Sizing a Common Habitat for Multiple Environments and Mission Durations

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A human mission to Mars and other deep space destinations will require a consistent habitation strategy that applies to disparate environments preferably using multiples of identical hardware. The crew will endure high-g forces during launch, microgravity during transit, and various partial gravities on the destination planet, moon, or asteroid. Habitable volume will likely need to be broken up into smaller modules that do not exceed the capacity of launch vehicles and entry-descent-landing technologies. Though it may be possible to design a different unique, optimized habitat for each environment that the crew may encounter, it is more likely that space agencies and other mission sponsors will only have the resources to develop and produce single multi-use hardware that can be used equally well in all environments, with minimal adaptation by the crew. When sizing habitable volume, mission duration and number of crew become important factors to consider. For example, a pressurized rover cabin may only need to support two crew members for a few days at a time, requiring less volume than a habitat that must support the same number of persons for an entire year. In this study the authors consider constraining factors such as launch vehicle capacity, mission duration, crew size, and Mars lander capacity and study how to divide total pressurized volume, subsystems, equipment, consumables, and supplies into multiple manifests. Preference has been given to solutions that use multiples of identical modules over unique optimized volumes. For example at one extreme, can all the habitat pressure vessels, logistic modules, Mars ascent stage cabins, rover cabins, and airlocks be constructed from multiples of the same small-diameter cylindrical modules? On the other extreme, can logistics, habitation volume, mobility, all be enclosed in a single monolithic volume habitat design? Though there may be advantages and disadvantages to either extreme, the conclusion of this study is that most functions can be distilled into two sizes for hardware: multiples of large diameter modules that generally stay in one place, and multiples of smaller volume cabins that can be moved around or function as cockpits for ascent stages, support vehicles, rovers, airlocks, and logistics delivery.

Nomenclature

D-RATS	=	NASA Desert Research and Technology Studies analog missions
ECLSS	=	Environmental Control and Life Support System
EDL	=	Entry, Descent, and Landing System
EMC	=	Evolvable Mars Campaign
HDU	=	Habitat Demonstration Unit
HERA	=	Human Exploration Research Analog
High-g	=	High acceleration forces (g = gravity)

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MAV = Mars Ascent Vehicle
MEL = Mass and Equipment List
MS2A = NASA SLS stage adapter between Orion and the Exploration Upper Stage (same as USA, below)
NEO/NEA = Near Earth Object, or Near Earth Asteroid
SLS = NASA Space Launch System
USA = Universal Stage Adapter (same as MS2A, above)

I. Introduction

A Variety of Mars habitat designs have been proposed over the years (Cohen 2015). Vertically-oriented module types similar to the Habitat Demonstration Unit (HDU) prototype (Kennedy, et al 2011; Howe, Kennedy, Gill 2013), or horizontally-oriented module types (Kennedy, et al 2010; Howe 2015) have been considered as habitability options for the Evolvable Mars Campaign surface missions (Howe, et al 2015; Simon, et al 2015). Microgravity optimized habitats such as TransHab / Bigelow inflatables (Kennedy 1999; Kennedy 2009) or propellant tank type habitats similar to Skylab II (Griffin, et al 2012) have been proposed for transit stack habitats. Habitats have also been proposed for Phobos exploration (Abercromby, et al 2015).

This paper attempts to converge habitation functions into a single habitat type that can be taken through mulitple environments (Simon, et al 2015): 1) high-g launch environment out of Earth's gravity well; 2) long-duration microgravity transit environment, such as to Mars or some other deep space destination; 3) low gravity environments, such as in the vicinity of Mars moons, asteroids, or Near Earth Objects (NEO); 5) Entry, Descent, and Landing (EDL) environment, such as to the surface of the moon or Mars; and 6) planetary surface environments, such as on the moon or Mars. This paper begins with an overview of the current habitat design assumptions and constraints in Section II before describing various monolithic and modular habitat concepts designed with various rationales in Section III. Finally, this paper provides recommendations based upon the better performing habitat concepts.

II. Habitat Sizing Constraints

One aspect of the NASA Evolvable Mars Campaign (EMC) mission assumed that habitat elements would be sent to Mars and returned to Earth several times on multiple missions. Our assumptions for mission duration included 1,100 days for Mars transit, 500 days for a Mars moons segment, and 500 days for a Mars surface mission. These durations define the amount of logistics needed, ECLSS capacities, equipment masses and volumes, and total pressurized volume needed. Our approach in this paper was to do a simple reshuffle / repartition of stowage and equipment among multiple volumes, even though a more refined study would likely increase volume and mass slightly because of redundancy in modules – for example adding air-handling and fire suppression equipment to each module over and above that needed for life support. Therefore in our simple analysis, the same mass and volume numbers for equipment, logistics, consumables, and subsystems were divided up as needed and used for comparison across a variety of module geometries and combinations during a 1,100 day transit (Table 1), a 500 day Mars moon mission segment (Table 2), and a 500 day Mars surface mission segment (Table 3).

Table 1: Equipment, logistics, consumables, and subsystem mass and volume for 1,100 days Mars transit

1,100 day Transit Subsystem	Mass (kg)	Volume (m3)
Habitat structure	Design dependent	Design dependent
Protection	Design dependent	Design dependent
Spacecraft Power Systems	1,554	0.58
Thermal Control System	1,083	0.21
Avionics	368	0.62
Crew Accommodations	1,757	6.39
Advanced Life Support Systems	2,965	8.97
EVA Life Support	95	
Airlock & EVA Systems	1,996	6.00
Outfitting		1.39
Utilization	1,250	6.88
Provisions (CTBE Storage)	17,661	79.13
Water Storage	698	0.47

Table 2: Equipment, logistics, consumables, and subsystem mass and volume for 500 days Mars Moon segment

500 day Moons Subsystem	Mass (kg)	Volume (m3)
Habitat structure	Design dependent	Design dependent
Protection	Design dependent	Design dependent
Spacecraft Power Systems	577	0.58
Thermal Control System	747	0.20
Avionics	453	0.62
Crew Accommodations	1,307	6.39
Advanced Life Support Systems	3,380	8.97
EVA Life Support	88	
Airlock & EVA Systems	1,370	6.00
Outfitting		1.36
Utilization	1,000	6.88
Provisions (CTBE Storage)	10,541	47.94
Water Storage	613	0.47

Table 3: Equipment, logistics, consumables, and subsystem mass and volume for 500 days Mars surface mission

500 day Mars Subsystem	Mass (kg)	Volume (m3)
Habitat structure	Design dependent	Design dependent
Protection	Design dependent	Design dependent
Spacecraft Power Systems	579	0.58
Thermal Control System	751	0.20
Avionics	453	0.62
Crew Accommodations	1,307	6.39
Advanced Life Support Systems	3,385	8.97
EVA Life Support	88	
Airlock & EVA Systems	1,370	6.00
Outfitting		1.37
Utilization	1,000	6.88
Provisions (CTBE Storage)	10,543	47.94
Water Storage	613	0.47

Assuming constant values for mass and volume of physical equipment, subsystems and stowage, the habitat size was calculated based on three critical factors: an assumed minimal habitable volume, the capacity of the assumed launch vehicle; and capacity of the assumed EDL system(s).

Habitable Volume: Though at least 25m^3 free habitable volume per crew member was maintained in this study, it must be noted that there is some evidence that habitable volume should not level out for long duration missions as is implied in the Celentano Curve (Celentano, et al 1963) or NASA STD-3000 (NASA 1995, Section 8), but may require a gradual increase of free volume as durations grow longer and longer. It is recommended that all space architects involved with volume allotments for space missions review an extensive study of required volume for long-duration habitats that was conducted by Cohen (2009).

Launch Vehicle Capacity: In this paper, the NASA Space Launch System (SLS) launch vehicle capacity is assumed to be the baseline. The resulting maximum habitat diameter of 7.2m came from the SLS shroud dynamic envelope constraint. Due to a volatile political funding climate, one contingency study considered the possibility that should only the SLS Block 1B Crew Configuration be funded, how might a Mars mission be conducted without the added capacity of full-sized Block 1B Cargo, or Block 2 Cargo launch vehicles be accomplished?

Entry, Descent, and Langing Capacity: The overriding mass constraint laid on a multi-environment habitat module design was the capacity of EDL systems to safely land the hardware on a planetary surface, such as Mars. This paper shows habitats broken up into 10,000kg, 18,000kg, and 20,000kg, increment manifests, depending on the capacity of lander technology.

III. SLS USA-Derived Habitats

Using habitat sizing constraints described in the previous section, a quick study was made on whether smaller habitats up to 10,000kg could be launched on the Space Launch System (SLS) Block 1B Crew configuration, perhaps avoiding the higher-cost SLS Block 2 Cargo vehicle. This study started with two approaches that might take advantage of SLS architecture and still be optimal for planetary surface outpost construction.

In the SLS Block 1B Crew configuration, the Orion crew vehicle is attached to the launch vehicle via Universal Stage Adapters (USA) that have a certain amount of volume available, as cargo "trunk" space. A Short Cone adapter could accommodate a small habitat volume integrated with the faring (Figure 1, left). The Short Cone Habitat could be fitted with inflatable elements that expand the habitable volume upon launch (Figure 1, right).

Other variations studied for a "trunk-derived" habitat include the Extended Cone adapter (Figure 2), Cylinder habitat (Figure 3), and Universal Stage Adapter (USA) Cone Cylinder habitat options (Figure 4).

Cone Habitat

Pressurized Volume (m3)	95
MS2A Mass (kg)	2,500
Hab Mass (kg)	686
Total Mass (kg)	3,186

Cone Habitat + Inflatable

Hab Volume (m3)	95
Inflatable Volume (m3)	248
Total Pressurized Vol	343
Hab / MS2A Mass (kg)	3,186
Inflatable Mass (kg)	652
Total Mass (kg)	3,838

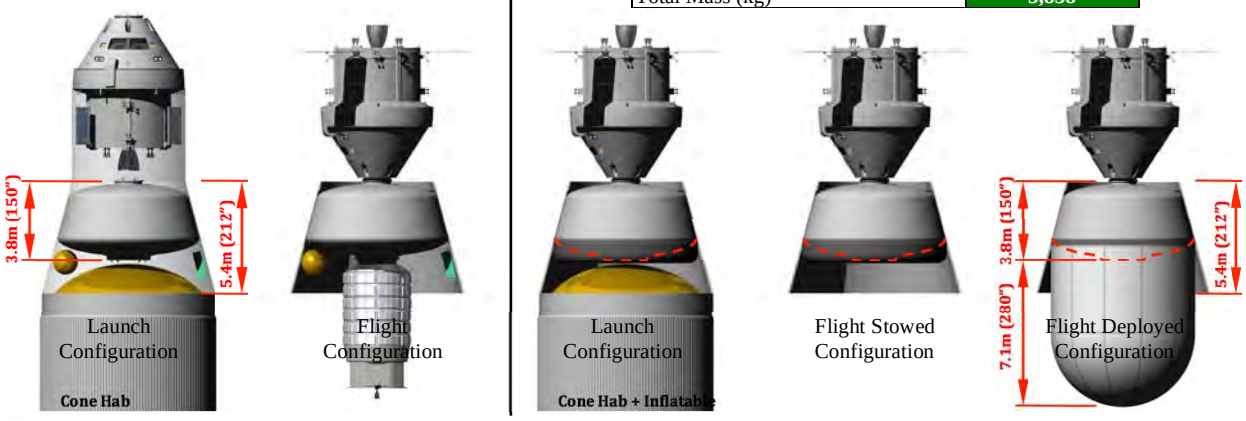

Figure 1: Space Launch System (SLS) Short Cone adapter habitat options, with Cone Habitat (left) and Habitat + Inflatable (right) (only structure masses are shown)

Extended Cone Habitat

Pressurized Volume (m3)	260
MS2A Mass (kg)	5,200
Hab Mass (kg)	711
Total Mass (kg)	5,911

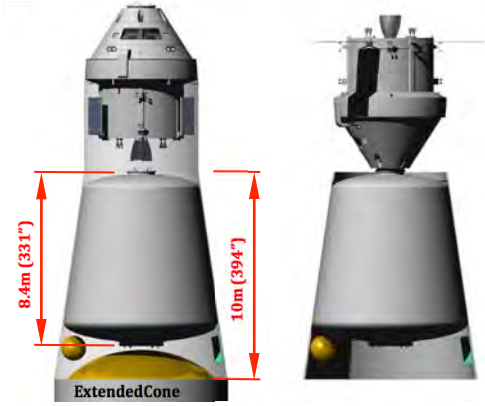

Figure 2: Space Launch System (SLS) Extended Cone adapter (only structure masses are shown)

Cylinder Habitat

Pressurized Volume (m3)	175
MS2A Mass (kg)	3,800
Hab Mass (kg)	1,645
Total Mass (kg)	5,445

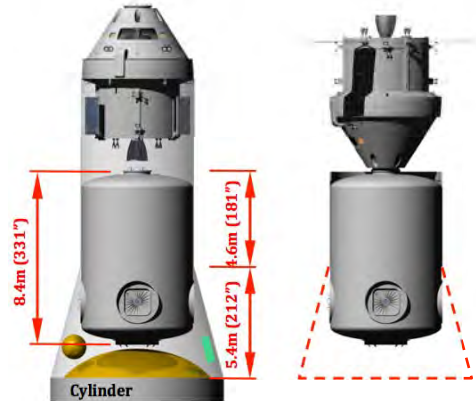

Figure 3: Space Launch System (SLS) Cylinder habitat option (only structure masses shown)

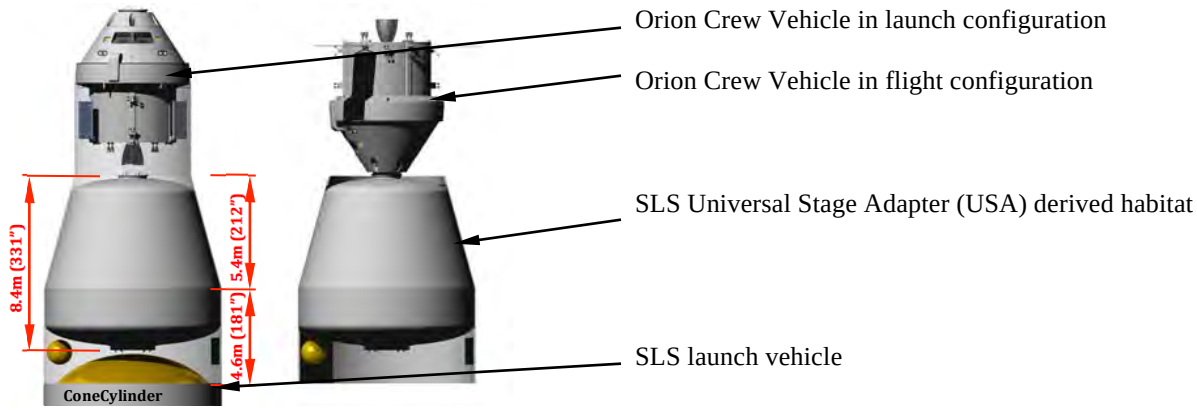

Figure 4: Space Launch System (SLS) Block 1B Crew Universal Stage Adapter (USA) Cone Cylinder habitat

Table 4: Space Launch System (SLS) Upper Stage Adapter (USA) ConeCylinder habitat study parameters

	Dome depth ratio	Faring Separate or Integrated[1]	Geometry Configuration	Pressurized Vol (m3)	Inside Dia (m)	Inside Height (m)	Floor Area (m2)	Skin Surface Area[2] (m2)	Number of Hatches	Notes
Volume Maximized	0.707 Dome	Separate	Cone	209.8	7.3	7.7	-	174.8	2	
			Cylinder	151.7	5.4	7.7	-	143.2	6	
		Integrated	Cone	264.6	8.2	7.7	-	202.6	2	
	0.5 Dome	Separate	Cone	222.0	7.3	7.7	-	183.7	2	
			Cone w Hatch	210.0	6.8	7.7	-	176.1	6	
			Cylinder	144.0	5.2	7.7	-	141.9	6	
		Integrated	Cone	283.0	8.2	7.7	-	214.3	2	
	0.25 Dome	Separate	Cone	237.0	7.3	7.7	-	197.2	2	
			Cone w Hatch	222.4	6.8	7.7	-	188.1	6	
			Cylinder	133.4	4.8	7.7	-	140.5	6	
		Integrated	Cone	305.0	8.2	7.7	-	231.4	6	Bubble hatch covers
			Cone w Hatch	280.8	7.5	7.7	-	217.5	6	
Floor Optimized	0.707 Dome	Separate	Cone	196.5	7.3	7.0	66.5	166.0	2	
			Cylinder	151.7	5.4	7.7	46.6	143.2	6	
		Integrated	Cone	264.5	8.1	7.7	86.5	202.5	2	
	0.5 Dome	Separate	Cone	210.3	7.3	7.1	75.2	175.8	2	
			Cone w Hatch	198.2	6.8	7.1	70.2	168.2	6	
			Cylinder	150.9	5.6	6.9	49.8	143.0	6	
		Integrated	Cone	283.0	8.2	7.7	94.5	214.3	2	
	0.25 Dome	Separate	Cone	195.3	7.3	5.7	80.4	171.3	2	
			Cone w Hatch	178.1	6.8	5.6	72.6	160.8	6	
			Cylinder	146.9	6.0	5.7	56.0	143.8	6	
		Integrated	Cone	259.4	8.2	6.1	100.9	207.0	6	Bubble hatch covers
			Cone w Hatch	232.0	7.5	6.0	88.4	191.6	6	

1. Separate faring opens up. Integrated case is where habitat is integral with faring wall
2. Skin surface area is provided to allow for structural mass estimates

A rigorous study using the USA Cone Cylinder habitat in various configurations was conducted, using 0.707 (optimal), 0.5, and 0.25 proportion end domes for faring enclosed and faring-integrated habitats (Table 4). In

particular, these configurations included volume-maximized vs floor-optimized approaches, which considered varying degrees of dependence on floor decks for internal layout and organization.

Though not detailed in this paper, the study showed that even though the small USA-derived modules would not exceed the capacity of launch vehicles or landers, reduced SLS co-manifested cargo capacities prevent the delivery of sufficient interior subsystems, crew equipment, and logistics to provide substantial operational capabilities. Additionally, it would require large numbers of them to construct the minimal required pressurized volume for the baseline 1,100 day mission, and would involved additional risks due to multiple hatches, pressurized dockings, and landings, not to mention an unacceptably large number of launches required. For these reasons, it was determined that a USA-derived habitat would not be practical, except for smaller logistics carriers or vehicle cabins.

IV. Modular / Monolithic Habitat Designs

Long-duration human missions will require multiple modules docked together to assemble sufficient habitable volume for the crew, but risk increases for each pressurized docking. Conventional wisdom seems to advocate grouping the volume into as few modules as possible, using a large-volume habitat combined with smaller pressurized cabins for rover vehicles, Mars Ascent Vehicle (MAV), and logistics carriers. Each new vehicle or cabin has its own functional requirements and uniqueness, which could multiply development costs for every new design. In addition, the various environments of Mars transit, Mars moons, and Mars surface each complicate configurations and internal layouts. A detailed discussion on the advantages of commonality, and an attempt to converge on as few unique types as possible is made in Griffin, et al (2015). For our study, habitable volume, cargo, equipment, logistics, subsystems, and structures were considered from launch to landing on Mars surface in an attempt to converge toward a single habitat module design that could be used in all three environments. It must be noted that the scope of this paper is strictly volume management – other differences between the various environments, such as microgravity versus gravity are not addressed.

Using a vertical cylinder design that could be launched using an SLS Block 1B Cargo or Block 2 Cargo configuration, we looked at several module alternatives that could be used singly, in multiples, or with inflatable elements to achieve various target volumes (Figure 5).

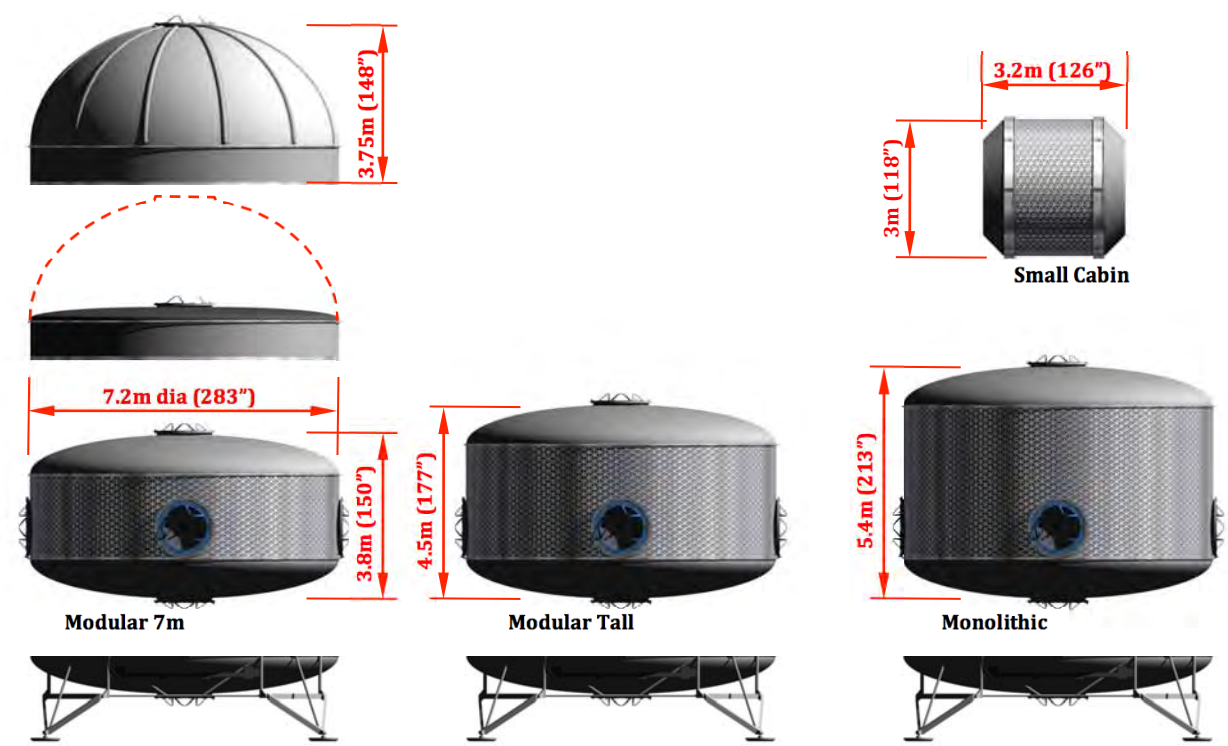

Figure 5: Vertical modular habitat alternative elements

A. Habitat Modules

Vertical cylinder habitats include the NASA Habitat Demonstration Unit (HDU) prototype at 5m diameter and 3m high (Kennedy, et al 2011; Howe, et al 2013). The HDU is currently renamed the Human Exploration Research Analog (HERA) undergoing analog missions studies at Johnson Space Center. Using the HDU as a starting point, the diameters of the habitats evaluated in this study were enlarged to 7.2m to maximize fit in the SLS shroud dynamic envelope. The various modules, with their masses and pressurized volume, are shown in Table 5.

The "types" of modules shown in Table 5 represent a gradation of pressurized volume from 90m^3 to 228m^3 capacities. Small Cabin commonality studies (Griffin, et al 2015) have also been folded in, where smaller volumes such as rover cabins, logistics modules, and ascent vehicle cockpits have been normalized into a single identical Small Cabin element. These Small Cabin elements are not compatible with the Logistics Vehicles shown at the bottom of Table 5, but would be used in place of those vehicles in an attempt to reduce the number of unique elements. Also, inflatable domes similar to that used on the HDU provide opportunities for additional volume once the dome is inflated. In addition to the habitat modules, peripheral support volumes can also be used to tally the total free habitable volume for each crew member, such as logistics carrier cabin volume, Orion spacecraft volume, pressurized rover volume, and ascent vehicle cabin volumes. In this paper Orion and rover cabin volume has been neglected in the final habitable volume per crewmember calculations.

Table 5: Habitat alternative elements considered in this study

	total	Masses (kg)					dimensions		Max	Payload
type	**vol (m3)**	element	hatches	**total**	floors	protection	dia (m)	height (m)	CTBs	Max (kg)
Habitat Modules										
Modular 6m	**90**	1,570	2,453	**4,023**	458	154	6.0	3.80		
Modular 7m	**130**	2,067	2,453	**4,520**	330	203	7.2	3.80		
Modular Tall	**159**	2,285	2,944	**5,228**	660	227	7.2	4.50		
Monolithic	**195**	2,565	2,944	**5,508**	660	257	7.2	5.40		
Monolithic Tall	**228**	2,813	2,944	**5,757**	660	284	7.2	6.20		
Inflatable Dome 7m	**90**	1,331	491	**1,822**	330	132	7.2	3.75		
Small Cabin										
Small Cabin	**21**	640	491	**1,522**	107	48	3.0	3.20		
Logistics Vehicles										
10t Cis Logistics	**69**	1,309	981	**2,290**	0	0	4.5	5.50	472	5770
15t Cis Logistics	**106**	1,809	981	**2,790**	0	0	4.5	8.20	772	9440
5t Mars Logistics	**42**	894	491	**1,385**	0	0	4.5	3.75	256	3100
10t Mars Logistics	**69**	1,234	491	**1,725**	0	0	4.5	5.50	472	5770

B. Volume Study Scenarios

Using the equipment, logistics, consumables, and subsystem mass / volume data in Table 1, Table 2, and Table 3, we have taken the various habitat elements in Table 5 and repackaged mission volumes and masses into various scenario combinations to see how many modules are needed, and whether similar sized modules could be used for all environments encountered by the mission.

Though the 7m diameter habitats are designed to fill out an SLS shroud, our study assumes that smaller cabin vehicles would likely be launched on smaller launch vehicles than the SLS. For nominal launch count in each scenario, we assume 1 module = 1 launch, and only count the number of launches in general without distinguishing between SLS or commercial launches. Combining multiple modules on a single launch would decrease the actual number of launches required, but such planning is outside of the scope of this paper.

For example, Figure 6 shows a Mars transit scenario using two large modules and several small logistics carriers. The scenario explores how to keep all elements below 10,000kg increments in order to stay within SLS Block 1B stage adapter capacity and minimize Mars entry mass. Using eight launches in Figure 6, two Modular 7m habitats and six logistics vehicles are brought together at a rendezvous point. The eight elements are docked together and their contents reshuffled in such a way that the logistics vehicles are completely emptied and their contents divided among the two hab modules. The two hab modules have enough volume capacity to carry all that extra stowage, but the logistics vehicles are needed because of the launch vehicle 10,000kg ceiling. Figure 6, right, shows the two hab modules in flight repacked with the contents from the logistics vehicles, now exceeding the 10,000kg launch limit for each module.

A key target for the Figure 6 scenario is to keep at least 25m^3 free habitable volume available for each crew member. Figure 6 habitable volume values are shown in red because the free volume is on the excessive side. During launch the free volume per crew member is over 65m^3 per person, and even after repacking the contents of the logistics vehicle into the two hab modules, the free volume per crew member is still a bit high at 33m^3/person. The reason for this is because the Modular 7m habitat already has the lowest ceiling height possible and cannot be shrunk any further while maintaining the 7.2m diameter.

(A) Transit Vertical Double Habitat (10ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**128.67**	**1.62**	**130.29**	**4,520**	**9,936**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Mass Growth Allowance					1,472	
Project Manager Res					736	
CTBE Storage			0.00		0	
Unusable Volume			0.21			
Modular 7m	**1**	**118.38**	**11.91**	**130.29**	**4,520**	**9,995**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Life Support			8.97		2,965	
Outfitting			1.39		0	
Mass Growth Allowance					1,538	
Project Manager Res					769	
CTBE Storage			0.00		0	
Unusable Volume			1.55		0	
Small Cabin Logistics	**6**	**13.21**	**113.69**	**127**	**9,132**	**37,234**
Structures (Internal)			0.00		0	
Protection			0.00		289	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Utilization			6.88		1,250	
Crew Accommodations			6.39		1,757	
Mass Growth Allowance					2,904	
Project Manager Res					1,452	
Water Storage			0.47		698	
CTBE Storage			79.13		17,661	
Unusable Volume			14.83			
Total		**260.25**		**387.48**		**57,164**

(B) Transit Vertical Double Habitat (10ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**65.42**	**64.87**	**130.29**	**4,520**	**22,322**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Mass Growth Allowance					1,546	
Project Manager Res					773	
CTBE Storage			55.00		12,275	
Unusable Volume			8.46			
Modular 7m	**1**	**67.94**	**62.35**	**130.29**	**4,520**	**22,706**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Life Support			8.97		2,965	
Crew Accommodations			6.39		1,757	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					2,557	
Project Manager Res					1,279	
CTBE Storage			24.13		5,386	
Water Storage			0.47		698	
Unusable Volume			8.13		0	
Total		**133.35**		**260.58**		**45,027**

*** Ceiling height constrained**

Figure 6: Habitat utilization scenario Mass and Equipment List (MEL) where launch constraints govern total mass per module (left), but once logistics and stowage is repackaged into the main modules, logistics carriers can be disgarded to reduce the number of modules in the stack (see Figure 10 in Appendix A for further explanation)

C. Scenario Matrices

A matrix was extablished for each environment (transit Table 6, Mars moons Table 7, Mars surface Table 8) that put mass ceilings on individual elements at launch and for Mars surface EDL. The mass ceilings are 10,000kg, 18,000kg, and 20,000kg read horizontally in the tables, with habitat geometries and approaches read vertically in the tables. Habitat approaches include a monolithic approach that attemps to put all volume into a single module, large habitat + small cabin combinations, and multiple habitat approaches. Special approaches include the use of a dedicated ECLSS module containing all ECLSS functions and equipment in a "machine room" approach, and the use of an inflatable dome to keep launch size compact. Blank cells in the matrices were scenarios that proved impractical or out of range. Each cell in the matrix lists nominal number of launches, list of habitat element types required to meet the needs of the mission, and free habitable volume available after all stowage, equipment, and subsystems have been accommodated. Final targets of 25m^3 free habitable volume per crewmember is noted, or whether the figure is over or under that target.

Table 6: Options and combinations for a Mars transit mission, showing element types from Table 5. Tallies of free habitable volume are totaled, with habitable volume per crewmember calculated for each cell scenario. Colors represent different ways of "slicing" the data. See Appendix A for detailed MELs of each of these scenarios.

	Monolithic Habitat	Hab + Small Cabin	Multiple Habitat	Habitat + ECLSS	Habitat + Inflatable
7m 10 ton max			8 LAUNCHES: Modular 7m 130m^3 Modular 7m 118m^3 Small Cabin Log 2m^3 Small Cabin Log 2m^3 Small Cabin Log 2m^3 Small Cabin Log 2m^3 Small Cabin Log 2m^3 Small Cabin Log 2m^3 **Total 260m^3** IN FLIGHT: Modular 7m 65m^3 Modular 7m 68m^3 **Total 133m^3** 33m^3 / person (over) (Fig 10 Appendix A)	7 LAUNCHES: Modular Tall 155m^3 Small Cabin ECLSS 1m^3 Small Cabin Log 0.4m^3 Small Cabin Log 0.4m^3 Small Cabin Log 0.4m^3 Small Cabin Log 0.4m^3 Small Cabin Log 0.4m^3 **Total 158m^3** IN FLIGHT: Modular Tall 82m^3 Small Cabin ECLSS 3m^3 Small Cabin Log 5m^3 Small Cabin Log 5m^3 **Total 95m^3** 24m^3 / person (Fig 11 Appendix A)	8 LAUNCHES: Modular 7m 129m^3 - Inflatable 7m 0m^3 Small Cabin ECLSS 4m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 **Total 151m^3** IN FLIGHT: Modular 7m 45m^3 - Inflatable 7m 70m^3 Small Cabin ECLSS 4m3 Small Cabin Log 20m3 **Total 139m^3** 35m^3 / person (over) (Fig 12 Appendix A)
7m 18 ton max		6 LAUNCHES: Modular 7m 107m^3 Small Cabin Log 0.5m^3 Small Cabin Log 0.5m^3 Small Cabin Log 0.5m^3 Small Cabin Log 0.5m^3 Small Cabin Log 0m^3 **Total 109m^3** IN FLIGHT: Modular 7m 86m^3 Small Cabin Log 0.5m^3 Small Cabin Log 0.5m^3 Small Cabin Log 0.5m^3 Small Cabin Log 0.5m^3 **Total 88m^3** 22m^3 / person (under) (Fig 13 Appendix A)	4 LAUNCHES: Modular 7m 106m^3 Modular 7m 69m^3 Small Cabin Log 0.5m^3 Small Cabin Log 0.5m^3 **Total 176m^3** IN FLIGHT: Modular 7m 59m^3 Modular 7m 74m^3 **Total 133m^3** 33m^3 / person (over) (Fig 14 Appendix A)	6 LAUNCHES: Modular Tall 121m^3 Small Cabin ECLSS 4m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 **Total 137m^3** IN FLIGHT: Modular Tall 71m^3 Small Cabin ECLSS 4m^3 Small Cabin Log 10m^3 Small Cabin Log 10m^3 **Total 95m^3** 24m^3 / person (Fig 15 Appendix A)	6 LAUNCHES: Modular 7m 103m^3 - Inflatable 7m 0m^3 Small Cabin ECLSS 2m^3 Small Cabin Log 1m^3 Small Cabin Log 1m^3 Small Cabin Log 1m^3 Small Cabin Log 1m^3 **Total 109m^3** IN FLIGHT: Modular 7m 78m^3 - Inflatable 7m 40m^3 Small Cabin ECLSS 4m^3 **Total 122m^3** 30m^3 / person (over) (Fig 16 Appendix A)
7m 20 ton max (10t Log)	5 LAUNCHES: Monolithic Tall 201m^3 10 ton Log 44m^3 10 ton Log 44m^3 10 ton Log 44m^3 10 ton Log 44m^3 **Total 377m^3** IN FLIGHT: Monolithic Tall 101m^3 **Total 101m^3** 25m^3 / person (Fig 17 Appendix A)	5 LAUNCHES: Modular 7m 99m^3 10 ton Log 45m^3 10 ton Log 45m^3 10 ton Log 45m^3 10 ton Log 45m^3 **Total 279m^3** IN FLIGHT: Modular 7m 31m^3 10 ton Log 55m^3 10 ton Log 55m^3 **Total 141m^3** 32m^3 / person (over) (Fig 18 Appendix A)			
7m 20 ton max (15t Log)	4 LAUNCHES: Monolithic Tall 200m^3 15 ton Log 73m^3 15 ton Log 73m^3 15 ton Log 73m^3 **Total 419m^3** IN FLIGHT: Monolithic Tall 101m^3 **Total 101m^3** 25m^3 / person (Fig 19 Appendix A)	4 LAUNCHES: Modular 7m 99m^3 15 ton Log 74m^3 15 ton Log 74m^3 15 ton Log 74m^3 **Total 321m^3** IN FLIGHT: Modular 7m 37m^3 15 ton Log 72m^3 **Total 109m^3** 27m^3 / person (Fig 20 Appendix A)			
6m 20 ton			3 LAUNCHES: Modular 6m 54m^3 Modular 6m 19m^3 Modular 6m 71m^3 **Total 144m^3** 36m^3 / person (over) (Fig 21 Appendix A)		

Table 7: Options and combinations for a Mars Moon mission segment, showing element types from Table 5. Tallies of free habitable volume are totaled, with habitable volume per crewmember calculated for each cell scenario. Colors represent different ways of "slicing" the data. See Appendix B for detailed MELs of each of these scenarios.

	Monolithic Habitat	Hab + Small Cabin	Multiple Habitat	Habitat + ECLSS	Habitat + Inflatable
7m 10 ton max			6 LAUNCHES: Modular 7m 124m^3 Modular 7m 117m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 **Total 253m^3** IN FLIGHT: Modular 7m 56m^3 Modular 7m 44m^3 **Total 100m^3** 25m^3 / person (Fig 22 Appendix B)	6 LAUNCHES: Modular Tall 152m^3 Small Cabin ECLSS 1m^3 Small Cabin Log 5m^3 Small Cabin Log 5m^3 Small Cabin Log 5m^3 Small Cabin Log 5m^3 **Total 173m^3** IN FLIGHT: Modular Tall 84m^3 Small Cabin ECLSS 4m^3 **Total 88m^3** 22m^3 / person (under) (Fig 23 Appendix B)	6 LAUNCHES: Modular Tall 128m^3 - Inflatable 7m 0m^3 Small Cabin ECLSS 1m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 **Total 145m^3** IN FLIGHT: Modular Tall 56m^3 - Inflatable 7m 90m^3 Small Cabin ECLSS 4m3 **Total 150m^3** 38m^3 / person (over) (Fig 24 Appendix B)
7m 18 ton max		4 LAUNCHES: Modular 7m 96m^3 Small Cabin Log 2m^3 Small Cabin Log 2m^3 Small Cabin Log 2m^3 **Total 102m^3** 26m^3 / person (Fig 25 Appendix B)	2 LAUNCHES: Modular 7m 95m^3 Modular 7m 74m^3 **Total 169m^3** 42m^3 / person (over) (Fig 26 Appendix B)	4 LAUNCHES: Modular Tall 114m^3 Small Cabin ECLSS 1m^3 Small Cabin Log 8m^3 Small Cabin Log 8m^3 **Total 131m^3** IN FLIGHT: Modular Tall 88m^3 Small Cabin ECLSS 1m^3 **Total 89m^3** 22m^3 / person (under) (Fig 27 Appendix B)	5 LAUNCHES: Modular 7m 108m^3 - Inflatable 7m 0m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 **Total 124m^3** IN FLIGHT: Modular 7m 39m^3 - Inflatable 7m 90m^3 **Total 129m^3** 32m^3 / person (over) (Fig 28 Appendix B)
7m 20 ton max (10t Log)	3 LAUNCHES: Monolithic Tall 189m^3 10 ton Log 43m^3 10 ton Log 43m^3 **Total 275m^3** IN FLIGHT: Monolithic Tall 137m^3 **Total 137m^3** 34m^3 / person (over) (Fig 29 Appendix B)				
7m 20 ton max (15t Log)	3 LAUNCHES: Monolithic Tall 189m^3 15 ton Log 80m^3 15 ton Log 80m^3 **Total 349m^3** IN FLIGHT: Monolithic Tall 137m^3 **Total 137m^3** 24m^3 / person (over) (Fig 30 Appendix B)				
6m 20 ton			2 LAUNCHES: Modular 6m 43m^3 Modular 6m 47m^3 **Total 90m^3** 23m^3 / person (Fig 31 Appendix B)		

Table 8: Options and combinations for a Mars surface mission segment, showing element types from Table 5. Tallies of free habitable volume are totaled, with habitable volume per crewmember calculated for each cell scenario. Colors represent different ways of "slicing" the data. See Appendix C for detailed MELs of each of these scenarios.

	Monolithic Habitat	Hab + Small Cabin	Multiple Habitat	Habitat + ECLSS	Habitat + Inflatable
7m 10 ton max			6 LAUNCHES: Modular 7m 123m^3 Modular 7m 116m^3 Small Cabin Log 1m^3 Small Cabin Log 1m^3 Small Cabin Log 1m^3 Small Cabin Log 1m^3 **Total 243m^3** IN FLIGHT: Modular 7m 87m^3 Modular 7m 73m^3 **Total 160m^3** 40m^3 / person (over) (Fig 32 Appendix C)	6 LAUNCHES: Modular Tall 151m^3 Small Cabin ECLSS 1m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 **Total 168m^3** IN FLIGHT: Modular Tall 80m^3 Small Cabin ECLSS 4m^3 **Total 84m^3** 21m^3 / person (under) (Fig 33 Appendix C)	6 LAUNCHES: Modular 7m 125m^3 - Inflatable 7m 0m^3 Small Cabin ECLSS 3m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 Small Cabin Log 3m^3 **Total 140m^3** IN FLIGHT: Modular 7m 52m^3 - Inflatable 7m 90m^3 Small Cabin ECLSS 4m3 **Total 146m^3** 36m^3 / person (over) (Fig 34 Appendix C)
7m 18 ton max		4 LAUNCHES: Modular 7m 95m^3 Small Cabin Log 1m^3 Small Cabin Log 1m^3 Small Cabin Log 1m^3 **Total 98m^3** 25m^3 / person (Fig 35 Appendix C)	2 LAUNCHES: Modular 7m 93m^3 Modular 7m 67m^3 **Total 160m^3** 40m^3 / person (over) (Fig 36 Appendix C)	4 LAUNCHES: Modular Tall 111m^3 Small Cabin ECLSS 1m^3 Small Cabin Log 7m^3 Small Cabin Log 7m^3 **Total 126m^3** IN FLIGHT: Modular Tall 83m^3 Small Cabin ECLSS 1m^3 **Total 84m^3** 21m^3 / person (under) (Fig 37 Appendix C)	6 LAUNCHES: Modular 7m 102m^3 - Inflatable 7m 0m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 Small Cabin Log 4m^3 **Total 118m^3** IN FLIGHT: Modular 7m 35m^3 - Inflatable 7m 90m^3 **Total 125m^3** 31m^3 / person (over) (Fig 38 Appendix C)
7m 20 ton max (5t Log)	5 LAUNCHES: Monolithic Tall 190m^3 5t Mars Log 27m^3 5t Mars Log 27m^3 5t Mars Log 27m^3 5t Mars Log 27m^3 **Total 298m^3** IN FLIGHT: Monolithic Tall 131m^3 **Total 131m^3** 33m^3 / person (over) (Fig 39 Appendix C)	5 LAUNCHES: Modular 7m 84m^3 5t Mars Log 29m^3 5t Mars Log 29m^3 5t Mars Log 29m^3 5t Mars Log 29m^3 **Total 200m^3** IN FLIGHT: Modular 7m 49m^3 5t Mars Log 27m^3 **Total 76m^3** 19m^3 / person (under) (Fig 40 Appendix C)			
7m 20 ton max (10t Log)	3 LAUNCHES: Monolithic Tall 190m^3 10t Mars Log 40m^3 10t Mars Log 40m^3 **Total 270m^3** IN FLIGHT: Monolithic Tall 132m^3 **Total 132m^3** 33m^3 / person (over) (Fig 41 Appendix C)	3 LAUNCHES: Modular 7m 84m^3 10t Mars Log 44m^3 10t Mars Log 44m^3 **Total 172m^3** IN FLIGHT: Modular 7m 55m^3 10t Mars Log 48m^3 **Total 103m^3** 26m^3 / person (Fig 42 Appendix C)			
6m 20 ton			2 LAUNCHES: Modular 6m 42m^3 Modular 6m 38m^3 **Total 80m^3** 20m^3 / person (under) (Fig 43 Appendix C)		

For example the scenario in the third cell, first row on Table 6 is an abbreviated summary of the Master Equipment List (MEL) shown in Figure 6. The scenario attempts to match habitat elements from Table 5 in such a way as to keep the total habitable volume around 25m^3 per crew member. Eight launches put two Modular 7m habitats and six Small Cabin logistics modules at the rendezvous point. Before reshuffling all the contents, each

element mass is below the 10,000kg mass ceiling. Since the mass ceiling is low, launch numbers are high because the same mass is spread out over more launch manifests. However, once contents can be reshuffled, most of the logistics modules can be jettisoned and still maintain a $25m^3$ habitable volume per crew member.

Detailed MELs similar to that shown in Figure 6 were derived for each scenario summary listed in the matrices in Table 6, Table 7, and Table 8, and are shown in Appendix A, B, and C of this paper.

D. Matrix Analysis

The results described in Table 6, Table 7, and Table 8 can be "sliced" in different ways depending on what the priorities of a mission might be. For example, if the main goal is to have as few launches as possible, the data shows (blue area) that large modules within the 20,000kg mass ceiling could function as both habitat volume and logistics module. With seven total launches, three Modular 6m elements could function as the Mars transit habitat, two more Modular 6m elements as a Mars moon habitat, and two more down on the surface of Mars as an outpost – no logistics carriers needed. Surely such a scenario would be the cheapest of all because it would require development costs for only one type of module manufactured seven times.

Alternatively, if the main goal was to have optimized, unique elements for each function (orange area, Table 6, Table 7, and Table 8), dedicated habitat modules, plus logistics carriers, plus unique rover cabins, plus optimized Mars Ascent Vehicle (MAV) cockpit would surely be the most expensive because there would be very little commonality between the various elements.

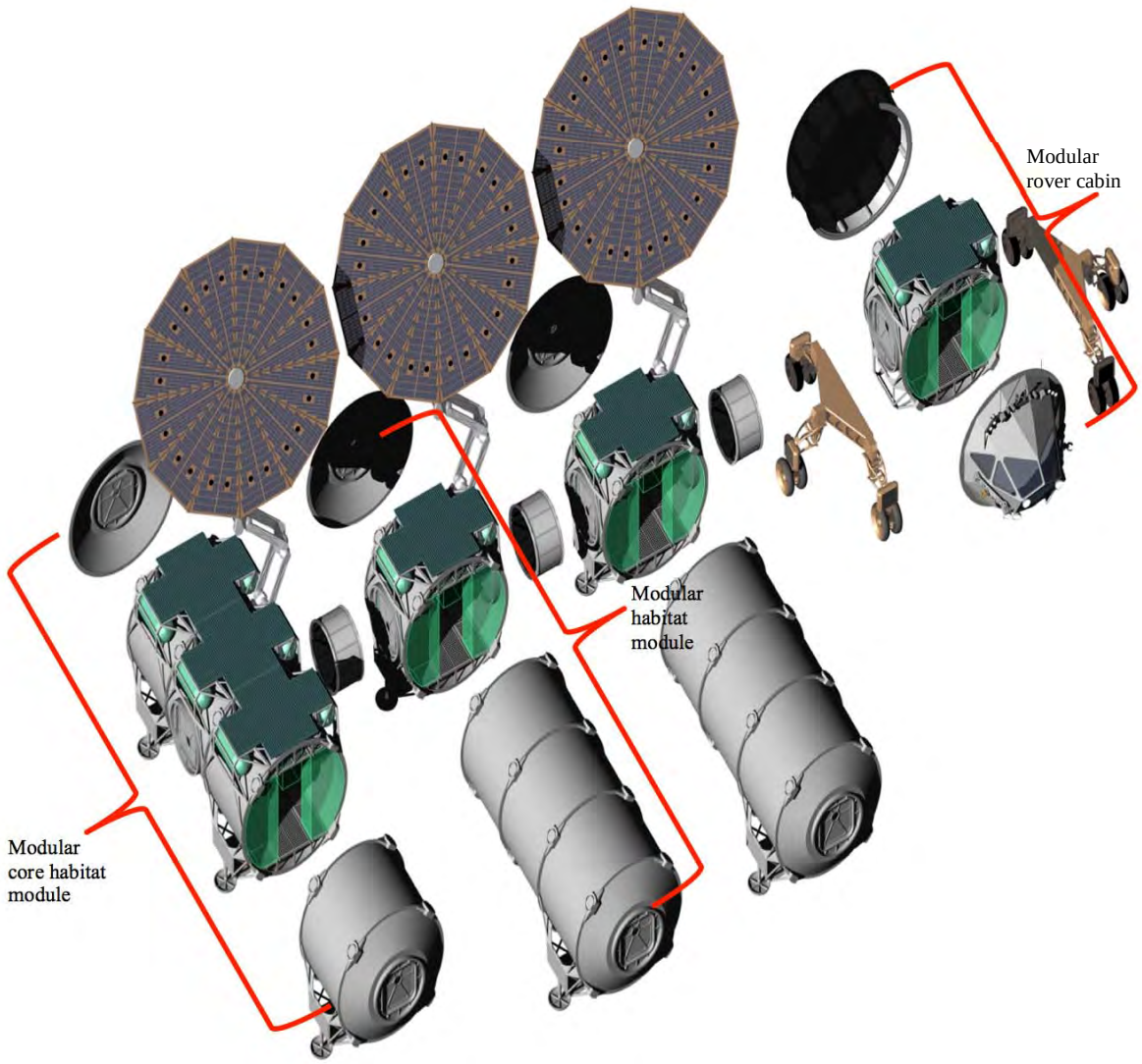

Figure 7: Small diameter common modularity for both habitat and vehicle cabins (Howe 2015)

A third way to "slice" the problem (green area, Table 6, Table 7, and Table 8) might result from a main goal to keep all the volume in a single module on a compact stack. In such a scenario multiple logistics modules stocking monolithic habitats in Cis-lunar space might make sense – ten total launches would result in a monolithic transit habitat stocked at Cis-lunar by three 15 ton logistics modules (subsequently jettisoned), a monolithic Mars moon habitat stocked at Cis-lunar by two 15 ton logistics modules (also jettisoned afterwards), and a monolithic Mars surface habitat stocked on the surface by two 10 ton surface logistics modules.

Other ways to "slice" the data are also possible, including least mass, lowest (or highest) volume, in-space assembly required, reshuffling of logistics required, etc.

E. Additional Studies Inspired by Search for a Common Habitat

Conventional thinking assumes that small cabin vehicles like short-duration pressurized rovers, logistics carriers, or MAV cockpits need to be smaller for more maneuverability and lower mass mobility systems. One modular approach may be to have mission-specific endcones or bulkheads manufactured into variable length barrels. The majority of development costs would be related to interfaces, endcones, mating processes and techniques, secondary / tertiary structures, and exterior subsystems without regard to whether the barrel is 8m or 9m long. Commonality between small cabins (Griffin, et al 2015) could be stretched to the habitat as well, keep all volumes at a similar small diameter of, say 3m (Howe 2015), using modular inflatable elements to create larger volumes on demand (Figure 7). Though supporting uniform commonality on manufacturing lines and modular subsystems, such a system would require many small elements, possibly expanding the number of launches needed.

Table 9: Transit MEL using a medium-sized "Modular 6m" common module

Transit Habitat (20ton increments)						
Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 6m	**1**	**54.80**	**35.68**	**90.48**	**4,023**	**19,818**
Structures (Internal)			0.00		0	
Protection			0.00		154	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					3,049	
Project Manager Res					1,524	
CTBE Storage			0.00		0	
Water Storage			0.00		0	
Unusable Volume			4.65			
Modular 6m	**1**	**18.64**	**71.84**	**90.48**	**4,023**	**19,966**
Structures (Internal)			0.00		0	
Protection			0.00		154	
Mass Growth Allowance					835	
Project Manager Res					418	
CTBE Storage			62.00		13,838	
Water Storage			0.47		698	
Unusable Volume			9.37			
Modular 6m	**1**	**70.78**	**19.70**	**90.48**	**4,023**	**9,253**
Structures (Internal)			0.00		0	
Protection			0.00		154	
Mass Growth Allowance					835	
Project Manager Res					418	
CTBE Storage			17.13		3,823	
Water Storage			0.00		0	
Unusable Volume			2.57			
Total		**144.21**		**271.44**		**49,037**

* Single size results in non-optimal volumes

Table 10: Mars moon mission segment MEL using the "Modular 6m" common module

Mars Moons Habitat (20ton increments)						
Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 6m	**1**	**42.79**	**47.69**	**90.48**	**4,023**	**19,840**
Structures (Internal)			0.00		0	
Protection			0.00		154	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.36		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,620	
Project Manager Res					1,310	
CTBE Storage			10.00		2,199	
Water Storage			0.47		613	
Unusable Volume			6.22			
Modular 6m	**1**	**46.85**	**43.63**	**90.48**	**4,023**	**13,772**
Structures (Internal)			0.00		0	
Protection			0.00		154	
Mass Growth Allowance					835	
Project Manager Res					418	
CTBE Storage			37.94		8,342	
Water Storage			0.00		0	
Unusable Volume			5.69			
Total		**89.64**		**180.96**		**33,612**

However on another extreme, it may be profitable to explore a system where all habitable elements use large or medium-sized modules. In Table 5 a "Modular 6m" module is included in the element lineup. Maintaining a 20,000kg ceiling for mass, a transit habitat stack would require 3 launches (Table 9), but no reshuffling and no logistics modules. Similarly, a Mars moon mission would only require 2 additional launches for a Phobos habitat stack, and no repacking or resupply from logistics modules.

Table 11: Mars surface mission segment MEL using the "Modular 6m" common module

Mars Surface Habitat (20ton increments)						
Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 6m	**1**	**41.51**	**48.96**	**90.48**	**4,023**	**19,791**
Structures (Internal)			4.11		458	
Protection			0.00		154	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,714	
Project Manager Res					1,357	
CTBE Storage			7.00		1,540	
Water Storage			0.47		613	
Unusable Volume			6.39			
Modular 6m	**1**	**38.14**	**52.34**	**90.48**	**4,023**	**15,642**
Structures (Internal)			4.11		458	
Protection			0.00		154	
Mass Growth Allowance					927	
Project Manager Res					463	
CTBE Storage			40.94		9,003	
Water Storage			0.47		613	
Unusable Volume			6.83			
Total		**79.65**		**180.96**		**35,432**

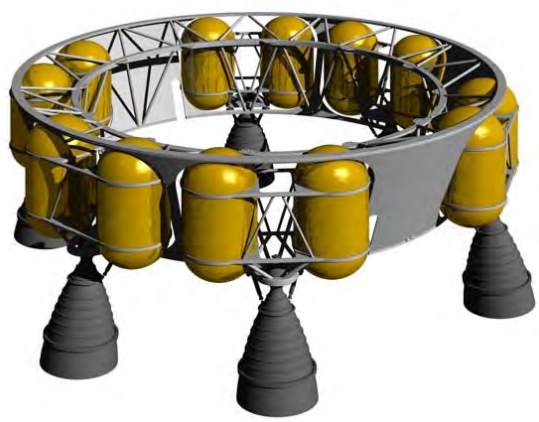

Figure 8: Ring-shaped lander design

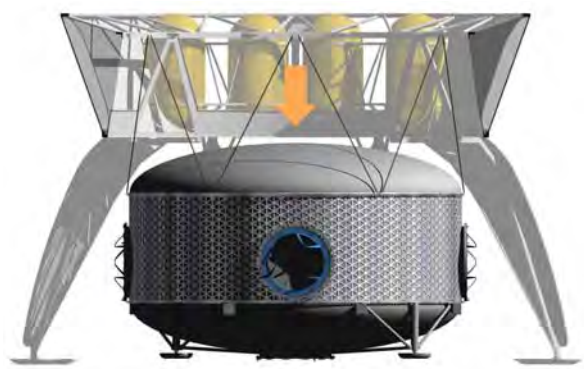

Figure 9: Habitat and other payloads can be dropped through bottom of ring lander

A "Modular 6m" medium-sized module would also need no restocking on the Mars surface (Table 11), where each module fits within a payload of a 20,000kg EDL lander (Figure 8) and can be lowered to the surface for repositioning (Figure 9). Our current prejudices call for a small rover vehicle that is maneuverable as a car or jeep. However since there are no highways, lanes, or confined traffic routes, using the "Modular 6m" module as a rover cabin may also be worth considering.

V. Conclusions and Recommendations

This paper provides a gradation of five habitat module sizes ranging from 90m^3 to 228m^3 pressurized volume. The volumes were chosen using a prestudy selection targeting 25m^3 free habitable volume per crew member and were analyzed to see how smaller support vehicles and reshuffling of stowage could allow a common habitat module type to emerge for all three legs of a Mars mission, regardless of changes in duration or environment. Our conclusion is that depending on metrics for the mission, grouping the volume into larger modules tends to reduce the number of launches required, and employ identical small cabins minimally refitted for unique purposes as needed.

We have so far placed emphasis on finding common identical fixed-size modules that can be used in all mission environments, whether that be microgravity transit, low gravity Mars moons / asteroids, or higher gravity Mars surface. Though the vertical cylinder barrel heights were adjusted somewhat arbitrarily to arrive at the range of volumes for the study, it may be an insignificant manufacturing cost to set up the manufacturing line so barrel heights can be adjusted to any parametric value. If such is the case, only the diameter would need to be maintained,

and barrel heights sized according to optimal constraints at each environment it is to be used. Other future work could include adding in measures of operational complexity in docking, unloading, and assembling modules after launch.

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Appendix A: Detailed Master Equipment Lists for Mars Transit Missions

The following pages show twelve (12) expanded Master Equipment Lists (MELs) showing mass breakdowns and manifest distributions for the results shown in Table 6. 1,100 day Mars transit mission equipment, logistics, consumables, and subsystems from Table 1 are manifested among multiple module elements. Detailed structure mass and dimensions of module elements are shown in Table 5.

(A) Transit Vertical Double Habitat (10ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**128.67**	**1.62**	**130.29**	**4,520**	**9,936**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Mass Growth Allowance					1,472	
Project Manager Res					736	
CTBE Storage			0.00		0	
Unusable Volume			0.21			
Modular 7m	**1**	**118.38**	**11.91**	**130.29**	**4,520**	**9,995**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Life Support			8.97		2,965	
Outfitting			1.39		0	
Mass Growth Allowance					1,538	
Project Manager Res					769	
CTBE Storage			0.00		0	
Unusable Volume			1.55		0	
Small Cabin Logistics	**6**	**13.21**	**113.69**	**127**	**9,132**	**37,234**
Structures (Internal)			0.00		0	
Protection			0.00		289	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Utilization			6.88		1,250	
Crew Accommodations			6.39		1,757	
Mass Growth Allowance					2,904	
Project Manager Res					1,452	
Water Storage			0.47		698	
CTBE Storage			79.13		17,661	
Unusable Volume			14.83			
Total		**260.25**		**387.48**		**57,164**

(B) Transit Vertical Double Habitat (10ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**65.42**	**64.87**	**130.29**	**4,520**	**22,322**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Mass Growth Allowance					1,546	
Project Manager Res					773	
CTBE Storage			55.00		12,275	
Unusable Volume			8.46			
Modular 7m	**1**	**67.94**	**62.35**	**130.29**	**4,520**	**22,706**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Life Support			8.97		2,965	
Crew Accommodations			6.39		1,757	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					2,557	
Project Manager Res					1,279	
CTBE Storage			24.13		5,386	
Water Storage			0.47		698	
Unusable Volume			8.13		0	
Total		**133.35**		**260.58**		**45,027**

*** Ceiling height constrained**

Figure 10 Appendix A: Using multiple habitat modules and small cabin logistics carriers, launch mass for each module is kept at 10,000kg increments (left). Once habitat modules and logistics carriers have launched, are in flight, and have completed rendezvous, the 10,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat modules and discarded (right). Even after the cargo has been reapportioned, total free habitable volume during flight is 133m^3, leaving 33m^3/person which is slightly over the target 25m^3/person. The "Modular 7m" element is already set at a minimal height due to required internal ceiling clearance, so the 33m^3 cannot be reduced down to the target 25m^3. Assuming one module element per launch, this scenario requires eight (8) launches.

(A) Transit Vertical Habitat + ECLSS Module (10ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**155.81**	**2.98**	**158.79**	**5,228**	**9,559**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Avionics			0.62		368	
Outfitting			1.39		0	
Mass Growth Allowance					1,471	
Project Manager Res					735	
CTBE Storage			0.00		0	
Unusable Volume			0.39			
Small Cabin ECLSS	**1**	**0.49**	**20.66**	**21**	**1,522**	**9,284**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Mass Growth Allowance					1,325	
Project Manager Res					663	
CTBE Storage			3.00		670	
Unusable Volume			2.70			
Small Cabin Logistics	**5**	**2.17**	**103.58**	**106**	**7,610**	**33,213**
Structures (Internal)			0.00		0	
Protection			0.00		241	
Thermal			0.21		1,083	
Crew Accommodations			6.39		1,757	
Utilization			6.88		1,250	
Mass Growth Allowance					2,388	
Project Manager Res					1,194	
Water Storage			0.47		698	
CTBE Storage			76.13		16,991	
Unusable Volume			13.51			
Total		**158.47**		**285.69**		**52,055**

(B) Transit Vertical Habitat + ECLSS Module (10ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**82.52**	**76.27**	**158.79**	**5,228**	**25,326**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					2,072	
Project Manager Res					1,036	
CTBE Storage			50.00		11,159	
Water Storage			0.47		698	
Unusable Volume			9.95			
Small Cabin ECLSS	**1**	**2.79**	**18.36**	**21**	**1,522**	**8,837**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Mass Growth Allowance					1,325	
Project Manager Res					663	
CTBE Storage			1.00		223	
Unusable Volume			2.40			
Small Cabin Logistics	**2**	**9.71**	**32.59**	**42**	**3,044**	**11,769**
Structures (Internal)			0.00		0	
Protection			0.00		96	
Thermal			0.21		1,083	
Mass Growth Allowance					845	
Project Manager Res					422	
CTBE Storage			28.13		6,278	
Unusable Volume			4.25			
Total		**95.02**		**222.24**		**45,932**

Figure 11 Appendix A: Using one habitat module, a dedicated "machine room" ECLSS module, and multiple small cabin logistics carriers, launch mass for each module is kept at 10,000kg increments (left). Once habitat module and logistics carriers have launched, are in flight, and have completed rendezvous, the 10,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). Since there is only one habitat module, two of the small cabin logistics carriers are retained for living volume. The total habitable volume of 95m^3 leaves 24m^3/person which is near the target 25m^3/person. Assuming one module element per launch, this scenario requires seven (7) launches.

(A) Transit Vertical Habitat + Inflatable (10ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**127.98**	**2.31**	**130.29**	**4,520**	**9,049**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Avionics			0.62		368	
Outfitting			1.39		0	
Mass Growth Allowance					1,018	
Project Manager Res					509	
CTBE Storage			0.00		0	
Water Storage			0.00		0	
Unusable Volume			0.30			
Inflatable Dome 7m	**1**	**0.00**	**0.00**	**0**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			0.00		0	
Small Cabin ECLSS	**1**	**3.94**	**17.21**	**21**	**1,522**	**8,614**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Mass Growth Allowance					1,325	
Project Manager Res					663	
CTBE Storage			0.00		0	
Unusable Volume			2.25			
Small Cabin Logistics	**6**	**19.20**	**107.70**	**127**	**9,132**	**37,944**
Structures (Internal)			0.00		0	
Protection			0.00		289	
Power			0.58		1,554	
Thermal			0.21		1,083	
Crew Accommodations			6.39		1,757	
Utilization			6.88		1,250	
Mass Growth Allowance					3,013	
Project Manager Res					1,507	
CTBE Storage			79.13		17,661	
Water Storage			0.47		698	
Unusable Volume			14.05			
Total		**151.12**		**278.34**		**55,607**

(A) Transit Vertical Habitat + Inflatable (10ton increments) in Flight

Element	Number	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**44.19**	**86.10**	**130.29**	**4,520**	**31,318**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					1,620	
Project Manager Res					810	
CTBE Storage			59.13		13,197	
Water Storage			0.47		698	
Unusable Volume			11.23			
Inflatable Dome 7m	**1**	**70.25**	**20.00**	**90**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			20.00		4,464	
Small Cabin ECLSS	**1**	**3.94**	**17.21**	**21**	**1,522**	**8,614**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Mass Growth Allowance					1,325	
Project Manager Res					663	
CTBE Storage			0.00		0	
Unusable Volume			2.25			
Small Cabin Logistics	**1**	**20.24**	**0.91**	**21**	**1,522**	**5,469**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Power			0.58		1,554	
Thermal			0.21		1,083	
Mass Growth Allowance					841	
Project Manager Res					421	
Unusable Volume			0.12			
Total		**138.62**		**262.84**		**45,401**

Figure 12 Appendix A: Using one habitat module, a dedicated "machine room" ECLSS module, an HDU-type inflatable dome, and multiple small cabin logistics carriers, launch mass for each module is kept at 10,000kg increments (left). Once habitat module and logistics carriers have launched, are in flight, inflated, and have completed rendezvous, the 10,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and inflatable dome and discarded (right). A single small cabin logistics carrier is retained for living volume. The total habitable volume of 139m^3 leaves 35m^3/person which is over the target 25m^3/person. Assuming one module element per launch, this scenario requires eight (8) launches.

Transit Vertical Single Habitat (18ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**105.87**	**24.42**	**130.29**	**4,520**	**17,987**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Mass Growth Allowance					2,557	
Project Manager Res					1,278	
CTBE Storage			3.00		670	
Water Storage			0.47		698	
Unusable Volume			3.19			
Small Cabin Logistics	**5**	**2.95**	**102.80**	**106**	**7,610**	**31,107**
Structures (Internal)			0.00		0	
Protection			0.00		241	
Crew Accommodations			6.39		1,757	
Utilization			6.88		1,250	
Mass Growth Allowance					2,172	
Project Manager Res					1,086	
CTBE Storage			76.13		16,991	
Unusable Volume			13.41			
Total		**108.82**		**236.04**		**49,094**

Transit Vertical Single Habitat (18ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**87.17**	**43.12**	**130.29**	**4,520**	**22,566**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Crew Accommodations			6.39		1,757	
Utilization			6.88		1,250	
Outfitting			1.39		0	
Mass Growth Allowance					3,158	
Project Manager Res					1,579	
CTBE Storage			6.00		1,339	
Water Storage			0.47		698	
Unusable Volume			5.62			
Small Cabin Logistics	**4**	**0.50**	**84.10**	**85**	**6,088**	**24,487**
Structures (Internal)			0.00		0	
Protection			0.00		193	
Mass Growth Allowance					1,256	
Project Manager Res					628	
CTBE Storage			73.13		16,322	
Unusable Volume			10.97			
Total		**87.67**		**214.89**		**47,052**

Figure 13 Appendix A: Using a single habitat module and multiple small cabin logistics carriers, launch mass for each module is kept at 18,000kg increments (left). Once habitat modules and logistics carriers have launched, are in flight, inflated, and have completed rendezvous, the 18,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). Four small cabin logistics carriers are retained for living volume. The total habitable volume of 88m^3 leaves 22m^3/person which is under the target 25m^3/person. Assuming one module element per launch, this scenario requires six (6) launches.

(A) Transit Vertical Double Habitat (18ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**105.87**	**24.42**	**130.29**	**4,520**	**17,987**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Mass Growth Allowance					2,557	
Project Manager Res					1,278	
CTBE Storage			3.00		670	
Water Storage			0.47		698	
Unusable Volume			3.19			
Modular 7m	**1**	**69.19**	**61.10**	**130.29**	**4,520**	**17,998**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Mass Growth Allowance					945	
Project Manager Res					472	
CTBE Storage			53.13		11,858	
Unusable Volume			7.97		0	
Small Cabin Logistics	**2**	**0.60**	**41.70**	**42**	**3,044**	**13,125**
Structures (Internal)			0.00		0	
Protection			0.00		96	
Crew Accommodations			6.39		1,757	
Utilization			6.88		1,250	
Mass Growth Allowance					1,229	
Project Manager Res					615	
CTBE Storage			23.00		5,133	
Unusable Volume			5.44			
Total		**175.65**		**302.88**		**49,110**

(B) Transit Vertical Double Habitat (18ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**59.57**	**70.72**	**130.29**	**4,520**	**27,922**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					3,158	
Project Manager Res					1,579	
CTBE Storage			30.00		6,696	
Water Storage			0.47		698	
Unusable Volume			9.22			
Modular 7m	**1**	**73.79**	**56.50**	**130.29**	**4,520**	**17,105**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Mass Growth Allowance					945	
Project Manager Res					472	
CTBE Storage			49.13		10,965	
Unusable Volume			7.37		0	
Total		**133.35**		**260.58**		**45,027**

*** Ceiling height constrained**

Figure 14 Appendix A: Using multiple habitat modules and small cabin logistics carriers, launch mass for each module is kept at 18,000kg increments (left). Once habitat modules and logistics carriers have launched, are in flight, and have completed rendezvous, the 18,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat modules and discarded (right). Even after the cargo has been reapportioned, total free habitable volume during flight is 133m^3, leaving 33m^3/person which is slightly over the target 25m^3/person. The "Modular 7m" element is already set at a minimal height due to required internal ceiling clearance, so the 33m^3 cannot be reduced down to the target 25m^3. Assuming one module element per launch, this scenario requires four (4) launches.

Transit Vertical Habitat + ECLSS Module (10ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**122.83**	**35.96**	**158.79**	**5,228**	**17,915**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Outfitting			1.39		0	
Mass Growth Allowance					1,687	
Project Manager Res					844	
CTBE Storage			28.00		6,249	
Water Storage			0.47		698	
Unusable Volume			4.69			
Small Cabin ECLSS	**1**	**3.94**	**17.21**	**21**	**1,522**	**8,614**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Mass Growth Allowance					1,325	
Project Manager Res					663	
CTBE Storage			0.00		0	
Unusable Volume			2.25			
Small Cabin Logistics	**4**	**10.55**	**74.05**	**85**	**6,088**	**23,486**
Structures (Internal)			0.00		0	
Protection			0.00		193	
Crew Accommodations			6.39		1,757	
Utilization			6.88		1,250	
Mass Growth Allowance					1,858	
Project Manager Res					929	
CTBE Storage			51.13		11,412	
Unusable Volume			9.66			
Total		**137.32**		**264.54**		**50,014**

Transit Vertical Habitat + ECLSS Module (10ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**70.78**	**88.01**	**158.79**	**5,228**	**28,966**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Utilization			6.88		1,250	
Outfitting			1.39		0	
Mass Growth Allowance					2,289	
Project Manager Res					1,144	
CTBE Storage			60.00		13,391	
Water Storage			0.47		698	
Unusable Volume			11.48			
Small Cabin ECLSS	**1**	**3.94**	**17.21**	**21**	**1,522**	**8,614**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Mass Growth Allowance					1,325	
Project Manager Res					663	
CTBE Storage			0.00		0	
Unusable Volume			2.25			
Small Cabin Logistics	**2**	**20.30**	**22.00**	**42**	**3,044**	**8,352**
Structures (Internal)			0.00		0	
Protection			0.00		96	
Mass Growth Allowance					628	
Project Manager Res					314	
CTBE Storage			19.13		4,270	
Unusable Volume			2.87			
Total		**95.02**		**222.24**		**45,932**

Figure 15 Appendix A: Using one habitat module, a dedicated "machine room" ECLSS module, and multiple small cabin logistics carriers, launch mass for each module is kept at 18,000kg increments (left). Once habitat module and logistics carriers have launched, are in flight, and have completed rendezvous, the 18,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). Since there is only one habitat module, two of the small cabin logistics carriers are retained for living volume. The total habitable volume of 95m^3 leaves 24m^3/person which is near the target 25m^3/person. Assuming one module element per launch, this scenario requires six (6) launches.

(A) Transit Vertical Habitat + Inflatable (18ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**103.63**	**26.66**	**130.29**	**4,520**	**17,952**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Outfitting			1.39		0	
Utilization			5.00		909	
Mass Growth Allowance					2,079	
Project Manager Res					1,039	
CTBE Storage			9.00		2,009	
Water Storage			0.00		0	
Unusable Volume			3.48			
Inflatable Dome 7m	**1**	**0.00**	**0.00**	**0**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			0.00		0	
Small Cabin ECLSS	**1**	**1.64**	**19.51**	**21**	**1,522**	**9,060**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Mass Growth Allowance					1,325	
Project Manager Res					663	
CTBE Storage			2.00		446	
Unusable Volume			2.55			
Small Cabin Logistics	**4**	**3.62**	**80.98**	**85**	**6,088**	**24,512**
Structures (Internal)			0.00		0	
Protection			0.00		193	
Utilization			1.88		341	
Mass Growth Allowance					1,324	
Project Manager Res					662	
CTBE Storage			68.13		15,206	
Water Storage			0.47		698	
Unusable Volume			10.50			
Total		**108.89**		**236.04**		**51,525**

(A) Transit Vertical Habitat + Inflatable (18ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**77.78**	**52.51**	**130.29**	**4,520**	**34,746**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					2,147	
Project Manager Res					1,074	
CTBE Storage			29.13		6,502	
Water Storage			0.47		698	
Unusable Volume			6.85			
Inflatable Dome 7m	**1**	**40.25**	**50.00**	**90**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			50.00		11,159	
Small Cabin ECLSS	**1**	**3.94**	**17.21**	**21**	**1,522**	**8,614**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Mass Growth Allowance					1,325	
Project Manager Res					663	
CTBE Storage			0.00		0	
Unusable Volume			2.25			
Total		**121.97**		**241.69**		**43,360**

Figure 16 Appendix A: Using one habitat module, a dedicated "machine room" ECLSS module, an HDU-type inflatable dome, and multiple small cabin logistics carriers, launch mass for each module is kept at 18,000kg increments (left). Once habitat module and logistics carriers have launched, are in flight, inflated, and have completed rendezvous, the 18,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and inflatable dome and discarded (right). The total habitable volume of 122m^3 leaves 30m^3/person which is over the target 25m^3/person. Assuming one module element per launch, this scenario requires six (6) launches.

Transit Habitat (20ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**202.28**	**25.72**	**228.00**	**5,757**	**19,978**
Structures (Internal)			0.00		0	
Protection			0.00		284	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			4.60		1,265	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			0.00		0	
Mass Growth Allowance					3,073	
Project Manager Res					1,537	
CTBE Storage			0.00		0	
Unusable Volume			3.35			
10t Cis Logistics	**4**	**174.50**	**101.50**	**276**	**9,160**	**37,021**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					480	
Control					0	
Avionics					280	
Thermal					680	
ECLSS					1,040	
Crew Systems					40	
Mass Growth Allowance					1,160	
Payload Adapter					2,520	
Project Manager Res					1,560	
CTBE Storage			79.13		17,661	
Water Storage			0.47		698	
Crew Accommodations			1.79		492	
Utilization			6.88		1,250	
Unusable Volume			13.24			
Total		**376.78**		**504.00**		**56,998**

Transit Habitat (20ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**100.78**	**127.22**	**228.00**	**5,757**	**40,601**
Structures (Internal)			0.00		0	
Protection			0.00		284	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					3,422	
Project Manager Res					1,711	
CTBE Storage			79.13		17,661	
Water Storage			0.47		698	
Unusable Volume			16.59			
Total		**100.78**		**228.00**		**40,601**

Figure 17 Appendix A: Using a monolithic habitat module and multiple 10 ton logistics carriers, launch mass for each module is kept at 20,000kg increments (10,000kg for logistics modules). Once habitat modules and logistics carriers have launched, are in flight (left), and have completed rendezvous, the 20,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right) leaving a monolithic habitat element. The total habitable volume of 101m^3 leaves 25m^3/person which is on target. Assuming one module element per launch, this scenario requires five (5) launches.

Transit Habitat (20ton increments) at launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**98.06**	**32.23**	**130.29**	**4,520**	**19,819**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			3.88		705	
Mass Growth Allowance					3,049	
Project Manager Res					1,525	
CTBE Storage			0.00		0	
Water Storage			0.00		0	
Unusable Volume			4.20			
10t Cis Logistics	**4**	**181.01**	**94.99**	**276**	**9,160**	**35,824**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					480	
Control					0	
Avionics					280	
Thermal					680	
ECLSS					1,040	
Crew Systems					40	
Mass Growth Allowance					1,160	
Payload Adapter					2,520	
Project Manager Res					1,560	
CTBE Storage			79.13		17,661	
Water Storage			0.47		698	
Crew Accommodations			0.00		0	
Utilization			3.00		545	
Unusable Volume			12.39			
Total		**279.07**		**406.29**		**55,644**

Transit Habitat fully stocked in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**32.04**	**98.25**	**130.29**	**4,520**	**33,279**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					3,158	
Project Manager Res					1,579	
CTBE Storage			54.00		12,052	
Water Storage			0.47		698	
Unusable Volume			12.75			
10t Cis Logistics	**2**	**109.10**	**28.90**	**138**	**4,580**	**14,069**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					240	
Control					0	
Avionics					140	
Thermal					340	
ECLSS					520	
Crew Systems					20	
Mass Growth Allowance					580	
Payload Adapter					1,260	
Project Manager Res					780	
CTBE Storage			25.13		5,609	
Water Storage			0.00		0	
Crew Accommodations			0.00		0	
Utilization			0.00		0	
Unusable Volume			3.77			
Total		**141.14**		**268.29**		**47,347**

Figure 18 Appendix A: Using a single habitat module and multiple 10 ton logistics carriers, launch mass for each module is kept at 20,000kg increments (10,000kg for logistics modules). Once habitat modules and logistics carriers have launched, are in flight (left), and have completed rendezvous, the 20,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). Two 10 ton logistics carriers are retained for living volume. The total habitable volume of 141m^3 leaves 32m^3/person which is over the target 25m^3/person. Assuming one module element per launch, this scenario requires five (5) launches.

Transit Habitat (20ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**200.81**	**27.19**	**228.00**	**5,757**	**19,965**
Structures (Internal)			0.00		0	
Protection			0.00		284	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			2.00		550	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			3.88		705	
Mass Growth Allowance					3,072	
Project Manager Res					1,536	
CTBE Storage			0.00		0	
Unusable Volume			3.55			
15t Cis Logistics	**3**	**217.97**	**100.03**	**318**	**8,370**	**35,381**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					540	
Control					0	
Avionics					210	
Thermal					780	
ECLSS					900	
Crew Systems					60	
Mass Growth Allowance					1,140	
Payload Adapter					1,890	
Project Manager Res					1,380	
CTBE Storage			79.13		17,661	
Water Storage			0.47		698	
Crew Accommodations			4.39		1,207	
Utilization			3.00		545	
Unusable Volume			13.05			
Total		**418.78**		**546.00**		**55,346**

Transit Habitat (20ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**100.78**	**127.22**	**228.00**	**5,757**	**40,601**
Structures (Internal)			0.00		0	
Protection			0.00		284	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					3,422	
Project Manager Res					1,711	
CTBE Storage			79.13		17,661	
Water Storage			0.47		698	
Unusable Volume			16.59			
Total		**100.78**		**228.00**		**40,601**

Figure 19 Appendix A: Using a monolithic habitat module and multiple 15 ton logistics carriers, launch mass for each module is kept at 20,000kg increments (15,000kg for logistics modules). Once habitat modules and logistics carriers have launched, are in flight (left), and have completed rendezvous, the 20,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right) leaving a monolithic habitat element. The total habitable volume of 101m^3 leaves 25m^3/person which is on target. Assuming one module element per launch, this scenario requires four (4) launches.

Transit Habitat (20ton increments) at launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**98.06**	**32.23**	**130.29**	**4,520**	**19,819**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			3.88		705	
Mass Growth Allowance					3,049	
Project Manager Res					1,525	
CTBE Storage			0.00		0	
Water Storage			0.00		0	
Unusable Volume			4.20			
15t Cis Logistics	**3**	**223.01**	**94.99**	**318**	**8,370**	**34,174**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					540	
Control					0	
Avionics					210	
Thermal					780	
ECLSS					900	
Crew Systems					60	
Mass Growth Allowance					1,140	
Payload Adapter					1,890	
Project Manager Res					1,380	
CTBE Storage			79.13		17,661	
Water Storage			0.47		698	
Crew Accommodations			0.00		0	
Utilization			3.00		545	
Unusable Volume			12.39			
Total		**321.07**		**448.29**		**53,994**

Transit Habitat fully stocked in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**36.64**	**93.65**	**130.29**	**4,520**	**32,386**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					3,158	
Project Manager Res					1,579	
CTBE Storage			50.00		11,159	
Water Storage			0.47		698	
Unusable Volume			12.15			
15t Cis Logistics	**1**	**72.50**	**33.50**	**106**	**2,790**	**11,591**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					180	
Control					0	
Avionics					70	
Thermal					260	
ECLSS					300	
Crew Systems					20	
Mass Growth Allowance					380	
Payload Adapter					630	
Project Manager Res					460	
CTBE Storage			29.13		6,502	
Water Storage			0.00		0	
Crew Accommodations			0.00		0	
Utilization			0.00		0	
Unusable Volume			4.37			
Total		**109.14**		**236.29**		**43,977**

Figure 20 Appendix A: Using a single habitat module and multiple 15 ton logistics carriers, launch mass for each module is kept at 20,000kg increments (15,000kg for logistics modules). Once habitat modules and logistics carriers have launched, are in flight (left), and have completed rendezvous, the 20,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). A single 15 ton logistics carrier is retained for living volume. The total habitable volume of 109m^3 leaves 27m^3/person which is on target. Assuming one module element per launch, this scenario requires four (4) launches.

Transit Habitat (20ton increments)

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 6m	**1**	**54.80**	**35.68**	**90.48**	**4,023**	**19,818**
Structures (Internal)			0.00		0	
Protection			0.00		154	
Power			0.58		1,554	
Thermal			0.21		1,083	
Avionics			0.62		368	
Crew Accommodations			6.39		1,757	
Life Support			8.97		2,965	
EVA Life Support					95	
Airlock & EVA			6.00		1,996	
Outfitting			1.39		0	
Utilization			6.88		1,250	
Mass Growth Allowance					3,049	
Project Manager Res					1,524	
CTBE Storage			0.00		0	
Water Storage			0.00		0	
Unusable Volume			4.65			
Modular 6m	**1**	**18.64**	**71.84**	**90.48**	**4,023**	**19,966**
Structures (Internal)			0.00		0	
Protection			0.00		154	
Mass Growth Allowance					835	
Project Manager Res					418	
CTBE Storage			62.00		13,838	
Water Storage			0.47		698	
Unusable Volume			9.37			
Modular 6m	**1**	**70.78**	**19.70**	**90.48**	**4,023**	**9,253**
Structures (Internal)			0.00		0	
Protection			0.00		154	
Mass Growth Allowance					835	
Project Manager Res					418	
CTBE Storage			17.13		3,823	
Water Storage			0.00		0	
Unusable Volume			2.57			
Total		**144.21**		**271.44**		**49,037**

*** Single size results in non-optimal volumes**

Figure 21 Appendix A: Using multiple habitat modules, launch mass for each module is kept at 20,000kg increments. No reapportioning or shifting of cargo is needed. Total free habitable volume is 144m^3, leaving 36m^3/person which is slightly over the target 25m^3/person. The "Modular 6m" element is already set at a minimal height due to required internal ceiling clearance, so the 33m^3 cannot be reduced down to the target 25m^3. Assuming one module element per launch, this scenario requires three (3) launches.

Appendix B: Detailed Master Equipment Lists for Mars Moon Missions

The following pages show ten (10) expanded Master Equipment Lists (MELs) showing mass breakdowns and manifest distributions for the results shown in Table 7. 500 day Mars moon mission equipment, logistics, consumables, and subsystems from Table 2 are manifested among multiple module elements. Detailed structure mass and dimensions of module elements are shown in Table 5.

(A) Mars Moons Vertical Double Habitat (10ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**125.23**	**5.06**	**130.29**	**4,520**	**9,920**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Life Support			3.00		1,131	
Mass Growth Allowance					1,526	
Project Manager Res					763	
CTBE Storage			0.00		0	
Unusable Volume			0.66			
Modular 7m	**1**	**117.26**	**13.03**	**130.29**	**4,520**	**9,944**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Life Support			5.97		2,249	
Outfitting			1.36		0	
Mass Growth Allowance					1,395	
Project Manager Res					697	
CTBE Storage			4.00		880	
Unusable Volume			1.70		0	
Small Cabin Logistics	**4**	**11.38**	**73.22**	**85**	**6,088**	**23,334**
Structures (Internal)			0.00		0	
Protection			0.00		193	
Crew Accommodations			6.39		1,307	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Utilization			6.88		1,000	
Mass Growth Allowance					2,009	
Project Manager Res					1,005	
CTBE Storage			43.94		9,661	
Water Storage			0.47		613	
Unusable Volume			9.55			
Total		**253.86**		**345.18**		**43,198**

(B) Mars Moons Vertical Double Habitat (10ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**56.23**	**74.06**	**130.29**	**4,520**	**23,113**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Life Support			3.00		1,131	
Mass Growth Allowance					1,526	
Project Manager Res					763	
CTBE Storage			60.00		13,194	
Unusable Volume			9.66			
Modular 7m	**1**	**44.03**	**86.25**	**130.29**	**4,520**	**25,113**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Life Support			5.97		2,249	
Crew Accommodations			6.39		1,307	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.36		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,148	
Project Manager Res					1,074	
CTBE Storage			47.94		10,541	
Water Storage			0.47		613	
Unusable Volume			11.25		0	
Total		**100.26**		**260.58**		**48,226**

Figure 22 Appendix B: Using multiple habitat modules and small cabin logistics carriers, launch mass for each module is kept at 10,000kg increments (left). Once habitat modules and logistics carriers have launched, are in flight, and have completed rendezvous, the 10,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat modules and discarded (right). The total free habitable volume during flight is 100m^3, leaving 25m^3/person which is on target. Assuming one module element per launch, this scenario requires six (6) launches.

(A) Mars Moons Vertical Habitat + ECLSS Module (10ton) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**155.07**	**3.72**	**158.79**	**5,228**	**9,984**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Outfitting			1.36		0	
Mass Growth Allowance					1,442	
Project Manager Res					721	
CTBE Storage			0.00		0	
Water Storage			0.47		613	
Unusable Volume			0.49			
Small Cabin ECLSS	**1**	**0.49**	**20.66**	**21**	**1,522**	**8,990**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,282	
Project Manager Res					641	
CTBE Storage			3.00		660	
Unusable Volume			2.70			
Small Cabin Logistics	**4**	**17.67**	**66.93**	**85**	**6,088**	**21,045**
Structures (Internal)			0.00		0	
Protection			0.00		193	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Mass Growth Allowance					1,718	
Project Manager Res					859	
CTBE Storage			44.94		9,881	
Unusable Volume			8.73			
Total		**173.23**		**264.54**		**40,019**

(B) Mars Moons Vertical Habitat + ECLSS Module (10ton) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**84.69**	**74.10**	**158.79**	**5,228**	**23,525**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Outfitting			1.36		0	
Utilization			6.88		1,000	
Mass Growth Allowance					1,903	
Project Manager Res					952	
CTBE Storage			47.94		10,542	
Water Storage			0.47		613	
Unusable Volume			9.67			
Small Cabin ECLSS	**1**	**3.94**	**17.21**	**21**	**1,522**	**8,331**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,282	
Project Manager Res					641	
CTBE Storage			0.00		0	
Unusable Volume			2.25			
Total		**88.62**		**179.94**		**31,855**

Figure 23 Appendix B: Using one habitat module, a dedicated "machine room" ECLSS module, and multiple small cabin logistics carriers, launch mass for each module is kept at 10,000kg increments (left). Once habitat module and logistics carriers have launched, are in flight, and have completed rendezvous, the 10,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). The total habitable volume of 88m^3 leaves 22m^3/person which is under the target 25m^3/person. Assuming one module element per launch, this scenario requires six (6) launches.

(A) Mars Moons Vertical Habitat + Inflatable (10ton) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**128.08**	**2.21**	**130.29**	**4,520**	**9,995**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.35		348	
Thermal			0.20		747	
Outfitting			1.36		0	
Mass Growth Allowance					1,164	
Project Manager Res					582	
CTBE Storage			0.00		0	
Unusable Volume			0.29			
Inflatable Dome 7m	**1**	**0.00**	**0.00**	**0**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			0.00		0	
Small Cabin ECLSS	**1**	**0.66**	**20.49**	**21**	**1,522**	**9,657**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Power			0.23		229	
Life Support			8.97		3,380	
Avionics			0.62		453	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,418	
Project Manager Res					709	
CTBE Storage			2.00		440	
Unusable Volume			2.67			
Small Cabin Logistics	**4**	**15.98**	**68.62**	**85**	**6,088**	**21,878**
Structures (Internal)			0.00		0	
Protection			0.00		193	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Mass Growth Allowance					1,718	
Project Manager Res					859	
CTBE Storage			45.94		10,101	
Water Storage			0.47		613	
Unusable Volume			8.95			
Total		**144.72**		**236.04**		**41,530**

(B) Mars Moons Vertical Habitat + Inflatable (10ton) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**56.45**	**73.84**	**130.29**	**4,520**	**24,473**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Power			0.35		348	
Thermal			0.20		747	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Outfitting			1.36		0	
Utilization			6.88		1,000	
Mass Growth Allowance					1,675	
Project Manager Res					838	
CTBE Storage			47.94		10,541	
Water Storage			0.47		613	
Unusable Volume			9.63			
Inflatable Dome 7m	**1**	**90.25**	**0.00**	**90**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			0.00		0	
Small Cabin ECLSS	**1**	**3.67**	**17.48**	**21**	**1,522**	**8,628**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Power			0.23		229	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,327	
Project Manager Res					664	
CTBE Storage			0.00		0	
Unusable Volume			2.28			
Total		**150.38**		**241.69**		**33,101**

*** Ceiling height constrained (dome)**

*** Optimized for transit**

Figure 24 Appendix B: Using one habitat module, a dedicated "machine room" ECLSS module, an HDU-type inflatable dome, and multiple small cabin logistics carriers, launch mass for each module is kept at 10,000kg increments (left). Once habitat module and logistics carriers have launched, are in flight, inflated, and have completed rendezvous, the 10,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and inflatable dome and discarded (right). The total habitable volume of 150m^3 leaves 38m^3/person which is over the target 25m^3/person. Assuming one module element per launch, this scenario requires six (6) launches.

Mars Moons Vertical Single Habitat (18ton increments)						
Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**95.56**	**34.73**	**130.29**	**4,520**	**17,991**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.36		0	
Mass Growth Allowance					2,268	
Project Manager Res					1,134	
CTBE Storage			12.00		2,639	
Water Storage			0.47		613	
Unusable Volume			4.53			
Small Cabin Logistics	**3**	**6.87**	**56.58**	**63**	**4,566**	**16,822**
Structures (Internal)			0.00		0	
Protection			0.00		144	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Mass Growth Allowance					1,404	
Project Manager Res					702	
CTBE Storage			35.94		7,699	
Unusable Volume			7.38			
Total		**102.42**		**193.74**		**34,813**

Figure 25 Appendix B: Using a single habitat module and multiple small cabin logistics carriers, launch mass for each module is kept at 18,000kg increments. No reapportioning or shifting of cargo is needed. All three small cabin logistics carriers are retained for living volume. The total habitable volume of 102m^3 leaves 26m^3/person which is near the target 25m^3/person. Assuming one module element per launch, this scenario requires four (4) launches.

Mars Moons Vertical Double Habitat (18ton increments)						
Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**95.56**	**34.73**	**130.29**	**4,520**	**17,991**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.36		0	
Mass Growth Allowance					2,268	
Project Manager Res					1,134	
CTBE Storage			12.00		2,639	
Water Storage			0.47		613	
Unusable Volume			4.53			
Modular 7m	**1**	**73.71**	**56.58**	**130.29**	**4,520**	**16,778**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Mass Growth Allowance					1,365	
Project Manager Res					683	
CTBE Storage			35.94		7,902	
Unusable Volume			7.38		0	
Total		**169.26**		**260.58**		**34,769**

*** Ceiling height constrained**

Figure 26 Appendix B: Using multiple habitat modules, launch mass for each module is kept at 18,000kg increments. No reapportioning or shifting of cargo is needed. Total free habitable volume during flight is 169m^3, leaving 42m^3/person which is over the target 25m^3/person. The "Modular 7m" element is already set at a minimal height due to required internal ceiling clearance, so the 42m^3 cannot be reduced down to the target 25m^3. Assuming one module element per launch, this scenario requires two (2) launches.

Mars Moons Vertical Habitat + ECLSS (18ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**113.94**	**44.85**	**158.79**	**5,228**	**17,931**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Outfitting			1.36		0	
Mass Growth Allowance					1,903	
Project Manager Res					952	
CTBE Storage			22.50		4,948	
Water Storage			0.47		613	
Unusable Volume			5.85			
Small Cabin ECLSS	**1**	**0.49**	**20.66**	**21**	**1,522**	**8,990**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,282	
Project Manager Res					641	
CTBE Storage			3.00		660	
Unusable Volume			2.70			
Small Cabin Logistics	**2**	**16.50**	**25.80**	**42**	**3,044**	**9,016**
Structures (Internal)			0.00		0	
Protection			0.00		96	
Mass Growth Allowance					628	
Project Manager Res					314	
CTBE Storage			22.44		4,934	
Unusable Volume			3.37			
Total		**130.93**		**222.24**		**35,937**

Mars Moons Vertical Habitat + ECLSS (18ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**88.14**	**70.65**	**158.79**	**5,228**	**22,601**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Outfitting			1.36		0	
Mass Growth Allowance					1,862	
Project Manager Res					931	
CTBE Storage			44.94		9,882	
Water Storage			0.47		613	
Unusable Volume			9.22			
Small Cabin ECLSS	**1**	**0.49**	**20.66**	**21**	**1,522**	**8,990**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,282	
Project Manager Res					641	
CTBE Storage			3.00		660	
Unusable Volume			2.70			
Total		**88.62**		**179.94**		**31,591**

Figure 27 Appendix B: Using one habitat module, a dedicated "machine room" ECLSS module, and multiple small cabin logistics carriers, launch mass for each module is kept at 18,000kg increments (left). Once habitat module and logistics carriers have launched, are in flight, and have completed rendezvous, the 18,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). The total habitable volume of 89m^3 leaves 22m^3/person which is under the target 25m^3/person. Assuming one module element per launch, this scenario requires four (4) launches.

(A) Mars Moons Vertical Habitat + Inflatable (18ton) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**108.78**	**21.51**	**130.29**	**4,520**	**17,893**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Outfitting			1.36		0	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					2,268	
Project Manager Res					1,134	
CTBE Storage			0.50		110	
Water Storage			0.47		613	
Unusable Volume			2.81			
Inflatable Dome 7m	**1**	**0.00**	**0.00**	**0**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			0.00		0	
Small Cabin Logistics	**4**	**14.79**	**69.81**	**85**	**6,088**	**21,595**
Structures (Internal)			0.00		0	
Protection			0.00		193	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Mass Growth Allowance					1,718	
Project Manager Res					859	
CTBE Storage			47.44		10,431	
Unusable Volume			9.11			
Total		**123.57**		**214.89**		**39,489**

(B) Mars Moons Vertical Habitat + Inflatable (18ton) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**38.97**	**91.31**	**130.29**	**4,520**	**31,324**
Structures (Internal)			0.00		0	
Protection			0.00		203	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Outfitting			1.36		0	
Utilization			6.88		1,000	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					2,729	
Project Manager Res					1,365	
CTBE Storage			47.94		10,541	
Water Storage			0.47		613	
Unusable Volume			11.91			
Inflatable Dome 7m	**1**	**90.25**	**0.00**	**90**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			0.00		0	
Total		**129.23**		**220.54**		**31,324**

*** Ceiling height constrained (dome)**

*** Optimized for transit**

Figure 28 Appendix B: Using one habitat module, an HDU-type inflatable dome, and multiple small cabin logistics carriers, launch mass for each module is kept at 18,000kg increments (left). Once habitat module and logistics carriers have launched, are in flight, inflated, and have completed rendezvous, the 18,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and inflatable dome and discarded (right). The total habitable volume of 129m^3 leaves 32m^3/person which is over the target 25m^3/person. Assuming one module element per launch, this scenario requires five (5) launches.

Mars Moons Habitat (20ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**189.24**	**38.76**	**228.00**	**5,757**	**19,966**
Structures (Internal)			0.00		0	
Protection			0.00		284	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Crew Accommodations			4.60		941	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.36		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,919	
Project Manager Res					1,460	
CTBE Storage			4.50		990	
Unusable Volume			5.06			
10t Cis Logistics	**2**	**85.45**	**52.55**	**138**	**4,580**	**18,990**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					240	
Control					0	
Avionics					140	
Thermal					340	
ECLSS					520	
Crew Systems					20	
Mass Growth Allowance					580	
Payload Adapter					1,260	
Project Manager Res					780	
CTBE Storage			43.44		9,551	
Water Storage			0.47		613	
Crew Accommodations			1.79		366	
Utilization			0.00		0	
Unusable Volume			6.85			
Total		**274.69**		**366.00**		**38,956**

Mars Moons Habitat (20ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**136.69**	**91.31**	**228.00**	**5,757**	**30,606**
Structures (Internal)			0.00		0	
Protection			0.00		284	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.36		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,993	
Project Manager Res					1,496	
CTBE Storage			47.94		10,541	
Water Storage			0.47		613	
Unusable Volume			11.91			
Total		**136.69**		**228.00**		**30,606**

Figure 29 Appendix B: Using a monolithic habitat module and two 10 ton logistics carriers, launch mass for each module is kept at 20,000kg increments (10,000kg for logistics modules). Once habitat modules and logistics carriers have launched, are in flight (left), and have completed rendezvous, the 20,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right) leaving a monolithic habitat element. The total habitable volume of 137m^3 leaves 34m^3/person which is over the target 25m^3/person. Assuming one module element per launch, this scenario requires three (3) launches.

Mars Moons Habitat (20ton increments) at Launch

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**188.78**	**39.22**	**228.00**	**5,757**	**19,934**
Structures (Internal)			0.00		0	
Protection			0.00		284	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Crew Accommodations			2.00		409	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.36		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,813	
Project Manager Res					1,407	
CTBE Storage			7.50		1,649	
Unusable Volume			5.12			
15t Cis Logistics	**2**	**159.91**	**52.09**	**212**	**5,580**	**20,583**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					360	
Control					0	
Avionics					140	
Thermal					520	
ECLSS					600	
Crew Systems					40	
Mass Growth Allowance					760	
Payload Adapter					1,260	
Project Manager Res					920	
CTBE Storage			40.44		8,892	
Water Storage			0.47		613	
Crew Accommodations			4.39		898	
Utilization			0.00		0	
Unusable Volume			6.79			
Total		**348.69**		**440.00**		**40,517**

Mars Moons Habitat (20ton increments) in Flight

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**136.69**	**91.31**	**228.00**	**5,757**	**30,606**
Structures (Internal)			0.00		0	
Protection			0.00		284	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.36		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,993	
Project Manager Res					1,496	
CTBE Storage			47.94		10,541	
Water Storage			0.47		613	
Unusable Volume			11.91			
Total		**136.69**		**228.00**		**30,606**

Figure 30 Appendix B: Using a monolithic habitat module and two 15 ton logistics carriers, launch mass for each module is kept at 20,000kg increments (15,000kg for logistics modules). Once habitat modules and logistics carriers have launched, are in flight (left), and have completed rendezvous, the 20,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right) leaving a monolithic habitat element. The total habitable volume of 137m^3 leaves 34m^3/person which is over the target 25m^3/person. Assuming one module element per launch, this scenario requires three (3) launches.

Mars Moons Habitat (20ton increments)						
Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 6m	**1**	**42.79**	**47.69**	**90.48**	**4,023**	**19,840**
Structures (Internal)			0.00		0	
Protection			0.00		154	
Power			0.58		577	
Thermal			0.20		747	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,380	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.36		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,620	
Project Manager Res					1,310	
CTBE Storage			10.00		2,199	
Water Storage			0.47		613	
Unusable Volume			6.22			
Modular 6m	**1**	**46.85**	**43.63**	**90.48**	**4,023**	**13,772**
Structures (Internal)			0.00		0	
Protection			0.00		154	
Mass Growth Allowance					835	
Project Manager Res					418	
CTBE Storage			37.94		8,342	
Water Storage			0.00		0	
Unusable Volume			5.69			
Total		**89.64**		**180.96**		**33,612**

Figure 31 Appendix B: Using two habitat modules, launch mass for each module is kept at 20,000kg increments. No reapportioning or shifting of cargo is needed. Total free habitable volume is 90m^3, leaving 23m^3/person which is slightly under the target 25m^3/person. Assuming one module element per launch, this scenario requires two (2) launches.

Appendix C: Detailed Master Equipment Lists for Mars Surface Missions

The following pages show twelve (12) expanded Master Equipment Lists (MELs) showing mass breakdowns and manifest distributions for the results shown in Table 8. 500 day Mars surface mission equipment, logistics, consumables, and subsystems from Table 3 are manifested among multiple module elements. Detailed structure mass and dimensions of module elements are shown in Table 5.

(A) Mars Vertical Double Habitat (10ton increments) at Landing

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**121.65**	**8.64**	**130.29**	**4,520**	**9,868**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Life Support			2.00		755	
Avionics			0.62		453	
Mass Growth Allowance					1,518	
Project Manager Res					759	
CTBE Storage			0.00		0	
Unusable Volume			1.13			
Modular 7m	**1**	**115.98**	**14.31**	**130.29**	**4,520**	**9,988**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Life Support			6.97		2,630	
Outfitting			1.37		0	
Mass Growth Allowance					1,537	
Project Manager Res					768	
CTBE Storage			0.00		0	
Unusable Volume			1.87			
Small Cabin Logistics	**4**	**5.25**	**79.35**	**85**	**6,088**	**24,354**
Structures (Internal)			1.33		107	
Protection			0.00		193	
Crew Accommodations			6.39		1,307	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Utilization			6.88		1,000	
Mass Growth Allowance					2,031	
Project Manager Res					1,015	
CTBE Storage			47.94		10,543	
Water Storage			0.47		613	
Unusable Volume			10.35			
Total		**242.88**		**345.18**		**44,210**

(B) Mars Vertical Double Habitat Fully Stocked on Surface

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**87.15**	**43.14**	**130.29**	**4,520**	**16,466**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Life Support			2.00		755	
Mass Growth Allowance					1,518	
Project Manager Res					759	
CTBE Storage			30.00		6,598	
Unusable Volume			5.63			
Modular 7m	**1**	**72.66**	**57.63**	**130.29**	**4,520**	**19,440**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Life Support			6.97		2,630	
Crew Accommodations			6.39		1,307	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,290	
Project Manager Res					1,145	
CTBE Storage			17.94		3,945	
Water Storage			0.47		613	
Unusable Volume			7.52			
Total		**159.81**		**260.58**		**35,906**

*** Ceiling height constrained**

Figure 32 Appendix C: Using multiple habitat modules and small cabin logistics carriers, Mars landing mass for each module is kept at 10,000kg increments (left). Once habitat modules and logistics carriers have landed and been carried and docked together in the outpost location, the 10,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat modules and discarded (right). Even after the cargo has been reapportioned, total free habitable volume of the outpost is 160m^3, leaving 40m3/person which is over the target 25m^3/person. The "Modular 7m" element is already set at a minimal height due to required internal ceiling clearance, so the 40m^3 cannot be reduced down to the target 25m^3. Assuming one module element per launch, this scenario requires six (6) launches.

(A) Mars Vertical Habitat + ECLSS Module (10ton) at Landing

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**150.31**	**8.48**	**158.79**	**5,228**	**9,917**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Outfitting			1.37		0	
Mass Growth Allowance					1,509	
Project Manager Res					754	
CTBE Storage			0.50		110	
Unusable Volume			1.11			
SC Medium ECLSS	**1**	**0.49**	**20.66**	**21**	**1,522**	**8,997**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,283	
Project Manager Res					641	
CTBE Storage			3.00		660	
Unusable Volume			2.70			
Small Cabin Logistics	**4**	**17.38**	**67.22**	**85**	**6,088**	**21,689**
Structures (Internal)			0.28		107	
Protection			0.00		193	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Mass Growth Allowance					1,739	
Project Manager Res					869	
CTBE Storage			44.44		9,773	
Water Storage			0.47		613	
Unusable Volume			8.77			
Total		**168.17**		**264.54**		**40,603**

(B) Mars Vertical Habitat + ECLSS Fully Stocked on Surface

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**79.96**	**78.83**	**158.79**	**5,228**	**23,963**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Mass Growth Allowance					1,970	
Project Manager Res					985	
CTBE Storage			47.94		10,544	
Water Storage			0.47		613	
Unusable Volume			10.28			
Small Cabin ECLSS	**1**	**3.94**	**17.21**	**21**	**1,522**	**8,337**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,283	
Project Manager Res					641	
CTBE Storage			0.00		0	
Unusable Volume			2.25			
Total		**83.89**		**179.94**		**32,300**

Figure 33 Appendix C: Using one habitat module, a dedicated "machine room" ECLSS module, and multiple small cabin logistics carriers, Mars landing mass for each module is kept at 10,000kg increments (left). Once habitat module and logistics carriers have landed and been carried and docked together in the outpost location, the 10,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). The total habitable volume of 84m^3 leaves 21m^3/person which is near the target 25m^3/person. Assuming one module element per launch, this scenario requires six (6) launches.

(A) Mars Vertical Habitat + Inflatable (10ton) at Landing

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**122.94**	**7.35**	**130.29**	**4,520**	**9,978**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.30		299	
Avionics			0.62		453	
Outfitting			1.37		0	
Mass Growth Allowance					1,161	
Project Manager Res					581	
CTBE Storage			0.00		0	
Water Storage			0.00		0	
Unusable Volume			0.96			
Inflatable Dome 7m	**1**	**0.00**	**0.00**	**0**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			0.00		0	
Small Cabin ECLSS	**1**	**3.38**	**17.77**	**21**	**1,522**	**9,677**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		3,385	
Power			0.28		280	
Thermal			0.20		751	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,489	
Project Manager Res					744	
CTBE Storage			0.00		0	
Unusable Volume			2.32			
Small Cabin Logistics	**4**	**13.35**	**71.25**	**85**	**6,088**	**22,459**
Structures (Internal)			0.28		107	
Protection			0.00		193	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Mass Growth Allowance					1,739	
Project Manager Res					869	
CTBE Storage			47.94		10,543	
Water Storage			0.47		613	
Unusable Volume			9.29			
Total		**139.67**		**236.04**		**42,114**

(B) Mars Vertical Habitat + Inflatable Fully Stocked on Surface

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**52.02**	**78.27**	**130.29**	**4,520**	**24,133**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.30		299	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Mass Growth Allowance					1,622	
Project Manager Res					811	
CTBE Storage			47.94		10,543	
Water Storage			0.47		613	
Unusable Volume			10.21			
Inflatable Dome 7m	**1**	**90.25**	**0.00**	**90**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			0.00		0	
Small Cabin ECLSS	**1**	**3.38**	**17.77**	**21**	**1,522**	**9,677**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		3,385	
Power			0.28		280	
Thermal			0.20		751	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,489	
Project Manager Res					744	
CTBE Storage			0.00		0	
Unusable Volume			2.32			
Total		**145.65**		**241.69**		**33,810**

*** Ceiling height constrained (dome)**

*** Optimized for transit**

Figure 34 Appendix C: Using one habitat module, a dedicated "machine room" ECLSS module, an HDU-type inflatable dome, and multiple small cabin logistics carriers, Mars landing mass for each module is kept at 10,000kg increments (left). Once habitat module and logistics carriers have landed, inflated, and been carried and docked together in the outpost location, the 10,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and inflatable dome and discarded (right). The total habitable volume of 146m^3 leaves 36m^3/person which is over the target 25m^3/person. Assuming one module element per launch, this scenario requires six (6) launches.

Mars Vertical Single Habitat (18ton increments)						
Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**93.13**	**37.16**	**130.29**	**4,520**	**17,995**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Mass Growth Allowance					2,336	
Project Manager Res					1,168	
CTBE Storage			10.00		2,199	
Water Storage			0.47		613	
Unusable Volume			4.85			
Small Cabin Logistics	**3**	**4.40**	**59.05**	**63**	**4,566**	**17,605**
Structures (Internal)			0.15		107	
Protection			0.00		144	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Mass Growth Allowance					1,425	
Project Manager Res					712	
CTBE Storage			37.94		8,344	
Unusable Volume			7.70			
Total		**97.53**		**193.74**		**35,600**

Figure 35 Appendix C: Using a single habitat module and multiple small cabin logistics carriers, Mars landing mass for each module is kept at 18,000kg increments (left). Once habitat modules and logistics carriers have landed and been carried and docked together in the outpost location, the 18,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). All three of the small cabin logistics carriers are retained for living volume. The total habitable volume of 98m^3 leaves 25m3/person which is on target. Assuming one module element per launch, this scenario requires four (4) launches.

Mars Vertical Double Habitat (18ton increments)						
Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**93.13**	**37.16**	**130.29**	**4,520**	**17,995**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Mass Growth Allowance					2,336	
Project Manager Res					1,168	
CTBE Storage			10.00		2,199	
Water Storage			0.47		613	
Unusable Volume			4.85			
Modular 7m	**1**	**66.68**	**63.61**	**130.29**	**4,520**	**17,912**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Mass Growth Allowance					1,472	
Project Manager Res					736	
CTBE Storage			37.94		8,344	
Unusable Volume			8.30		0	
Total		**159.81**		**260.58**		**35,906**

*** Ceiling height constrained**

Figure 36 Appendix C: Using two habitat modules, Mars landing mass for each module is kept at 18,000kg increments. No reapportioning or shifting of cargo is needed. Total free habitable volume is 160m^3, leaving 40m^3/person which is over the target 25m^3/person. The "Modular 7m" element is already set at a minimal height due to required internal ceiling clearance, so the 40m^3 cannot be reduced down to the target 25m^3. Assuming one module element per launch, this scenario requires two (2) launches.

Mars Vertical Habitat + ECLSS Module (18ton increments) at Landing

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**112.09**	**46.70**	**158.79**	**5,228**	**17,818**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Outfitting			1.37		0	
Mass Growth Allowance					1,970	
Project Manager Res					985	
CTBE Storage			20.00		4,399	
Water Storage			0.47		613	
Unusable Volume			6.09			
Small Cabin ECLSS	**1**	**0.49**	**20.66**	**21**	**1,522**	**8,997**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,283	
Project Manager Res					641	
CTBE Storage			3.00		660	
Unusable Volume			2.70			
Small Cabin Logistics	**2**	**13.30**	**29.00**	**42**	**3,044**	**9,706**
Structures (Internal)			0.28		107	
Protection			0.00		96	
Mass Growth Allowance					649	
Project Manager Res					325	
CTBE Storage			24.94		5,485	
Unusable Volume			3.78			
Total		**125.87**		**222.24**		**36,521**

Mars Vertical Habitat + ECLSS Module Fully Stocked on Surface

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m Tall	**1**	**83.41**	**75.38**	**158.79**	**5,228**	**23,303**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Outfitting			1.37		0	
Mass Growth Allowance					1,970	
Project Manager Res					985	
CTBE Storage			44.94		9,884	
Water Storage			0.47		613	
Unusable Volume			9.83			
Small Cabin ECLSS	**1**	**0.49**	**20.66**	**21**	**1,522**	**8,997**
Structures (Internal)			0.00		0	
Protection			0.00		48	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					1,283	
Project Manager Res					641	
CTBE Storage			3.00		660	
Unusable Volume			2.70			
Total		**83.89**		**179.94**		**32,300**

Figure 37 Appendix C: Using one habitat module, a dedicated "machine room" ECLSS module, and multiple small cabin logistics carriers, Mars landing mass for each module is kept at 18,000kg increments (left). Once habitat module and logistics carriers have landed and been carried and docked together in the outpost location, the 18,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). The total habitable volume of 84m^3 leaves 21m^3/person which is below the target 25m^3/person. Assuming one module element per launch, this scenario requires four (4) launches.

(A) Mars Vertical Habitat + Inflatable (18ton increments) at Landing

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**104.02**	**26.27**	**130.29**	**4,520**	**17,833**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Outfitting			1.37		0	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					2,336	
Project Manager Res					1,168	
CTBE Storage			1.00		220	
Unusable Volume			3.43			
Inflatable Dome 7m	**1**	**0.00**	**0.00**	**0**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			0.00		0	
Small Cabin Logistics	**4**	**14.50**	**70.10**	**85**	**6,088**	**22,239**
Structures (Internal)			0.28		107	
Protection			0.00		193	
Crew Accommodations			6.39		1,307	
Utilization			6.88		1,000	
Mass Growth Allowance					1,739	
Project Manager Res					869	
CTBE Storage			46.94		10,323	
Water Storage			0.47		613	
Unusable Volume			9.14			
Total		**118.52**		**214.89**		**40,073**

(B) Mars Vertical Habitat + Inflatable Fully Stocked on Surface

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**34.25**	**96.04**	**130.29**	**4,520**	**31,769**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Mass Growth Allowance					2,797	
Project Manager Res					1,399	
CTBE Storage			47.94		10,543	
Water Storage			0.47		613	
Unusable Volume			12.53			
Inflatable Dome 7m	**1**	**90.25**	**0.00**	**90**	**1,822**	
Structures (Internal)			0.00		0	
Protection			0.00		48	
Mass Growth Allowance					374	
Project Manager Res					187	
CTBE Storage			0.00		0	
Total		**124.50**		**220.54**		**31,769**

*** Ceiling height constrained (dome)**

*** Optimized for transit**

Figure 38 Appendix C: Using one habitat module, an HDU-type inflatable dome, and multiple small cabin logistics carriers, Mars landing mass for each module is kept at 18,000kg increments (left). Once habitat module and logistics carriers have landed and been carried and docked together in the outpost location, the 18,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and inflatable dome and discarded (right). The total habitable volume of 125m^3 leaves 31m^3/person which is over the target 25m^3/person. Assuming one module element per launch, this scenario requires six (6) launches.

Mars Surface Habitat (20ton increments) at Landing

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**189.79**	**38.22**	**228.00**	**5,757**	**19,969**
Structures (Internal)			4.11		660	
Protection			0.00		284	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Utilization			5.00		727	
Mass Growth Allowance					3,072	
Project Manager Res					1,536	
CTBE Storage			0.00		0	
Unusable Volume			4.98			
5t Mars Logistics	**4**	**108.46**	**57.54**	**166**	**5,540**	**21,669**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					880	
Control					0	
Avionics					220	
Thermal					460	
ECLSS					900	
Crew Systems					60	
Mass Growth Allowance					960	
External Frame					300	
Project Manager Res					920	
CTBE Storage			47.94		10,543	
Water Storage			0.47		613	
Utilization			1.88		273	
Unusable Volume			7.26			
Total		**298.24**		**394.00**		**41,638**

Mars Surface Habitat Fully Stocked on Surface

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**131.96**	**96.05**	**228.00**	**5,757**	**31,481**
Structures (Internal)			4.11		660	
Protection			0.00		284	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Mass Growth Allowance					3,127	
Project Manager Res					1,563	
CTBE Storage			47.94		10,544	
Water Storage			0.47		613	
Unusable Volume			12.53			
Total		**131.96**		**228.00**		**31,481**

Figure 39 Appendix C: Using a monolithic habitat module and multiple 5 ton surface logistics carriers, Mars landing mass for each module is kept at 20,000kg increments (5,000kg for logistics modules). Once habitat modules and logistics carriers have landed and been carried and docked together in the outpost location, the 20,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right) leaving a monolithic habitat element. The total habitable volume of 131m^3 leaves 33m^3/person which is over the target per person volume. Assuming one module element per launch, this scenario requires five (5) launches.

Mars Surface Habitat (20ton increments) at Landing

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**83.62**	**46.66**	**130.29**	**4,520**	**19,894**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,797	
Project Manager Res					1,399	
CTBE Storage			5.00		1,100	
Water Storage			0.47		613	
Unusable Volume			6.09			
5t Mars Logistics	**4**	**116.62**	**49.38**	**166**	**5,540**	**19,683**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					880	
Control					0	
Avionics					220	
Thermal					460	
ECLSS					900	
Crew Systems					60	
Mass Growth Allowance					960	
External Frame					300	
Project Manager Res					920	
CTBE Storage			42.94		9,443	
Water Storage			0.00		0	
Utilization			0.00		0	
Unusable Volume			6.44			
Total		**200.25**		**296.29**		**39,578**

Mars Surface Habitat Fully Stocked on Surface

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**49.12**	**81.16**	**130.29**	**4,520**	**26,492**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,797	
Project Manager Res					1,399	
CTBE Storage			35.00		7,698	
Water Storage			0.47		613	
Unusable Volume			10.59			
5t Mars Logistics	**1**	**26.62**	**14.88**	**42**	**1,385**	**5,405**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					220	
Control					0	
Avionics					55	
Thermal					115	
ECLSS					225	
Crew Systems					15	
Mass Growth Allowance					240	
External Frame					75	
Project Manager Res					230	
CTBE Storage			12.94		2,845	
Water Storage			0.00		0	
Utilization			0.00		0	
Unusable Volume			1.94			
Total		**75.75**		**171.79**		**31,898**

Figure 40 Appendix C: Using a single habitat module and multiple 5 ton surface logistics carriers, Mars landing mass for each module is kept at 20,000kg increments (5,000kg for logistics modules). Once habitat modules and logistics carriers have landed (left) and been carried and docked together in the outpost location, the 20,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). One 5 ton surface logistics carrier is retained for living volume. The total habitable volume of 76m^3 leaves 19m^3/person which is well under the target 25m^3/person. Assuming one module element per launch, this scenario requires five (5) launches.

Mars Surface Habitat (20ton increments) at Landing

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**189.79**	**38.22**	**228.00**	**5,757**	**19,969**
Structures (Internal)			4.11		660	
Protection			0.00		284	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Utilization			5.00		727	
Mass Growth Allowance					3,072	
Project Manager Res					1,536	
CTBE Storage			0.00		0	
Unusable Volume			4.98			
10t Mars Logistics	**2**	**80.46**	**57.54**	**138**	**3,450**	**17,689**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					440	
Control					0	
Avionics					110	
Thermal					340	
ECLSS					520	
Crew Systems					30	
Mass Growth Allowance					580	
External Frame					220	
Project Manager Res					570	
CTBE Storage			47.94		10,543	
Water Storage			0.47		613	
Utilization			1.88		273	
Unusable Volume			7.26			
Total		**270.24**		**366.00**		**37,658**

Mars Surface Habitat Fully Stocked on Surface

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Monolithic 7m Tall	**1**	**131.96**	**96.05**	**228.00**	**5,757**	**31,481**
Structures (Internal)			4.11		660	
Protection			0.00		284	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Mass Growth Allowance					3,127	
Project Manager Res					1,563	
CTBE Storage			47.94		10,544	
Water Storage			0.47		613	
Unusable Volume			12.53			
Total		**131.96**		**228.00**		**31,481**

Figure 41 Appendix C: Using a monolithic habitat module and multiple 10 ton surface logistics carriers, Mars landing mass for each module is kept at 20,000kg increments (10,000kg for logistics modules). Once habitat modules and logistics carriers have landed (left) and been carried and docked together in the outpost location, the 20,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right) leaving a monolithic habitat element. The total habitable volume of 132m^3 leaves 33m^3/person which is over the target volume. Assuming one module element per launch, this scenario requires three (3) launches.

Mars Surface Habitat (20ton increments) at Landing

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**83.62**	**46.66**	**130.29**	**4,520**	**19,894**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,797	
Project Manager Res					1,399	
CTBE Storage			5.00		1,100	
Water Storage			0.47		613	
Unusable Volume			6.09			
10t Mars Logistics	**2**	**88.62**	**49.38**	**138**	**3,450**	**15,703**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					440	
Control					0	
Avionics					110	
Thermal					340	
ECLSS					520	
Crew Systems					30	
Mass Growth Allowance					580	
External Frame					220	
Project Manager Res					570	
CTBE Storage			42.94		9,443	
Water Storage			0.00		0	
Utilization			0.00		0	
Unusable Volume			6.44			
Total		**172.25**		**268.29**		**35,598**

Mars Surface Habitat Fully Stocked on Surface

Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 7m	**1**	**54.87**	**75.41**	**130.29**	**4,520**	**25,393**
Structures (Internal)			4.11		330	
Protection			0.00		203	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,797	
Project Manager Res					1,399	
CTBE Storage			30.00		6,598	
Water Storage			0.47		613	
Unusable Volume			9.84			
10t Mars Logistics	**1**	**48.37**	**20.63**	**69**	**1,725**	**7,075**
Structures (Internal)			0.00		0	
Protection			0.00		0	
Propulsion					0	
Power					220	
Control					0	
Avionics					55	
Thermal					170	
ECLSS					260	
Crew Systems					15	
Mass Growth Allowance					290	
External Frame					110	
Project Manager Res					285	
CTBE Storage			17.94		3,945	
Water Storage			0.00		0	
Utilization			0.00		0	
Unusable Volume			2.69			
Total		**103.25**		**199.29**		**32,468**

Figure 42 Appendix C: Using a single habitat module and multiple 10 ton surface logistics carriers, Mars landing mass for each module is kept at 20,000kg increments (10,000kg for logistics modules). Once habitat modules and logistics carriers have landed and been carried and docked together in the outpost location (left), the 20,000kg cap per element is no longer applicable and logistic carrier contents can be emptied into the habitat module and discarded (right). A single 10 ton surface logistics carrier is retained for living volume. The total habitable volume of 103m^3 leaves 26m^3/person which is on target. Assuming one module element per launch, this scenario requires three (3) launches.

Mars Surface Habitat (20ton increments)						
Element	No	Hab V (m3)	Non V (m3)	Tot V (m3)	Sys M (kg)	Tot M (kg)
Modular 6m	**1**	**41.51**	**48.96**	**90.48**	**4,023**	**19,791**
Structures (Internal)			4.11		458	
Protection			0.00		154	
Power			0.58		579	
Thermal			0.20		751	
Avionics			0.62		453	
Crew Accommodations			6.39		1,307	
Life Support			8.97		3,385	
EVA Life Support					88	
Airlock & EVA			6.00		1,370	
Outfitting			1.37		0	
Utilization			6.88		1,000	
Mass Growth Allowance					2,714	
Project Manager Res					1,357	
CTBE Storage			7.00		1,540	
Water Storage			0.47		613	
Unusable Volume			6.39			
Modular 6m	**1**	**38.14**	**52.34**	**90.48**	**4,023**	**15,642**
Structures (Internal)			4.11		458	
Protection			0.00		154	
Mass Growth Allowance					927	
Project Manager Res					463	
CTBE Storage			40.94		9,003	
Water Storage			0.47		613	
Unusable Volume			6.83			
Total		**79.65**		**180.96**		**35,432**

Figure 43 Appendix C: Using multiple habitat modules, Mars landing mass for each module is kept at 20,000kg increments. No reapportioning or shifting of cargo is needed. Total free habitable volume is 80m^3, leaving 20m^3/person which is well under the target 25m^3/person. Assuming one module element per launch, this scenario requires two (2) launches.