity for a specific DAC to refine the design outside of Phase 1. However, the Phase 1 studies were all brought to an equal level of development, and the Phase 2 metallic and Phase 3 composite were brought to an equal level of development which is one design cycle above the 7.0 m and inflatable.

Figure 13 below shows the subsystem mass per module configuration. The 7.0 m metallic and the inflatable module results are from Phase 1, 5.5 m Metallic is from Phase 2, and the composite is from Phase 3.

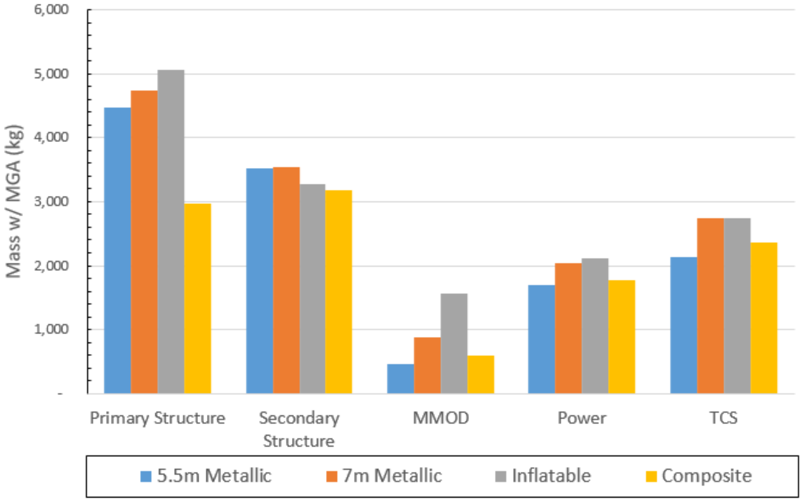


Fig. 13 Subsystem Comparison of 5.5m/7.0m Metallic, Inflatable, and Composite Modules

The Primary Structure comparison shows the composite structure is 33% lighter than the next closest configuration and 41% lighter than the inflatable option. The 7.0 m has a heavier radial bulkhead and the inflatable has heavier bulkhead connections and requires the internal Core structure. Secondary structure shows the metallic modules being the heaviest with the inflatable and composite modules having the advantage. MMOD shows significant deviations between the configurations with the 5.5 m benefitting from the larger standoff multi-shock shield followed by the composite, 7 m module and then the inflatable (3x more mass than the metallic 5.5 m). The inflatable requires significant more shielding since the softgood restraint layer cannot sustain any damage and could not take advantage of rigid multi-functional body mounted radiators that also provide shielding. Power did not show drastic changes between the configurations with the 5.5m and composite performing best and the 7m and inflatable grouped at a higher mass value. The Thermal Control Systems mass favored the metallic 5.5m and the composite and the 7 m and inflatable were again grouped at the higher mass value due to the limited usage of body mounted radiators and the need for deployable radiator systems.

Overall system mass values were calculated for each configuration and a common approach to mass margin management was applied. All four modules' total mass value is compared against the dry, Mars departure mass target of 26.4 mT. A list of mass threats and opportunities was developed to help gauge the risk of meeting the mass target. Figure 14 below shows the total system mass comparison of each configuration relative to the target mass and the error band represents the mass threats and opportunities.

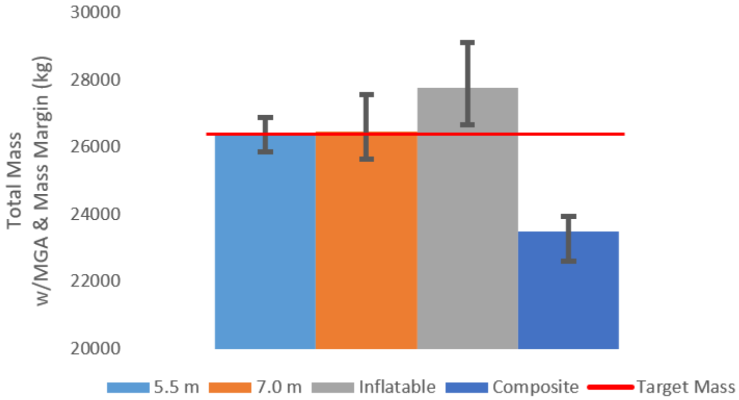


Fig. 14 Total Mass Comparison of 5.5m/7.0m Metallic, Inflatable, and Composite Modules

The two metallic options total just above the mass target but are both within the error band, those the 7.0 m mass threats and opportunities are larger. The inflatable module is sizably larger and even with all mass opportunities realized does not reach the target mass. The composite module significantly outperforms all other options in terms of minimum mass coming in 11% beneath the mass target.

VII. Conclusion

A comprehensive trade was performed to evaluate and compare the merits of two different metallic configurations, an inflatable configuration, and a composite configuration modeled after the highest performing metallic. Using the same reference mission and GR&A's allow direct comparisons between the three different material types. Since volume was constant amongst the configurations, the mass to volume ratio is depends only on the mass. The composite module clearly outperforms the other modules in terms of minimum mass. Since a composite habitat has not flown in space before, Boeing is continuing to mature composite habitat designs, has developed a certification path [7], and is conducting testing to increase the Technology Readiness Level. Composite habitats open new opportunities for higher mission performance by reducing total mass or reallocating mass the saved mass to other subsystems that further the mission objectives.

Acknowledgments

The authors would like to thank the entire Boeing Mars Transit Habitat project team for their contributions over the various phases and Mai Huynh for assembling the final project report.

References

[1] D. W. Harris, P. D. Kessler, T. M. Nickens, A. J. Choate, B. L. Horvath, M. A. Simon, C. Stromgren, Moon To Mars (M2M) Habitation Considerations: A Snap Shot As Of January 2022, NASA/TM-20220000524

[2] M. Ziglar, X. Simon, Metallic Vs Inflatable Primary Structure: A Comprehensive Trade for a Mars Transit Habitat, IAC-22-C2.1.12, 73rd International Astronautical Congress, Paris, France, 18-22 September 2022.

[3] T. P. Polsgrove, J. D. Waggoner, D. V. Smitherman, T. K. Percy, R. L. Howard, Transit Habitat Design for Mars Exploration, AIAA 2018-5143, 2018 AIAA SPACE and Astronautics Forum and Exposition, 17-19 September 2018, Orlando, FL
[4] K. J. Kennedy, J. Raboin, G. Spexarth, G. Valle, Inflatable habitats, AIAA Progress in Astronautics and Aeronautics Vol 191, Chp 21, 527-552.
[5] J. Valania, Sierra Nevada Corporation's Mars Transit Habitat, IAC-21,A5,2,1,x65786, 72nd International Astronautical Congress, Dubai, United Arab Emirates, 2021, 25 - 29 October.
[6] G. D. Valle, J. J. Zipay, D. Littleken, E. L. Christiansen, T. C. Jones, System Integration Comparison Between Inflatable and Metallic Spacecraft Structures, 978-1-5386-6854-2/19, IEEE 2019
[7] J. Eichinger, M. Ziglar, M. Bland, B. Gingras, Certification of a Composite Habitat for Deep Space, 2024 AIAA ASCEND, July 30-August 1, 2024, Las Vegas, NV.