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Design of a Multipurpose Extensible Habitat - Vanguard

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In an era focused on human space exploration beyond low Earth orbit with a flat NASA budget profile, cost effective strategies will be required to sustain humans in deep space beyond the safety of Earth's magnetic shield and the ability to always abort to safety. Vanguard is proposed as a multipurpose extensible habitat that will support four crew for up to two years at most of the realistic, near-term targets for human exploration. Vanguard will be capable of operating in low Earth orbit, lunar distant retrograde orbit (or other stable Earth-Moon Lagrange point orbits), low lunar orbit, interplanetary space between Earth and Mars, as well as in various Martian orbits. The extent to which the spacecraft requirements for the different destinations affected the specifics of Vanguard's design were noted and the primary differences, thermal and power system masses, were compared to determine which environments exerted the maximum impact on the launch mass of the spacecraft. Systems analysis methods were used to size the habitat module, select between rigid or inflatable structure, determine mission conops, detail internal layouts, design environmental control and life support systems, and select power and thermal designs. Cost analysis was conducted and Vanguard was designed to be relevant in multiple environments to motivate multiple unit production, minimize nonrecurring costs, and reduce the average cost per spacecraft. This strategy will allow NASA to maximize on their investment in the next human spacecraft. As a result of this analysis, this paper aims to prove the value of designing a habitat to be the vanguard that paves the way for human exploration and habitation beyond low Earth orbit.

Nomenclature

LEO = Low Earth Orbit
ISS = International Space Station
LLO = Low Lunar Orbit
LDRO = Lunar Distant Retrograde Orbit
LMO = Low Mars Orbit
TRL = Technology Readiness Level
SLS = Space Launch System
BEAM = Bigelow Expandable Activity Module
MMOD = Micrometeoroid and orbital debris
EVA = Extra Vehicular Activity
ECLSS = Environmental Control and Life Support Systems
FBMS = Four Bed Molecular Sieve
DDT&E = Design Development Testing and Evaluation

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I. Introduction

In a few years, the nation will reach the convergence of both 50 years since the last human mission out of low Earth orbit (LEO), and the end of government-organized human LEO spaceflight with the deorbiting of International Space Station (ISS). While there is a desire on the part of many inside and outside of NASA to focus government efforts on planetary exploration, there are still many things to be learned for LEO operations, driving an ongoing need for extended scientific and (potentially) industrial efforts in low Earth orbit. A logically-planned space program would require the development and launch of a replacement space habitat in LEO to supplement and ultimately replace ISS, which programmatically would likely be initiated, developed, and operated entirely as a commercial endeavor. The design of such a habitat would require many of the same or extended capabilities compared to ISS, but at substantially less cost and with lower maintenance requirements.

At the same time, development of human spacecraft is the most expensive class of space development activities, and similar habitat systems will be required in support of human exploration of the lunar surface, Mars orbit, and ultimately Mars surface. Conceptually, it would be ideal if the next-generation habitat for the commercial development of LEO might be equally applicable to support exploration activities in low lunar orbit (LLO), lunar distant retrograde orbit (LDRO), or in Mars orbit. This paper documents the design activities at the University of Maryland (UMd) in the consideration of a multirole habitat module initially designed for low Earth orbit applications, but capable of being replicated or moved to required exploration sites such as those mentioned above. Rather than design a LEO station and then seek to adapt it to other locations, the design effort started with the development of a set of design requirements applicable to each of four reference locations: low Earth orbit, low lunar orbit, a lunar distant retrograde orbit, and low Mars orbit (LMO). Each of these locations has different implications on power, propulsion, and thermal control, as well as communications and associated avionics systems. The use of a set of requirements allowed assessment of the degree of accommodation required for each destination, which will inform future decisions on where to site a habitat and how the site drives habitat mass.

Critical design decisions, such as the choice of inflatable or fixed-shell habitat structure, type and emplacement of power systems, and accommodation for additional modules and/or hosted vehicles were considered during the design of Vanguard. The design of the baseline habitat included the selection of life support systems and other crew accommodations, and internal layouts examined alternative placement of crew accommodations, life support systems, airlocks, windows, and other crew systems. Operational challenges considered included number, location, and type of docking interfaces; and energy storage for all orbital eclipse patterns at Earth, the Moon, and Mars.

All component systems were designed for Earth launch in a 5 meter fairing and payload limitations for launch on ULA heavy-lift, New Glenn, or a lengthened Falcon Heavy fairing. While the size (total payload volume and mass) of the launch vehicle has a strong effect on the final design of the habitat and related systems, the choice also has a significant impact on the overall system's costs, which were also analyzed as part of the ultimate configuration decision criteria. The UMd design team also tracked technology readiness levels (TRL) for critical habitat systems, and included cost allocations for advancing the TRL levels of selected systems where appropriate.

While differing considerably from International Space Station, the University of Maryland multipurpose extensible space habitat (Vanguard) demonstrates that a single baseline design for a next-generation space habitat can be successfully applied to a wide variety of potential destinations for human space exploration. Vanguard is envisioned to be a spacecraft that can become a major workhorse of human spaceflight with applications as a commercial/research destination in LEO, or an exploratory platform enabling visits and prolonged stays in LLO, LDRO or Mars orbit. With small investments, modifications and add-ons, Vanguard could also be repurposed to land on bodies without atmospheres including near-Earth asteroids, the Moon, or Phobos and Deimos.

II. Mission Requirements

Developing a habitat with the capability to visit all of the planned destinations will ensure that it maintains its relevance regardless of its initial application. To guide the design of such a spacecraft, a set of requirements was created to support crew safely in these different environments. System level mission requirements were established to determine what the crewed spacecraft must be capable of in order to operate in the four environments detailed above. Utilizing this document, Vanguard was designed to meet the requirements of the most limiting environments to ensure it is capable of operating in each location. The design requirements can be found in *Appendix A*.

III. Design and Sizing

Vanguard is designed to be launched on existing and/or upcoming heavy lift launch vehicles. The habitat module and service module, which are integrated on the ground prior to launch, are sized to fit inside the 5m wide, long variant payload fairings of the ULA heavy-lift, New Glenn, Space Launch System (SLS), and potentially lengthened Falcon Heavy fairing.[1,2] This reduces dependency on any particular launch vehicle, given the uncertain nature of new launch vehicle programs. The existing payload fairing of the Delta IV Heavy / Atlas V, being one of the more volume limited of the proposed vehicle fairings, drove the bounding volume in stowed launch configuration. Vanguard's dimensions in the stowed configuration can be seen (in blue) inside the Delta IV Heavy payload fairing dynamic envelope dimensions (in black) in Figure 1.

Vanguard is designed to NASA's long duration net habitable volume requirement of 25 m^3 per crew member.[3] A coarse assumption, that 40% of the internal volume was habitable, was initially made to allow rough sizing of the spacecraft, then a more detailed analysis of the internal layout was conducted to determine final sizing of the spacecraft.

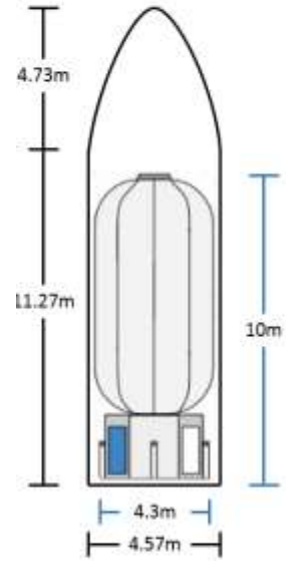


Figure 1: Vanguard inside 4.57m dynamic envelope

In order to meet the volume requirement for the spacecraft within the confines of the planned launch vehicle payload fairings, analysis was conducted to determine whether a rigid or inflatable structure would be ideal. For this analysis, the inflatable habitat baseline structure (core metal structure to handle launch loads and to house ground-installed flight critical components, and an external fabric structure that unfolds when pressurized) is derived from the NASA Johnson Space Center TransHab program.[4-8] In launch configuration, the fabric layer is folded around the core, and the core structure is designed to take the launch loads and vibrations that Vanguard will experience. For the rigid option, the pressure vessel structure carries the launch loads and vibrational environment. The loads both options were designed for are as follows: a load factor of 6 axially, load factor of 3 laterally, a compressive natural frequency exceeding 25 Hz, and a bending natural frequency exceeding 10 Hz as determined from the rockets' user guides.[1,2] The structures were then examined for thin walled buckling and tensile failure modes.

Structural mass for both the rigid pressure vessel and the inflatable core was calculated by varying module length and designing the wall thickness to handle the loads mentioned above. The inflatable structural mass was calculated by first sizing the rigid core structure and then the outer fabric layers and adding their masses together. The fabric mass was determined by backing out the fabric wall thickness of the Bigelow Expandable Activity Module (BEAM) based on the documented length, diameter, and internal volume.[9] Using this wall thickness, the total fabric volume was calculated and divided by the module's overall mass (less common berthing mechanism and the aluminum bulkheads which were assumed to contribute a combined ~400 kg of the 1360 kg module mass).[9,10] Based on this calculated wall thickness and fabric density, the fabric volume of Vanguard was calculated and multiplied by the fabric density to determine the fabric mass. The fabric mass was then added to the core structural mass to provide the combined inflatable structural mass. In addition, when calculating rigid pressure vessel mass, micrometeoroid and orbital debris (MMOD) shielding was added to the rigid pressure vessel because BEAM already has shielding in the fabric layup. Based on the limited duration in LEO, for Vanguard as compared to ISS, the shielding was reduced compared to ISS values, but still maintained an areal density of 0.5 g/cm^2 and a standoff distance of 10 cm.[11,12,13]

The results of this analysis are detailed in Figure 2a; it shows a rapid increase in inflatable mass as module length increases. This trend is a result of the narrow core radius and large length, which require significantly increased thickness as the length grows to avoid buckling conditions during launch. Comparisons of the total volume of rigid and inflatable modules, based on maximizing the stowed radius in the payload fairing and then changing module length, are shown in Figure 2b. This analysis determined that only the inflatable option with a length greater than 8m provides enough volume on orbit for four crew on a long duration mission. Finally, comparison of the structural mass per volume efficiency factor, shown in Figure 2c, helped identify the location at which the module length was optimal to provide the most volume for the least mass while meeting the habitable volume requirement. Future work will seek to define the fabric layup and associated fabric density of the multi-layer insulation, MMOD shielding, spacer layers, restraint layers, pressure bladder, and the internal wear / protection layer to improve upon the extrapolated BEAM fabric density and allow fine-tweaking of MMOD shielding based on the anticipated orbital debris environments.

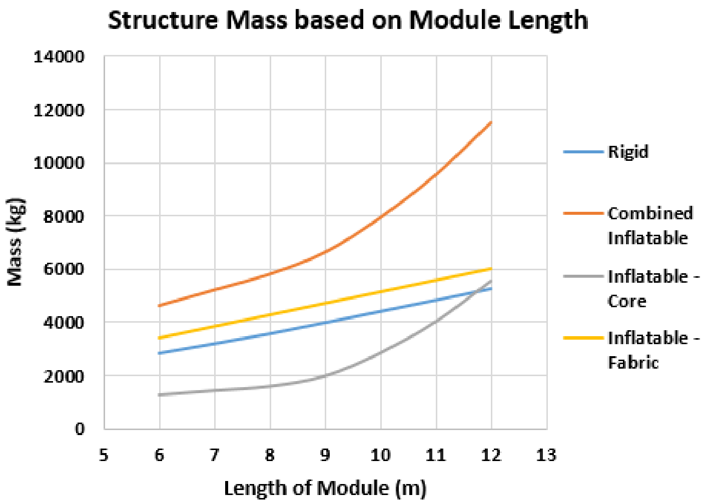


Figure 2a: Structure mass comparison between rigid and inflatable pressure vessel

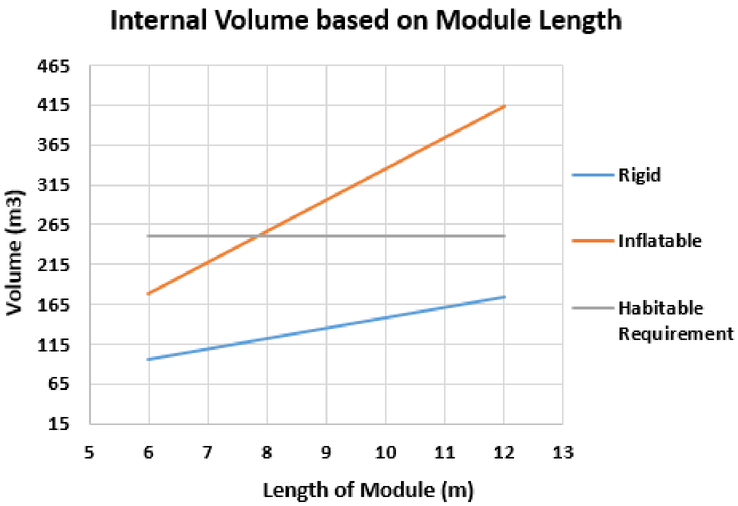


Figure 2b: Total volume comparison between rigid and inflatable pressure vessel

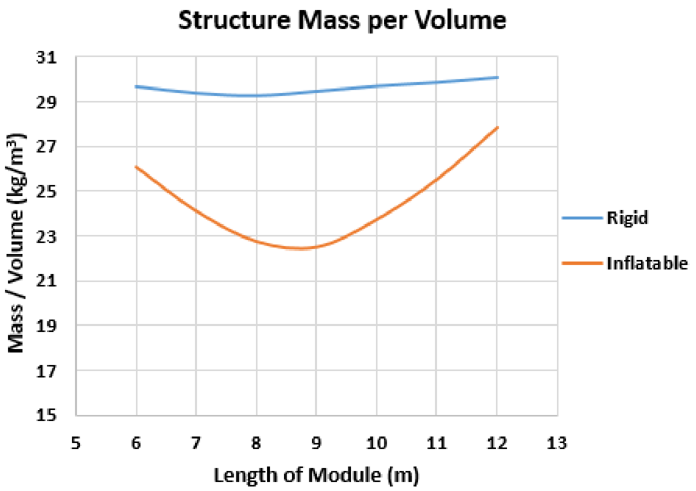


Figure 2c: Structure mass per unit volume

Analysis determined when a four crew human spacecraft, requiring roughly 250 m^3 of pressurized volume to provide 100 m^3 of habitable volume, is confined to the current Falcon 9 fairing, both inflatable and rigid spacecraft required two Falcon 9/Heavy launches just to meet the volume requirements. For the Atlas V and Delta IV Heavy long-variant fairings, the inflatable spacecraft only required one launch to reach the required volume while the rigid habitat module required two. The representative dimensions of the pressure vessels for this analysis are detailed in Table 1. The only planned vehicle fairing that can deliver a fully loaded, and preassembled (rigid), long duration habitat for four crew in one launch is the 8.4 m SLS fairing. Vanguard was ultimately designed to the 5 m fairings because SLS is expected to start with a 5 m fairing and the flexibility to launch on multiple vehicles, as well as the reduced cost associated with commercial launches, was determined to be more valuable than the ability to launch flight ready.

Table 1: Volumetric Analysis of Rigid and Inflatable Habitats Inside Falcon 9 and Atlas V Fairings

	Falcon 9		DIVH / Atlas V Long	
	Rigid	Inflatable	Rigid	Inflatable
Stowed External Radius (m)	2.05	2.15	2.05	2.15
Expanded Internal Radius (m)	2.05	3.75	2.05	3.75
Core Structure Radius (m)	0.00	1.25	0.00	1.25
Length (m)	5.00	5.00	8.50	8.50
Endcap Height (m)	0.50	0.50	0.50	0.50
Internal Volume (m^3)	83.6	215.7	129.8	353.2
Two Launch Volume (m^3)	167.2	431.4	259.7	353.2

Of note here is that inflatable spacecraft require significant in-space assembly of handholds, footholds, exercise equipment, workstations, common areas, crew quarters, structural flooring, room partitions, and experimental racks. This means that at a minimum, a second launch is required to bring all of the equipment and logistics that could not be stored in the central core during the launch, and a crew also needs to devote significant time at the start of a mission to set up the habitat. This analysis suggests that if the design is constrained to a Falcon 9 fairing or Atlas V / Delta IV Heavy long fairing, each option requires two launches for setup and a third to have crew onboard and ready for their mission.

The trade is not quite as simple as this, though, because the concept of operations for each option is significantly different. In the case of the inflatable, the first launch is constrained to deliver the habitat and service module, while the second launch has some flexibility. Because Vanguard's service module also contains a crew passthrough which doubles as an airlock, a potential option for the second launch is a pressurized vessel filled with logistics and consumables for the crew; after being emptied, this could serve as an additional airlock and/or node module with additional docking ports for visiting vessels. This second module could be launched on another commercial launch vehicle, or it could be a co-manifested payload with an SLS and Orion crew, which would have the potential of entirely eliminating a third launch. Finally, if the co-manifest payload was unable to deliver enough logistics to support a two year mission or a crew was not launched with the second module, the third launch would be the assembly and first mission crew.

For the rigid habitat, the first launches would be integrated habitat and service module one and two, and the third launch would be the first mission crew. Vanguard was ultimately selected to be an inflatable because, while both options require the same number of launches, the packaging efficiency allows the inflatable habitat to maintain volume advantage for less mass than the rigid habitat. The inflatable version of Vanguard is 4.3 m in diameter when stowed, and 10 m long. When fully inflated, Vanguard expands to 8.2 m in diameter and remains 10 m long. This provides a total available internal volume of ~350 m^3.

IV. Internal Layout

Because Vanguard is an inflatable, it has two internal areas of importance. The first is the core structure layout, seen in Figure 3. The following floor description references parts of the habitat labeled in that figure. The core structure is the internal ring and dividing sections that house all of the flight critical hardware that is likely to need servicing, including the crew's bathroom (N), the O_2 and N_2 gas canisters for initial pressurization of the habitat (E), the heating and ventilation paths (D), the thermal cooling loops (C), food refrigerators (G), the other Environmental Control and Life Support Systems (ECLSS), environmental monitoring sensors (B), avionics packages (F), flight navigation and guidance computers (F), and crew passthroughs to the docking ports fore and aft of the vehicle (A). For reference, the crew passthroughs are sized to allow for a 95th percentile male in an EVA suit so the aft end of the vehicle can double as a pressurized airlock and so equipment can be transported between floors without temporarily needing to take apart the floor.

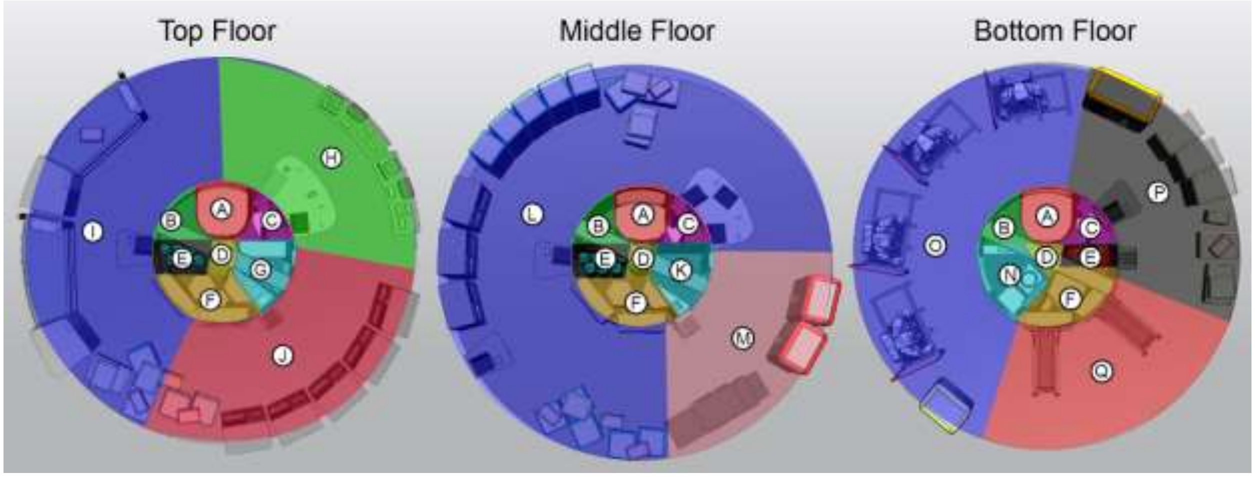


Figure 3: Floor Layouts - Top Down View

The Vanguard vehicle has three separate main floors, the first of which houses the crew quarters (I), the crew's galley (complete with food rehydrator, food warmer, and microgravity table with restraints) (H), two separate workstations (I & H), experiment racks (J), and windows. The second floor contains a clothes washer and dryer (L), other workstations (L), adaptable medical station (M), experiment racks (L), hygiene space (K), and another window. The third floor contains the workout area with a treadmill, bicycle, resistive exercise device (Q), the storage and donning location for the EVA suits (O), bathroom (N), and the waste collection area (P).

There also exists a fourth "half floor" that serves as extra storage space. This space is accessible through removable floor panels on the third floor. Shared with the various equipment located around the habitat, there exists 150 m^3 of stowage space to store consumables, spare parts and crew personal items. Vanguard's separate floors can be seen in a cutaway in Figure 4.

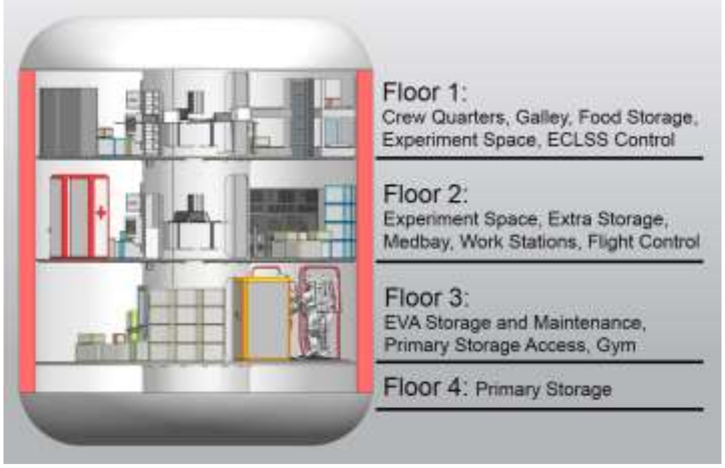


Figure 4: Vanguard Side Cutaway

V. Environmental Control and Life Support Systems

As the desire to extend human reach beyond LEO continues to develop and coalesce, further capabilities are needed to support and sustain human life in the new environments it will encounter. The environments beyond LEO are even more unforgiving and less favorable for resupply or crew abort, necessitating increased crew autonomy, system reliability, and logistics stowage. Crews will also be subject to increased psychological stress, exposure to ionizing radiation, and longer duration missions. Each of these challenges requires significant effort from spacecraft designers to effectively address the challenge without impacting mission feasibility.

The ISS currently uses an atmospheric pressure of approximately 101.3 kPa and an oxygen concentration of 21%. This keeps the system at the normoxic level and removes one more variable from complicating physiological studies of the astronauts. In its design, space station used mechanical systems to process the CO_2 and electrolysis to split H_2O into oxygen that is introduced into the habitat and hydrogen that is dumped out of the station. Current ECLSS on Space Station require frequent maintenance and a significant amount of the astronauts' time. For future endeavours, a focus on high reliability, low maintenance, closed loop systems to sustain the atmosphere is crucial to maintain astronaut health.

Two promising systems for atmospheric control are the use of Sabatier reactors in combination with a four bed molecular sieve (4BMS) and the use of water walls. The 4BMS in combination with a Sabatier reactor is proven technology; however, the goal is to have a system with the highest reliability, and inherently, the complexity and expendables in this system may not be ideal for the future of deep space travel. Water walls have the capability of regulating the atmosphere through the use of algae or cyanobacteria growth.[14] This system is mostly passive and only requires valves and a pump to push the gray water into the system and guarantee consistent flow throughout each bag. This system is reliant on forward osmosis bags that have been tested and flown, putting them at TRL-7. The oxygen production from algae ranges based on lighting and algae culture depth, but each astronaut requires approximately 600 liters of oxygen per day. So for an average crew of four, 2400 litres of oxygen is required per day. Looking at published data, with 12 cm^2 of cells, at a thickness of 1 cm, algae can produce oxygen at a rate of approximately 1 L/hr. Keeping thickness constant, and avoiding delving into light intensity, this requires approximately 1200 cm^2.[15] The output of the algae can be greatly regulated by limiting the light levels in order to avoid oxygen buildup.

For the new generation of manned spacecraft, radiation protection will be a design driver. Currently, water walls seem to have advantages that out perform many other designs. Water walls are particularly interesting because they provide a storage solution for potable water that is needed for long duration manned space flight, as well as a high concentration of hydrogen bonds that help block radiation from the sun. As mentioned earlier, some companies have even begun designing water walls that incorporate algae and passive graywater filtration through the use of forward osmosis. This algae system has many added benefits, but provides uncertainties in radiation shielding. The water walls design referenced from Cohen and Flynn, uses a series of connected bags.[14] The packing of these bags may be an issue for radiation shielding, if they are unable to find a way to insure that there are no gaps in the radiation protection. However, for the baseline, the bags and algae have been removed from the assumptions to determine a required water wall thickness. Following NASA standards, the astronauts' lifetime increase in radiation exposure induced death must be less than 3% to a 95% confidence interval[16]. For LEO missions, Earth's magnetic field will provide most of the needed radiation protection. However, for deep space missions, shielding will be required. For reference, human beings on Earth are exposed to roughly 4 mSv every year, and NASA allows a range from 0.44 Sv to 1.17 Sv for astronauts across a one year mission.[16] This limit is the lifetime radiation dose limit and the variation is a result of age and gender tolerances. It is desired to stay well below this limit, because astronauts should be able to operate across multiple missions without reaching their lifetime limit.

Water's ability to block radiation is an exponentially decaying relationship with increasing wall thickness; as a result, the mass efficiency for the thickness of a wall filled with water is in the region of 10-20 g/cm^2. At Solar Maximum, 0.35 Sv get through 10 g/cm^2 and 0.25 Sv get through 20 g/cm^2. Thicknesses past 20 g/cm^2 see minimal decreases. However, as mentioned earlier, the water walls are in polyethylene bags which, depending on thickness, can get the annual radiation levels down below 0.2 Sv. Additional, module shielding will also need to be present during solar minimum.

The water walls forward osmosis process does have the capability to process graywater and provide potable water. However, the rate at which it does this is uncertain, and may even be inconsistent. As a result, early missions utilizing the water walls, in LEO, should use vapor compression distillation as a guaranteed source of water. Vapor compression distillation is a TRL 9 system that could easily be hooked into the same lines as the bags.

In terms of food, 1.3 kg per crewmember per day taking up a volume of 0.005 m^3 per crewmember per day is a rough estimate for dry goods. So, for a 90 day mission with 4 astronauts, it comes out to ~470 kg and a required stowage space of 1.8 m^3. For extended missions a regenerative food supply will be needed due to the nutritional shelf life of foods and loss of nutritional value over time. As mentioned before, water walls with algae incorporated have many benefits. Yet another benefit is the nutritional value that can be found in algae such as spirulina. Per 100 g, spirulina can give 290 calories, which includes fat, sodium, potassium, carbohydrates, and 57 g of protein. Vitamin D and vitamin B-12 supplements will still be needed, or an alternative will have to be found. Assuming that the algae is not regenerating above the consumption rate, and the astronauts are not consuming above 100 g/CM-day, the new dry food requirements change from 1.3 kg/CM-day to approximately 1.1 kg/CM-day based on caloric intake. Therefore, using the algae as a food source saves roughly 73 kg/CM-year.

As mentioned earlier, the inflatable habitable volume is 7.5 m in diameter and 7.5 m tall before getting into the endcaps. For radiation protection, the barrel section and one endcap incorporate the water wall design which provides ample protection without having to enforce strict pointing requirements past that required for the solar arrays. This shape provides approximately 220 m^2 of surface area. As seen in Table 2a, the exposed available surface area for algae growth is dependent on water wall thickness, which in turn is based on radiation limits. Despite that, each configuration shown in Table 2a still easily provides the 300 cm^2/CM for crews of four and up, allowing for spare algae bags to be stored in minimum light environments to reduce excess O_2 buildup.

Table 2a: ECLSS Requirements based on orbital location

	LEO	LLO	LDRO	LMO	
Radiation Protection (Water)	6	15	15	20	g/cm^2
Mass of WW using Walls w/ one endcap	13	32	32	43	MT (Tonne)
New internal exposed surface area	216	210	210	206	m^2

The driving design parameter for Vanguard has been to create a livable environment for future space endeavors. As it turns out, the driving parameter for this endeavour is crew safety and radiation protection. The advantage of a water wall system that uses forward osmosis bags and algae for water filtration, atmospheric control, and food generation is presented in Table 2b. This table uses published[17] values for the oxygen generation system (OGS) and water recovery system (WRS) mass onboard the International Space Station, as well as the recurring mass requirements for repairs and resupply. The recurring OGS costs come out to approximately 0.02 kg/kg of O_2 produced. Although it is not a very large margin, Table 2b shows that the multipurpose use of water walls impacts total vehicle mass on the tonne level.

Radiation shielding has a very significant impact on overall habitat mass for long duration missions which cannot be ignored with the current NASA requirements. There are not many good options to reduce the impact on habitat mass for these long duration missions either, but further study to reduce the uncertainty about radiation's impacts on the human body could potentially allow the existing radiation requirements to be relaxed. Even still, the required shield mass to reduce the astronauts' exposure to this level will still be significant.

Table 3b: ECLSS Requirements based on Mission Duration and a Crew of Four

	90 (Short)	365 (Medium)	1000 (Long)	days
Water Wall (WW)	13	32	43	MT (Tonne)
Food - WW algae	99	402	1100	kg/CM
Total	**13.4**	**33.6**	**47.4**	**MT (Tonne)**
OGS Rack Non-recurring	1487	1487	1487	kg
OGS Rack Recurring	2	6	16	kg/CM
WRS Rack Non-recurring	3042	3042	3042	kg
WRS Rack Recurring	33	135	370	kg/CM
Comparable Polyethylene Radiation Shielding	12.6	31	41.7	MT (Tonne)
Food	117	474.5	1300	kg/CM
Total	**17.8**	**38.0**	**53.0**	**MT (Tonne)**

VI. Propulsion

The power and thermal requirements detailed in *Appendix A* drove the baseline design of the habitat service module. The service module was designed to be pre-integrated with the habitat to allow easier launch load transfer and to allow docking and crew transfer via a passthrough between the aft of the habitat and a vehicle docked to the aft docking port. The service module is designed to be integrated to the payload attachment fitting at the bottom of the stack during launch, and houses the batteries, radiators, solar panels, propellant tanks, and reaction control system thrusters. The aft bipropellant tanks inside the service module are pressurized tanks sized to hold 200 m/s^2 ΔV capability. This allocation of ΔV provides enough propellant to perform multiple slow rendezvous and docking maneuvers, orbital maintenance maneuvers and attitude corrections. These biprop tanks feed four thruster quads on extendable booms offset from the radiators and solar panels to avoid plume impingement on them or the habitat. 200

m/s ΔV was determined acceptable for the purposes of the spacecraft's built in service module because the delivery of the Vanguard module to the various orbits examined in this study, is expected to be on an additional propulsion system. The design of a propulsion system large enough to deliver Vanguard fully outfitted and supplied for a two year mission, to the various orbits detailed in this paper, could be the focus of a future study.

VII. Thermal

The Vanguard service module also houses part of the thermal loops that connect the hot internal habitat equipment to the cool radiator sinks: a notional thermal loop diagram can be seen in Figure 5. There is 120 m^2 of extendable radiator area which reject up to 40 kW of internally generated and externally absorbed heat for the entire habitat. This allows the spacecraft to reject the reflected sunlight and infrared backloads of LEO and LLO, as well as the incident solar light on the habitat. When not in LLO, the radiators will operate at significantly reduced capacity because the incident thermal load will be significantly reduced. A notional thermal loop shows how the ventilation pushes the warm habitat air through the core structure of Vanguard, and directs the air down to one of the cool heat exchangers which links to the radiators. Cold plates also transfer their thermal loads to the radiators through a pumped liquid loop. The radiators then dump the heat to deep space while shadowed by the solar panels.

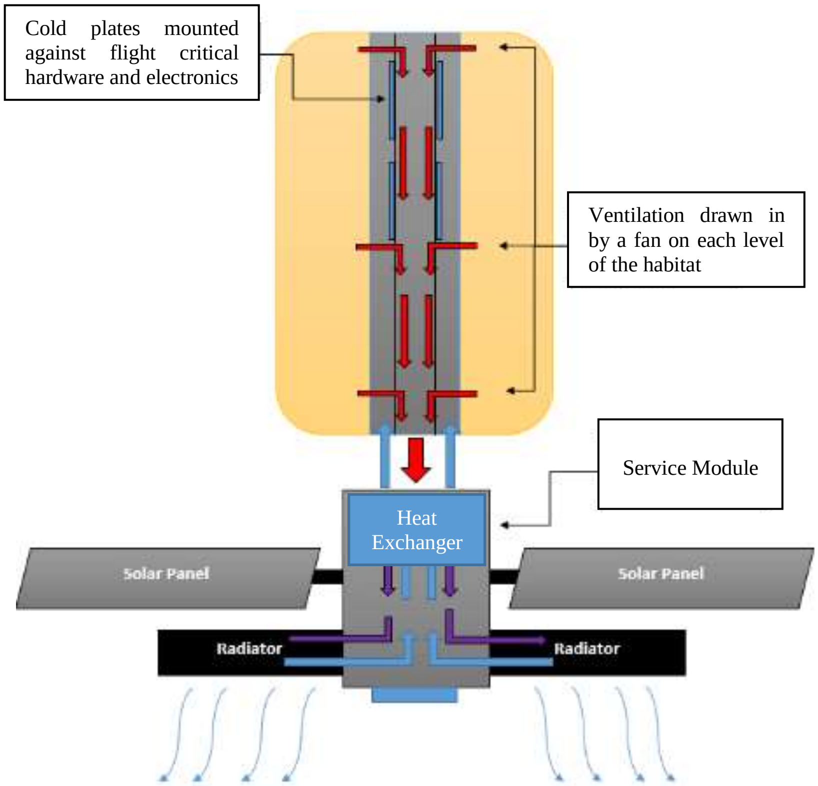


Figure 5: Vanguard Thermal Loop Diagram

VIII. Power

The solar arrays for the service module are triple junction ZTJ cells sized to provide 47 kW of electrical power to the habitat in LEO, which requires 125 m^2 of array area. The habitat peak power requirement is 15 kW at any given time and the nominal power requirement is 10 kW, but the arrays are sized larger to power the habitat in Mars orbit which is 1.65 times the distance from the Sun at apogee, requiring 2.7 times the array area to provide an equivalent power level. The arrays are also sized to provide extra power to charge the batteries during the day passes. This extra power is determined based on the orbital daylight to eclipse ratio, required power during eclipse, and the time in sunlight to generate for the corresponding orbits. In LEO, LLO, and LDRO the solar arrays will be required to maintain solar incidence angles greater than 0° to avoid overloading the thermal loops.

The results of sizing the arrays and batteries based on the orbit's sunlight to eclipse ratio is laid out in Table 3. The batteries for the service module are Lithium Ion batteries with a specific energy of 200 W-hr/kg and energy density of 250 kW-hr/m^3. In order to survive the eclipses in LDRO, with the habitat operating in a contingency power mode which reduces energy use to 10 kW, the batteries weigh 560 kg and require 0.5 m^3 of volume in the service module. This analysis assumes a worst case 9 hour eclipse in LDRO (a lunar eclipse and an Earth eclipse combined) and an 80% battery depth of discharge to increase battery lifetime and avoid ever fully discharging the batteries. For comparison, battery mass for the next limiting case, Low Lunar Orbit with 55 minute eclipses, is only 110 kg, and the battery only requires 0.1 m^3 of volume in the service module, a significant decrease from the LDRO eclipse case. The LLO case also reduces the depth of discharge to 50% due to the significant increase in the number of eclipses that will occur over the lifetime of the vehicle.

Table 3: Battery and Array Sizing

	LEO	LLO	LDRO	LMO
Eclipse Time (hr)	0.6	0.75	9	0.46
Orbit Light to Dark time ratio	2.6	1.7	20	4.3
Depth of Discharge	0.5	0.5	0.8	0.5
Required Energy Storage (kW-hr)	18	23	113	14
Required Array Power at Earth (kW)	19	21	16	47
Required Battery Mass (kg)	90	110	560	70
Required Battery Volume (m^3)	0.07	0.09	0.45	0.06

To compare the impact of operating in the different thermal and power environments, system mass breakdowns for the Vanguard vehicle designed to operate in each environment can be seen in Table 4. The analysis suggests, that the total effect on vehicle mass to operate in all of the different environments is significant, but within reason, resulting in a 14.7% difference in total vehicle mass. This effect is primarily a result of increased radiator and thermal control system mass to reject the additional heat loads in LLO as well as additional battery sizing to accommodate long eclipses in LDRO, and increased solar panels to charge batteries and provide the habitat with enough power in Mars orbit. Wrapped in the habitat structural mass listed in the table is the core structure, secondary structure, inflatable shell with micro meteoroid orbital debris shielding, and two International Docking Adapters to support visiting vehicles.

Table 4: Vanguard System Mass Breakdown based on orbital location

	LEO	LLO	LDRO	LMO	Combined Case
Thermal Control System	1060	2120	1060	1060	2120
Solar Panels	130	140	100	310	310
Batteries	90	110	560	70	560
Habitat Structure	7300	7300	7300	7300	7300
Service Module	1660	1660	1660	1660	1660
Propellant	1400	1400	1400	1400	1400
Total (kg)	11640	12730	12080	11800	13350
Percent Change Compared to LEO	N/A	9.4	3.8	1.4	14.7

IX. Cost Analysis and Expansion Paths

NASA's human spaceflight program has begun to set its sight beyond LEO again, and this time with a relatively flat budget. Better technology exists, but operations costs and human spacecraft costs have not been reduced. In order to realize the vision of a human presence beyond LEO and maintain that capability, a new approach must be taken to significantly reduce the cost of designing, developing, and operating the spacecraft that will take and keep us there. The best way to ensure that the money spent leaving LEO will be spent effectively is to develop a multi-purpose habitat that will be designed from the start to work in a large majority of the realistic near-term destinations for human spaceflight.

Incorporating the ability to visit multiple solar system locations allows Vanguard to enable multiple paths of human exploration and incentivizes multiple unit production, thus maintaining the quality of the production lines and reduced cost of the spacecraft. It accomplishes this by reducing unique investments for design, development, testing and evaluation (DDT&E), and taking advantage of production learning curves which reduce cost of production as more units are built. In order to reduce total program costs, commonality and large batches of consistent production at a regular pace is necessary.

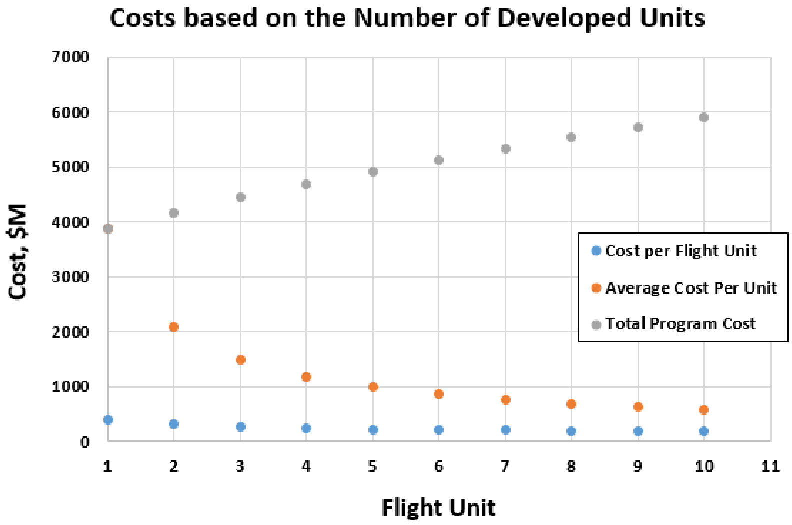


Figure 6: Cost by Number of Units

Based on the Arney and Wilhite cost model, DDT&E for Vanguard is expected to require a nonrecurring cost of $3.48 billion.[19] The production of the first flight unit is expected to cost $385 million. The 80% production learning curve assumed in this model, seen in Figure 6, shows the cost of each flight unit as the production line improves its processes and reduces inefficiencies. Also seen in Figure 6 is that, while developing a single Vanguard unit costs $3.87 billion, developing a second only costs an additional $310 million. This means that as more Vanguard units are produced, the average cost per unit is driven down, while the investment to develop the first unit remains a constant $3.87 billion. The additional cost to develop 10 units, instead of a single one, is $2.04 billion, but reduces the average amortized cost per unit from $3.87 billion to $590 million. There is significant value to be gained from increasing unit production to reduce the unique investment spent developing a system. Eventually, if enough units were produced, the average cost would be driven down to approach the price of unit production.

In addition to this, Vanguard is designed with potential upgrade paths in mind to maintain its relevance and allow new technology to be included as it is developed, expanding upon the module’s capabilities as desired. Currently, potential upgrade paths include utilizing multiple modules to develop the first artificial gravity habitat, development of an additional module to allow landing on small solar system bodies or the Moon, or docking with multiple modules and other space-based assets to develop a habitat capable of supporting more than four crew members.

X. Conclusion

Given the cost constraints likely to persist in future human exploration programs, the development of relatively low-cost systems with applicability to a variety of missions would be an advantageous use of limited resources. The Vanguard concept represents such an approach to affordable exploration missions. Vanguard supports up to a crew of four, and is designed from the outset to work in orbital space anywhere from low Earth orbit to Mars orbit. As a self-contained habitat system, it is capable of being added with minimum impact to any human exploration program, providing a livable long-term home for the crew. Adoption of a modular, common habitat concept such as Vanguard will provide economy of production scale across multiple programs, and stretch the limited exploration budget across additional potential mission destinations.

The effect of designing the Vanguard habitat to apply to many of the near term targets for human exploration is significant, but not dramatic. The study found that the combined effects of changing the thermal control and power management systems amount to a 14.7% change in total mass compared to the LEO baseline design, but ensure that NASA’s investment in the next human spacecraft will be applicable to the destinations of the foreseeable future. While Vanguard is not strictly optimal in any of the above environments, the near-global applicability and ability to be launched on multiple vehicles is a valuable trait that will help NASA reduce the cost of human exploration and enable NASA to visit more than one destination without designing another new spacecraft.

Future work in the design and analysis of this concept would focus on refining the radiator sizing and mass, in addition to re-evaluating the combined case to ensure that the increased thermal rejection system in LLO with LMO sized arrays is truly sufficient. The authors would also like to determine the effect of Vanguard’s lifetime on the mass of the system in the future to investigate the effects of reusability. Future analytical work will also seek to define logistics approaches, and determine how resupply strategies associated with the different orbital environments affect the required Vanguard consumables mass.

There are a number of unresolved issues with the initial set-up and nominal operations of inflatable habitats which would be best addressed via ground-based experimentation and simulation. Converting the habitat from the central core with inflated pressure envelope to a functioning habitat in microgravity could possibly involve a great deal of crew time, which would best be done in neutral buoyancy to provide a long-term simulation of the microgravity environment. Given the presence of the Neutral Buoyancy Research Facility on the University of Maryland College Park campus and the robotic systems operating in the UMd Space Systems Laboratory, a detailed study of the outfitting and operation of an inflatable habitat would be ideally suited to the University of Maryland team. This would involve both humans and telerobotic systems to perform the outfitting and initial maintenance functions, with the goal of quantifying the effects of human/robot collaboration in ongoing space operations.

This paper represents a brief synopsis of the work done to date on the Vanguard concept. Results indicate that the use of modular inflatable habitat elements is both feasible and favored over more traditional rigid-shelled structures, but further research, in greater detail, is necessary to refine the analysis and validate some of the underlying design decisions. While a significant majority of governmental funding in human space exploration is currently going to transportation systems, namely launch and crew entry vehicles, there needs to be a parallel, comparable effort aimed at the near-term development of affordable in-space crew habitat such as Vanguard.

Appendix A

Mission Requirements

1 Spacecraft shall be able to operate in Low Earth Orbit, Low Lunar Orbit, Lunar Distant Retrograde Orbit, and Low Mars Orbit.

1.1 The spacecraft shall be able to operate in Low Earth Orbit (LEO)
1.1.1 The spacecraft shall be capable of handling the thermal environment of Earth while maintaining internal temperature between 20-22C
1.1.1.1 The spacecraft shall maintain temperature through 40 minute eclipses at Earth
1.1.1.2 The spacecraft shall reject heat to maintain internal temperature during solar illumination
1.1.2 The spacecraft shall be capable of powering the habitat at 1 AU from the Sun
1.1.2.1 The spacecraft shall have solar arrays to provide the necessary power
1.1.2.2 The spacecraft shall have battery capacity to power the spacecraft during the eclipse determined in requirement 1.1.1.1

1.2 The spacecraft shall be able to operate in Low Lunar Orbit (LLO)
1.2.1 The spacecraft shall be capable of handling the thermal environment of Low Lunar Orbits while maintaining internal temperature between 20-22C
1.2.1.1 The spacecraft shall be able to maintain temperature through up to 70 minute eclipses
1.2.1.2 The spacecraft shall be able to reject heat to maintain internal temperature during solar illumination
1.2.2 The spacecraft shall be capable of powering the habitat at LLO
1.2.2.1 The spacecraft shall have solar arrays to provide the necessary power
1.2.2.2 The spacecraft shall have battery capacity to power the spacecraft during the eclipse determined in requirement 1.2.1.1

1.3 The spacecraft shall be able to operate in Lunar Distant Retrograde Orbit (LDRO)
1.3.1 The spacecraft shall be capable of handling the thermal environment of Lunar Distant Retrograde Orbits while maintaining internal temperature between 20-22C
1.3.1.1 The spacecraft shall be able to maintain temperature during up to 9 hour eclipses or make maneuvers to avoid the eclipses
1.3.1.2 The spacecraft shall be able to reject heat to maintain internal temperature during solar illumination
1.3.2 The spacecraft shall be capable of powering the habitat at LDRO
1.2.2.1 The spacecraft shall have solar arrays to provide the necessary power
1.2.2.2 The spacecraft shall have battery capacity to power the spacecraft during the eclipse determined in requirement 1.3.1.1

1.4 The spacecraft shall be able to operate in Low Mars Orbit (LMO)
1.4.1 The spacecraft shall be capable of handling the thermal environment of Low Mars Orbit while maintaining internal temperature between 20-22C
1.4.1.1 The spacecraft shall be able to maintain temperature during 50 minute eclipses or maneuver to avoid them
1.4.1.2 The spacecraft shall be able to reject heat to maintain internal temperature during solar illumination
1.4.2 The spacecraft shall be capable of powering the habitat at LDRO

1.4.2.1 The spacecraft shall have solar arrays to provide enough power to the spacecraft at Mars apoapse (2.7x required power at Earth)

1.4.2.2 The spacecraft shall have battery capacity to power the spacecraft during the eclipse determined in requirement 1.4.1.1

2 The spacecraft shall be capable of supporting up to 4 crew for 1100 days

2.1 The spacecraft shall have an Environmental Control and Life Support System that can support the

2.1.1 The ECLSS system shall be capable of removing the CO_2 produced by the crew each day

2.1.2 The ECLSS system shall be capable of producing or supplying the O_2 required by the crew each day

2.1.3 The ECLSS system shall be capable of producing or supplying the H_20 required by the crew each day

2.1.4 The ECLSS system shall be capable of eliminating or processing the remaining quantities of harmful gases produced by the crew or spacecraft components each day

2.1.5 The ECLSS system shall be capable of monitoring and maintaining atmospheric composition and pressure inside the spacecraft

2.1.6 The spacecraft shall have a method for storing, removing, and/or processing human solid waste

2.1.7 The spacecraft shall have a method for storing, removing, and/or processing human liquid waste

2.1.8 The spacecraft shall have an ECLSS system that is equal to or more reliable than the ISS and if it is not significantly more reliable than that of the ISS it shall be far easier to fix

2.2 The spacecraft shall have crew exercise equipment

2.2.1 The spacecraft shall have a cardiovascular exercise device to try to maintain heart health

2.2.2 The spacecraft shall have a resistance based exercise device to maintain bone density

2.3 The spacecraft habitable volume shall be equal to or greater than 25 m^3 / crew-member

2.4 The spacecraft shall store enough food to provide for the crew and duration detailed in requirement 2, if necessary this may be supplemented by additional modules

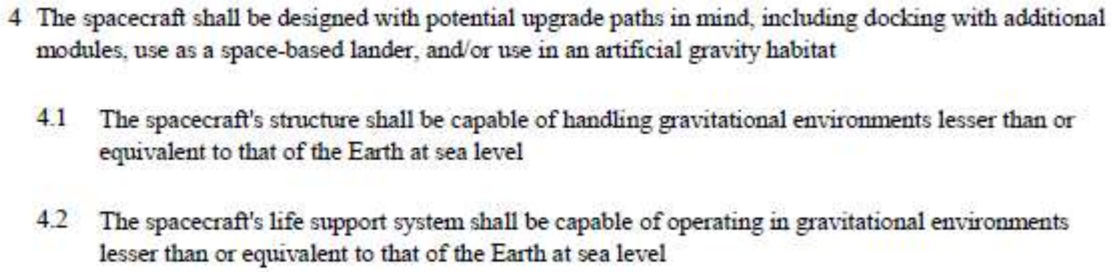
3 The spacecraft shall be capable of launching to LEO on an Atlas V, a Falcon Heavy (with a long Fairing variant), or an SLS

3.1 The spacecraft launch mass shall not exceed 18.5t

3.2 The spacecraft volume and dimensions shall not exceed the keepout range of the fairings on any of the EELVs listed in requirement 3

3.3 The spacecaraft shall be capable of sustaining the expected structural launch loads associated with

3.4 The spacecraft shall be capable of sustaining the vibrational modes of the associated launch vehicle



4 The spacecraft shall be designed with potential upgrade paths in mind, including docking with additional modules, use as a space-based lander, and/or use in an artificial gravity habitat

4.1 The spacecraft's structure shall be capable of handling gravitational environments lesser than or equivalent to that of the Earth at sea level

4.2 The spacecraft's life support system shall be capable of operating in gravitational environments lesser than or equivalent to that of the Earth at sea level

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