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A Modular Habitation System for Human Planetary and Space Exploration

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A small-diameter modular pressure vessel system is devised that can be applied to planetary surface and deep space human exploration missions. As one of the recommendations prepared for the NASA Human Spaceflight Architecture Team (HAT) Evolvable Mars Campaign (EMC), a compact modular system can provide a Mars-forward approach to a variety of missions and environments. Small cabins derived from the system can fit into the Space Launch System (SLS) Orion "trunk", or can be mounted with mobility systems to function as pressurized rovers, in-space taxis, ascent stage cabins, or propellant tanks. Larger volumes can be created using inflatable elements for long-duration deep space missions and planetary surface outposts. This paper discusses how a small-diameter modular system can address functional requirements, mass and volume constraints, and operational scenarios.

Nomenclature

ATHLETE = All-Terrain Hex-Limbed Extra-Terrestrial Explorer robotic mobility system
CBM = Common Berthing Mechanism
CH4 = Methane fuel for propellant
DEVAP = Deployable EVA Platform
DSH = Deep Space Habitat
EAM = NASA Exploration Augmentation Module
ECLSS = Environmental Control and Life Support System
EMC = Evolvable Mars Campaign
EVA = Extra-Vehicular Activity
HAT = NASA Human Spaceflight Architecture Team
HDU = Habitat Demonstration Unit
ISS = International Space Station
LEO = Low Earth Orbit
LDSD = Low-Density Supersonic Decelerator
LOX = Liquid Oxygen oxidant for propellant
MAV = Mars Ascent Vehicle
Midex = Mid-expandable hybrid inflatable pressure vessel module
NASA = National Aeronautics and Space Administration of the United States of America
NDS = NASA Docking System
PEV = Pressurized Excursion Vehicle
RAF = Random Access Frames
RCS = Reaction Control System
SLS = NASA Space Launch System
STAR = Space Technology & Advanced Readiness node

I. Introduction

THE NASA Evolvable Mars Campaign (EMC) is a Human Spaceflight Architecture Team (HAT) effort to explore mission trades for human missions on Mars and its moons. Habitability concepts for the EMC Mars outpost work builds upon NASA Deep Space Habitat (DSH) studies (Griffin, et al 2013), Habitat Demonstration

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Unit (HDU) studies (Kennedy, et al 2011), and particularly Constellation lunar outpost architecture studies (Toups, et al 2008; Kennedy, et al 2010).

The Evolvable Mars Campaign assumes multiple Space Launch System (SLS) launches to assemble precursor spacecraft, landers, transit stacks, habitation elements, rovers, and other surface elements, which would be brought sequentially to the Mars system. Exploration would begin with Mars orbital activities and the moons of Mars, followed by sequential landings that could result in a permanent outpost or settlement. As of this writing, a summary of the Evolvable Mars Campaign can be found in the proceedings of the 2015 IEEE Aerospace Conference, in particular a brief discussions of the findings for habitability options (Howe, et al 2015). Lander capacity for delivery of assets to the Mars surface are still under consideration, but have been narrowed down to four sizes -- 15 ton, 18 ton, 27 ton, and 41 ton landers. The current efforts have been centered on implications for choosing one lander type over another, and how to break up habitable volume and surface elements into manifests that can be carried by the lander under consideration. Options for Mars habitability that fit within the context of the EMC studies and the four lander classes include monolithic habitat, vertical modular HDU-type habitat (Kennedy, et al 2011), SLS-derived “Skylab II” habitats (Griffin, et al 2012), and modular horizontal habitats (continuation of previous work by Toups, et al 2008, and Kennedy, et al 2010), with the possibility of additional volume provided by inflatable elements.

While the full range of habitability options was presented in Howe, et al 2015, some of the work described under the four options went into considerable depth and deserve discussion on their own. Therefore the work described in this paper specifically addresses a small-diameter modular pressure vessel system applied across all aspects of pressurized volume, including habitats, ascent vehicle cabins, rovers, logistics modules, and airlocks.

II. Modular System for Exploration

The horizontal modular exploration system concept consists of a uniform 3m diameter barrel with modular internal and external bulkheads, and add-on mobility, equipment racks, power, radiators, propulsion, tankage, and EVA elements (Figure 1). In addition to habitats, rovers, and other elements, a modular lander system was also expored, resulting in a “ganged” approach to propulsion that could be assembled in space and customized for various payload capacities. What this study did not cover, and indeed there still remain gaps, is how such a system would fit into a Mars descent aeroshell or other entry, descent, and landing concept.

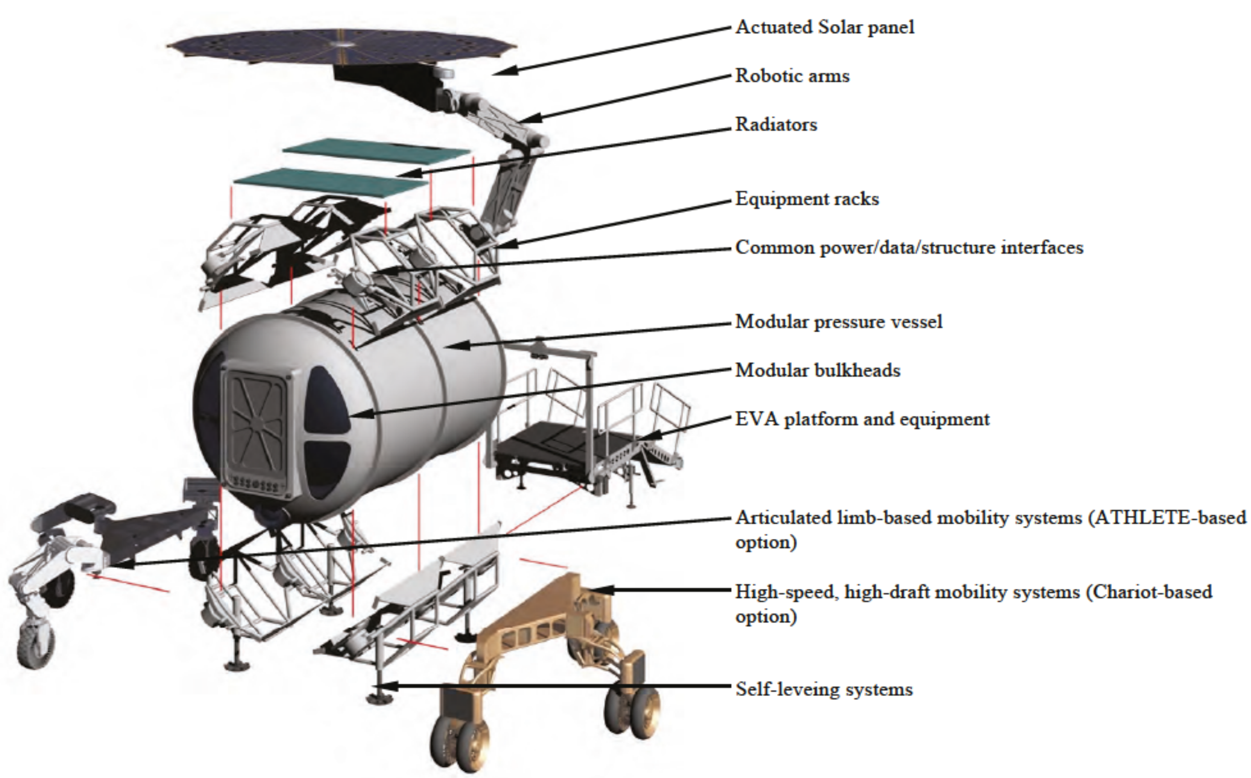


Figure 1: Modular exploration system: pressure vessel, tertiary structures, power systems, EVA, and mobility

First will be a discussion of the modular lander system, followed by pressure vessel concepts, modular life support, Extra-Vehicular Activity (EVA) functions, module to module docking concepts, and mobility systems.

A. Modular Lander System

Various commercial efforts have resulted in demonstration landers that can take off and land with stable attitude control and pinpoint accuracy. NASA efforts include the MORPHEUS lander project that consists of spherical propellant tanks in a compact tubular truss structure and a single gimbaled thruster (Figure 2).

Figure 2: MORPHEUS prototype test lander (left, photo by author), in flight (right, photo from MORPHEUS promotional materials)

Discussions with MORPHEUS team members revealed their vision for future demonstrations that include the possibility of fixed propulsion modules ganged together to reach desired payload capacity. The modular lander system described in this paper is inspired by such an additive concept. A single propulsive module would be self-contained with its own structure, avionics, attitude control system, propellant, and engine to provide thrust for a target cargo capacity, which could be bolted to other modules to double, triple, or n-times the capacity.

Table 1: Modular Lander mass estimates (adapted from Petro 1999, p410)

Element	Percentage		Mass	
Structure	56	%	644	kg
Mechanisms	8	%	92	kg
Thermal Protection	9	%	104	kg
Attitude Control	2	%	23	kg
Power	15	%	173	kg
Avionics and Control	10	%	115	kg
Dry Mass w/o Propulsion System	100	%	1,150	kg
Propulsion System	27	% Propellant	550	kg
Dry Mass			1,700	kg
Cargo			6,800	kg
Inert Mass			8,500	kg
Main Propellant			2,040	kg
Gross Mass Estimate			**10,540**	**kg**

A completely propulsive landing on Mars from Low Mars Orbit to the surface would cost approximately 3,600m/s delta-v, which symmetrically is what would be needed by an ascent vehicle from the surface back to Mars orbit. However, for the purposes of this study the assumption is to have some reduction of the descent delta-v cost by using Mars' atmosphere for deceleration. Using a combination of aeroshell, Low-Density Supersonic Decelerator (LDSD), parachute, and heavy thrusting, an initial lower delta-v estimate could be the starting basis for sizing propellant and engines. This study does not include configuration or packaging of aeroshell or LDSD systems, but a large thrust engine with liquid oxygen (LOX) / methane (CH4) propellant could allow for a final quick deceleration after the atmospheric devices have been deployed.

Table 1 shows the mass estimates for a single module capable of landing 6,800kg of cargo onto the Mars surface. A modular interface system currently under development would be applied to all eight faces of the lander module to allow various combinations and geometries of lander systems (Figure 3). In addition, a deployable lander leg system would interface with the lander module using the same modular interface.

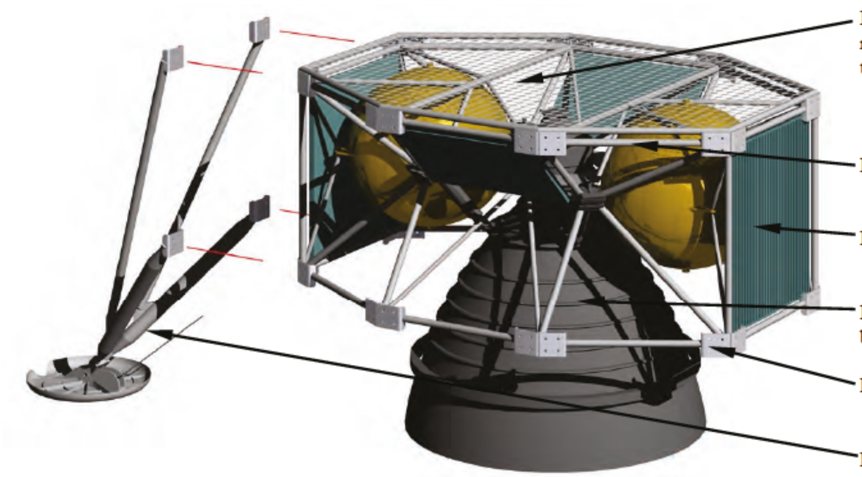


Figure 3: Lander module parts -- 6,800kg cargo capacity for single module, plus estimated 100kg lander legs

Using the single 6,800kg capacity module ganged together in various symmetrical combinations will result in a close approximation of the target 15,000kg, 18,000kg, 27,000kg or 41,000kg lander capacities.

Table 2: Lander size options

Element	Modules	Legs	Leg Mass		Dry Mass		Cargo		Total Mass	
15,000 Class Lander	2	4	400	kg	3,400	kg	13,600	kg	**21,480**	**kg**
18,000 Class Lander	3	3	300	kg	5,100	kg	20,400	kg	**31,920**	**kg**
27,000 Class Lander	4	4	400	kg	6,800	kg	27,200	kg	**42,560**	**kg**
41,000 Class Lander	6	6	600	kg	10,200	kg	40,800	kg	**63,840**	**kg**

Figure 4: Modular lander studies: 27,200kg capacity top-loaded (left), 40,800kg capacity top-loaded (right)

Figure 5: Modular side-slung payload lander 27,200kg capacity

These modular landers will alternatively be 13.6 ton, 20.4 ton, 27.2 ton, and 40.8 ton capacity landers as shown in Table 2. Since the purpose in this discussion is to create a flexible modular kit-of-parts system that can be used for all purposes, the lander sized will not be a significant factor for volumetric sizing, since a smaller 27,200kg capacity lander could carry smaller modules using the same kit-of-parts system (Figure 4, left), as opposed to 40,800kg capacity lander carrying larger modules or multiples of modules (Figure 4, right).

For this discussion the assumption was to use a limbed mobility system such as the All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) for cargo off-load as discussed in Wilcox (2012). However, the possibility of underslung or side-slung payloads that bring the modules closer to the ground (Figure 5) has also been studied. In this case, a method for independently supporting lander modules while habitat modules are unbolted and moved away would need to be designed and might impact the mass of the system.

B. Modular Pressure Vessel System

The horizontal modular system proposed in this study assumes complete pressure vessels assembled on Earth on the same factory line with different lengths, end domes, and bulkheads. Figure 6 shows a variety of parametric pressure vessels manufactured using this concept, such as short or long "hard can" vessels, radial ports, pressurized cores for TransHab-like inflatable habitats, mid-expandable "midex" membrane barrel pressure vessels, and propellant tanks. Structures were estimated based on Dorsey, Wu, and Smith (2008), and outfitting concepts were based on evolving models, previous experience, and published sources (Larson & Pranke 1999).

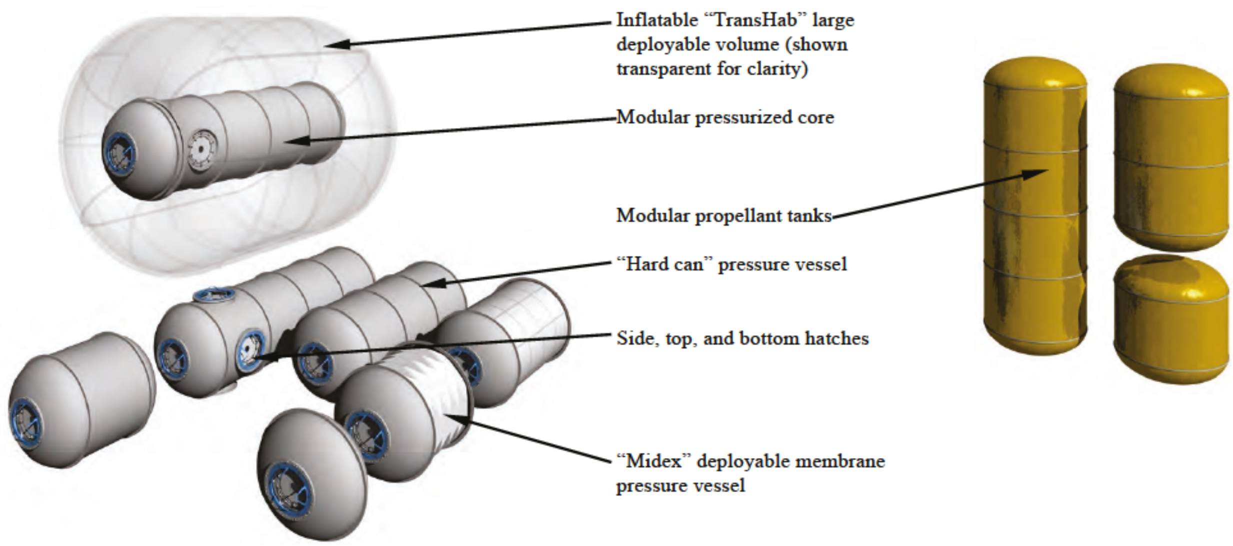


Figure 6: Modular pressure vessel variety

Some initial concepts for modular propellant tanks and habitats using the same assembly line include an underslung payload lander (Figure 7, left), where habitat modules can be dropped onto a mobility chassis (Figure 7, right). "Habitank" concepts (Kennedy 2007; Griffin et al 2012) have been considered for either wet (reuse of propellant tanks as habitable volume after draining left-over fuel), or dry (using flexible liners) propellant tank habitats. A Mars lander would use modular propellant tanks already fitted with hatches (Figure 8), and lowered down to an outpost configuration using winches (Figure 9). In a "habitank" concept, critical equipment and permanent outfitting could be installed in a dedicated pressurized "closet", with deployable outfitting pulled out and installed in the former propellant tank once the crew arrives for housekeeping.

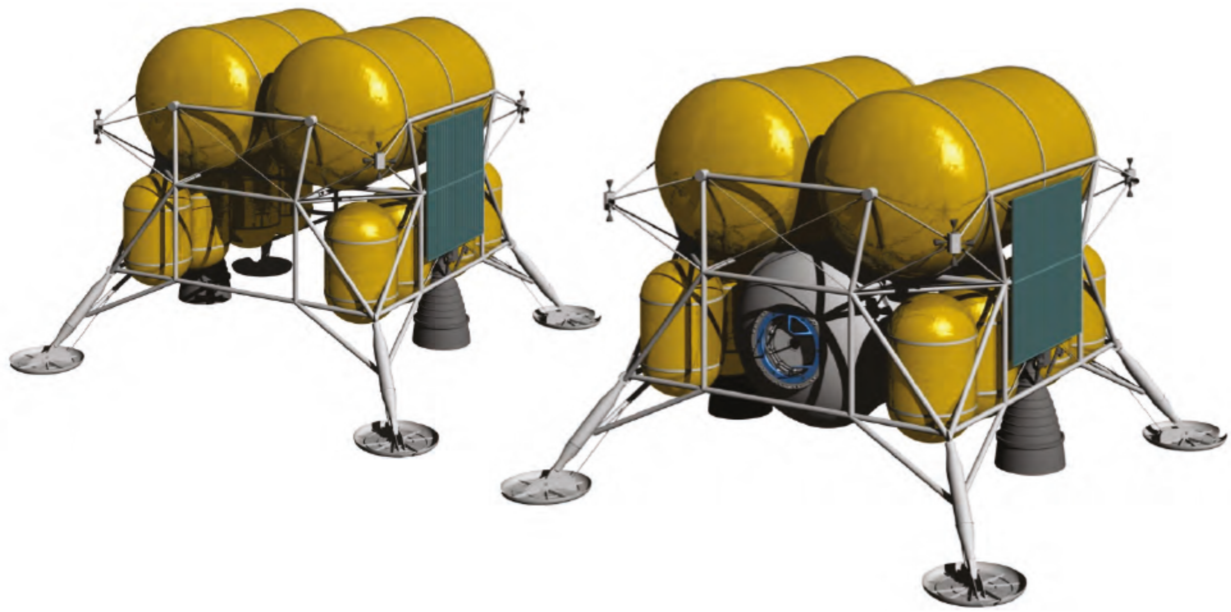


Figure 7: Bottom-slung payload lander using modular propellant tanks

Figure 8: Dry or wet "habitank" concepts that turn lander into surface outpost

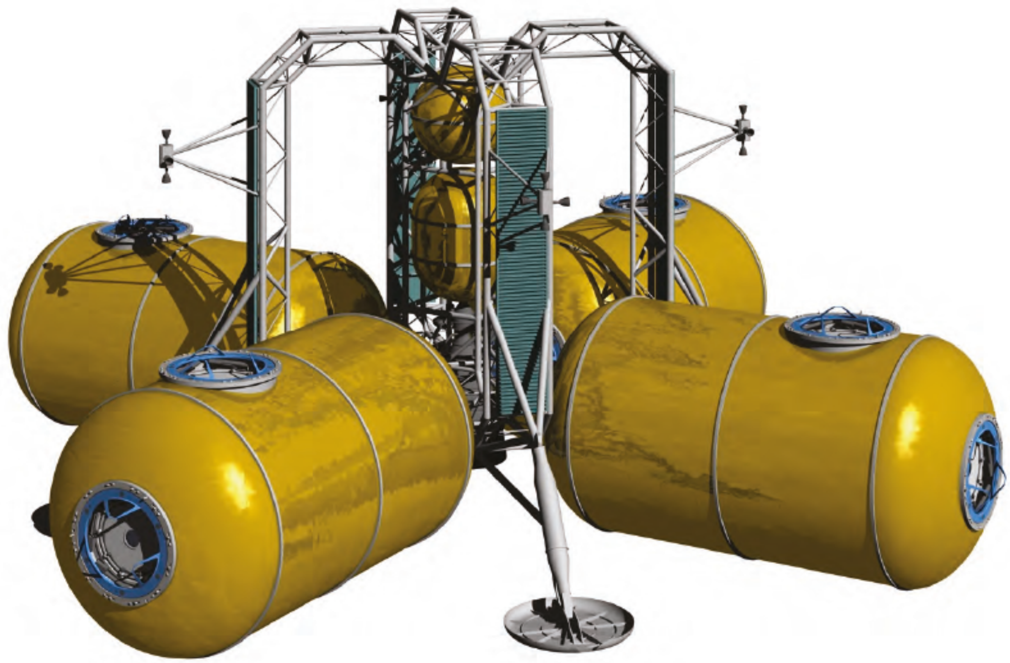


Figure 9: "Habitank" surface outpost deployed from lander

Though actual assembly line construction of pressure vessels may proceed with parametric lengths, for planning purposes the kit-of-parts system included 1m cylinders, 2m cylinders, 1m “midex”, and 2m “midex” modules (Figure 10) combined as needed for target volume.

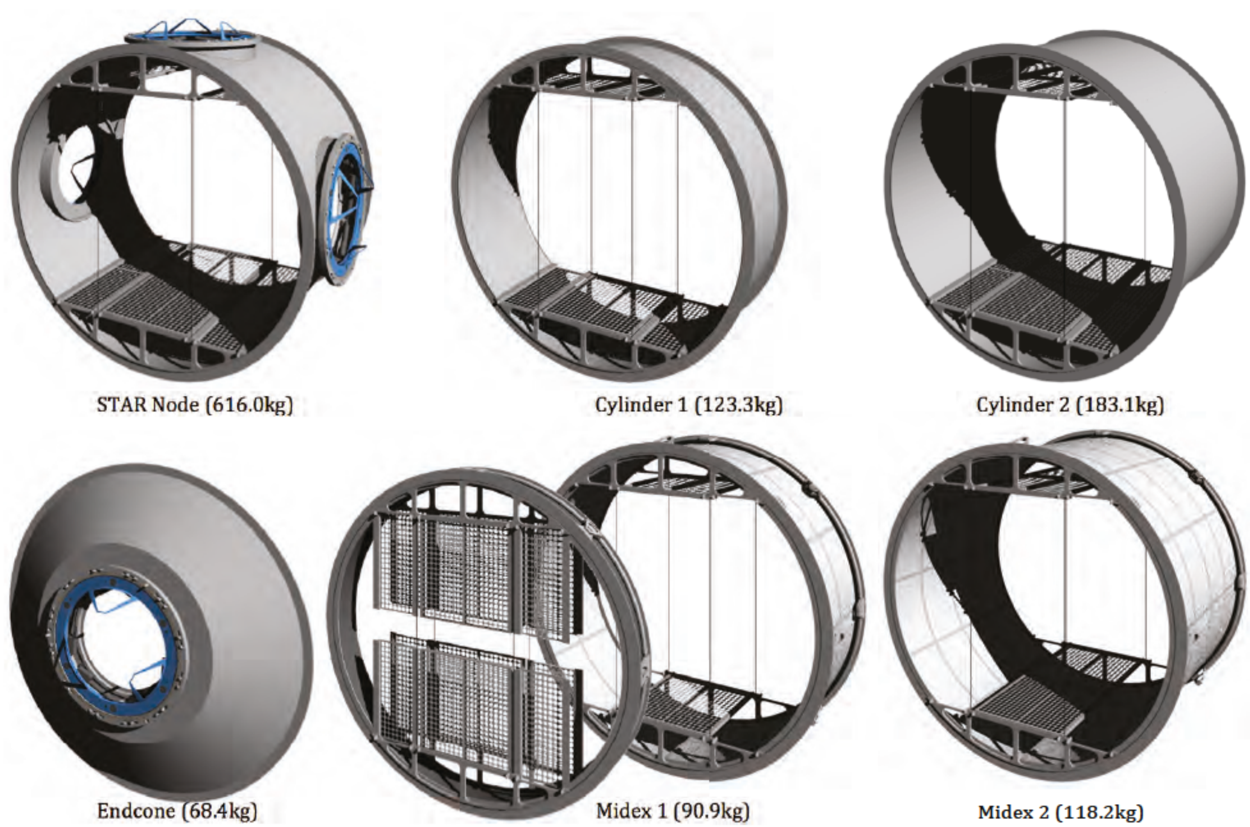


Figure 10: Modular pressure vessel components -- “Midex” module shown stowed and deployed

Each of the modules included tertiary internal framework for fixed outfitting or Random Access Frames (RAF) or other kit-of-parts systems (Howe & Polit-Casillas 2014). Various end dome / end cone conditions are possible (Figure 11), with various sized hatches, internal bulkheads, rover pilot stations, and plain bulkheads part of the kit-of-parts system (Figure 12). A dilemma has been hatch sizing. For zero-g "shirtsleeve" (without an EVA suit) translation small 32" diameter hatches are sufficient, which is the size of the Orion crew vehicle docking hatch. However, for EVA purposes larger hatches of 40" square may be required. Surface translation in variable gravity will have crew persons walking upright and therefore 40"x60" rectangular, or other door-like hatch sizes have been proposed. The current ISS-style hatches are even larger for the purpose of transferring and swapping out racks. However, One study determined that the ISS-style hatch and Common Berthing Mechansim (CBM) is obsolete, and there are many advocates for the smaller 40" hatch to be made standard. Since the conclusion is far from settled, this study proposes a swap-out bulkhead based on the CBM diameter, and allowing for any type of swap-out bulkhead with custom hatches without significantly increasing manufacturing costs (Figure 11).

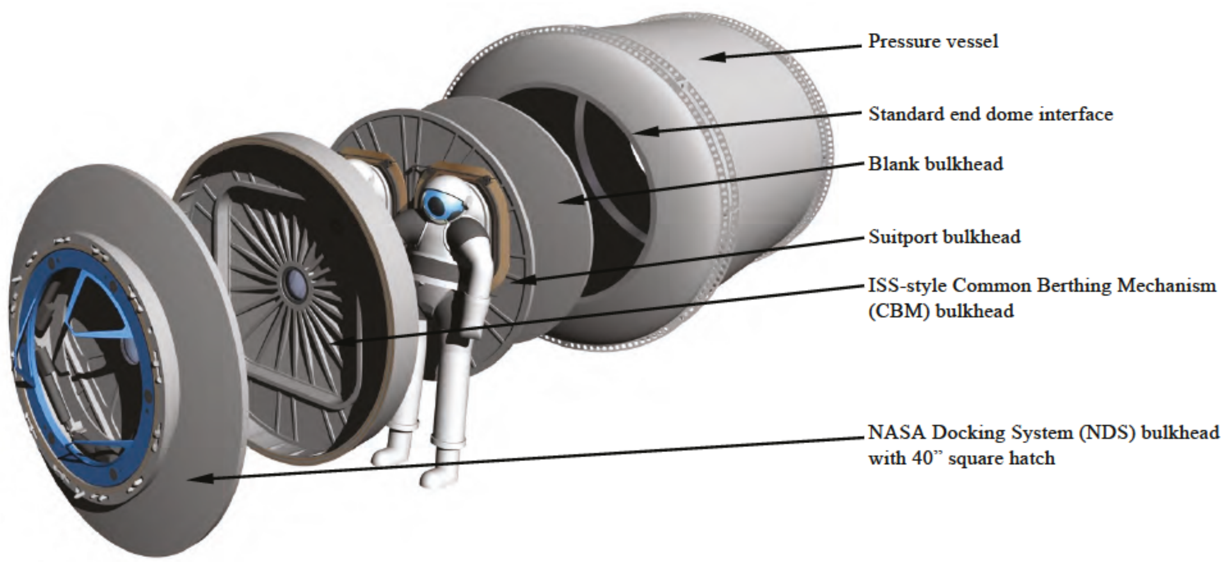


Figure 11: Standard bulkhead system accommodating multiple hatches and conditions

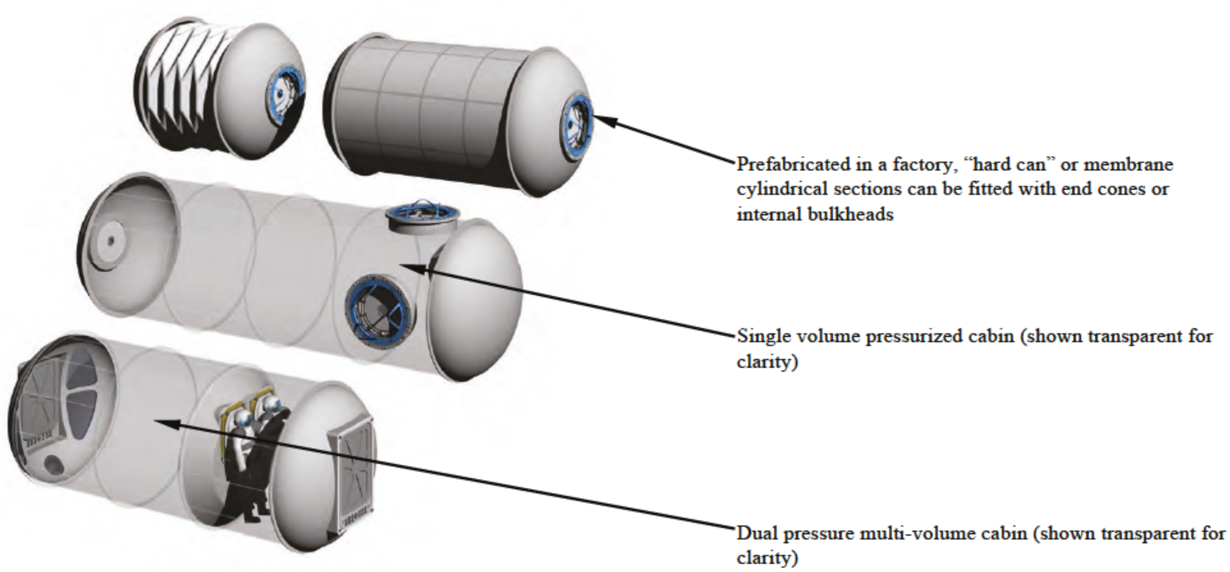


Figure 12: Modular bulkheads

C. Core Node / STAR Node Life Support System

When considering the division of volumes and how to break up critical systems in a modular way, space habitats should have redundant systems in case of failure. However, it would be impractical to duplicate all critical systems into many small modules. Instead, it is important to extablish a hierarchy of systems, particularly if life support functions in one module could be used to support all other connected volumes. In previous habitation research, it was determined that closed loop life support (or as closed as practical with current technology) need only be functional in a single location in an outpost, and all other volumes would only need to have air handling, fire suppression, and other local functions for power and data (Kennedy, et al 2010; Howe, et al 2010). This means that modules that are separated from the core life support system may have limited or no Environmental Constrol & Life Support (ECLS) capability by themselves, and would not be fit to be occupied by crew until they are docked back to life support functions again. The lunar outpost "Pressurized Core Module" was designed to contain closed life support, where peripheral "Pressurized Excursion Modules" and "Pressurized Logistics Modules" could be attached or separated to support roving exploration crews; while underway no crew could enter the module unless it could borrow life support functions from the core or from pressurized rovers. Alternatively, small exploration vehicles with limited open loop life support could support crew for a few days, until redocked to the main life support facility and charged up again.

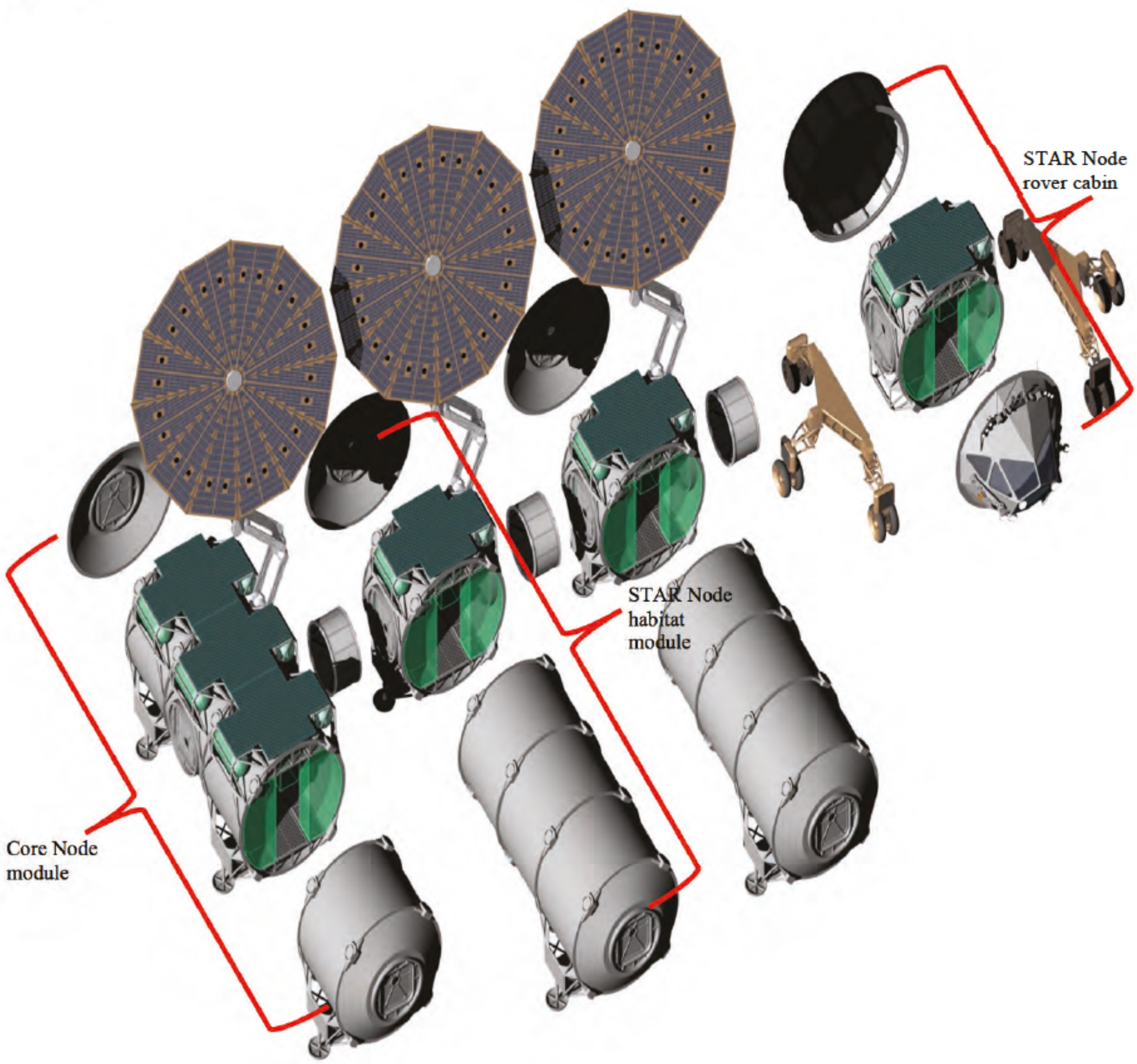
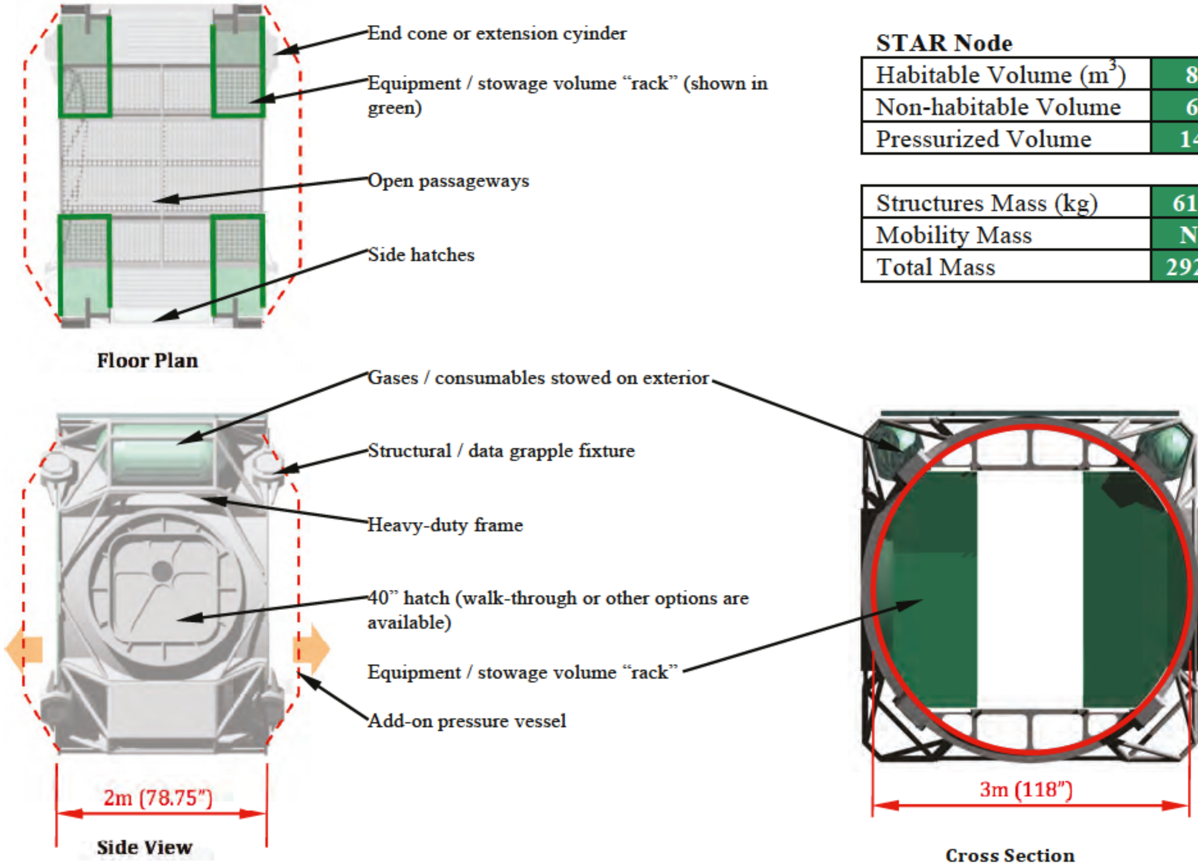


Figure 13: STAR Node / Core Node can be used to derive habitats, small rover cabins, and other elements



STAR Node

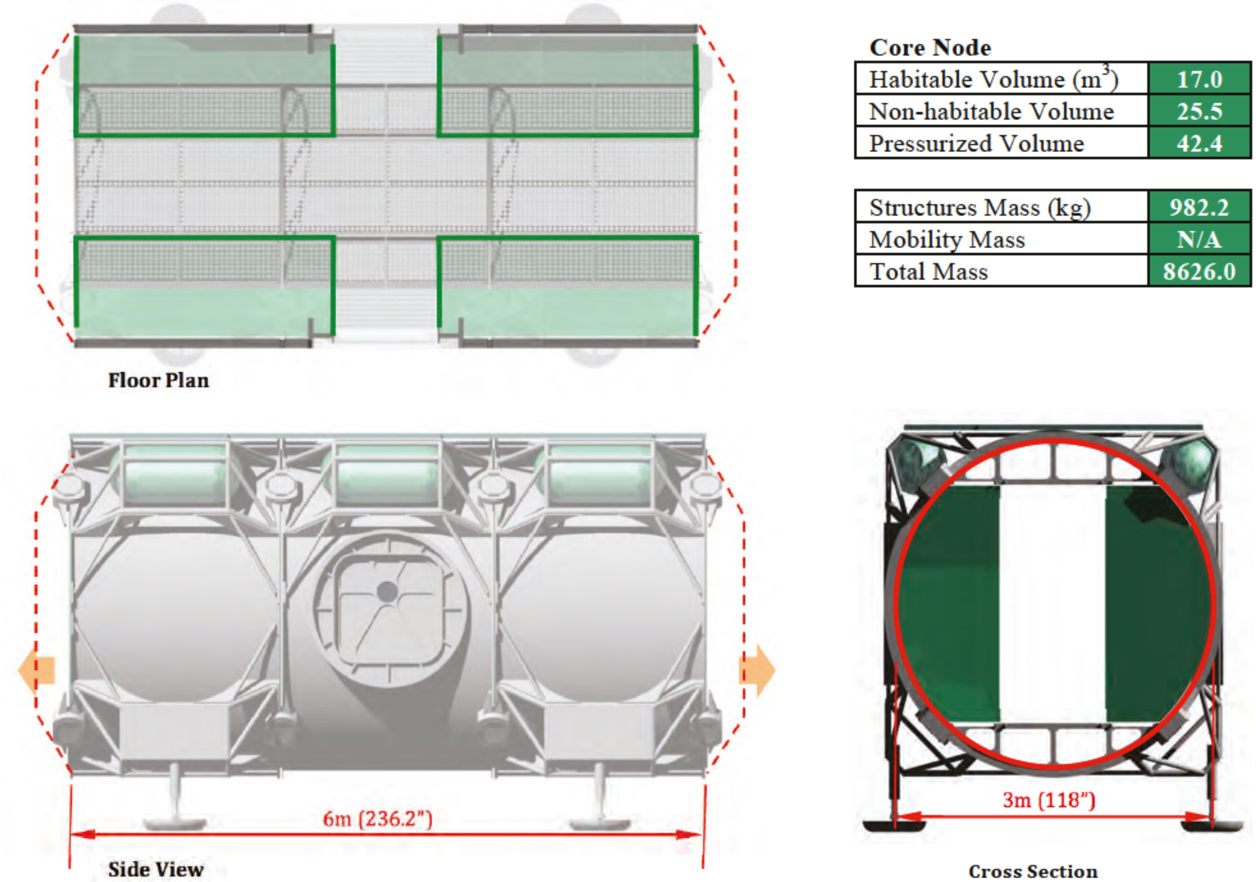
Habitable Volume (m^3)	8.1
Non-habitable Volume	6.0
Pressurized Volume	14.1

Structures Mass (kg)	616.0
Mobility Mass	N/A
Total Mass	2924.0

Figure 14: STAR Node component for short-duration, open-loop life support

NASA's Habitable Air Lock (HAL) team came up with a standard concept for minimal life support and habitability. The standardized Space Technology & Advanced Readiness (STAR) node evolved from the small pressurized rover Lunar Electric Rover, Multi-Mission Space Exploration Vehicle, and HAL research by assuming that the vehicle cabin itself should be equipped with open life support and habitability functions for a short duration, and could be recharged from fully equipped core life support functions housed elsewhere. The cabin could then be used as a node for growing volume that borrows from the life support functionality of the original cabin.

The Core Node / STAR Node life support system grew from these previous concepts, fitted into the modular pressure vessel concept. Figure 13 illustrates how the concept works -- a single Core Node is a module in itself, functioning as a "machine room" with all critical closed loop life support systems and spares, only leaving enough free habitable volume for system access and maintenance. Other attached volumes are used for living, and are equipped with open loop life support STAR Node that supports the Core Node life support functionality. Similarly, rover and small vehicle cabins that can be separated and provide habitability for short durations also are built around STAR Node open loop life support, and would recharge every time the vehicle re-attaches to the Core Node. Figure 14 shows the STAR Node concept applied to a barrel section of pressure vessel -- the module volume would be built around this node, which also functions as a translation node for circulation. Figure 15 shows the Core Node conept as a "machine room" that could be fitted with end domes as an independent module or extra volume could also be added as needed. Overall functional zones for the Core Node are shown in Figure 16.



Core Node	
Habitable Volume (m^3)	17.0
Non-habitable Volume	25.5
Pressurized Volume	42.4

Structures Mass (kg)	982.2
Mobility Mass	N/A
Total Mass	8626.0

Figure 15: Core Node for medium to long-duration closed-loop (as near as possble) life support

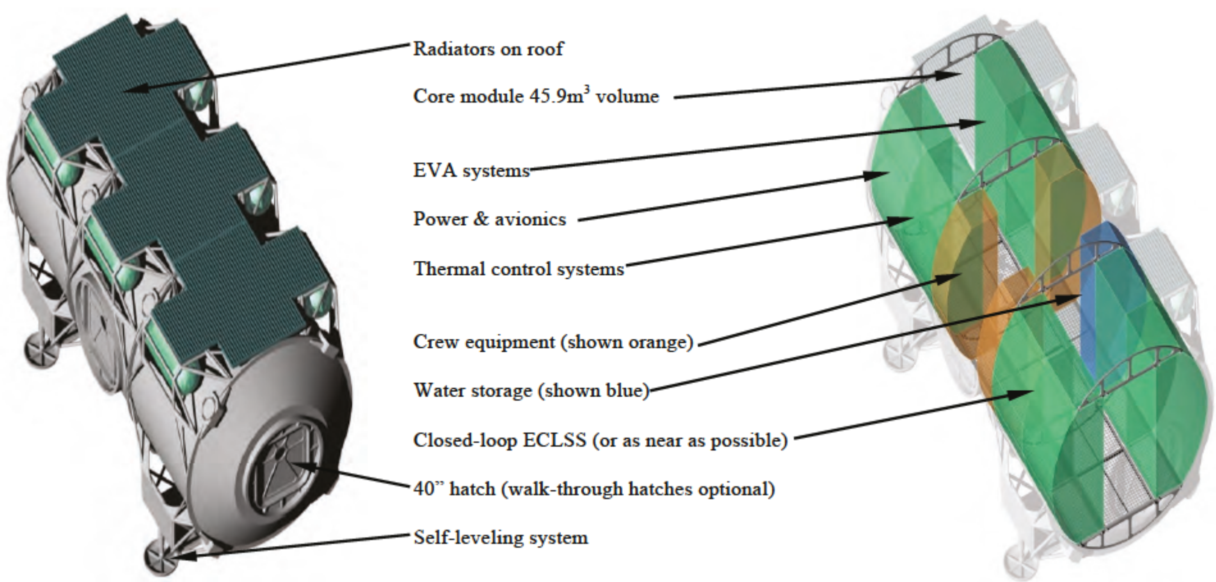


Figure 16: Core Node Module "machine room" with closed-loop ECLSS (or as near as possible)

D. Extra-Vehicular Activity (EVA) Alternatives

Extra-Vehicular Activity (EVA) is where crewmembers put on pressure suits to exit the habitat or vehicle and transfer out to the zero or low-pressure environment. EVA is a particularly risky activity, in that differences of air pressure are necessary in order to perform any work. If the EVA suit were to be filled with cabin pressure required for the crew to function day to day in the habitat, the soft material would balloon up and it would be impossible for the crew person to move their arms or legs. Therefore the suit pressure must be greatly reduced in order to allow for freedom of movement -- the crewmember must be able to overpower the tensile forces working through the suit membranes in order to move limbs. This creates a dilemma in that considerable pre-breathing becomes necessary to remove nitrogen from the blood stream to allow the person to healthily function in a lower pressure environment. Once a crewmember exits the habitat, dust and contamination that may be present in the natural environment are sure to be tracked back in, creating a health hazard.

The modular exploration system described herein brings together EVA functions and alternatives from previous work, such as the dual chamber suitport airlock (Howe, Kennedy, Guirgis & Boyle 2011) that provides two chambers for step-down cabin pressures and dust control. The inner chamber remains pressurized and could function as a low pressure transition for EVA. The outer chamber nominally stays unpressurized, or equalized with the external environment, and would only be pressurized for infrequent suit maintenance. The bulkhead separating the two chambers would contain suitports (Cohen 1989; Cohen 2001) that allow for a minimal air loss during depressurization and undocking. Figure 17 shows an illustration of the dual chamber suitport airlock concept.

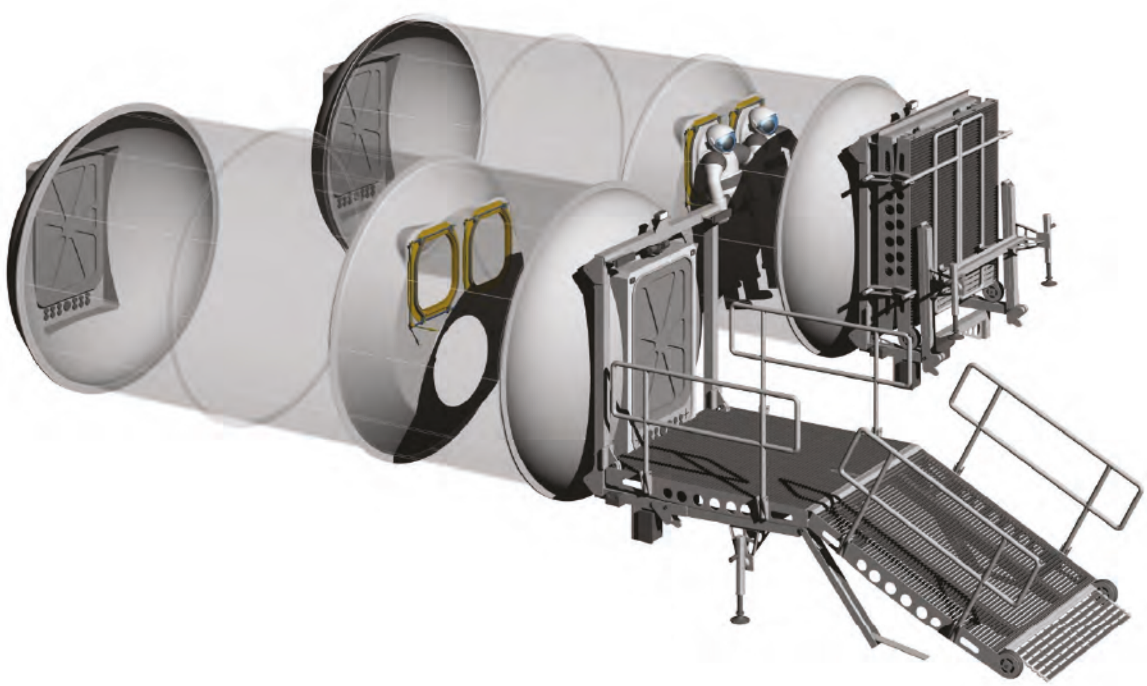


Figure 17: Dual-chamber suitlock design allows for suitports, step-down cabin pressures, and nominal ambient EVA operational atmosphere – Deployable EVA Platform (DEVAP) developed for Habitat Demonstration Unit (HDU) is shown stowed and deployed

EVA-centered surface vehicles could consist entirely of a dual chamber suitport airlock, with rear Deployable EVA Platform (DEVAP) ramp (Howe, Merbitz & Dokos 2012). The DEVAP platform stows compactly and deploys for EVA use (Figure 17). Figure 18 shows an early version of a low-gravity Phobos hopper vehicle with DEVAP platform during mobility (Figure 18, left) and EVA activities (Figure 18, right).

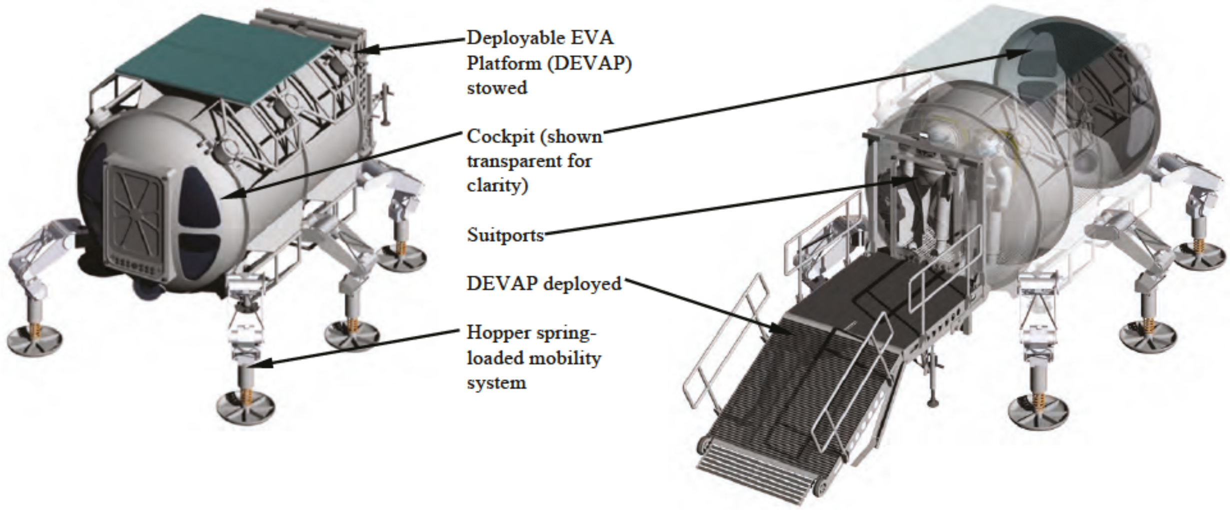


Figure 18: EVA-centered vehicles -- early version of Phobos hopper shown

Other versions of EVA-centered vehicles include application of the gull wing (also developed by the MMSEV / HAL team) shown in Figure 19, where the outer chamber provides dust protection but is not pressurized. Lighter versions of the DEVAP concept include external suitports with lightweight EVA stair (Figure 20), and compact dual chamber with lightweight EVA stair (Figure 21).

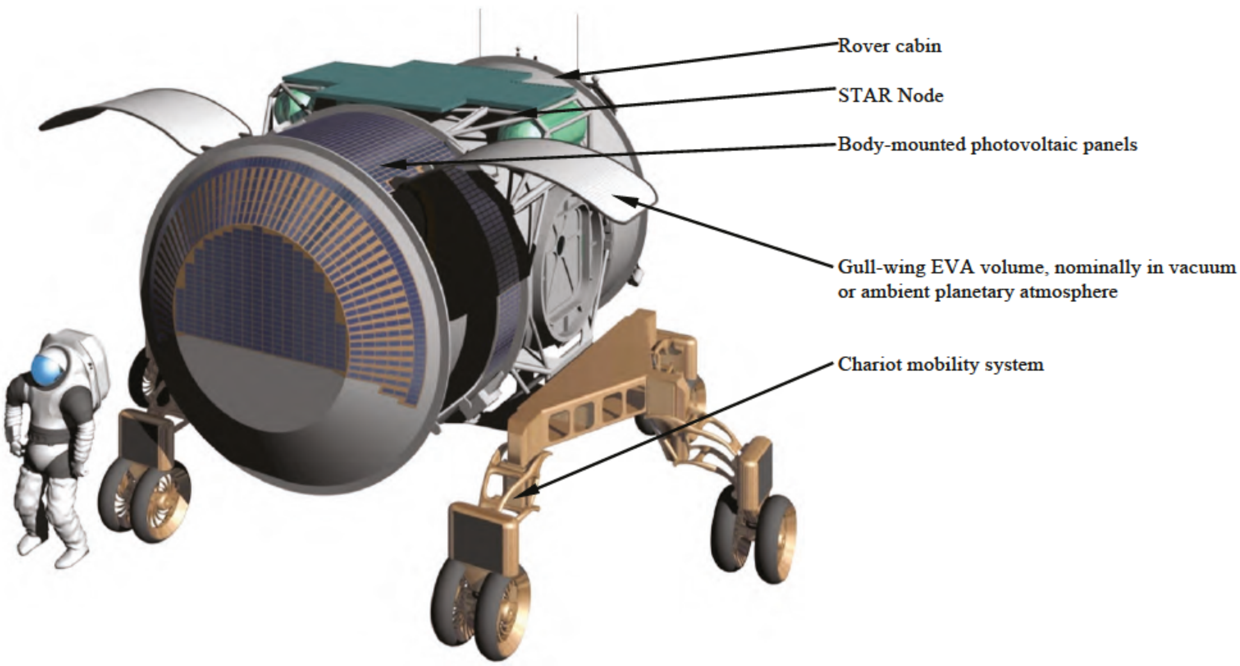


Figure 19: Gull-wing unpressurized EVA volume

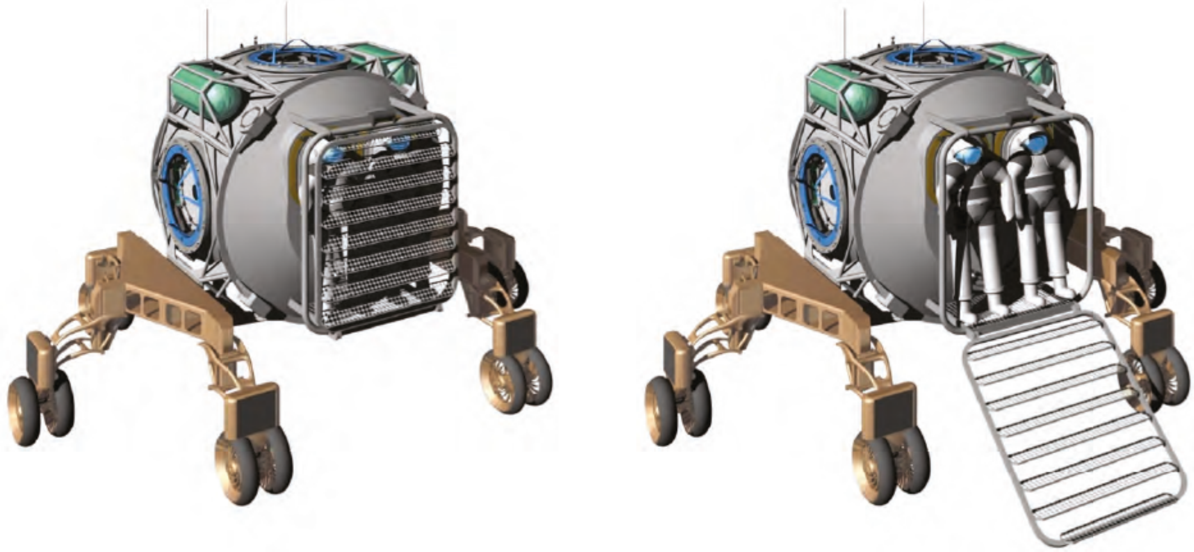


Figure 20: External Suitports with lightweight EVA stairs: stowed (left) and deployed (right)

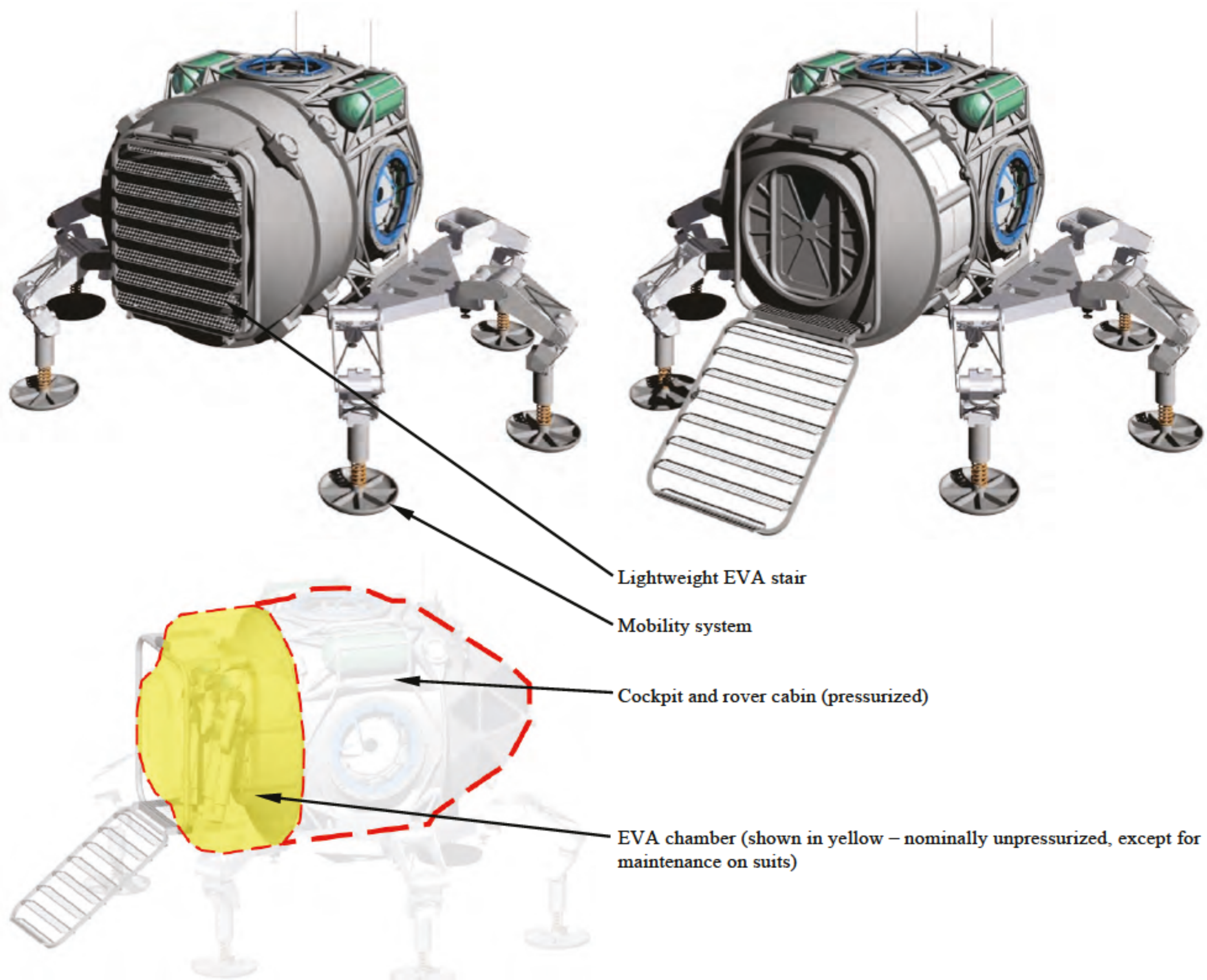


Figure 21: Compact dual-chamber suitlock, with lightweight EVA stair stowed (upper left), deployed (upper right), and volume description (lower left)

Dedicated lightweight deployable airlocks can also be made from the kit-of-parts, by using pneumatic beam supported barrel sections that can be collapsed or expanded as needed (Figure 22).

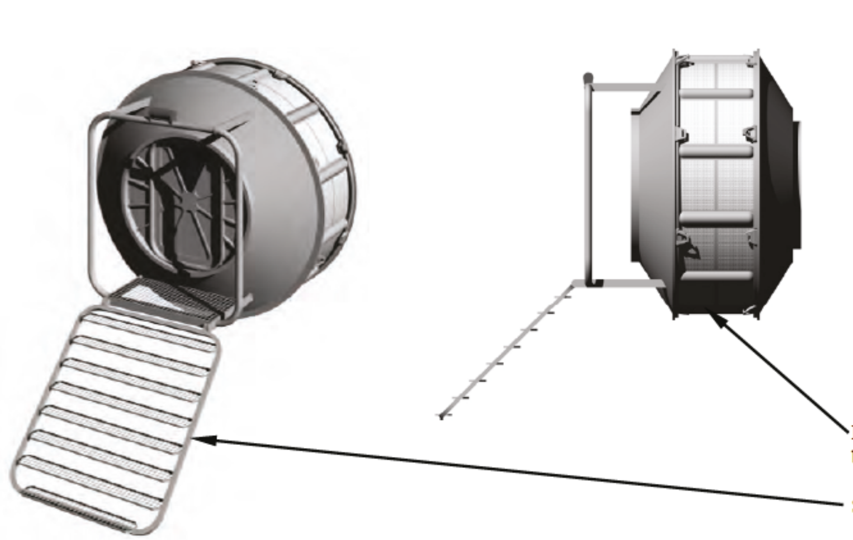


Figure 22: Airlock module deployed (left, middle) and stowed (right) -- using a modular system, a variety of configurations could include larger volumes, dual chambers, or "hard can" vs inflatable

E. Surface Docking System – Pressurized Tunnel Adapter

Pressurized docking between modules resting on a planetary surface creates unique problems that have not been solved yet. As an interim solution, the Constellation Lunar Surface Systems lunar outpost design used an "Active-active Mating Adapter" that assumed a pressurized tunnel could bridge across, being flexible enough to adjust to uneven terrain with six degrees of freedom, but firm enough to hold cabin pressure for "shirtsleeves" transfer, as between a habitat module and a rover (Figure 25). In this concept the six degree of freedom has been solved matching using two docking frames on a Stewart Platform for skewed hatch frames offset in roll, pitch, or yaw. However once the two modules have been hard docked a problem remains when the tunnel (membrane tube, as an interim solution) is to be pressurized -- any configuration not perfectly parallel (which would include almost all realistic configurations) would produce tremendous strain in the membrane as it takes on the tensile forces caused by pressurization. Assuming that such a solution would be the next step, a walk-through pressurized tunnel could be easily accommodated using the previously described CBM bulkhead modularity, where heritage CBM large-diameter frames allow for walk-through translation in the tunnels (Figure 24, top). Step-down pressurized tunnels can be used when multiple hatch sizes are mixed (Figure 24, bottom).

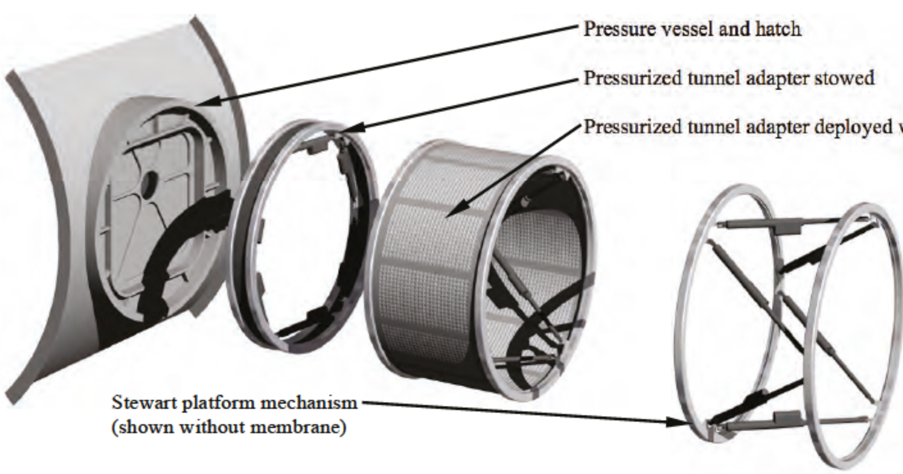


Figure 23: Pressurized tunnel adapter docking system

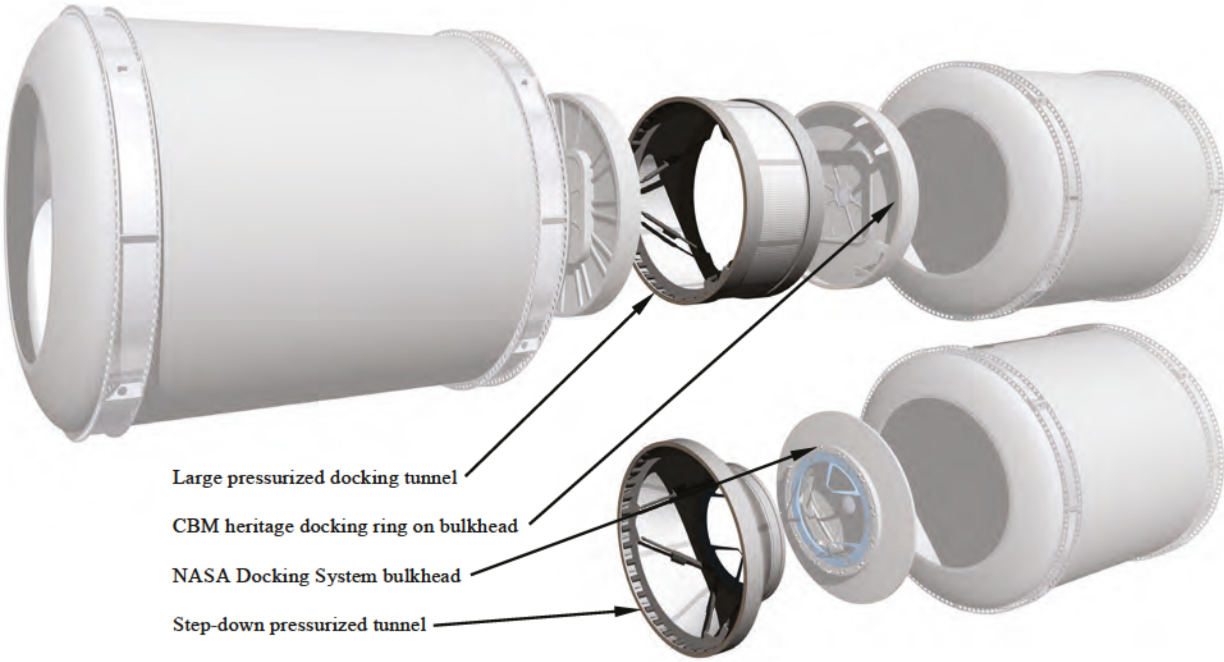


Figure 24: Large-diameter modular pressurized tunnel using heritage Common Berthing Mechanism (CBM) bulkheads (top), step-down pressurized tunnel for NASA Docking System (NDS)

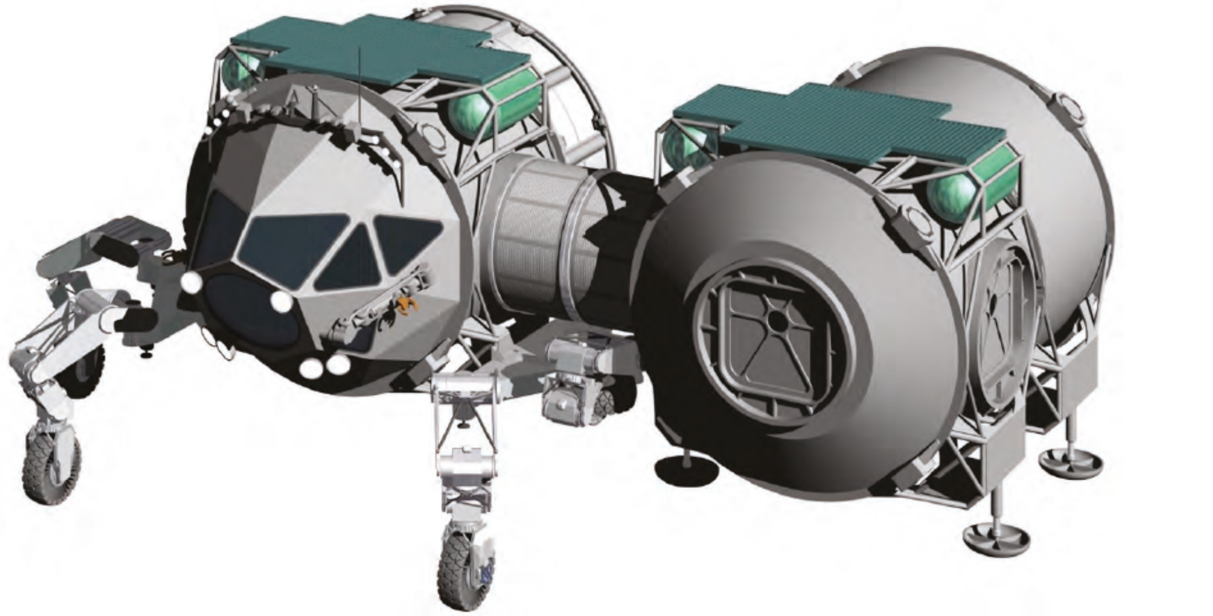


Figure 25: Double docking tunnel using pressurized tunnel adapter pair

F. Mobility Systems

The proposed modular exploration system interfaces with several mobility systems tailored to unique environments. A Reaction Control System (RCS) sled would be used in zero-g deep space and transit environments. This concept was pioneered by the MMSEV / HAL development team as a means for swappable propulsion and mobility chassis, depending on whether the cabin will be used in space or on a planetary surface. ATHLETE and Chariot mobility systems have also been designed to carry a multitude of payloads, including habitat modules or vehicle cabins.

Figure 26 is a diagram that shows how a single Pressurized Excursion Vehicle (PEV) cabin can be fitted with multiple propulsion and mobility systems for various environments -- the cabin can be fitted with an RCS sled for zero-g (Figure 26, left), refitted with a propulsion stage for deep space taxi (Figure 26, middle top), Mars Ascent Vehicle cabin, low-gravity Phobos hopper (Figure 26, middle bottom), and wheeled rover for Mars surface (Figure 26, right bottom).

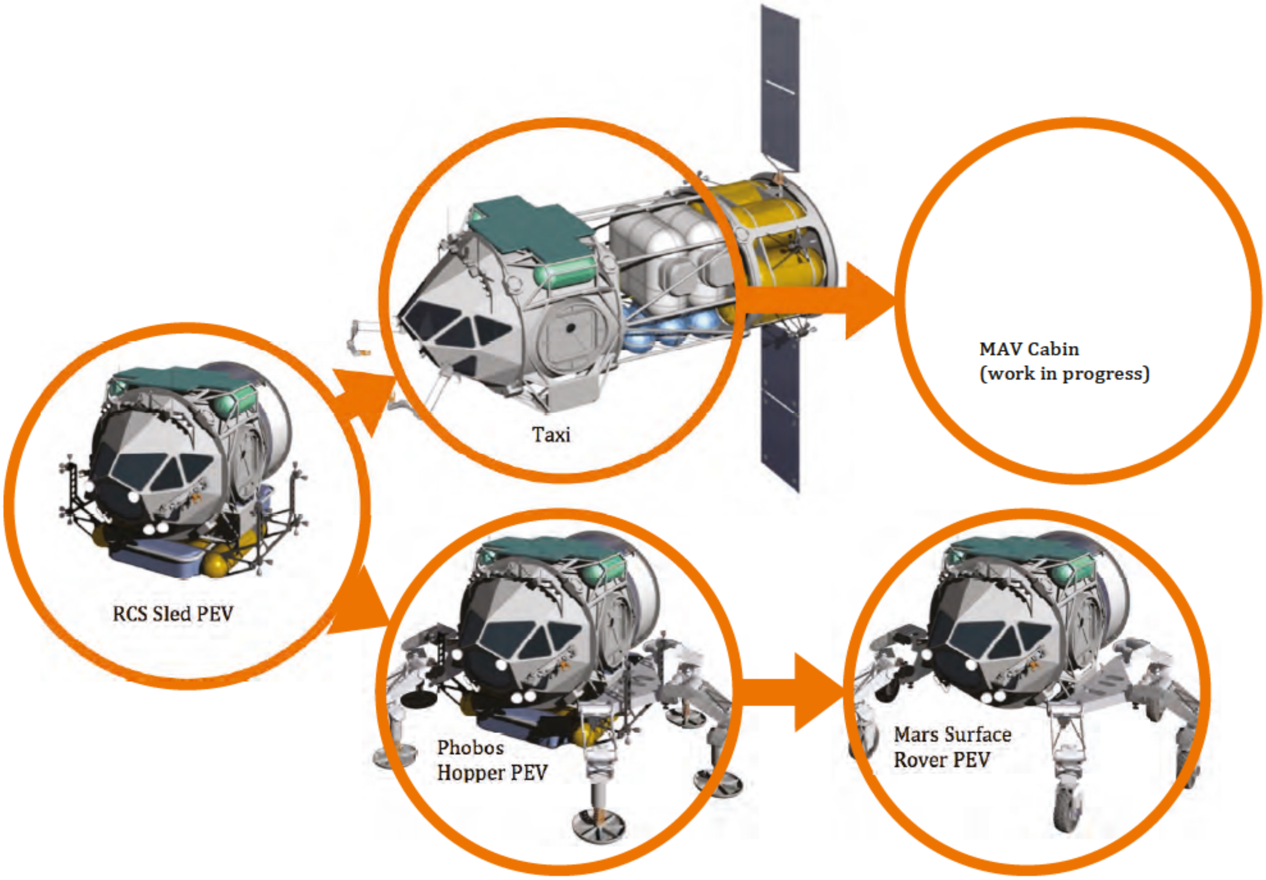


Figure 26: In-space and surface mobility commonality – small cabins can be fitted with a variety of in-space propulsion or surface mobility systems

Though various mobility systems such as NASA's Chariot chassis are applicable and may be default planetary surface mobility due to higher speeds and fast maneuverability, special attention was given to the highly modular articulated limb All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE), which is designed to swap out tools and end effectors very quickly (Wilcox 2011). The ATHLETE system is most applicable as a cargo carrying system and multi-purpose manipulator, but can also be used to move habitats or for Pressurized Exploration Vehicle cabin mobility. The ATHLETE is particularly applicable as a Phobos hopper, where spring actuators are another implement in the tool suite. It is possible to take the same ATHLETE fitted out as a hopper mobility system (Figure 26, bottom middle) down to the Mars surface, swap out the spring actuators with wheels in a matter of minutes, and proceed as a wheeled mobility platform (Figure 26, bottom right) for carrying habitat modules and other payloads.

Mass and volume details for an RCS in-space excursion vehicle is shown in Figure 27. The same cabin with the RCS sled + ATHLETE hopper mobility is shown for Phobos in Figure 28. Remove the RCS sled, swap the hopper spring actuators for wheels and a Mars surface rover is born (Figure 29). Once Chariot chassis becomes available, the ATHLETE can be undocked, and used for carrying habitats, cargo, logistics modules, and as an articulated manipulator for science and technology purposes. The same cabin shown with ATHLETE removed and Chariot-type mobility is shown in Figure 30.

RCS Sled PEV

Hab Vol (m^3)	14.7
Non-habitable Vol	6.0
Pressurized Vol	20.7

Struct Mass (kg)	1031.0
Mobility Mass	1049.0
Total Mass	5522.0

Figure 27: Reaction Control System (RCS) Sled Pressurized Excursion Vehicle (PEV) for in-space translation

Low-gravity Hopper

Hab Vol (m^3)	14.7
Non-habitable Vol	6.0
Pressurized Vol	20.7

Struct Mass (kg)	1031.0
Mobility Mass	2948.0
Total Mass	7422.0

Figure 28: Spring-loaded hopper for low gravity environments (includes RCS Sled)

Articulated (ATHLETE)

Hab Vol (m^3)	14.7
Non-habitable Vol	6.0
Pressurized Vol	20.7

Struct Mass (kg)	1031.0
Mobility Mass	2019.0
Total Mass	6492.0

Figure 29: Articulated limb (ATHLETE) mobility system for extreme terrain

High-speed (Chariot)

Hab Vol (m^3)	14.7
Non-habitable Vol	6.0
Pressurized Vol	20.7

Struct Mass (kg)	1031.0
Mobility Mass	969.0
Total Mass	5442.0

Figure 30: High-speed (Chariot) mobility system for cross-country traverse

III. Outpost Scenarios

Using the modular exploration system kit-of-parts, a series of outpost configuration scenarios were studied. These outpost configurations are also discussed in Howe, et al 2015. Lander manifests are not described in this paper, but were considered for the four classes of 15 ton, 18 ton, 27 ton, and 41 ton capacities, to see how modularity could be applied. When the lander capacity is on the high end, such as 41 tons, it becomes practical to use monolithic habitats and manifest rovers and other equipment together on less flights. However, when the lander capacity is smaller, modularity becomes much more of a driver because of flexibility in how the pressurized volume can be broken up in different manifests. The conclusion is that larger landers require less flights and fewer habitability elements, while smaller landers require more flights and many modules docked together.

In the context of the Evolvable Mars Campaign, multiple habitation strategies were considered addressing 500 day durations, including monolithic, vertical modular, SLS-derived, and the subject of this discussion, horizontal modular. Of the horizontal modular exploration system kit-of-parts, three major outpost configurations were explored. The "hard can" outpost used a Core Node, two hab modules, two rovers, and an inflatable airlock, with a total of 203.9m^3 pressurized volume, and a total of 49,017kg mass for habitability elements and rovers (Figure 31).

Hard Can Outpost

Hab Vol (m^3)	97.4
Non-habitable Vol	106.5
Pressurized Vol	203.9

Core Node (kg)	9827.0
Hab Module	11371.0
Hab Module	11371.0
Rover	6492.0
Rover	6492.0
Inflatable Airlock	3464.0
Total Mass	49017.0

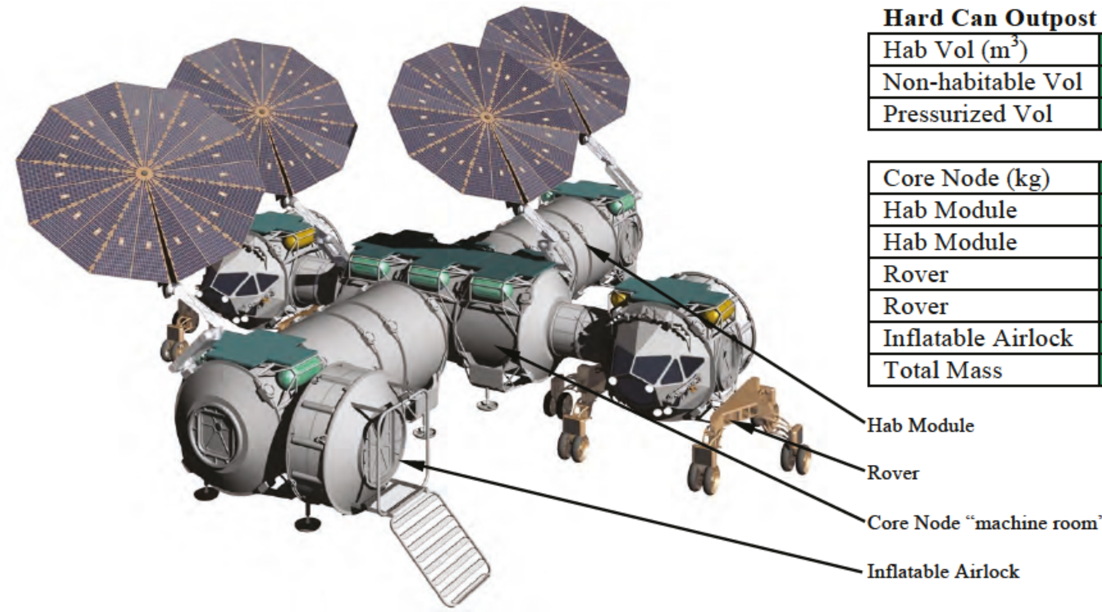


Figure 31: Mars outpost using "hard can" pressure vessel components

A spreadsheet tool was developed that tracked total volume, habitable volume, non-habitable volume, and mass in both deployed and stowed configurations. This was not as critical in the "hard can" case, but in inflatable configurations it was important to keep a minimal amount of non-habitable volume to accommodate equipment and logistics. The mid-expandable "midex" outpost used a Core Node, two midex hab modules, two rovers, and inflatable airlock for a total of 217.9m^3 volume, and 48,835kg mass for habitability elements and rovers (Figure 32). Each of the midex hab modules could be collapsed to half their length during transport, leaving pressurized "closets" at each end packed with deployable outfitting. Once the midex module is expanded to its final length, the empty volume could be creatively utilized for partitioned spaces, workstations, stowage, and logistics.

Midex Outpost

Hab Vol (m^3)	139.2
Non-habitable Vol	78.7
Pressurized Vol	217.9

Core Node (kg)	9827.0
Hab Module	11280.0
Hab Module	11280.0
Rover	6492.0
Rover	6492.0
Inflatable Airlock	3464.0
Total Mass	48835.0

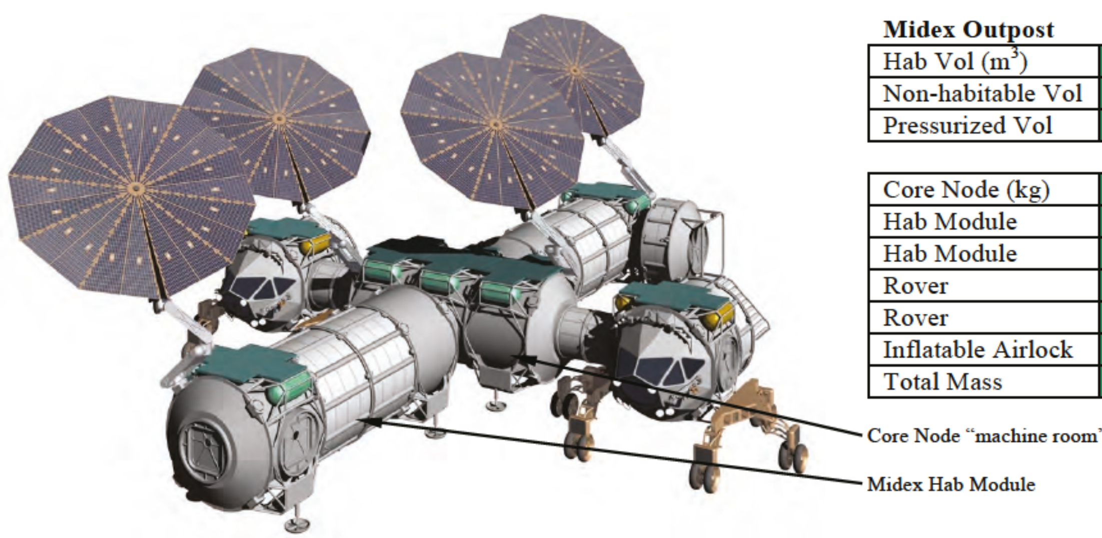


Figure 32: Midex expandable outpost configuration

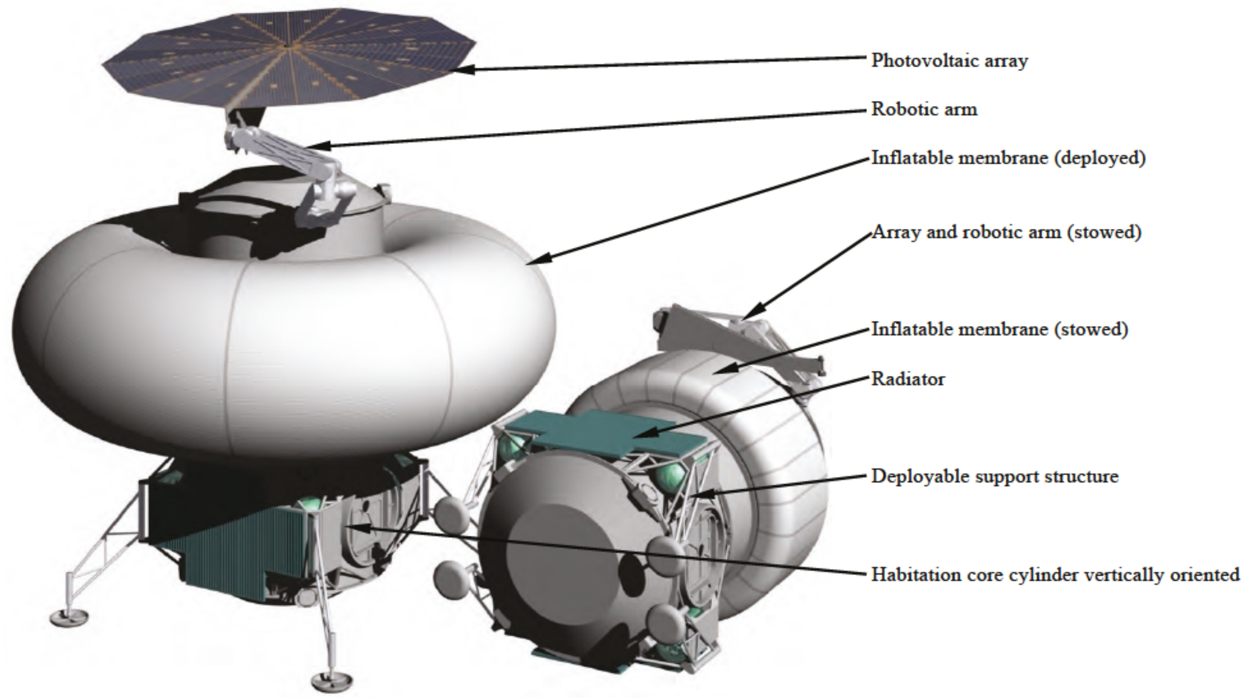
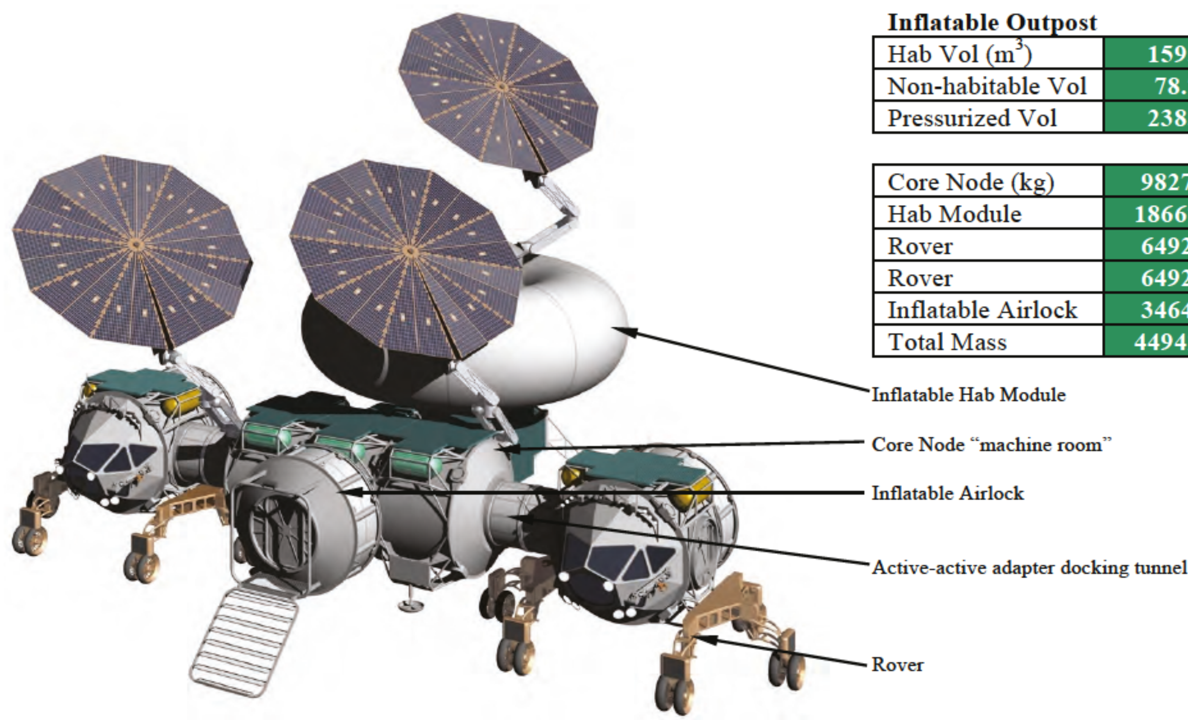


Figure 33: Inflatable hab module deployed (left) and stowed (right)



Inflatable Outpost

Hab Vol (m^3)	159.7
Non-habitable Vol	78.7
Pressurized Vol	238.4

Core Node (kg)	9827.0
Hab Module	18667.0
Rover	6492.0
Rover	6492.0
Inflatable Airlock	3464.0
Total Mass	44942.0

Figure 34: Inflatable module outpost configuration

The last configuration using the modular exploration system required the introduction of a torus inflatable that, when expanded, created a very large free volume (Figure 33). This "inflatable" outpost consisted of one Core Node, a single inflatable hab module, two rovers, and an inflatable airlock, totaling 238.4m^3 volume and 44,942kg mass for all the habitability elements and rovers (Figure 34). The inflatable habitat module, though resulting in the greatest habitable volume, proved difficult because most of the volume was unavailable during transport to the Mars surface, leaving little volume for logistics and stowage. The current iteration of the "inflatable" consideration was felt to be awkward, but still had potential.

Finally, some studies on using the modular exploration system for Phobos missions were conducted, limited to preliminary configuration work. A Core Node was underslung in a "sky crane" descent / ascent stage, which could be used to support two rovers outfitted with hopper mobility systems (Figure 35).

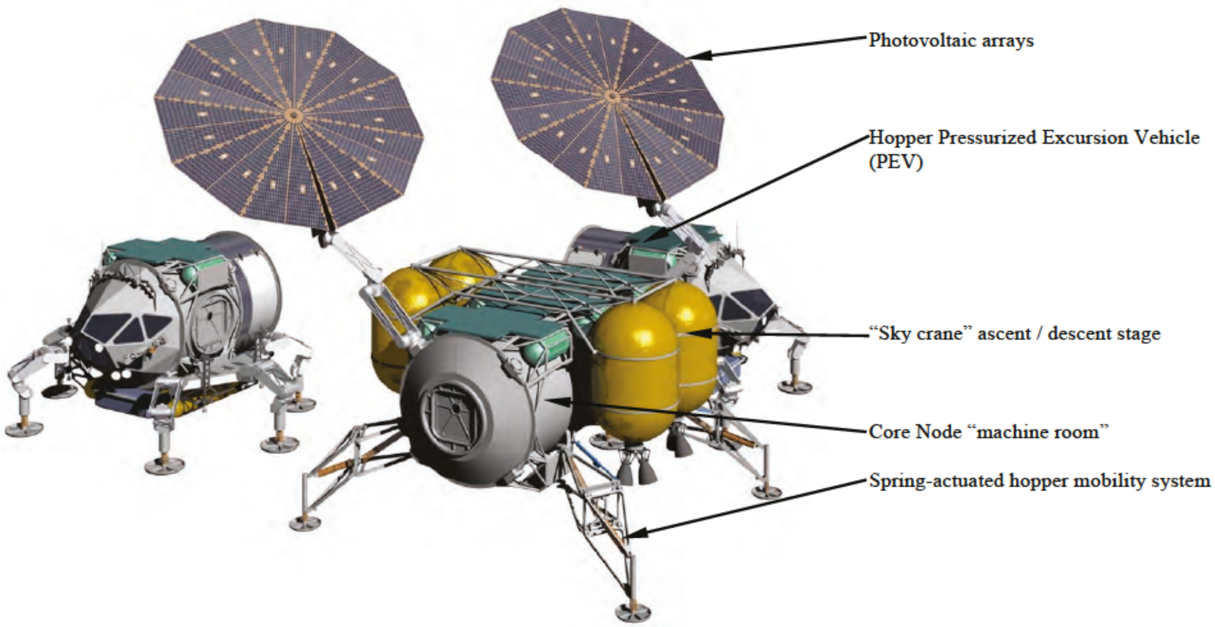


Figure 35: Phobos Core Node outpost configuration

IV. Mars Forward from Low Earth Orbit (LEO)

The modular exploration system proposed herein may be appropriate for initial Low Earth Orbit (LEO) technology shake-out missions that can grow incrementally into transit habitat and Mars missions. Another side study for the kit-of-parts system included concepts for deployable habitats brought up with the SLS Orion "trunk" as a means for habitat build-up using multiple small identical modules (Figure 36). We applied modular pressure vessel systems with deployable "midex" expanding volume to create larger habitats. Small modules can be lifted to LEO with each Orion, but would result in a fragmented approach with many elements docked together.

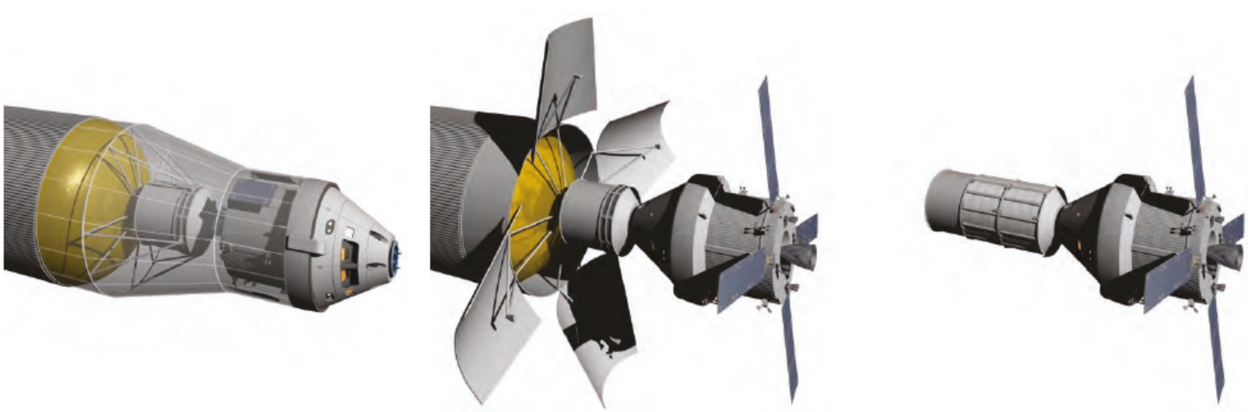


Figure 36: SLS "trunk" – compact transport with the Orion crew vehicle

NASA is currently studying ways to develop, test, and flight qualify critical Mars exploration mission technologies in the form of an Exploration Augmentation Module (EAM) that extends the range and duration of Orion missions in cis-lunar space. One of the studies proposed the development of a Core Node "machine room" as the basis for the EAM module. In such a scenario, a Core Node sized module would be docked at the International Space Station and fitted out with the latest Environmental Control and Life Support (ECLS) system. The module could be sealed off from the rest of the ISS for short, medium, and long duration tests, or undocked and flown to cis-lunar locations such as Earth-Moon Legrange points L1, L2, and beyond. As ECLS technology improves and miniaturization results in compact systems, older subsystems can be swapped out until the Core Node EAM approaches the target fidelity of partial closure for a Mars transit mission (Figure 37, left). The Mars transit habitat would then consist of the exact same Core Node as a pressurized core for a Bigelow / TransHab inflatable habitat. Figure 37, right, shows a Bigelow / TransHab habitat with a Core Node "machine room" pressurized core (inflatable membrane shown partially transparent for clarity), and dedicated dual chamber suitport airlock module.

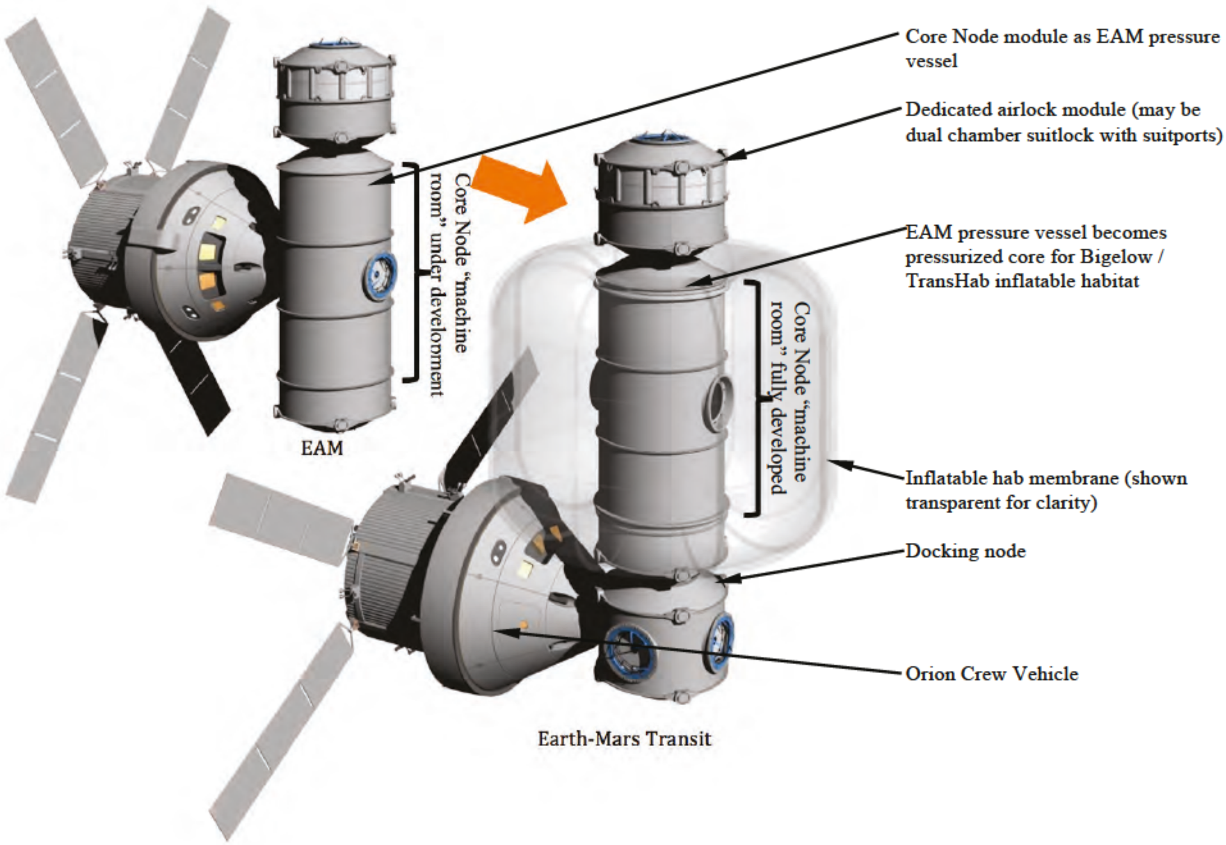


Figure 37: Concept for Exploration Augmentation Module (EAM) evolution into Mars transit habitat (propulsion stage not shown)

V. Conclusions

Several Mars habitation options were explored under the NASA Evolvable Mars Campaign studies, including monolithic, vertical modular, SLS-derived, and horizontal modular (the system highlighted in this discussion).

Monolithic habitats may be possible with larger landers such as the 41 ton class, and would require fewer landers to set up an outpost. However, monolithic modules may be difficult to congregate in a single location and may need to be left on the descent stage at the point of landing.

Vertical modular (HDU-style) habitats can be sized for various class landers and are sure to be a flexible solution for outpost design and build-up, since they can be sized for surface transport and relocation. However, a vertical modular system still requires multiple pressure vessels and would not be appropriate for small cabins like rovers, MAVs, or space taxis.

The SLS-derived habitat has similar problems as the monolithic, being unmovable once the descent stage touches down. However, advantages include use of elements manufactured on the same assembly line as the Space Launch System (SLS) and would provide for spacious volume.

Only the horizontal modular exploration system described in this paper would be appropriate with a single small-diameter solution for fixed-sized habitats, expandable habitats, small rover cabins, MAVs, space taxis, air locks, dual chamber suitport airlocks, logistics modules, large volume transit habitats, and early prototype EAM modules. The system assumes that various length modules, including habitats and rover cabins can all be manufactured on the same assembly line, using parametric barrel lengths and modular end domes and interior bulkheads. A major disadvantage of the horizontal modular exploration system discussed herein is that multiple small volumes need to be docked together creating greater risk of leakage and the possibility that multiple docking events could be unsuccessful. Fewer modules that need to be docked together reduce this risk.

None of the options have been eliminated yet. Future work will narrow down the possible descent stage landers to hopefully a single lander, which would further drive the final decision for which habitability option is appropriate. Future work may also allow for additional refinement of the horizontal modular exploration system described in this paper.

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