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Metallic Vs Inflatable Primary Structure: A Comprehensive Trade for a Mars Transit Habitat

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Abstract

Large diameter inflatable habitat solutions are hypothesized to have an advantage over traditional metallic habitats of equal volume and functional requirements in terms of minimizing mass. A fair and comprehensive trade of metallic primary structure versus inflatable softgoods primary structure for a Mars Transit Habitat was conducted by The Boeing Company under the NASA Next Space Technologies for Exploration Partnerships-2 (NextSTEP-2) Appendix A contract in order to determine the minimum mass option from a system level. A Mars Transit Habitat is a major system mass driver because small increases in the mass can create large mass changes in the propulsive stage, adding complexity and cost to the mission.

Three different vehicle configurations were traded using a fixed volume constraint and the same Ground Rules and Assumptions (GR&A) provided by NASA [6]. The configurations were 1) 5.5 m diameter metallic habitat, 2) 7.0 m diameter metallic habitat, and 3) 7.63 m diameter inflatable habitat. In order to complete the trade, each configuration was analyzed and sized, but a system level approach had to be taken to ensure other aspects and subsystems besides the structure were captured.

The primary functions (i.e. restraint layer, bladder, multilayer insulation [MLI], micro-meteoroid orbital debris [MMOD]) and strength advantages of softgoods are well understood, but there were other system level impacts that were discovered or addressed that are unique to softgoods. For the metallic structure, a modern and mass optimal material and manufacturing process was adopted to ensure the lightest weight options were evaluated. Two different aluminium lithium structures were evaluated, a longer length 5.5 m diameter and a shorter length 7 m diameter structure.

The trade demonstrates that each configuration is feasible and close to the target dry mass for the Mars Transit Habitat at Trans-Martian Injection burn. System level mass was the primary consideration, but since the three concepts were close in total mass, a clear winner did not arise. Secondary factors were evaluated such as architecture habitability (human factors), development considerations, on-orbit activation and outfitting, extensibility to other applications, and configuration flexibility. The aggregation of the lowest mass, most benefits, and fewest challenges resulted in the 5.5m diameter metallic configuration being the most favorable.

Keywords: metallic structure, inflatable softgoods, Mars Transit Habitat

Acronyms/Abbreviations
Bigelow Expandable Activity Module (BEAM)
Factor of Safety (FS)
Finite Element Method (FEM)
Ground Rules and Assumptions (GR&A)
High Earth Orbit (HEO)
International Space Station (ISS)
Multi-layer Insulation (MLI)
Micro-Meteoroid Orbital Debris (MMOD)
NASA Docking System (NDS)
Safe Haven Airlock Compartment (SHAC)
Space Launch System (SLS)
Technology Readiness Level (TRL)
Thermal Control Systems (TCS)
Transfer and Attitude Control (TAC)
Transit Habitat (TH)

1. Introduction

In order to achieve the goal of sending humans to Mars, the challenge of developing an ultra-mass efficient Mars transit system must be solved. The mass of the Transit Habitat is a major driver of the overall transit system that includes the habitat and the propulsion system. Even small increases in the Transit Habitat's mass can drive large mass changes in the propulsion stage which add complexity and cost to the mission.

The primary structure of the pressurized Transit Habitat is one of the largest mass subsystems in the architecture and was therefore the focus of this study in order to find the most mass optimized configuration and material system that can still meet the requirements. Developmental hurdles, whether technical or programmatic, were not considered as constraints to the design space since mass reduction was the key objective.

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1.1 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. Most recent examples of built and flow of 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 22 years. A conceptual metallic Mars TH was previously studied by NASA [1]. 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 is preparing for its first test flight.

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 1). 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 loads, a rigid core is typically implemented to hold the softgoods and other need equipment prior to inflation in-space.

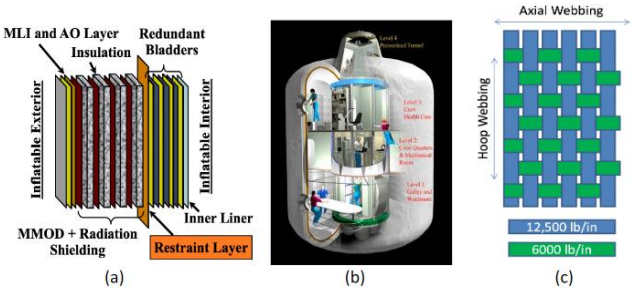


Fig. 1. TransHab Inflatable Shell Layers [2]

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 [3] that went through design and development testing before being cancelled. The LIFE module is another in development [4]. Built and flown examples include the Bigelow Expandable Activity Module that has flown to ISS, Genesis I, and Genesis II which are solo uncrewed space habitats placed into LEO.

System level comparisons between metallic and inflatable spacecraft structures have been attempted in the past [5]. However, as stated in Ref. [5] 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 seeks to perform a specific trade of metallic and inflatable habitats designed for the same mission so a true comparison can be performed.

2. 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.

2.1 Ground Rules and Assumptions

In this study, the Mars Transit Habitat design, regardless of the configuration, needs to meet the Ground Rules and Assumptions (GR&A) provided by NASA [6]. 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)

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2.2 Concept of Operations

The 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 Delivery Bus are launched and attached to Gateway in Cis-Lunar orbit. The crew arrives at Gateway with Orion and the 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.

2.3 Trade Study Configurations

Boeing conducted the Transit Habitat 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 advanced 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 2 shows the three structures configurations that were assessed for the Mars Transit Habitat.



Fig. 2. Mars Transit Habitat Configurations Options

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. 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.

2.3.1 Metallic 5.5m

The key features of the 5.5 m diameter configuration are:

- Habitat length ~ 12.1 m (dome to dome, excluding the SHAC)
- 4 levels
- Tall cylinder section built by welding two barrel sections (utilizing SLS experience)
- Optimized dome shape and construction
- Basic SHAC (volume is ~15 m^3) attached to Aft Dome only
- Skirt – attaches endring/cylinder section to 5.5m diameter delivery bus. Mounts external equipment (batteries, pumps, tanks, etc.)
- Body mounted radiators
- Wall mounted internal secondary structure

2.3.2 Metallic 7.0 m

The key features of the 7.0 m diameter configuration are:

- Habitat length ~ 8.1 m (dome to dome, excluding the SHAC)

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- 3 levels
- Single barrel cylinder comprises the whole cylinder section
- Optimized dome shape and construction
- Basic SHAC (volume is ~15 m^3) attached to Aft Dome only
- Aft dome mounts external equipment (batteries, pumps, tanks, etc.)
- Body mounted radiators plus small deployable radiator
- Wall mounted internal secondary structure

2.3.3 Inflatable Module

The key features of the inflatable configuration are:

- Stowed softgood pressure shell during launch that inflates to full volume once on-orbit
- Habitat length ~ 6.4 m (Bulkhead to bulkhead, excluding the SHAC)
- 2 levels
- Enhanced metallic SHAC (volume is ~19 m^3) attached to Aft Dome above and bus interface below
  - Lengthened to accommodate external equipment (batteries, pumps, tanks, etc.)
  - Strengthened to accommodate launch loads with module above (primary launch load path)
- Rigid center core from axial bulkhead to bulkhead, 2.5 m in diameter
- Core mounted internal secondary structure (internal core equipment launched in place, external core equipment on-orbit installed)
- Deployable radiators
- Deployable floors and partitions

For the inflatable module, the required radial port placement was traded between the metallic SHAC and the inflatable portion. The mass conscious solution favored adding the radial port to the inflatable softgoods rather than further expanding the metallic SHAC. The metallic SHAC was lengthened because addition space was required to mount launched in place external equipment, which on the metallic configurations was mounted to either the Skirt or the Aft Dome. The inflated end cap shape was also traded and evaluated based on mass and volume efficiency. An elliptical and toroidal end cap configuration was assessed and the toroidal shape demonstrated greater volume and mass efficiency.

3. Analysis Methods

The intent of the trade was to quantify the impacts on overall system mass of each of the two primary structural 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.

The analysis methodology and tools varied between the metallic configurations and the inflatable 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 dependant and calculated analytically. Webbings were sized based on the calculated loads. A FEM model was employed to trade and size the metallic center core.

3.1 Structures Trade Criteria

In order to have a valid trade between the three configurations, the trade criteria was 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 structure analysis was orchestrated to be able to properly size the primary structure and output the subsystem mass that meets the requirements.

3.2. Loads and Boundary Conditions

Loads and boundary conditions are common across all of the configurations.

3.2.1 Transit Habitat Loads

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. Four load sets at the worst case axial/lateral load combinations were applied and the lateral loads were clocked every 30°.

The Maximum Design Pressure (MDP) was set to 15.2 psi and applied to the module shell. For FEM models of the pressure shell, equivalent pressure forces were applied to hatch cut outs in the structure.

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.

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3.2.2 Transit Habitat Boundary Conditions

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 3 below shows the boundary condition locations on the three FEM models (the inflatable habitat FEM model only represents the metallic core)

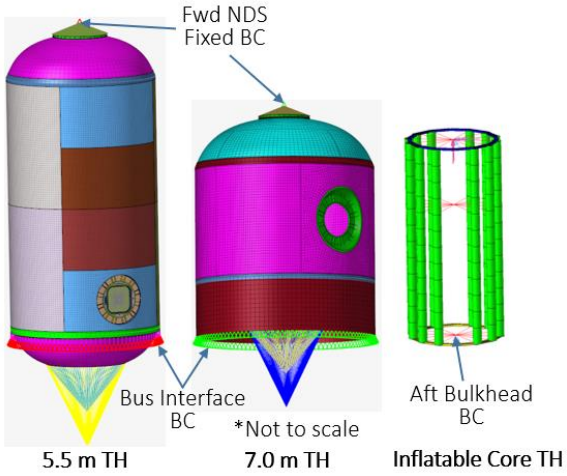


Fig. 3. Boundary Conditions on the Models

3.2.3 Load Combinations

Multiple loading cases can occur simultaneously. For the launch event, the launch loads were coupled with a pressure load of 20% the MDP. On-orbit a pressure only case is evaluated. When attached to Gateway, pressure and NDS interface loads at each docking port individually and all three simultaneously were applied. Finally, the TMI burn acceleration load cases were combined with pressure. In total 98 load cases were run.

3.3 Factors of Safety

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

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 it's susceptibility to creep, which is a complex phenomenon that is difficult to characterize and requires long testing. 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 will not be a concern. If a full scale inflatable module undergoes long term testing in space there would be rational to lower the FS.

3.4 Metallic Module 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.

3.4.1 Metallic Module FEM Setup

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. At the NDS interfaces to the bulkheads, two 'soft' rigid body elements (RBE3) connect to bulkhead flange. The outer element is at the NDS mated interface and is used to apply the mated loads while the inner element is at NDS center of gravity (CG) and contains a concentrated mass to represent the mass of that system. The SHAC was not sized in this exercise, but the effect of it was captured in the model. Similar to the NDS modeling, one rigid body elements (RBE2) extends from the NDS interface aft of the SHAC (for applied interface loads) and the other end connects to the Aft dome (the aft dome does not contain the bulkhead, it is on the SHAC's forward end). The other 'soft' rigid body element (RBE3) is at the SHAC CG and contains the concentrated mass representing the total mass of the SHAC. The skirt of the 5.5 m module was not modeled in this study but was included in the 7.0 m model. Figure 4 shows the whole 5.5 m diameter habitat model and Figure 5 shows the whole 7.0 m diameter model.

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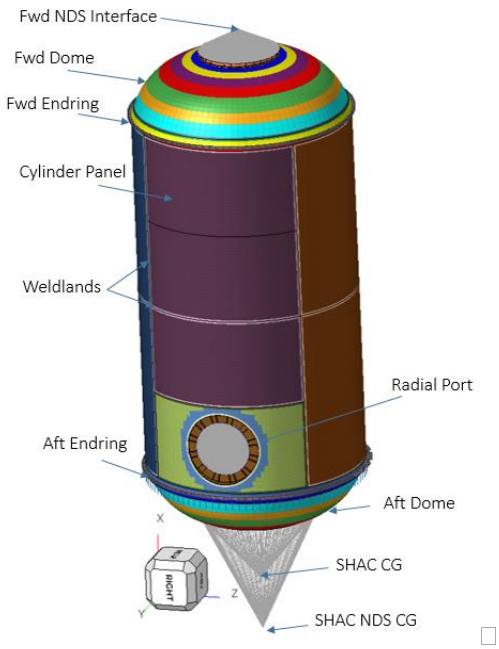


Fig. 4. FEM Model of 5.5 m

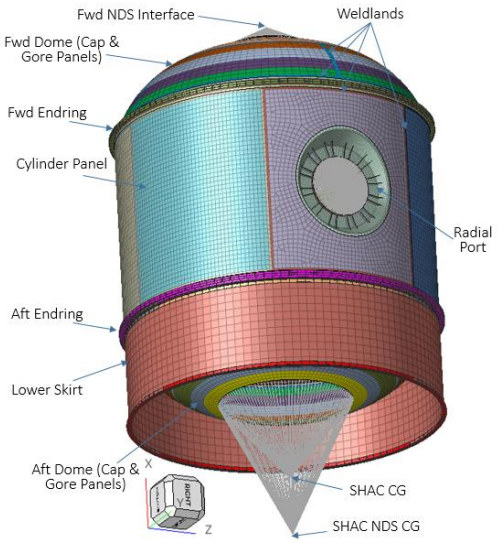


Fig. 5. FEM Model of 7.0 m

Each model was discretized into separate property card groupings to be sized independently once run in HyperSizer. For example, the domes are discretized into separate bands (as seen in Figure 4) so the height of the sized material can vary at different portions of the dome. The cylinder was discretized by cylinder panel. Each welded component has a 2 inch wide weldland at the weld interface. In the sizing, separate welded material allowables were applied to these regions that are reduced from the parent material allowables.

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 lumped mass was tied into the structure via RBE3 elements. The remaining mass was smeared over the pressure shell via non-structural mass. Figure 6 below shows the locations on the FEM models where concentrated mass was applied.

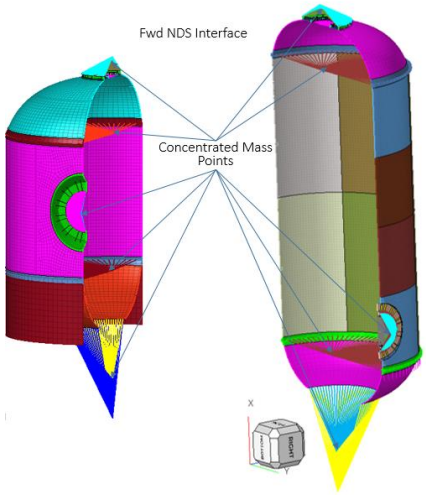


Fig. 6. Concentrated Mass Locations

Table 2 lists the mass assigned to the major components as either smeared mass or point mass for both metallic configurations and breaks out the launch mass versus the fully outfitted Mars mass. Most component's mass increases for the Mars Outfit column because it's assumed that equipment is launch-deferred and installed once on-orbit. The considerable amount of smeared mass on the cylinder is the massive amount of logistics supplies that are required and are attached to the cylinder wall.

Table 2. Mass Distribution on Metallic Modules [kg]

Assembly	5.5m		7.0m	
	Launch (kg)	Mars Outfit (kg)	Launch (kg)	Mars Outfit (kg)
Aft Axial Port (incl SHAC)	2586	2793	2143	2793
Aft Dome NSM	719	883	820	984
Aft Endring CONM	1985	2310	992	1317
Cylinder NSM	6928	34681	6407	34159
Fwd Endring CONM	1959	1959	2227	2227
Fwd Dome NSM	719	883	1706	1870
Fwd Axial Port CONM	438	438	881	438
Radial Port CONM	840	840	935	925
Skirt NSM	1802	1802	1802	1802
sum	17975	46589	17913	46516

3.4.2 Metallic Structural Sizing

HyperSizer was used to size the metallic structure. Each component had a structural concept assigned. For the domes and cylinder sections, grid stiffened concepts

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of orthogrid and isogrid structure were applied. The Endring, which connects a dome to the cylinder, was allowed to trade between an I, T, and web beam section while the dome and cylinder flanges were set to a plate concept. Each weldland was assigned 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. For the dome, rib heights were constrained to ≤2.0" to ensure the dome can be machined from a 3" blank. The cylinder panel rib heights were constrained to ≤3.0". And the skin of each of the pressure shell components was set to ≥0.08" to comply with non-destructive evaluation and NASA fracture/life requirements.

3.5 Inflatable Module

The structural portions of the inflatable module analysed 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.

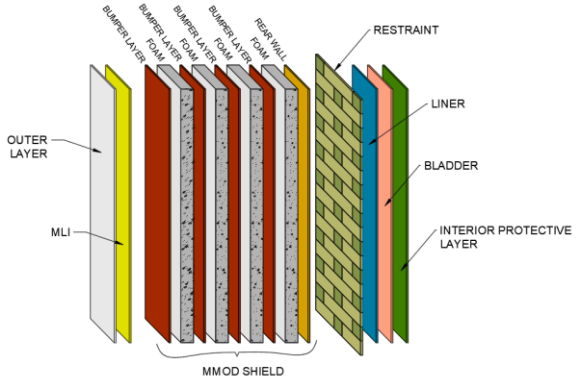


Fig. 7. Inflatable Softgood Layers

3.5.1 Restraint Layer Analysis

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.

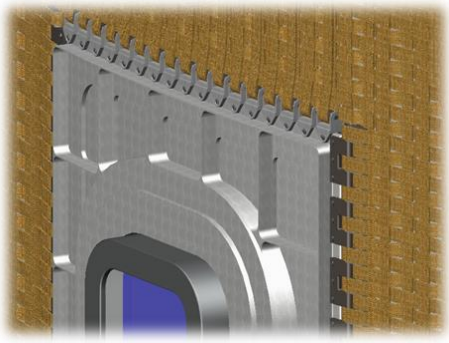


Fig. 8. Restraint Layer Webbing

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.

Webbing sizing calculations were performed for several different cases that varied the process parameter maturity (i.e. knockdown or efficiency factors), module outer diameter, single vs. double layer webbing, and burst pressure factor of safety so impacts to restraint layer mass could be observed. Mass opportunities were noted for areas where fuller development could lead to improved performance.

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.

3.5.2 Core Analysis

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 RBE2 element connecting them. This assumes

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that the bulkhead is much stiffer than the struts in the lateral direction. The restraint layer loads into the bulkhead were not considered for this phase. Figure 9 below shows the Core FEM model.

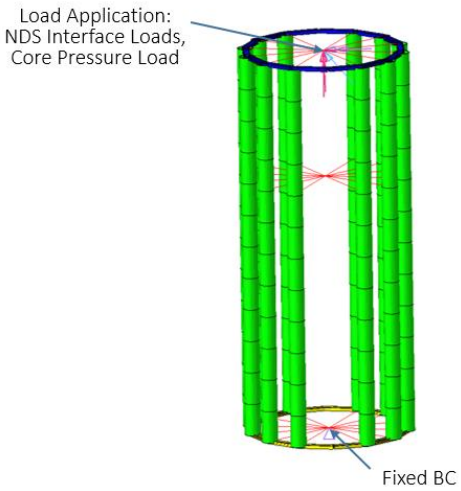


Fig. 9. Core FEM Model

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.

Mass distribution over the Core was accomplished by applying point masses at discrete locations such as forward, aft and radial ports and the SHAC and also by applying smeared mass over the strut length for the softgood mass and internal equipment mounted.

Once the Core FEM model was run, it was input into HyperSizer and run. The struts cross-section was traded between circular, rectangular, I, and C sections and circular tubes were optimum.

3.6 Other Sub-Systems

Each other major sub-system of the Transit Habitat was also evaluated for the three 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 three configurations as far as total mass are: Connection and Separation Systems, Command and Data Handling, Guidance Navigation & Control, Communications & Tracking, Crew/Habitation Systems, EVA, Payload Provisions.

Sub-systems that noted differences between the three concepts included MMOD, Power, Thermal Control Systems (TCS), and Environmental Control Systems. The inflatable habitat has unique considerations that required different design solutions than the metallic options. The MMOD sub-system, designed for the full mission environments, required to be more robust due to a requirement for no damage to the restraint layers (metallic 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 was a challenge unique to softgoods that required additional ventilation and thermal control solutions.

4. Results and Discussion

The first direct comparison of the primary structure shows that all three configurations are very similar when only the pressurized habitat structure is evaluated and hardware common among all three solutions are removed (i.e. bulkheads [which could be heavier for the inflatable due to radial strap loads], hatches, etc.). In order to compare the inflatable primary structure to the metallic, the multiple layers required to perform the same function as the metallic primary structure were summed, such as the inner layer, bladder, and liner in addition to the restraint layer, the core, and port interfacing hardware. The port interfacing hardware includes the mounting flanges, bladder clamp rings, and multiple webbing brackets/pins for each terminating webbing. The radial port hardware also includes launch support structure and permanent radial port deployed support structure. The 5.5 m structure was primarily driven by launch loads and the majority of the structural mass was in the cylinder section. The 7.0 m structure was primarily driven by launch, but also had a significant amount of structure sized by pressure loads due to its larger diameter. The inflatable restraint layer is driven solely by the pressure load and the Core was driven by launch loads. Table 3 shows the primary structure comparison.

Table 3. Pressurized Habitat Primary Structure Comparison

Metallic Assembly	Metallic Mass (kg) 5.5 m	7.0 m	Inflatable Assembly	Inflatable Mass (kg)
Aft Dome	164	403	Restraint Layers	717.8
Aft Endring	156.8	236	Inner Layer	132.3
Cylinder Panel	1520	955	Bladder	164.9
Fwd Endring	111	156	Liner	24.12
Fwd Dome	260	403	Fwd/Aft Port Hardware	259.7
			Radial Port/ Window Hardware	488.7
			Core	403.2
Total	2211	2154		2191

The above table shows that the 7.0 m module has slightly less total mass for the direct comparison of pressurized structure only and the other two modules are within 2-3%. It was observed that the restraint layer

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mass was only 33% of the inflatable primary structure mass and that the addition of the radial port did not impact the restraint layer mass adversely. Since the restraint layer mass is only 1/3 the compared habitat primary structure in Table 3 above, changing the softgoods design factor of safety or reducing efficient knockdowns for the webbing will not have a significant effect on the overall mass.

4.1 Subsystem Mass Comparison

Since the focus of the study was on minimizing mass based on variations of the primary structure, many subsystem mass estimates were common across all configurations. There were some differences in specific subsystem masses due to the unique attributes of inflatable softgood solution as compared to metallic alloys as specified in Section 3.6. Subsystem mass comparisons between each of the configurations are shown in Figure 10.

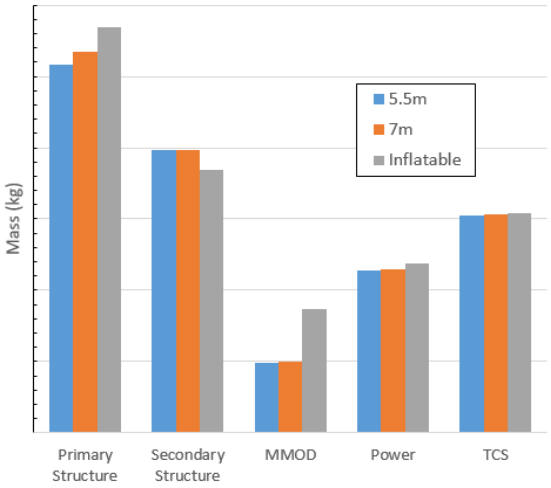


Fig. 10. Subsystem Mass Comparison

Both of the metallic primary structures were very 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 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.

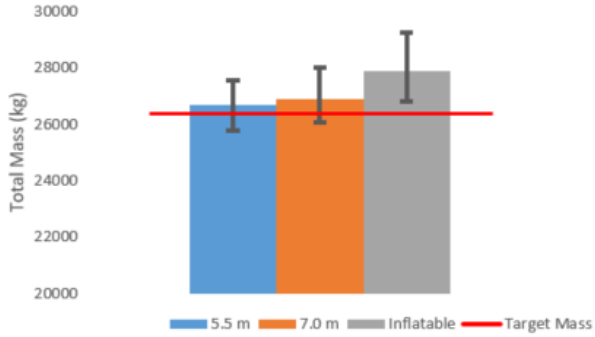


Fig. 11. Total System Mass Comparison

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

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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.

4.2 Secondary Factors

Since the primary trade criteria of mass did not produce a clear winner, the secondary factors were evaluated further. These secondary factors include architecture habitability (human factors), development considerations, on-orbit activation and outfitting, extensibility to other applications, and configuration flexibility.

For architecture habitability, no clear discriminator arose as each configuration can support the requirements and have unique pros and cons.

For development considerations of the metallic habitats, there will be some amount of development of advanced manufacturing techniques for the aluminum lithium alloy options such as radial port integration. SLS producibility experience would aid in development considerations. For the inflatable, experts from both NASA and industry commented on the need for an in-space demonstration to assess a softgoods based habitat deployment, lifetime and materials performance in a deep space environment. While the Bigelow Expandable Activity Module (BEAM) is on ISS as a technology demonstration, it is not used as a primary habitable structure. Additional development testing would be needed for penetrations and radial port integration and deployment.

Extensibility of the habitat designs to other applications beyond Mars transit was assessed and all configurations are extensible to other applications.

On-orbit activation and outfitting evaluations showed the metallic configurations have the opportunity to launch fully outfitted (minus logistics) and therefore not require costly crew outfitting missions. The 5.5 m configuration is expected to have lower secondary structure and integration needs compared to the 7.0 m. The inflatable design carries inflation failure risk and more extensive on-orbit outfitting and activation due to equipment not being able to be installed prior to the inflation. Secondary structure attachment is also more problematic since the softgood walls are not as conducive to mount.

5. Conclusions

Boeing performed this trade under the NextSTEP-2 contract in order to have a fair and comprehensive evaluation of the metallic and inflatable primary structure options presented in this paper for a Mars Transit Habitat. Each of the modules were developed to a similar level of fidelity and under the same GR&A's for the mission. Each of the primary structure configurations proved to be low mass and feasible, but when the secondary factors were evaluated the preferred system level solution for this study proved to be the 5.5m diameter metallic module.

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