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Vanguard: A Common Habitable Module for Future Space Endeavors

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Abstract

This paper investigates the potential for taking a single generic habitat design and adapting it for use at a number of potential human exploration targets, including on-orbit, on or near small solar system bodies, or on the surface of the Moon or Mars. The paper reviews the design of Vanguard, a four-person inflatable habitat sized for launch on a Falcon Heavy or larger vehicle as a supplement or, ultimately, a replacement for the International Space Station in low Earth orbit. The first extension of the application domain of the habitat is as a "Deep Space Habitat" in a periodic distant orbit of the Moon, where it is no longer shielded from radiation by the Earth's magnetic fields. The next step in terms of habitat modifications is to support human exploration of near-Earth objects or the moons of Mars, where the habitat will be located on the surface of the body and the internal systems will have to accommodate milligee-level gravitation. Extending habitat applications to the surface of the Moon or Mars changes the nature of the design from microgravity to substantial gravitational levels, with entirely separate challenges in landing the habitat on the Moon as compared to entry, descent, and landing on Mars. The final application of interest is the use of multiple Vanguard modules to create an artificial-gravity research station, using active wire tension elements to support the structures and damp out oscillations. Results of this study indicate that the investment in the development and implementation of a small modular LEO habitat will reap dividends due to its application across a broad spectrum of future exploration applications.

Nomenclature

EDL = entry, descent, and landing
LEO = Low Earth Orbit
LLO = Low Lunar Orbit
LDRO = Lunar Distant Retrograde Orbit
LMO = Low Mars Orbit
WW = water wall
SOA = state of the art
ECLSS = environmental control and life support system
PPT = power propulsion and thermal
MER = mass estimating relations
CER = cost estimating relations
CM = crew member
DSH = deep space habitat
DOD = (battery) depth of discharge
ISS = International Space Station
CM = Crew Member

I. Introduction/Background

As humans plan to leave the relatively benign environment of low Earth orbit for the first time in nearly five decades, there are a variety of possible mission destinations. Many of the current discussion are focused on a

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Deep Space Gateway, providing the experience of living beyond the protection of Earth's magnetic field while remaining close enough to Earth to allow a quick return in the event of a problem. There is still interest in human missions to near-Earth objects (NEOs), both for exploration and for potential industrialization through the use of in-situ resources. The "ultimate" instantiation of small solar system body exploration would be Phobos and Deimos, the moons of Mars. These bodies would be ideal staging points for eventual human exploration of the surface of Mars, and may be sources of in-situ resources themselves. There is still much to explore on the moon, and many people are focusing on the idea of extended human lunar exploration. On the other hand, concerns over the long-term effects of lower gravity levels, such as those of the moon and Mars, argue for a near-term development of an artificial gravity station to provide the necessary data prior to an extended mission to Mars.

While all of these disparate destinations offer both challenges and opportunities, they all have one thing in common: each will require a local habitat for humans that is over and above the habitable volume of the crew launch and entry vehicle. While the Apollo crew could live in the command module for several days on the way to the Moon, it would be unreasonable to live in any of the human vehicles under development for many weeks or months as required for these candidate missions.

Each of these mission destinations require a unique set of accommodations from a crew habitat. Yet, each have many common elements with other missions. Would it be possible to design a single, standardized habitat which, with some minor mission-specific modifications, could be adapted to each of these candidate missions? And, since each of these possible destinations in space is competing with the others for severely limited funding, could the standard crew habitat be a relatively small, low-cost system rather than a very expensive system subsuming all possible destinations into one design? These questions are the focus of this paper.

The analysis starts with the selection of Vanguard as the standard LEO habitat element. The Vanguard system was designed by a University of Maryland team in response to the NASA RASC-AL design program, for a mission theme focusing on a low-cost human LEO habitat to supplement the International Space Station and to take over its role following the termination of that program. As such, Vanguard is typical of the class of such small stations, based on a single heavy-lift launch vehicle flight and using inflatable technologies to expand the pressurized and habitable volumes on-orbit. While the team chose Vanguard largely on the basis of its familiarity (and availability of design details), the study process would be equally applicable to any other habitat design of this class.

In the following sections, we will start with an overview of the design of Vanguard in its baseline configuration as a LEO station focusing on commercial space operations. The specifics of the physical design will be followed by a section relating the nominal operating conditions and capabilities in LEO applications. With those two sections as a "baseline" for the design, the bulk of the paper will focus on a series of alternative habitat applications, focusing primarily on changes from the Vanguard baseline design required to fulfill mission requirements and sustain human life in different conditions in space. The specific targets of interest are

- Lunar distant retrograde orbit (or other long-term stable distant orbit of the moon)
- Near-Earth objects
- Phobos or Deimos
- Mars surface base
- Lunar surface base
- Artificial-gravity space station

While this order of applications may seem strange, and definitely non-chronological, it will be shown that the rationale behind the ordering represents a spectrum of design complexity from simplest to most challenging. As such, the degree of design modification will be monotonic, which will allow the assessment of whether a design modification is needed for a variety of future missions, or only specific to an individual destination.

The LEO mission will provide a new space station to supplement and eventually replace the ISS, as well as acting as a proving ground for a new system. LEO is an ideal testbed for extended duration human isolation studies as well, since it does not come with the health issues arising from being outside of the Earth's magnetic field. With NASA's plans to deorbit the ISS within the next decade, a new station capable of supporting further science missions is needed.

LDRO (or other long-term stable orbit in cislunar space) provides an environment away from the protection of the Earth, and in particular Earth's magnetic fields. After LEO, this orbit provides an excellent test bed for further missions. In addition to testing Vanguard for a harsher radiation environment, LDRO will also be used to evaluate operations and procedures for a long duration orbit outside of LEO.

Missions to small solar system bodies, such as near-Earth asteroids or comets or the moons of Mars, will involve additional duration and distance, as well as the need to operation in extended contact with the surface of a low-gravity world. The former issues can be dealt with via additional logistics stowage space; the latter requires legs or other structures to allow long-term attachment to the surface at gravity levels on the order of 1/1000 that of Earth. Although listed as two destinations in the list above, the difference is one of scale rather than content, and both mission destinations will be considered as one.

A mission to either the lunar or Martian surface brings the added challenge of landing on a body with substantial gravity. While Mars entry, descent, and landing (EDL) involves significant aerodynamic and aerothermodynamic challenges, it simplifies the actual landing process by limiting the final deceleration to approximately 500 m/sec due to the terminal velocity in the lower Martian atmosphere. On the other hand, a lunar landing involves a total of nearly 3000 m/sec of delta-V, but does not require aeroshells or other protective layers. Both systems will require the accommodation of extensive surface infrastructure and operations, including the potential for interfacing to multiple pressurized rovers and accommodating daily extravehicular activities for surface exploration. Ultimately, the greatest discriminator between Mars and lunar surface habitats is the greatly prolonged lunar day and night, giving rise to the most extreme thermal variations of any exploration destination, and greatly complicating power systems and energy storage. Ultimately, the two destinations will be considered separately, with Mars as an overall simpler challenge for the surface base designer than the Moon.

As the duration of time spent in space increases, such as during Mars transit, the long-term effects of varying gravity levels on the human body becomes an increasingly important. While results from long-duration missions on International Space Station indicate that humans can endure the nine-month nominal duration of a Mars transit, there is no information at all on the long-term effects of reduced gravities (whether at Mars or the Moon) on the human body, nor on transitions between partial- and micro-gravity levels. An artificial gravity spacecraft will have a major role in understanding issues relating to astronaut health for Mars transit, as well as other long-term missions. This system will be designed to accommodate a range of gravity levels in the habitats up to one Earth gravity for research purposes. In line with the simple design elements of the basic Vanguard habitat, emphasis on the artificial gravity station will be to keep the system small and light enough to allow it to be economically and operationally feasible for use as a transit habitat to and from Mars for human missions.

To adequately design Vanguard for each of these six missions, it will be necessary to include the specific design of all required onboard systems. Some will be common across mission applications, while others will be specific for individual destinations. One of the critical needs for habitat design is for logistics, particularly stowage. LEO missions will have a schedule for routine logistics flights, whereas a Martian transit habitat may well have to carry crew consumables for two to three years of operations without resupply. One of the primary drivers of internal layout for the habitat will be volumes which are suitable for stowage, and convertible to other uses as logistics are consumed.

One immediate design decision is the degree of self-sufficiency desirable for Vanguard. While it is likely that some of the missions will have alternative support systems, such as power, thermal control, and communications, it was decided that Vanguard would have greater multi-mission viability if it is essentially a "stand-alone" unit. To that extent, the basic Vanguard architecture includes communications, propulsion for attitude control and limited maneuvering, thermal control, communications, and data control and handling systems. Obviously, as a habitat it must have full life support capabilities, which will vary depending on whether a given unit is intended for operations solely in microgravity, a planetary surface, or rotating for artificial gravity. An external service module will provide mounting locations for systems which are not suitable for locating inside the pressurized volume, such as propulsion systems or some thermal radiator fluids. The service module will provide docking interfaces for Vanguard for crew rotation and logistics support, as well as mounting reaction control system thrusters and all other external systems, eliminating external structural connections to the inflatable pressure envelope.

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II. Vanguard Overview

Vanguard is a crewed spacecraft designed to support a crew of four for over 1000 days in each of the environments detailed above. There are many requirements which come from this mission statement, many of which focus on maintaining a healthy and safe environment for the crew.

A driving constraint was designing Vanguard to fit in any of the probable heavy-lift launch vehicles in the coming decade. The Vanguard system is sized to fit inside the 5m wide fairing, which is a variant of the payload fairing for a number of launch vehicles and will reduce dependency on any particular launch vehicle.

A rigid structural core runs down the center of the inflated habitat module. This core connects to a Common Berthing Mechanism on each end, with the service module attached to one end. This service module contains elements which are hazardous or unnecessary to have in the habitable workspace, such as maneuvering thrusters, fuel tanks, solar arrays, battery banks, and radiators.

Together the service module and the habitat module make up a Vanguard module. The habitat module provides the living and pressurized workspaces while the service module provides power, data, thermal, and propulsion. The rigid core is designed to handle all launch loads and provide a pass-through for transit between floors. It also houses critical vehicle equipment. The inflatable habitat baseline structure is derived from the NASA Johnson Space Center Transhab program, and has a total estimated mass of 7.3MT.

Vanguard is 4.3 m in diameter when stowed, and 10 m long. When fully inflated, Vanguard expands to 8.2 m in external diameter, providing a total available internal volume of ~350 m^3, 7.5m tall and 7.5m internal diameter. Excluding the central core structure from the habitable volume gives approximately 300m^3. Adding on a conservative factor that only 30% of pressurized volume is habitable volume provides 90m^3. If the conservative factor is calculated without excluding the central core, the habitable volume comes out to be 105 m^3. Another useful metric for spacecraft sizing is floor space. Although floor space is not very demanding for microgravity, it is important for partial gravity situations. Again

Table 1: System Power Requirements

System	Avg. Power (kW)
C&DH	4.08
CHECS	0.11
CTS	2.90
ECLSS	5.31
EPS	2.02
ESA	2.04
FCES	1.07
FGB	1.80
GN&C	0.62
JEM	5.35
MECH	0.19
MPLM	0.56
MSS	1.20
PAYLOAD	10.39
SM	3.64
TCS	8.72
TOTAL	**50kW**

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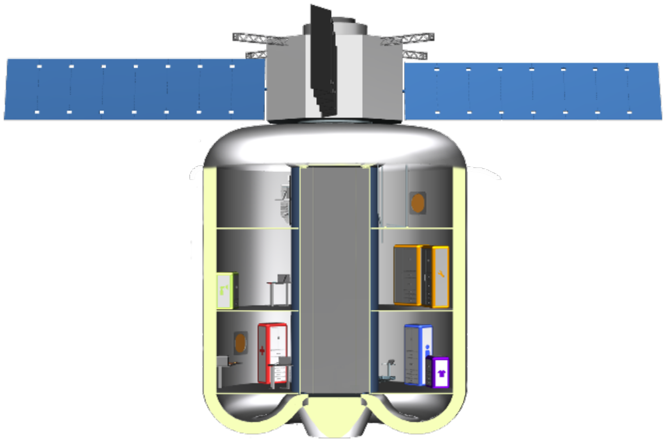

removing the central core structure from habitable area gives a floor space of ~118m^2. This allows for the allocation of ~25m^3/CM and 30m^2/CM given the respective gravity environment.

Vanguard's baseline system, the LEO habitat, can be adapted to LLO, LDRO, a Mars transit habitat with centrifugally-generated artificial gravity, and surface habitats for conditions on the Moon and Mars. The common Vanguard system, as currently designed, is pictured in Figure 1 and Figure 2.

The Vanguard total power budget of 50kW will remain as a constant through this paper. However, the distribution of this 50kW will vary depending on location. Most of the variation will be borrowed from the "Payload" system seen in Table 1. This table is based off of ISS power requirements[3]. The solar arrays and battery type will also remain constant with lithium batteries with an assumed specific energy of 200 W-hr/kg, energy density of 250 kW-hr/m^3, and depth of discharge (DOD) limit of 50%. It is also assumed that when the batteries are being used, the power draw for the spacecraft will be dropped to 20kW. For solar array sizing, it is assumed that there is a 3% loss from radiation, UV and thermal cycling each year.

III. LEO Mission Applications

The Vanguard system in LEO will serve as the 'baseline' design as a reference for all other missions discussed in this paper. As described above, Vanguard is a crewed spacecraft designed to support a crew of four for over 1000 days and must be able to be launched in any of the planned heavy-lift launch vehicles in the coming decade. The major modifications for LEO operations are seen in the resupply schedule, radiation shielding, power, and thermal systems. LEO allows for resupply every 90days or so depending on launch operations, but we will also look at 1000 day missions to standardize across all variations. The 90day resupply is based off of current ISS resupply scheduling. The resupply module has the option of docking at either end of Vanguard, but will prioritize docking at the end that does not have the service module on it. Table 2 shows the system mass breakdown for the LEO configuration. The battery mass does not change between mission durations because the 50% DOD is assumed to provide a cycle life of 1000 days. These assumption will be removed in future work.

Table 2: Mass Breakdown for 4 crew, LEO Mission

	Mass (kg) 90 days	Mass (kg) 1000 days
Food + Water (OGS+WRS)	5137	11273
Radiation Protection (Polyethylene)	12600	12600
Habitat Structure	7300	7300
Service Module	1660	1660
Batteries	120	120
Solar Arrays	345	366
Thermal Control System	3250	3250
Propellant	1400	1400
TOTAL Mass (kg)	31812	37969

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The thermal loop for LEO consists of an internal flow loop with coldplates, and flow through external radiators with a flash evaporator. This system was chosen instead of current ISS flight units due to the mass efficiency of the system.

IV. LDRO

The logical "next step" for human space exploration would be to move beyond the protection of the Earth's magnetic fields to experience the conditions present in "deep space"; this is currently under consideration as a "deep space habitat (DSH)" element of a "deep space gateway". Since the primary change in this move is the unattenuated radiation environment, one could technically get the same effect in any Earth orbit above 72,000 km altitude. However, much of the recent conversation of DSH has focused on a lunar distant retrograde orbit, or other similar orbit thousands of kilometers from the surface of the Moon which offers long-term stability in the Earth-Moon-Sun system. Such an orbit requires minimal orbital maintenance, and offers advantages in connection with manifold trajectories offering low delta-V options to Earth-Moon and Earth-Sun libration points.

Variations in system and mission requirements regarding life support, propulsion, and power intake for LEO and LDRO missions result in significant mass differences between the Vanguard modules. The most drastic of these comes from the life support systems. In LDRO, Vanguard is beyond the protection of Earth's magnetic field and requires a much more robust protection against the additional radiation. While there are a number of intermediate options, such as additional protections for the crew sleeping quarters which double as "storm shelters" in the case of a solar particle event, the ultimate approach would be to triple the amount of polyethylene shielding to 31 MT, which represents a total areal mass of shielding of 15 gm/cm^2. This would reduce the crew's expected annual radiation dosage and be within current NASA guidelines for acceptable yearly crew radiation exposure.

Another significant difference in mass arises from the power requirements for sustaining the habitat in each orbit, as solar array and battery size depend heavily upon an orbit's sunlight to eclipse ratio, which changes dramatically between orbits. In LDRO, for example, a habitat may experience eclipses lasting up to 9 hours; it therefore requires more battery mass to compensate for the lack of solar power during these events.

Table 3: Mass Breakdown for 4 crew, 1000 day LDRO Mission

	Mass (Kg)
Food + Water (OGS+WRS)	11273
Radiation Protection (Polyethylene)	31000
Habitat Structure	7300
Service Module	1660
Batteries	1800
Solar Panels	382
Thermal Control System	3250
Propellant	1400
TOTAL	58065

V. Martian Base

One of the major applications of a multipurpose habitat would be to serve as a Mars surface base. Standard conjunction-class missions require approximately 15 months at Mars while waiting for a return window for reasonable mission delta-V; the best use of humans at Mars would be to remain on the surface performing exploration for as much of that time as practical.

Adaptation of the station for surface operations will require a number of changes. Many of the baseline life support systems were designed for microgravity use, and will require major redesign or replacement for use in substantial gravity fields. This also calls into question the use of the habitat for use in both Mars transit and surface operations, as many of the life support units would have to duplicated for the two gravity conditions.

External accommodations of the habitat would also need to be redesigned for surface operations. Concern over potential toxicity of the Mars regolith would encourage maximal efforts to minimize internal contamination, which could lead to nominal use of suitports to keep the suits exteriorized as much as possible. Surface exploration systems, such as pressurized rovers, will need docking ports to allow shirtsleeve transfer from the habitat. In Mars gravity, climbing ladders or extensive stairways would be discouraged; airlock(s) need to be located near the surface to simplife

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ingress and egress. To support all of these activities, a surface access module needs to be located on the bottom of the habitat in close proximity to the surface.

Table 4: Mass Breakdown for 4 crew, 1000 day Martian Surface Mission

	Mass (Kg)
Food + Water (OGS+WRS)	11273
Radiation Protection (Polyethylene)	41000
Habitat Structure	7300
Service Module	1660
Batteries	2465
Solar Panels	8140
Thermal Control System	8500
Propellant	1400
Airlock	6000
EDL (Heatshield and propulsive stage)	~5000
TOTAL	92738

A. EDL

One of the greatest challenges for Vanguard applications is the issue of entry, descent, and landing (EDL) on Mars. Whether in terms of mass or volume, Vanguard is at least an order of magnitude larger than anything landed to date on Mars.

Figure 3: Mars Entry Architecture

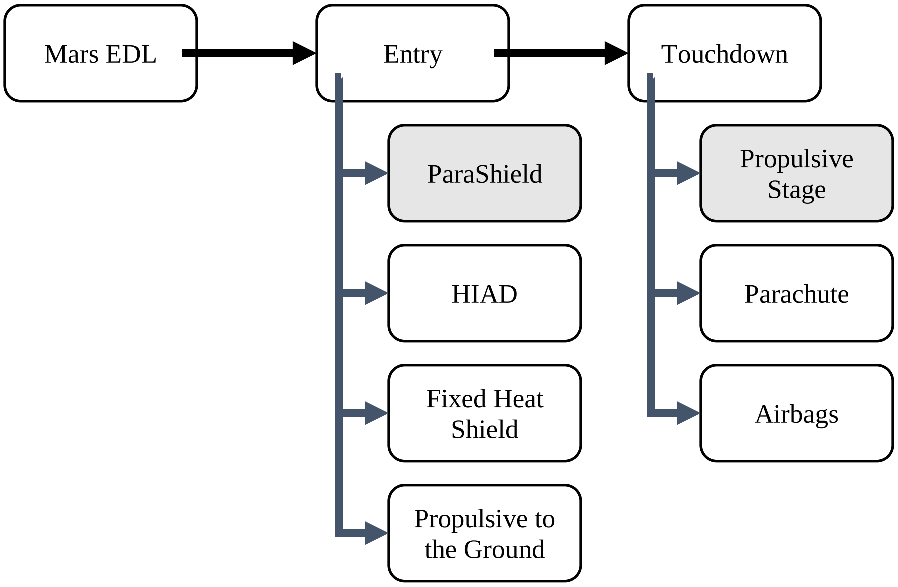

Figure 3 shows the entry and descent options that were qualitatively compared. The shaded boxes are the chosen configuration. Entry protection will require a heat shield for aerothermodynamic issues. The size of Vanguard, even with the habitat skin deflated, prohibits an all-enveloping aeroshell; the system will have to rely on the lee surface of the heat shield for protection, along with some surface insulation to protect against radiation from the wake. The heat shield will need to be at least 8-10 meters in diameter to keep the Vanguard habitat inside the potential wake convergence zone.

One approach would be an inflatable heat shield, such as the HIAD system currently under development. However, perhaps the most promising approach would be in the area of ultra-low ballistic coefficient vehicles, such as the ParaShield concept. On Earth, ParaShield is a mechanically deployed heat shield which serves for both entry heating protection and terminal deceleration, resulting in a terminal velocity around 10-15 m/sec and requiring only some form of impact attenuation. On Mars, a ParaShield system for Vanguard with a ballistic coefficient of 15 kg/m2 would

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be 15-18 meters in diameter, and would be folded around the deflated habitat for cruise and deployed prior to entry. Since it does not rely on pressurization and the integrity of pressure bladders, the ParaShield could be deployed any time during cruise to ensure full deployment and locking prior to entry. A small offset of the system center of gravity from the centerline of the ParaShield will result in lift-drag ratios comparable to early crewed capsule designs, allowing control of the entry flight path and targeting of specific landing sites throughout entry.

Unlike Earth, the terminal velocity of Vanguard with ParaShield would be approximately 250 m/sec at a MOLA altitude of 0 km. At that point, the ParaShield would be jettisoned and a propulsive landing would take place. Incorporating additional delta-V for gravity losses and a margin for hover for landing site selection, the overall delta-V requirement for the propulsive landing system would be 400m/sec. While the goal for the propulsive landing unit would be to set the habitat down as gently as possible, the habitat design will have to incorporate landing legs to attenuate impact energy and provide stability in case of landing on a slope or with one or more feet on obstacles.

Table 5: Propulsive Stage Requirements

RP1	2870	kg
LOX	8620	kg
V RP1	3.50	m^3
V LOX	7.56	m^3
RP1 Tank	42.5	kg
LOX Tank	92.2	kg
LOX Insulation	20.9	kg
Avionics	648	kg
Wiring	484	kg
Landing Gear	2790	kg
	15.6	**MT**

VI. Minor Bodies

Minor bodies such as planetary moons and asteroids seem like a resonable stepping stone on the path to deep space exploration. They offer radiation protection, raw metals, and even the possibility of water. Something that they don't have, that's of great benefit, is a large gravity well. These bodies have much smaller gravity gravitational pulls so landing and ascending from their surface is fairly affordable, when compared to planets. Landing structures don't need to disapate much built up energy from descent, and descent can be done purely on RCS, depending on the minor body. Anchors are now needed to prevent bounce off, and to properly secure the habitat to the surface. However, because of the low gravitational pull of these bodies, walking during an EVA may not be practical.

EVA on a minor body such as Phobos would be less like that of the moon, and more similar to an EVA in LEO. Lunar gravity is approximately 16% of Earth gravity, but Phobos is 0.05% of Earth gravity. In this environment, and astronaut could fairly easily launch debris in to orbit by kicking or throwing it. This creates a potional for debris cloud to be formed that could harm the astronaut on EVA, or the habitat sitting on the surface. A more controlled way to perform an EVA on such a small body would be to use a robotic system that can walk across the surface in a slow, controllled manner. The alternative is to have an EVA system hover over the surface. Systems such as single person spacecraft such as SCOUT and Genesis Engineering's "Single Person Spacecraft". Another alternative is NASA's multi mission space exploration vehicle (MMSEV). These vehicles are yet another reason for multiple docking assemblies around the base of the landed module.

VII. Lunar Base

The goal of a Vanguard surface base is to provide a permanent human presence on the Moon and Mars. For the purpose of this study, a focus is on missions which will allow a crew to remain on the surface of either the moon or Mars for an entire Earth year. As stated earlier, the habitation module and service module structure numbers are assumed from a previous study[4]. The mass assumptions on Vanguard include all necessary ECLS with spares, dry food, batteries, radiators, and all other subsystems needed for extended duration.

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The baseline Vanguard design does not include landing gear nor a propulsion system for descent. The main addition for a lunar base is the addition of the Entry, Descent, and Landing (EDL) system and an airlock to allow access to the surface. The propulsive system is only meant for a soft descent, and no ascent stage is included. In order to minimize setup, and descent vehicles, Vanguard will land after being pressurized and inflated in LEO. A propulsive descent requiring a Delta-V of 2.7km/s is the driving force for Lunar EDL. However, since a landing stage is also needed for Martian descent, a similar descent stage will be produced for lunar descent.

The only additional asset needed are the landing gear, descent stage, and an airlock to allow EVA out of the base of the spacecraft. Building on heritage hardware, and using the interpolated mass of a flight airlock adds another 6MT to the vehicle fixed mass. Using a fixed mass of 84.2MT and an MER for landing gear, the required propulsion system for descent is calculated. The detailed mass breakdown is in Table 5.

The power requirements for a lunar base are greatly influenced by the extended durations of darkness. This extended period drives up the battery mass significantly. To get around this, we are making an assumption that the batteries only need to supply ECLSS power (5.3kW). The solar arrays, will still be able to receive reflected sunlight from the Earth and creates the possibility of flying reflectors that would be capable of redirecting solar energy to the solar arrays on the lunar surface to reduce

Table 5: Mass Breakdown for 4 crew, 1000 day Lunar Surface Mission

	Mass (Kg)
Food + Water (OGS+WRS)	11273
Radiation Protection (Polyethylene)	31000
Habitat Structure	7300
Service Module	1660
Batteries	17800
Solar Panels	2700
Thermal Control System	5100
Propellant	1400
Airlock	6000
EDL (2 propulsive stages w/ propellant)	91500
TOTAL	176 MT

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A. EDL Breakdown (with Mass Breakdown)

The entirety of the spacecraft mass comes from the 84.2MT fixed mass of Vanguard, as well as an airlock and landing gear assembly. The airlock mass is based on the heritage airlocks and assumed to be approximately 6MT. All of the descent stage masses come from mass estimating relations. Stage 2 utilizes RP1/LOX instead of a higher ISP LH2/LOX mixture, because of the reduced stowage volume needed for RP1. This reduced stowage volume increases mobility around the airlock at the bottom of the spacecraft after landing.

Table 6: Mass Breakdown for Lunar EDL

Stage 1		Stage 2		
LH2	10300	RP1	2759	kg
LOX	62100	LOX	8278	kg
V LH2	145	V RP1	3.37	m^3
V LOX	54.5	V LOX	7.26	m^3
LH2 Tank	1324	RP1 Tank	40.8	kg
LOX Tank	664	LOX Tank	88.6	kg
LH2 Insulation	385			
LOX Insulation	78.0	LOX Insulation	20.4	kg
Avionics	785	Avionics	639	kg

Wiring	631	Wiring	474	kg
		Landing Gear	2680	kg
Total	**76.5**		**15.0**	**MT**

VIII. Centrifugal Artificial Gravity Habitat

For this setup, we are looking at creating a system that is capable of operating at up to 1G, but will be possible to operate at Lunar or micro gravity ranges. The idea is to have Vanguard modules connected via an inflatable tunnel, and a series of cables similar to that of a Stewart platform to translate the forces between the modules for spin up/down, and thrusting. For short axis spinners such as the one we are attempting to make, a two spoke, or rod setup, would make for an unstable system. However, with a three spoke system we have a more stable system. A three spoke system was chosen because it was the minimum module setup that was dynamically stable. However, this system is not as simple as sticking three Vanguard modules to a three spoke tunnel system. This system will require on orbit assembly, a propulsive unit capable of spinning up the entire system, and a method capable of servicing the system post spin-up.

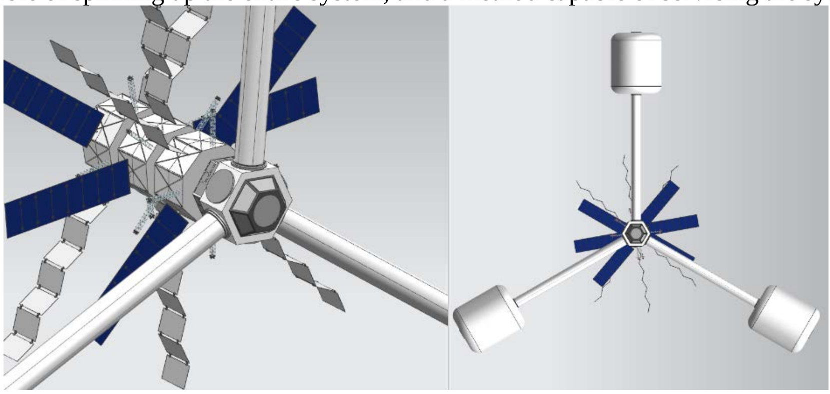

Figure 4: Artificial Gravity Setup

A. Sizing

The system must be capable of providing up to a 1G artificial gravity environment. The two driving forces in the system are the artificial gravity differential between the head and feet of an astronaut, as well as the maximum allowable rpm of the system. The restriction based on head/foot gravity variation is based on blood pressure. From ground based testing, tolerances on the rotation speed (rpm) can range from 1-10 rpm with estimates that 90% of the population can handle 3-4rpm and trained individuals can handle up to 7 rpm. Since most astronauts will most likely undergo months of training it seems reasonable to expect a tolerance of up to 7rpm. However, a higher rpm creates a larger energy cost for spin-up and spin-down. Given these two requirements we can determine an appropriate size for the tunnels connecting the three Vanguard modules.

Looking at the Bigelow BEAM module launched to the ISS, we see that an expansion rate of 1.85 can be achieved with current inflatable space structures. Using that and our interest in minimizing costs, we want each tunnel to be capable of fitting in a single Falcon 9 fairing which restricts us to a 13.1m fairing allowing a maximum possible expansion length of 24.2m. The dynamic envelope for the fairing is closer to 11m which restricts the possible expanded tunnel size to 20.4m. Using a single 20.4m tunnel would require a spin rate of 6.6rpm. Checking the head/foot height variation gives a 8.8% variation for a 1.8m tall astronaut and 10% for a 2m tall astronaut. If each spoke was two tunnels long the angular velocity could be reduced to 4.7rpm.

To counteract the forces present during spin up and spin down, the central core connecting the tunnels is made of an aluminum hexagon, with an internal cylindrical pressure vessel. Each module has a series of cables that run from the central core out to the habit modules and are used to transmit the loads through a stewart platform esc system. This avoids excess loading of the inflatable tunnel sections.

B. On Orbit Assembly and Maintenance

The final configuration of the artificial habitat involves berthing three tunnel modules to one central core with a Vanguard habitat module at the end of each spoke. However, post berthing, the Vanguard modules will undock the service module and the service modules will be placed in line with the spin axis. This restricts the spin axis to always point at the sun in order to allow the solar arrays and radiators to be properly oriented.

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IX. COSTING ANALYSIS

There are two ways to go about trying to make a low cost system such as Vanguard come to life. One method is to design it for the combined worst case scenario so that it can serve in any of the mission types listed above. This path would benefit the most from a learning curve, since every subsystem is constant across all missions. However, this method would involve launching excess mass for every mission, since there is no one case that serve as the driving force. Lunar surface has the largest battery requirements, Martian surface has the largest case solar and thermal, and LEO with 90-day resupply has the lowest requirements on all subsystems.

The other path for creating a cost-effective series of vanguard modules is to create a common core (inflatable structure, rigid core, service module) that can serve across multiple missions, and is able to incorporate the changes needed at each destination. That is the path that we have outlined, with the hopes that subsystem CER's can show minimal price variation across the Vanguard variants.

X. Conclusion

Although still at a high level, the results of this study show that a single habitat design is capable of being modified to support most exploration destinations currently under discussion. While the primary impact is on the requirement for radiation protection, there are also substantial changes in configurations for lunar and Mars surface due to landing requirements, as well as more ambitious requirements for surface exploration vehicles and access.

The most massive components in this series of vehicle configurations are the radiation shielding requirements and power requirements. Radiation shielding is very costly when trying to cover the entire shell of the inflatable, not to mention logistics issues for packing and inflating when having 16cm of polyethylene along with pressure bladders and thermal layers. The mass additions for such protection would be affordable if it could serve additional purposes, such as potable water storage and algea growth. However, a water wall system requires an additional launch dedicated to MT's of water so it is most likely only beneficial for long duration missions where an additional launch vehicle for setup would be less than one large initial launch vehicle. With the arrival of the Space Launch System and its larger fairings, and lifting capacity, it will be possible to launch the 32MT needed for lunar habitats or the 43MT needed for Martian habitats, but for our efforts this iteration we focused on polyethylene shielding. The restrictive power case came from the multiple day eclipse times on the lunar surface. This drives battery mass requirements far above any other case.

One of the most ambitious modifications to Vanguard would be to incorporate multiple units into an artificial gravity research station, due both to the structural requirements of a spinning station and the need to have life support systems which are functional in both microgravity and substantial gravity conditions. Such as system will be essential, however, in learning about human adaptation to gravity conditions such as the moon or Mars prior to sending humans there for extended stays.

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