A Crew and Logistics Lander for the Common Habitat Architecture

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Abstract— **The Common Habitat Architecture is a conceptual study that explores the use of a large habitat derived from the Space Launch System (SLS) liquid oxygen tank as a core habitation element that can be used for crew missions or training in 0g, 1/6g, 3/8g, and 1g. This is not part of current NASA Artemis mission planning, but instead represents an architecture that could potentially follow after the Artemis missions and initial human Mars landings. This architecture leverages Starship-derived vehicles for crew landing on and ascent from the Moon and Mars in support of long-duration surface missions with pressurized crew transfer baselined as a nominal capability. This is not the Human Landing System variant of Starship but represents a number of modifications to enable long-duration surface missions with an eight-person crew size. A rapid brainstorming study was conducted in February of 2021, using only public data, to identify options to deliver the 90-ton Common Habitat to the surface and emplace it at the intended habitation site. This study compared three lunar lander concepts and three Mars lander concepts before ultimately selecting the SpaceX Starship as the most viable lander. The Common Habitat Architecture assumes that this Starship variant can further be modified for crew and cargo delivery, assuming that the use of a common system will lead to cost benefits. It is assumed that the Starship will expend too much propellant in landing crew and logistics to be able to launch, given the assumed absence of surface propellant production. Consequently, a separable ascent stage is used for crew ascent. The pressurized elements of this modified Starship are discussed: Starship Ascent Module, Airlock, Transfer Tunnel, Pressurized Crew Transfer Module, and Logistics Modules. For each element, a description, dimensions, rough mass estimates, core capabilities, and design features are presented. Key mechanisms and internal structures of the starship are also discussed. This will include flame diverters for the ascend module, the orbital docking hatch, Pressurized Crew Transfer Module Garage door, Starship Ascent Module fairing, flame diverter blow-out panels, Pressurized Crew Transfer Module lift system, logistics module lift system, contingency crew ascent via the logistics module lift system, internal catwalks, and structural interfaces. Concept of Operations will be discussed for both Moon and Mars. This will include in-space crew rendezvous and transfer, crewed landing, shirtsleeve crew transfer, crew departure, contingency surface operations, and final element disposition. Key differences for Mars will be discussed, such as the Martian atmosphere, dust storms, the absence of crew handover, and Deep Space Exploration Vehicle rendezvous. Contingency microgravity maintenance access will also be discussed. This work will demonstrate viable pressurized crew transfer with a Starship-based lander architecture. Forward work includes Garage lighting and camera systems, Starship Ascent Module propulsion system and docking port trades, contingency habitation trades, and mass/power equipment estimation. Finally, forward work includes developing a heavy cargo return system derived from the Crew and Logistics Starship. The goal of this system is the return of at least 10,000 kg payloads from the surfaces of the Moon and Mars.**

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1. INTRODUCTION

Common Habitat Architecture Overview

The Common Habitat Architecture is a conceptual study based on the use of a Space Launch System liquid hydrogen tank as the pressure vessel for a long-duration habitat with a common design for use in 0g, 1/6g, 3/8g, and 1g environments [1]. It serves as the core element of a lunar surface base camp [2], a Mars surface base camp [2], and a Deep Space Exploration Vehicle (DSEV) [3]. It is not part of the current Artemis program but reflects a study of possible options for human exploration in the timeframe that might immediately follow Artemis. This is primarily a volunteer study, with limited NASA innovation grant support and extensive student intern and university design studio engagement. All missions involving the Common Habitat utilize a crew size of eight.

The Common Habitat Architecture's lunar base camp is a continuously occupied facility with overlapping, 370-day annual expeditions, while the Mars base camp is not

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continuously occupied, with surface missions ranging from roughly 500-700 days. An analysis with the NASA Ames Trajectory Browser suggests four Mars expeditions can be conducted in a ten-year period. [3] The DSEV is used both for crew transportation to Mars and for other in-space exploration throughout the inner solar system. DSEV transits could potentially approach 1000 days.

Surface Mission Overview

Because the Common Habitat Architecture assumes a time period immediately after Artemis and perhaps one or more human Mars landings the assumption is a very limited surface infrastructure. It does not assume that Artemis developed any surface systems it can utilize. For instance, while Artemis may have deployed test articles and pilot plants, it is assumed that there is no in-situ resource utilization (ISRU) available for propellant production to refuel a lander for ascent.

Both Moon and Mars surface base camps are identical. They are divided into four zones: a Habitation Zone, Landing Zone, Resource Production Zone (also not at a scale to refuel a lander and not necessarily producing propellant), and Power Zone. [2] The Power Zone does provide power for the entire base camp, including power to the Landing Zone that can be connected to a lander on the surface.

Pressurized crew transfer is a required capability for arriving and departing crews, but the capacity also exists to perform suited transfer should there be a contingency need or operational desire to do so.

The crew transportation path involves numerous options. There are at least five US spacecraft assumed to be capable of providing crew launch from Earth by the timeframe of this architecture: the Boeing Starliner, NASA/Lockheed Orion, Sierra Space Dream Chaser, SpaceX Dragon, and SpaceX Starship. There may also be spacecraft available from international partners. Starliner, Dragon, and Dream Chaser are limited in range to Low Earth Orbit (LEO) and must therefore transfer their crews at that location. Orion and Starship could do the same, but also have the option to reach Cislunar space and transfer crews there. Earth entry for crew return assumes those same transfer points. It is not required that all crew utilize the same spacecraft to depart Earth or return to Earth in the same type of spacecraft they launched in. This suggests an emergence of Earth launch/entry as a service; in the same way that a person traveling from Atlanta to New York might fly the outbound and inbound legs on different types of aircraft or even different airlines.

With the exception of Starship, none of these launch and entry spacecraft can carry the full eight-person crew. Thus, an aggregation point may be needed. For lunar missions, depending on the rendezvous point elected (LEO vs. Cislunar), this might be a space station developed under the NASA Commercial LEO Destinations project, or it might be Gateway, or it could under certain circumstances be the lander itself. The crew will transfer to the lander at this aggregation point. For Mars missions, the aggregation point is the Deep Space Exploration Vehicle and is performed in LEO. (The DSEV refuels in LEO and that orbit also serves as the orbit for crew arrival and departure.) [3] The crew will transfer between the DSEV and the lander in a 5-Sol Mars orbit. This is typically accomplished not by the lander docking directly with the DSEV, but by using the DSEV's two Pressurized Rovers for In-Space Missions (PRISM) as transfer vehicles, thereby avoiding the propellant use and operational risks of docking the two large vehicles. All docking activities are assumed to use the Common Habitat Architecture's Multi-Gravity Active-Active Mating Adapter. [4]

The lander will deliver not only the crew to the destination surface, but also the logistics needed for their surface stay. This consolidates the needed lander missions to one per crew expedition, which is particularly valuable for Mars expeditions. Any cargo capacity remaining after the provision of expedition logistics is available for other use, including co-manifesting of new elements or experiments.

Lander Selection Study

In keeping with the Common Habitat's emphasis on a common design for all destinations, a brief study was conducted in February 2021. [5] The desire was to identify a common lander approach for both the Moon and Mars, but it did not exclude the possibility of using destination-specific landers. There was also a goal to use a common lander family (not an identical lander configuration) for both crew/logistics delivery and base camp element delivery. The Common Habitat, with dimensions of 8.4 meters in diameter and 15.6 meters in length and a control mass of 90 metric tons, is the driving payload for this study.

The study did not attempt to develop a lander, but instead evaluated existing lander concepts. Five landers were evaluated in this study, two of which are dedicated lunar landers, two are dedicated Mars landers, and one is both a Moon and Mars lander. Because this study occurred at the same time as the NASA Human Landing System (HLS) competition, a decision was made to limit study data to publicly available sources of information.

The landers evaluated were the Dynetics Autonomous Logistics Platform for All-Moon Cargo Access (ALPACA), National Team Integrated Lander Vehicle (ILV), NASA Hypersonic Inflatable Aerodynamic Decelerator (HIAD), NASA Mid Lift over Drag (Mid L/D), and SpaceX Starship.

Starship was the lander selected in the trade study, but it was too small to physically accommodate the Common Habitat. Consequently, the barrel section of the payload volume was increased by 7.68 meters. This stretched Starship is used as the common dimensions for all Starship variants in the Common Habitat architecture. It is important to note that due to industry sensitivities, no commercial data was used in this study.

All industry lander data was obtained from publicly available sources and all Starship images were created in CAD by interns using public data (Google searches, Wikipedia, and the Starship Users Guide).

2. CREW AND LOGISTICS LANDER OVERVIEW

The Crew and Logistics Lander is not the HLS Starship. In addition to the increased vehicle height, the features of this lander are substantially different. The same variant is used for both the Moon and Mars. Thus, the vehicle is equipped with a heat shield and aerodynamic flaps.

The Crew and Logistics Lander is not able to launch after landing. It is assumed that the cargo mass will require expending most of its propellant during descent. Because the surface infrastructure lacks ISRU propellant production, it cannot refuel and thus cannot lift off again. As a result, the crew must ascend on a separable element.

The Crew and Logistics Lander effectively acts as a carrier vehicle for five distinct elements contained within the payload volume of the Starship, referred to in this paper as the Garage. Each of these elements will be discussed in the following section:

1. Starship Ascent Module
2. Transfer Tunnel
3. Airlock
4. Pressurized Crew Transfer Module
5. Logistics Modules

The Rhode Island School of Design (RISD) played an integral part in development of the lander and these encapsulated elements. RISD has received funding from the Rhode Island Space Grant to fund space-related design activity through their Industrial Design department. They hold a Design for Extreme Environments studio course every spring semester and send one or more interns to JSC every summer. The Center for Design and Space Architecture has been partnered with RISD for more than twenty years. The spring 2022 studio class focused on cabin design for the Starship Ascent Module and two summer 2023 interns built on that work and prior volunteer work to update the Crew and Logistics Lander, including the encapsulated elements.

3. ENCAPSULATED ELEMENTS

Starship Ascent Module

The Starship Ascent Module, shown in Figure 1, provides accommodation for the crew during entry, descent, and landing while berthed within the Garage. It provides ascent, rendezvous, and docking in a separated flight mode. It can sustain the crew for up to fourteen days. The propulsion system, shown in Figure 2, is sized to reach Gateway in a lunar surface ascent and reach a 5-Sol orbit in a Mars surface ascent. The element has been roughly sized with a control mass of 10,000 kg dry mass and 40,000 kg wet mass.

A notional placeholder for main propulsion is two Aeon-1 LOX-Methane rockets, made by Relativity Space, which has performance in the desired ballpark. [6] Propellant is supplied by two liquid oxygen tanks and two liquid methane tanks. Reaction Control System (RCS) thrusters also use LOX-Methane propellant. A 100-lbf LOX-Methane thruster has been developed by Aerojet [7] and serves as a placeholder. These thrusters are configured in four quads of four thrusters each. Each quad includes small liquid oxygen and liquid methane tanks that are topped off by the main propulsion propellant tanks.

Figure 1. Starship Ascent Module

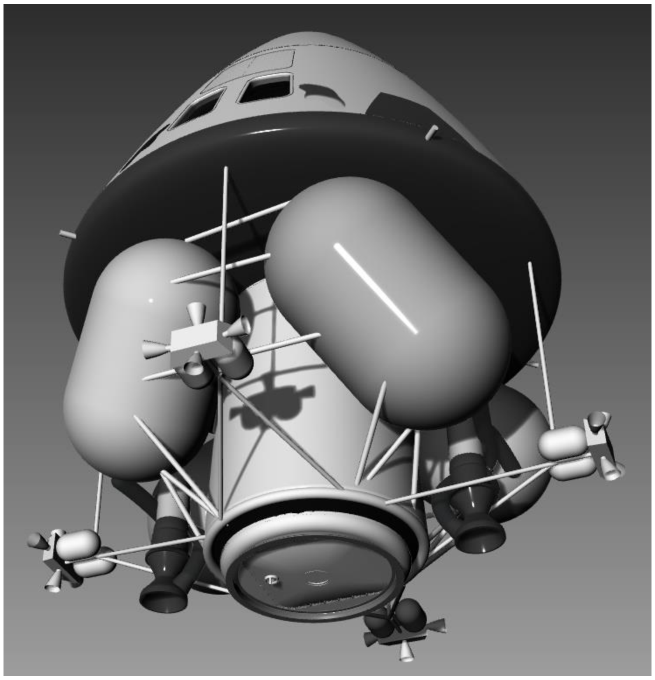

Figure 2. Starship Ascent Module Propulsion System

The power and thermal subsystems are not presently sized, but the initial assumption is that the ascent module utilizes deployable soliators and batteries. The soliator is a concept proposed by NASA engineers to merge the functionality of a solar array and a radiator panel, such that one side of the device contains solar cells and the other side is a radiative surface. The batteries would be mounted between the propellant tanks and the soliators would mount to the four vertical struts linking the RCS quads to the cabin, visible in Figure 1 and Figure 2.

The crew cabin includes three 40-inch by 40-inch square hatches, a zenith hatch, visible in Figure 4, a nadir hatch, visible in Figure 2, and a cabin-tunnel hatch, visible in Figure 3. A window lies at the center of each hatch. Five additional cabin windows provide crew visibility, two for the two pilots and three for the remaining six crew.

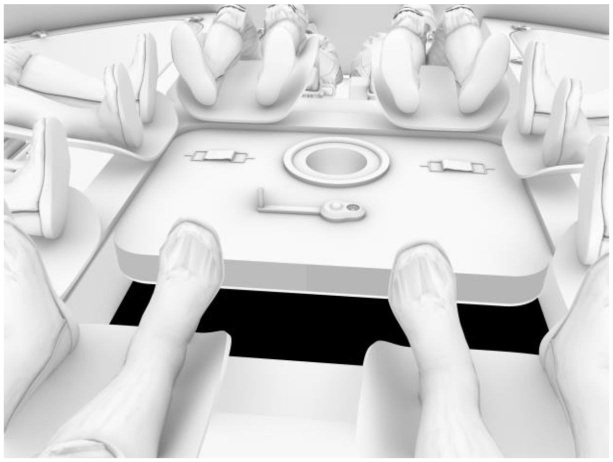

Figure 3. Cabin-Tunnel Hatch

Crew seating is at the base of the cabin, shown in Figure 4. The eight crew are seated in four pairs of two, arranged in a cross configuration. A vertical translation path lies at the center of the cabin.

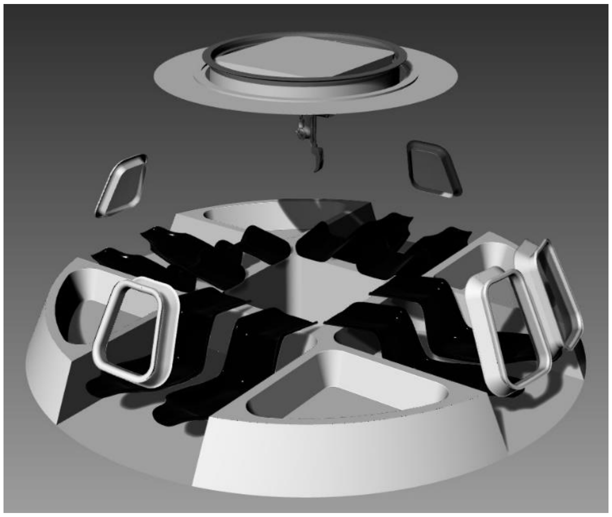

Figure 4. Cabin Lower Section

A three-monitor display and control interface is provided for the two pilots, as shown in Figure 5. Hand controllers are also visible in Figure 6 and Figure 7.

Figure 5. Display and Control Interface

The displays retract upwards against the ceiling when not needed to allow room for seat ingress and egress. The retracted configuration is shown in Figure 6 and the deployed configuration is shown in Figure 7.

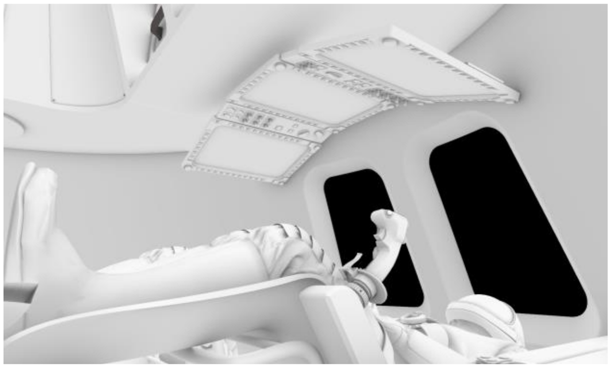

Figure 6. Retracted Display and Control Interface

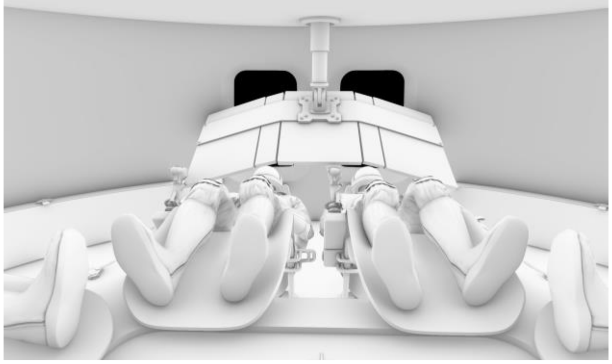

Figure 7. Deployed Display and Control Interface

A subsystems and stowage bay is mounted above the cabin lower section. This bay includes stowage, environmental control and life support systems (ECLSS), a water tank and dispenser, food warmer, the waste management system, and trash. Ascent module stowage in the bay includes ambient stowage, shown in Figure 8, and cold stowage, shown in Figure 9.

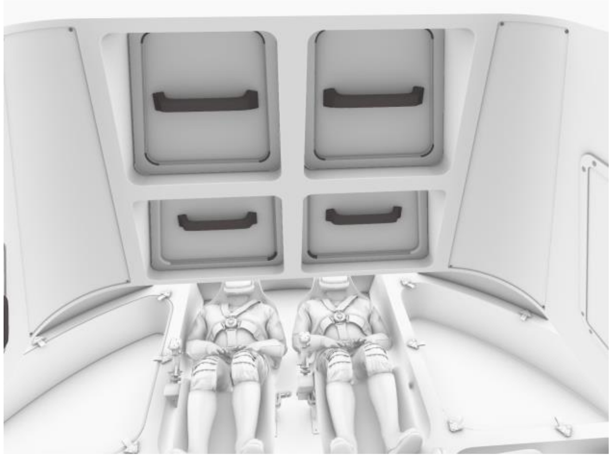

Figure 8. Ambient Stowage

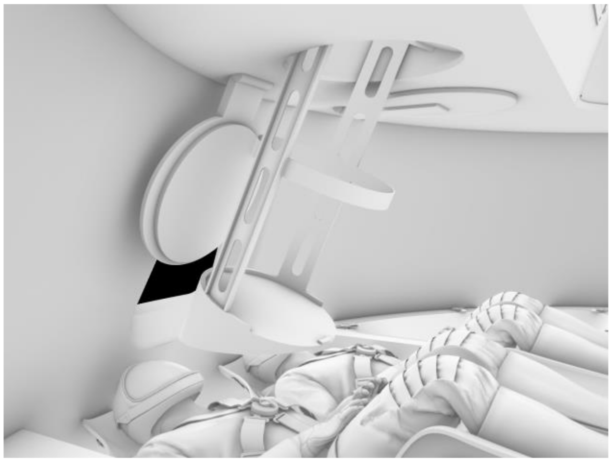

Figure 9. Cold Stowage

The waste management system stows in the bay when not in use as shown in Figure 10, and deploys out into the vertical translation path for use, as shown in Figure 11. Hygiene kits are also stowed in this section of the bay.

Figure 10. Waste Management System in Stowed Configuration

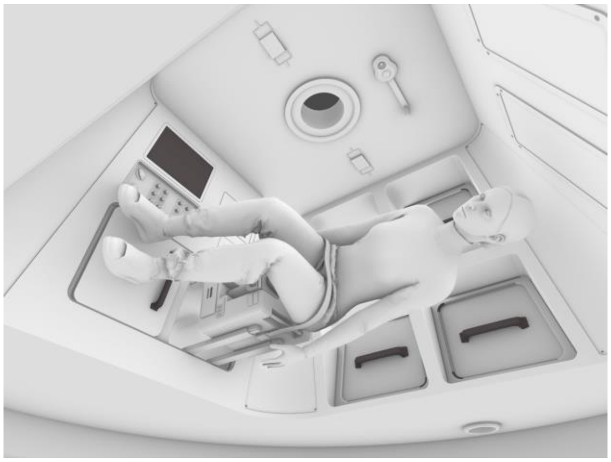

Figure 11. Waste Management System Deployed for Use

A hoist visible in Figure 4 is in its deployed position, centered over the vertical translation path. In this configuration it can lift incapacitated crew or cargo into the cabin. When stowed, it is retracted into the stowage and subsystems bay. Additional stowage is also visible in Figure 4 in the form of four general stowage volumes positioned between the crew seat pairs. An exercise device, medical supplies, food, operational supplies, and launch-entry suits are all stowed in these volumes.

A vertical tunnel extends below the cabin, shown in Figure 12. This tunnel provides a translation path from the ascent module cabin down into the other elements. A ladder inside the tunnel helps facilitate crew translation.

Figure 12. Vertical Tunnel

Transfer Tunnel

The Transfer Tunnel serves as the linkage to provide shirtsleeve crew transition between the Starship Ascent Module and the Airlock. It is approximately a rounded rectangle in cross-section and contains a zenith docking port near the center and a nadir pressure hatch at one end that is permanently welded to the Airlock. The zenith port contains an active multi-gravity active-active mating adapter (MGAAMA) [4] port to dock to the Starship Ascent Module's Vertical Tunnel, which contains a passive MGAAMA port. The Transfer Tunnel and Airlock are shown together in Figure 13.

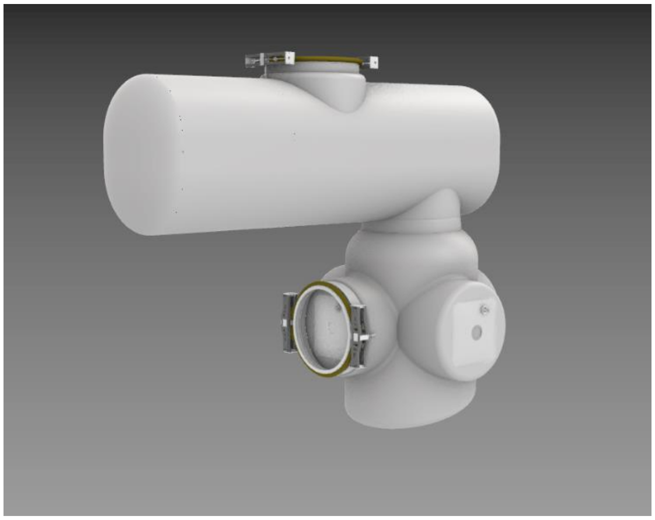

Figure 13. Transfer Tunnel and Airlock

There are no windows in the Transfer Tunnel, except for the windows in the zenith and nadir hatches. The Transfer Tunnel contains only minimal subsystems, primarily power management and distribution, cabin lighting, and fans and ducting for airflow.

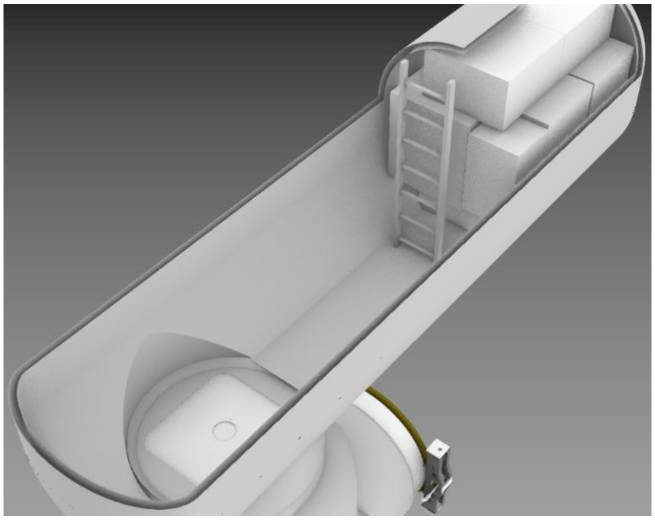

Figure 14. Transfer Tunnel Stowage

All eight crew surface suits are stowed for Earth launch at the far end of the tunnel behind a removable ladder, as shown in Figure 14. Suits are moved to the Pressurized Crew transfer Module (PCTM) for surface activity and nominally do not return to the Crew Transfer Tunnel. If the crew has to return to the airlock suited, the suits will be re-stowed in the Crew Transfer Tunnel. A ceiling-mounted winch can lift incapacitated crew and equipment through the nadir hatch from the Airlock. The winch in the Starship Ascent Module can lift equipment or incapacitated crew from the Transfer Tunnel into the ascent module through the zenith hatch. Stowage at the opposite end of the tunnel from the suits, immediately adjacent to the hatch in the floor leading down to the Airlock, is designated for food stowage. Food items stowed here can supplement food stowage in both the Starship Ascent Module and the PCTM.

Airlock

The Airlock serves not only the traditional airlock function of enabling a transition from intravehicular activity (IVA) to extravehicular activity (EVA), but also the function of serving as the Crew and Logistics Lander's docking port, as well as the function of serving as a node to connect multiple pressurized elements.

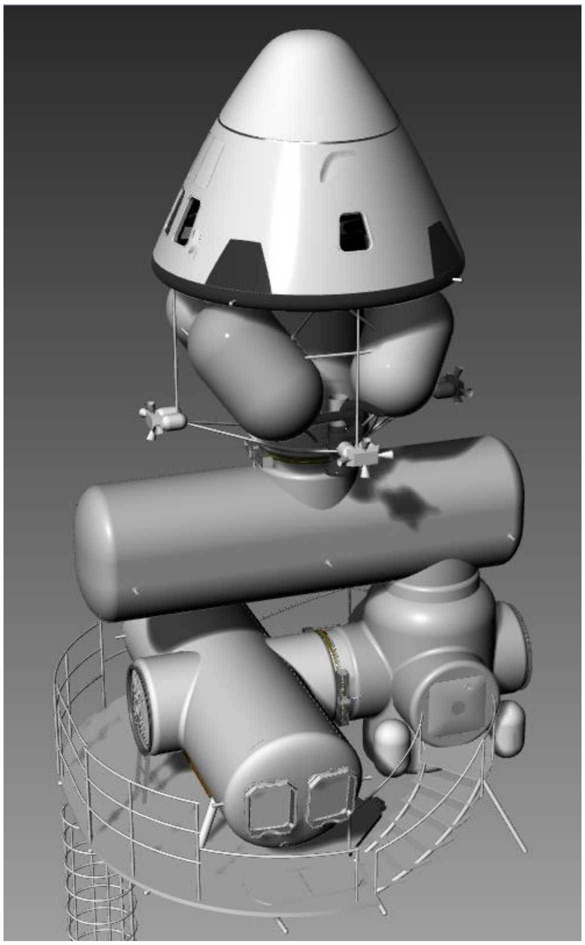

Figure 15. Airlock Integrated with Other Lander Elements

The Airlock provides suit donning and doffing for two crew members in parallel in a gravity environment. It also provides volume for suit configuration and limited suit servicing. Figure 15 shows the Airlock berthed to the Pressurized Crew Transfer Module and permanently attached to the Transfer Tunnel.

The Airlock's pressure vessel shares a common design heritage with the Common Habitat Architecture's Pressurized Rover, which itself is modeled after the NASA Generation 3A Small Pressurized Rover (SPR) cabin [8], a concept vehicle that originated with the former Constellation Program. The NASA Gen 3A vehicle is no longer in development but was used as a starting point within the Common Habitat Architecture because it is highly adaptable [9] and offered many of the features needed by multiple architectural elements.

Figure 16. Airlock Outboard Docking Port

The Airlock features five passageways. The previously mentioned zenith hatch is a permanent attachment to the Transfer Tunnel. An inboard berthing port features an active MGAAMA mechanism. Two port and starboard hatches, one of which is visible in Figure 15, support EVA transfers. An outboard docking port, shown in Figure 16 features a passive MGAAMA flange. The only windows are in the hatches.

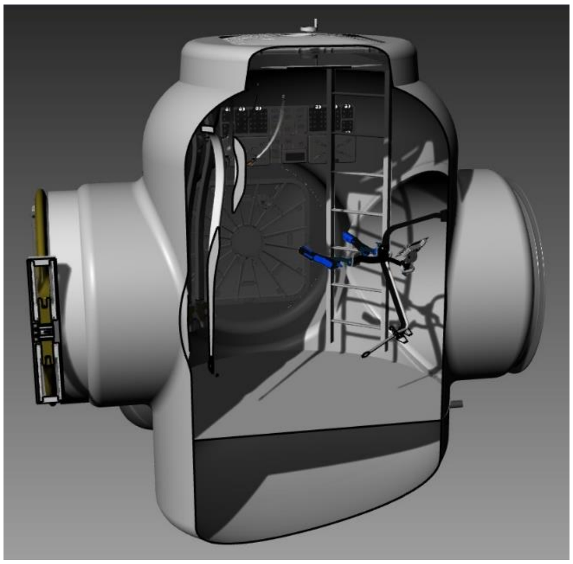

Figure 17. Airlock Interior

Internally, as shown in Figure 17, the Airlock includes a ladder leading up towards the Transfer Tunnel, two deployable donning stands, suit umbilicals, interface panels, and small item stowage. The ECLSS is located beneath the floor, with nitrogen and oxygen tanks outside the pressure vessel, some of which can be seen in Figure 15.

Pressurized Crew Transfer Module

Like the Airlock, the PCTM is also derived from the NASA Gen 3A SPR cabin. However, the PCTM effectively stretches and then duplicates the rear half of the SPR It features two side facing passive MGAAMA docking / berthing ports, two forward suitports, and two aft suitports. It is mounted on a deck surface as shown in Figure 18 and Figure 19.

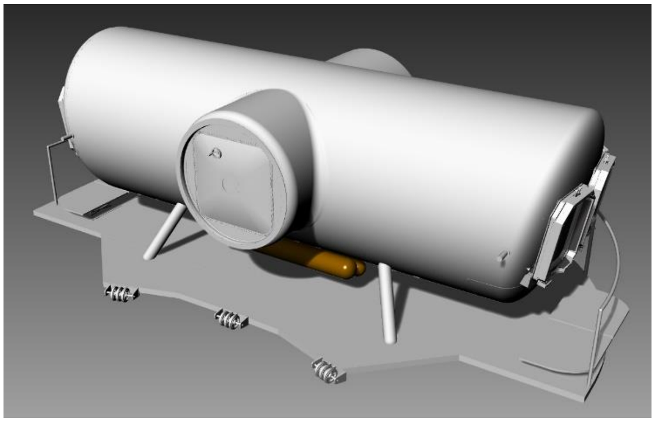

Figure 18. Pressurized Crew Transfer Module

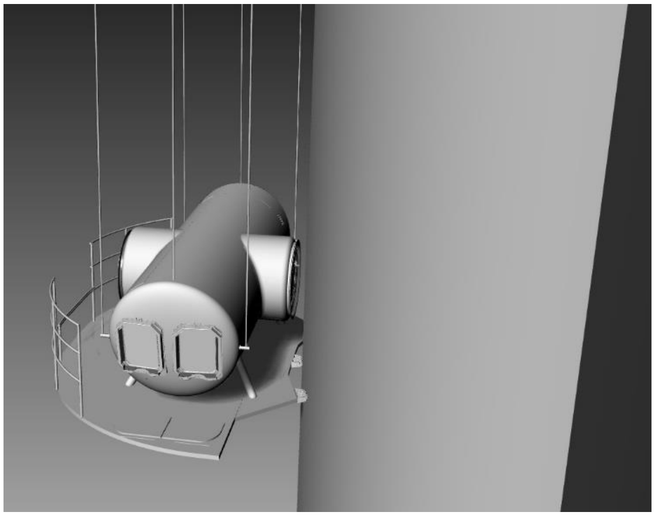

Figure 19. PCTM Transported by Lift System

The PCTM enables both suited and unsuited crew transfer between the Starship Ascent Module and the surface. It provides crew situational awareness during such transfers. It can support short duration / lifeboat mode crew habitation of up to 14 days. Crew can remotely command the Crew and Logistics Lander or other elements from within the PCTM. It can perform its own heat rejection, but does not perform power generation or communications, instead relying on the lander for those services. The PCTM is equipped with trunnions that the lift system grapples for raising and lowering the PCTM. It also is equipped with a series of rollers that help maintain stable contact with the Starship fuselage during lift operations. The trunnions and roller wheels are visible in Figure 18 and Figure 19.

Inside the cabin, handrails (four total) are positioned above and to the right of each suitport to aid in suit ingress and egress. These are seen in Figure 20 along with two dip bars that protrude into the cabin from the bulkhead wall. The dip bars are located to the right of the suitport immediately below the vertically oriented handrails.

Figure 20. Suitport Internal Handrails

When used for suited transfers, the suitports, two on the forward bulkhead and two on the aft bulkhead, allow for transfer of four crew at a time, requiring two lifts to transfer all eight crew. Each suitport includes a lift platform, visible in Figure 21.

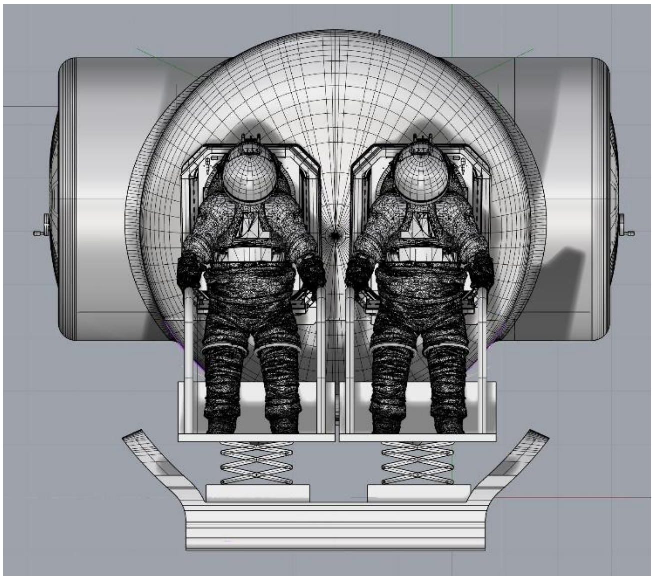

Figure 21. Suit Port Lift Platforms

A guardrail, visible in Figure 18 and Figure 19 protects crew on the outboard side of the PCTM. Because this guardrail would otherwise block access to the Pressurized Rover's MGAAMA for surface shirtsleeve transfer, the center rails lower to allow docking access. They are visible in the lowered configuration in Figure 19 and can be seen in the raised configuration in Figure 26. The only windows in the PCTM are those on the hatches.

During vertical lifts from the Garage to the surface, the crew will sit on benches, similar to those in the NASA SPR. Four crew will sit on each side of the cabin. Figure 22 shows four crew seated on one side of the cabin. A deployable seat back provides support for each crew member. Because the crew bring their surface suits with them, they are stowed in the cabin along with the crew. The suit Portable Life Support System (PLSS) are particularly large and present a stowage challenge. The design solution implemented is to store each crew member's PLSS on the bench to the immediate left of the crew member.

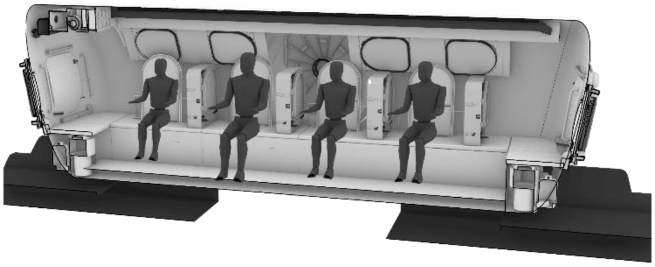

Figure 22. Seated Configuration

The rest of the surface suits are stowed inside the benches. Accessing the suits is a multi-step process. First, the seat backs are folded and stowed against the cabin wall. Then, each PLSS must be removed from the bench and stowed on the bottom of the stowed sleep bunks. The sleep bunks are visible behind and above the crew in Figure 22 in their stowed configuration. The four PLSS units can be shown mounted to the underside of stowed sleep bunks in Figure 23, two on each bunk. The crew can then raise the bunk top surfaces to reveal access to the suits.

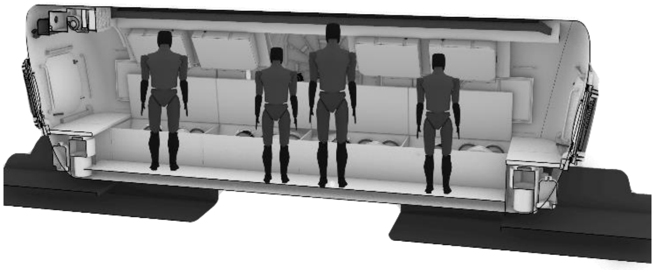

Figure 23. Suit Access

The stowed suits can then be retrieved. Figure 24 shows how the suits are stowed in each bench. The suit gloves are stowed inside the helmet, which is stowed inside the Hard Upper Torso (HUT), with arms compressed, which is placed in the bench stowage compartment. The legs of the Lower Torso Assembly (LTA) are compressed, and it is stowed next to the HUT. The boots are compressed and stowed next to the LTA. Suit stowage was the primary driver for PCTM length.

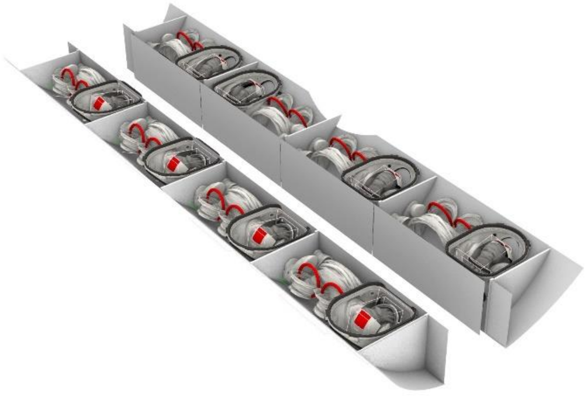

Figure 24. Suit Storage

The PCTM can support multi-day habitation. The previously mentioned sleep bunks can be deployed, as shown in Figure 25 and Figure 26. Four crew will sleep on the benches and four crew will sleep on the bunks above them. Two toilets are located in the PCTM, one at each end of the aisle, similar to the placement in the NASA SPRs.

There are three primary drivers for multi-day habitation using the PCTM. During crew arrival, the crew will spend several days in space traveling from Gateway or a 5-Sol Mars orbit. Crew can live in the shared space that includes the Starship Ascent Module, Transfer Tunnel, Airlock, and PCTM. Second, during lunar crew rotations, the arriving crew may live return to the PCTM at night and live in the shared volume between the two Pressurized Rovers and the PCTM. Midway through the handover period, they will change places with the departing crew who will do the same until liftoff. Both of these may conceivably involve up to fourteen days of habitation. The third driver is a contingency scenario where the PCTM is stuck between the Garage and the surface. MCC will have the option to have the crew spend the night in the PCTM while they diagnose the problem. If desired, the crew can spend several days in this configuration before choosing to implement the EVA contingency solution referenced later in this paper.

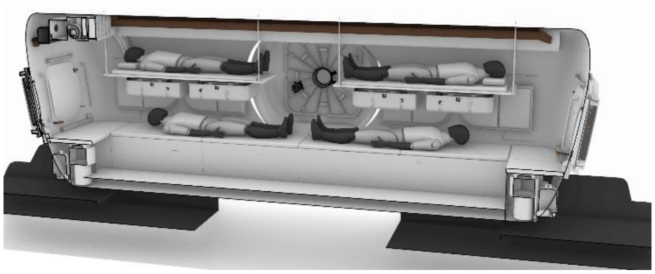

Figure 25. Sleep Configuration

The power subsystem is primarily external to the cabin. Power is provided by the Crew and Logistics Lander and is embedded within the lift cables. Blind mate connections on the trunnions connect to the cable grapple system. Power is transferred from the six trunnions to a power management and distribution unit that provides power to PCTM lighting, utility interfaces, and subsystems. Utility interface panels at each seating location and on the bunks allow crew to plug in small electronics. A battery bank beneath the pressure vessel provides contingency power in the event of loss of lander power.

The avionics subsystem includes a sensor suite that determines PCTM position, velocity, and acceleration relative to the Airlock, lander exterior, and surface. Cabin interior and exterior lighting is incorporated into the avionics subsystem and is integrated into the PCTM caution and warning system, using both color and light patterns to indicate vehicle status. Interior and exterior cameras are positioned to support two-way video communication and PCTM position and status. Two crew laptops are stowed in the PCTM and can connect to the vehicle network via Wi-Fi or LAN via the utility interface panels. The laptops provide the crew's primary human machine interface to access PCTM systems. Redundant lift system controls are hardwired into panels at each side hatch as a backup to the laptops. Wired data connectivity to the lander is achieved through the lift cables with blind mate connections between the lift cable grapple system and the trunnions. The wired connectivity is supplemented with Wi-Fi within and immediately adjacent to the cabin and a 3G or greater cellular system mounted on the PCTM exterior.

Thermal control is achieved through a mixture of cabin air heat exchangers and cold plating. Heat rejection is performed by means of radiator panels (not pictured) mounted on the roof of the PCTM. Actuators can articulate to change the angle of incidence with the sun. This is not necessary for lunar missions due to the low sun angle but will be needed for Mars missions.

The largest PCTM subsystem with respect to use of cabin interior volume is ECLSS. The ECLSS ducting is visible in Figure 26. ECLSS subsystem components are stowed primarily in the side hatch alcoves and adjacent to the toilets. Water, oxygen, and nitrogen are stored externally in tanks attached to the bottom of the pressure vessel.

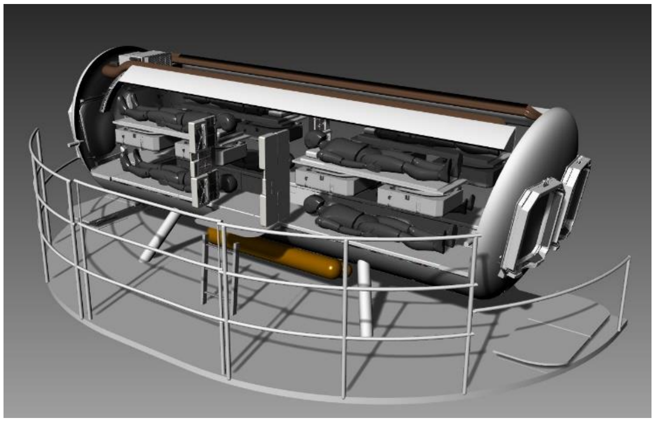

Figure 26. ECLSS Ducting

The placement of additional habitation stowage remains as forward work. There is stowage under the floor of the cabin aisle and stowage in the ceiling adjacent to the ECLSS ducts.

The ceiling stowage is partially available to the spacesuits for stowage of compressible items such as the liquid cooling and ventilation garment and drink bags. Any remaining stowage volume may be available to other systems.

Two combination aerobic/resistive devices are stowed under the floor. PCTM exercise is comparable to crew exercise performed in the NASA SPR concept vehicles. [10] Also stowed under the floor are medical systems. While the NASA SPR concepts never fielded more than a first aid kit, analytical studies did show that a medical capability roughly equivalent to the ISS medical inventory could be stored in the Gen 3A cabin. [11]

Two food warmers and two water dispensers are located within the PCTM for meal preparation. The food warmers are on the forward and aft bulkheads, positioned to the right of the suitports. The water dispensers are located in the side hatch alcoves. Food stowage is distributed across any unused stowage spaces under the floor and in the ceiling.

Each crew member is allocated one cargo transfer bag (CTB) for stowage of clothing and personal items. Placement of this bag is at crew discretion, with the most likely available volume being behind their deployable seat back.

Logistics Module

Measuring 4.5 meters in diameter and 7 meters in length, the Logistics Module is slightly shorter and slightly wider than the US laboratory module (Destiny) on the International Space Station (ISS). Up to two Logistics Modules can be carried by the Crew and Logistics Lander, but only one is needed for most surface expeditions. As shown in Figure 27, the Logistics Module uses the same system of trunnions and same wheel system as the PCTM.

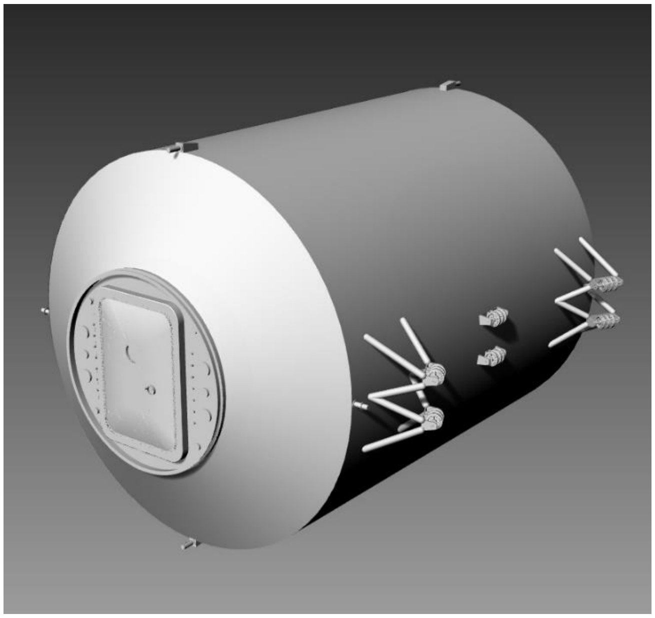

Figure 27. Logistics Module

The Logistics Module has two 40” x 60” hatches, one at each end, with a MGAAMA-compatible passive docking port. The only windows in the modules are the hatch windows.

A transparent view of Figure 28 shows the placement of the major subsystems. The Logistics Module uses the subsystem pallet architecture pioneered by Collins [12] for the Gateway program. The Logistics Module includes three ECLSS pallets, one avionics pallet, and one power half size pallet. The Logistics Module does not include fixed water tanks, but conformal water bags can be filled and hung in the end domes.

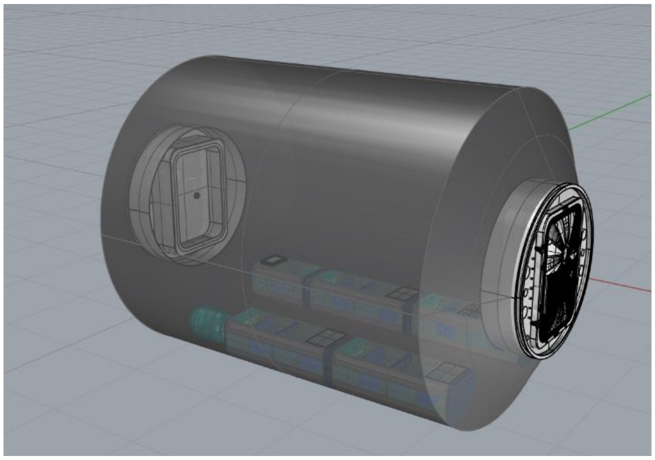

Figure 28. Major Subsystems

Stowage within the Logistics Module is configured to store the maximum amount of logistics. Each module can accommodate up to 766 cargo transfer bag equivalents (CTBE), organized in a mixture of bag sizes ranging from a half CTB to a 10-CTB bag. The CTB configuration is shown in Figure 29.

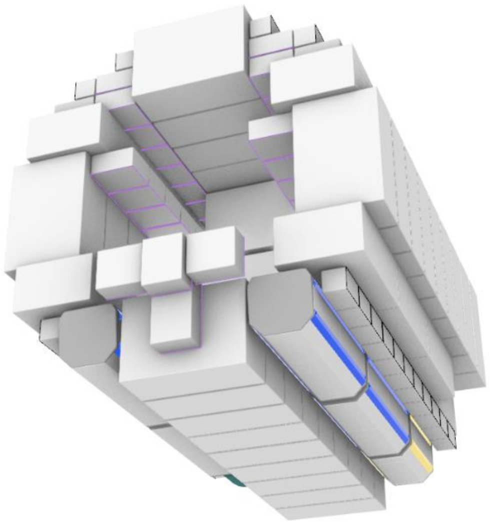

Figure 29. Stowage Configuration

The Logistics Modules are only transported by the Crew and Logistics Lander. There is no means for crew to enter the modules and access their contents. They remain inaccessible until they have been delivered to the surface base camp and berthed to the Common Habitat.

4. KEY MECHANISMS AND INTERNAL STRUCTURES

As previously noted, the Crew and Logistics Starship is neither the Artemis HLS Starship nor the orbital prototype Starships currently under development. In order to transport the previously described elements, a number of key mechanisms and internal structures are needed.

Flame Diverter

The Flame Diverter deflects the exhaust of the Starship Ascent Module's main propulsion system during initial takeoff. Shown in Figure 30, it channels the exhaust away from the Garage and the elements contained within, instead venting it to the vehicle exterior.

Figure 30. Flame Diverter

Garage Doors and Hatches

Numerous doors, hatches, and other access panels are placed throughout the lander exterior to support the previously mentioned elements.

The Starship Ascent Module Fairing is the nosecone of the Crew and Logistics Lander. It splits open, as shown in Figure 31 and Figure 32 to create an egress path for the Starship Ascent Module to take upon launch. The fairing remains closed until the crew has returned to the Starship Ascent Module at the end of a surface expedition and has initiated launch preparation procedures.

Figure 31. Starship Ascent Module Fairing Opening

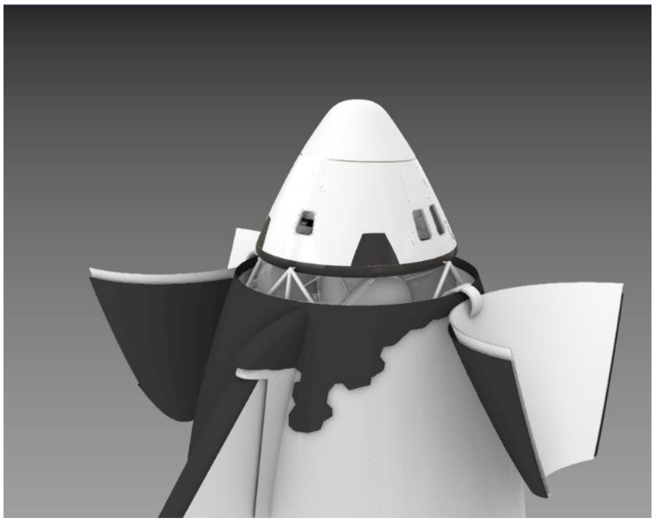

Figure 32. Starship Ascent Module Fairing Fully Opened

Flame Diverter Blow-Out Panels

The Flame Diverter Blow-Out Panels are used in concert with the Flame Diverter. These four panels are located where the Flame Diverter intersects with the lander fuselage. The panels are blown outward, as shown in Figure 33, by the force of the rocket exhaust.

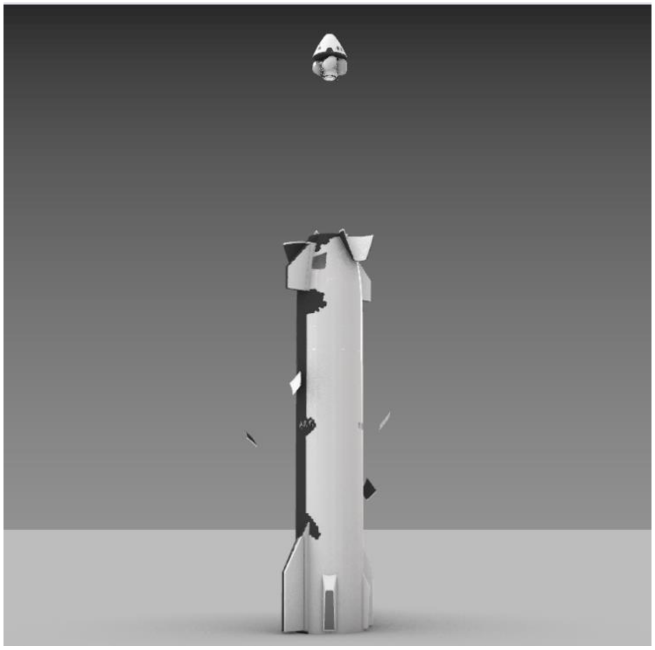

Figure 33. Flame Diverter Blow-Out Panels

Orbital Docking Access Panel

The Orbital Docking Access Panel is a hatch on the heat shield side of the lander that flips open roughly 180 degrees to provide a docking vehicle with access to the Airlock's docking port. The access panel is shown in the open position in Figure 34

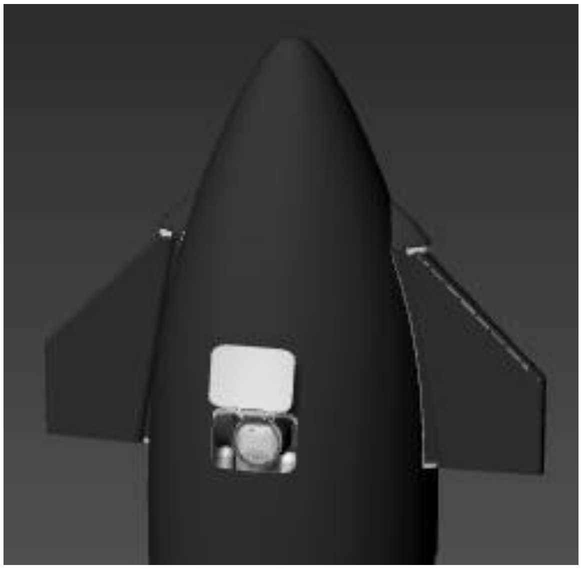

Figure 34. Orbital Docking Access Panel

The lander features two large Garage doors, one on each side of the fuselage for the Logistics Module on the heat shield side of the spacecraft and for the PCTM on the opposite side. These doors, shown in Figure 35, are driven open and closed by actuators inside the Garage and are sized to allow passage of their respective elements.

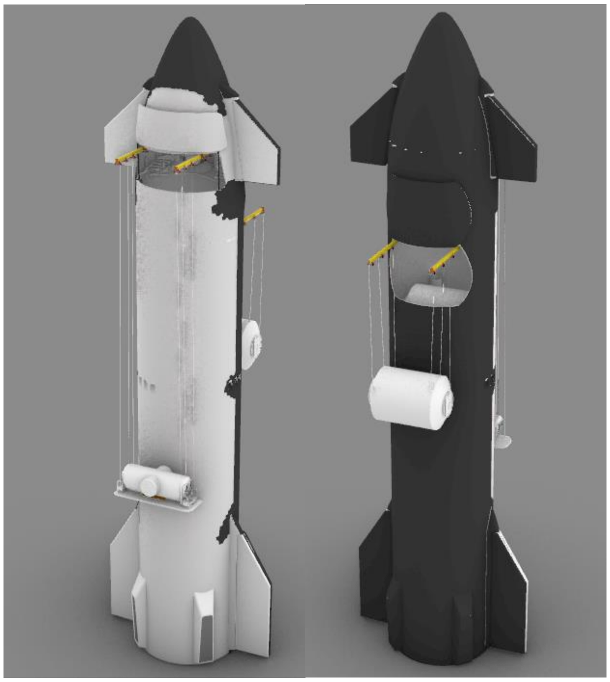

Figure 35. PCTM and Logistics Module Garage Doors

Lift Systems

The Lift Systems are the telescopic boom overhead cranes that are used to raise and lower the PCTM and lower the Logistics Modules. Identical lift systems are used for the PCTM and Logistics Module. Each system features twin telescopic booms with three hoists on each boom. The hoists, shown in Figure 36, can traverse the length of the telescoping portion of the boom. Each hoist is driven by two motors, with the capability that one motor can back drive the other and power the hoist in the event of a motor failure. As previously mentioned, each cable includes power and data wiring, terminating in a grapple fixture that can autonomously mate with the element's trunnions, resulting in six channels of power and data delivery to the PCTM and Logistics Modules.

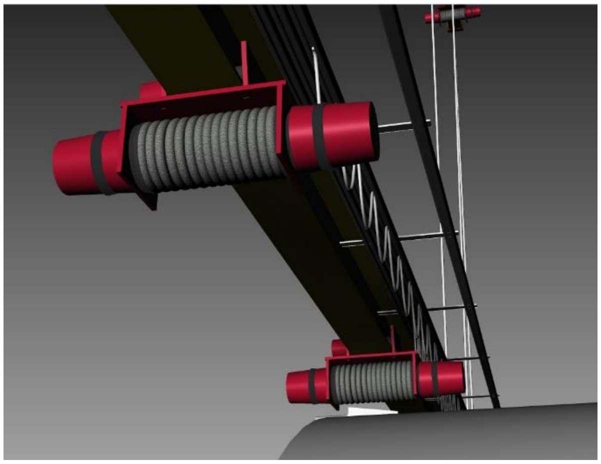

Figure 36. Hoist and Drive Motors

Figure 37 shows the lift systems with all booms retracted. Figure 38 shows the Logistics Module Lift System deployed and lowering the first Logistics Module. Figure 39 shows the PCTM Lift System deployed and lowering the PCTM.

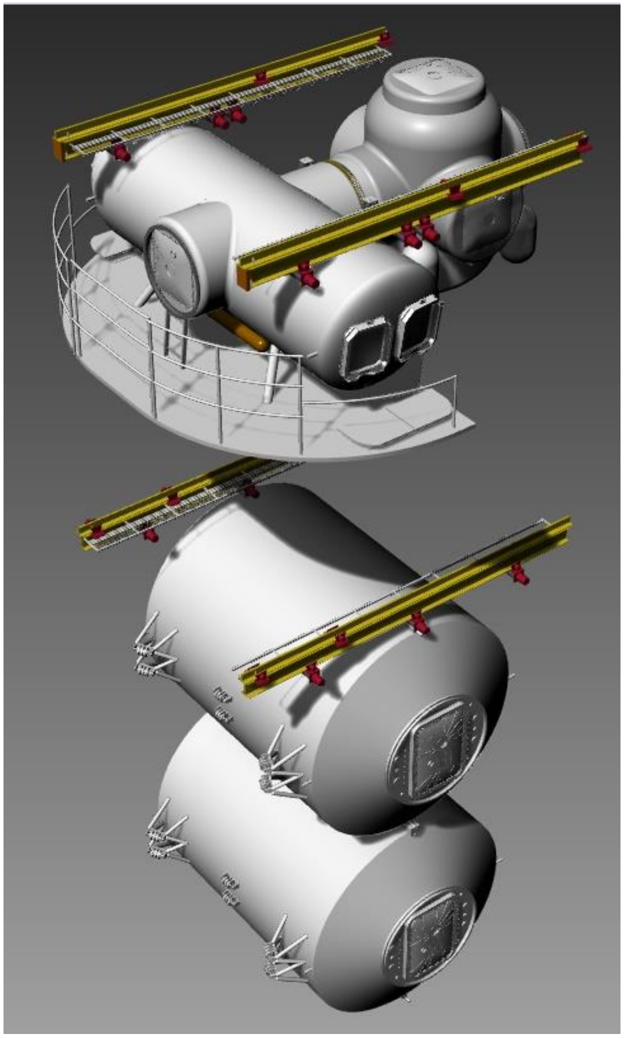

Figure 37. PCTM and Logistics Module Stowed Positions

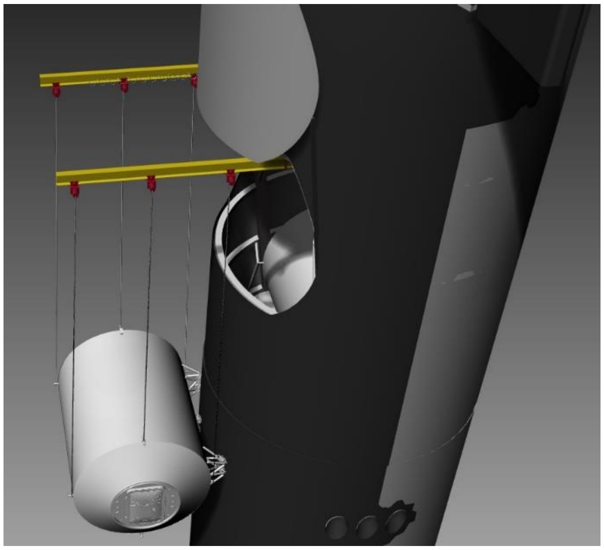

Figure 38. Logistics Module Being Lowered

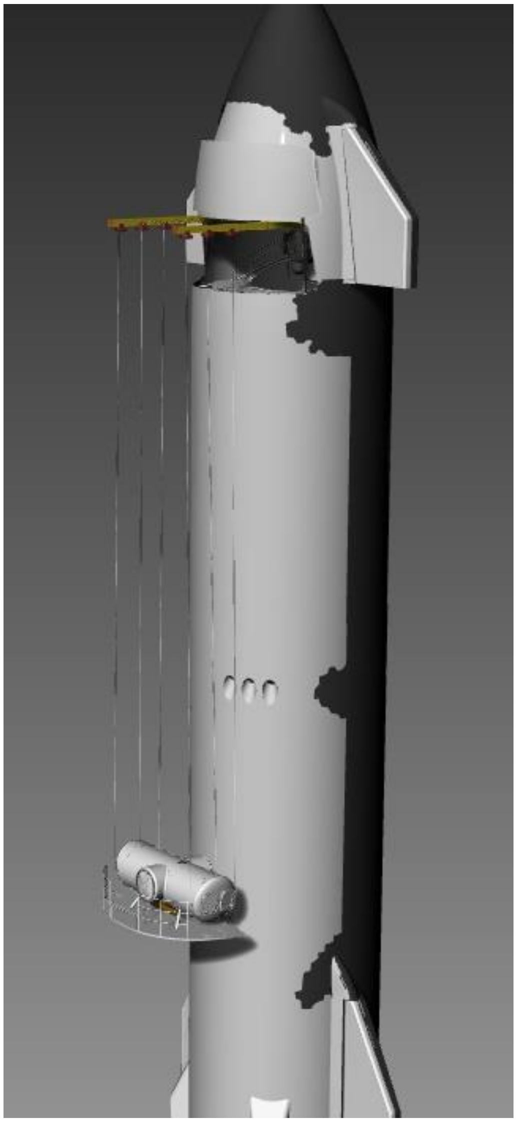

Figure 39. PCTM Being Lowered

Catwalks and Ladders

A catwalk system, shown in Figure 40, is located in the Garage at the level of the Airlock and PCTM. It consists of a floor that the PCTM rests on top of and two circular stairs from the PCTM to landings on each side of the Airlock.

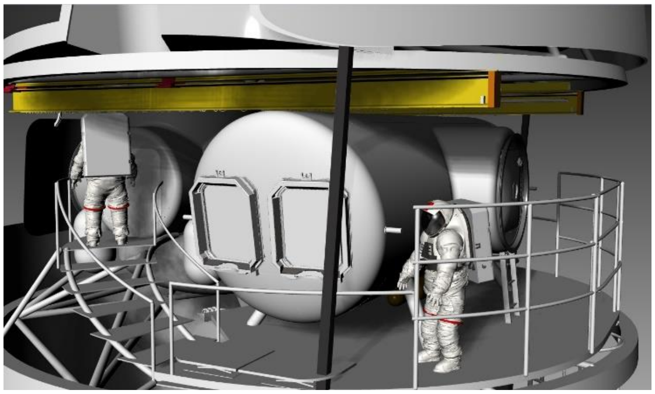

Figure 40. Garage Catwalk

An EVA access ladder runs from the PCTM level down to the floor of the Garage, shown in Figure 41. This ladder can be used by EVA crew to traverse between the two levels. If the PTCM is present it does cover the ladder egress point. Consequently, a trap door in the PCTM deck can open to allow crew access.

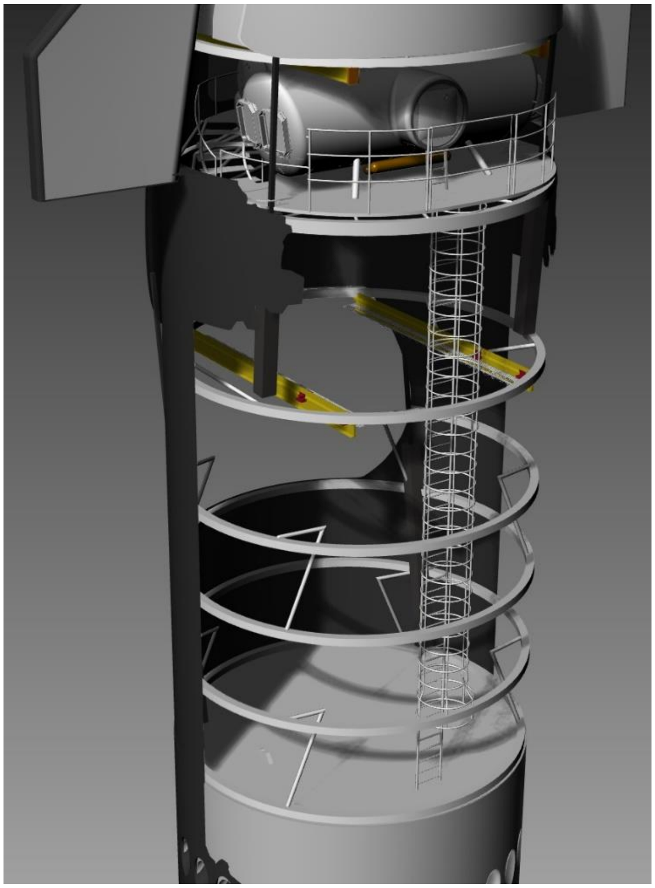

Figure 41. Garage Ladder

Element to Vehicle Structural Interfaces

Trunnions on each element attach to structural interfaces to hold the element securely during dynamic flight and on the surfaces of the Moon and Mars. A series of ring frames attached to the interior of the fuselage provide interface points for structural interfaces to attach.

Figure 42 shows three of the Starship Ascent Module's four trunnions connected to support structures leading to a ring frame. Figure 43 shows trunnions on the Transfer Tunnel and Airlock connected to support structures on two ring frames. Figure 44 shows support structures supporting the catwalk. Figure 45 shows Logistics Module trunnions connected to support structures tying to five ring frames and the Garage floor.

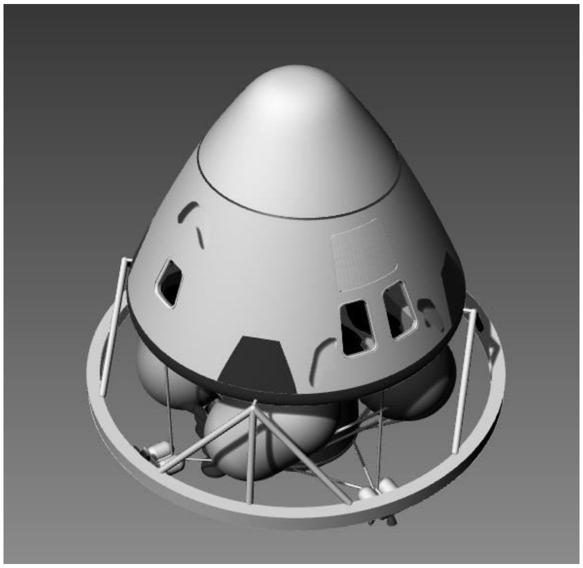

Figure 42. Starship Ascent Module Structural Interfaces

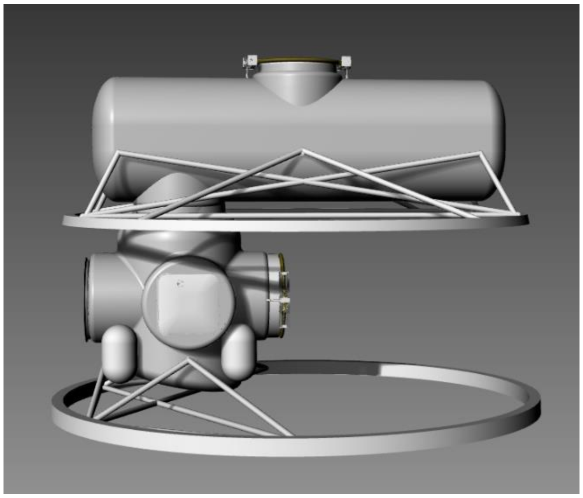

Figure 43. Transfer Tunnel and Airlock Structural Interfaces

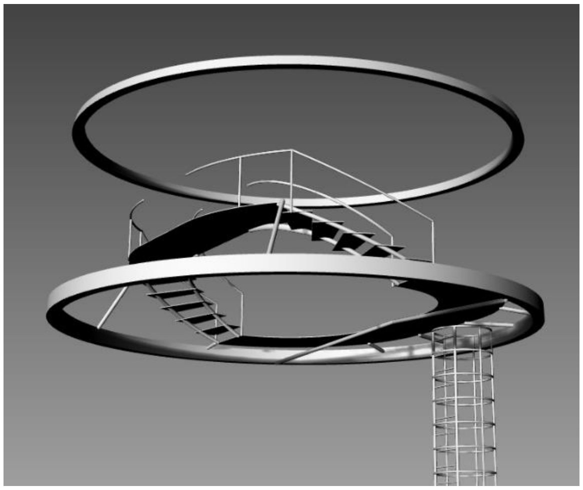

Figure 44. Catwalk Structural Interfaces

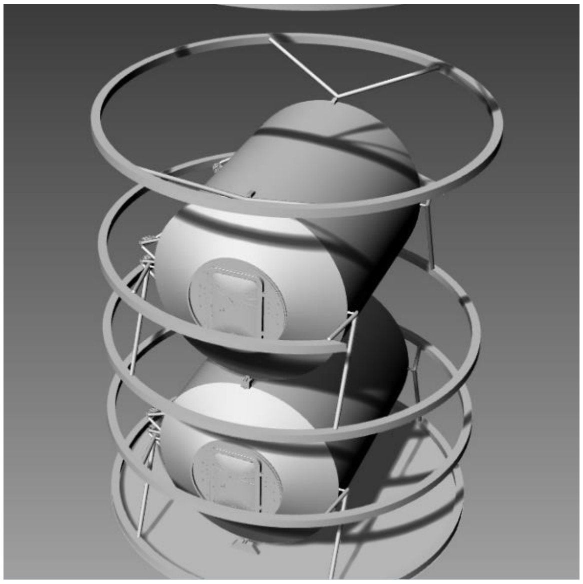

Figure 45. Logistics Module Structural Interfaces

Power and Thermal Assumptions

Several key assumptions are made regarding Starship power and thermal subsystems that are not explored in this paper. It is assumed that cryocoolers are needed to prevent boiloff of Starship Ascent Module propellant. It is also assumed that body mounted solar arrays and radiators are needed to provide vehicle power during Cislunar or Trans-Mars cruise. In both cases, it is assumed that no acreage is available on the heat shield side of the vehicle, resulting in placement of radiators and solar arrays on the portions of the vehicle exterior not covered in heat shield tiles. A surface power umbilical interface is assumed to be added to the base of the Starship. This will allow surface robotic systems to connect a power umbilical to the lander, providing vehicle power until the crew depart and power is no longer needed. (Power could remain connected if the lander has any post-crew departure functions identified.)

5. CONCEPT OF OPERATIONS

Lunar Concept of Operations

In-space crew rendezvous and transfer can take place in LEO, Cislunar space, or low lunar orbit (LLO). The Crew and Logistics lander will begin with an uncrewed launch into LEO, where it will rendezvous and dock with tanker starships for fueling operations. It then will undock from the tanker and has three options to receive crew.

It can await crew in LEO. Crews can launch in one or more launches and dock to the lander. Once the crew have transferred and the visiting vehicles have departed, it can perform a trans-lunar injection burn, cruise to the Moon, then deorbit and land.

Alternately, it can meet the crew in Cislunar space. It can transfer uncrewed to Cislunar space, where it can await a crew launch vehicle, or it can dock to Gateway if crew are already there awaiting it. Once the crew have boarded, it can undock, propel itself to the Moon, deorbit, and land.

Finally, it can transfer uncrewed all the way to the Moon and capture into LLO. There, it will await the crew. Once the crew have docked, transferred over from the spacecraft that delivered them, the lander can undock, deorbit, and land.

Prior to deorbit, the crew will don pressure suits (analogous to those worn by crews during launch and entry in Orion or Dragon) and strap into seats in the Starship Ascent Module cabin. As directed by MCC, the crew will perform deorbit and landing operations. Once on the surface, the crew will doff and stow their pressure suits.

The crew will unpack their surface suits from the launch stowage location in the Transfer Tunnel and will relocate them to the Pressurized Crew Transfer Module. Any additional stowed items in the Starship Ascent Module or Transfer Tunnel that need to accompany the crew to the base camp will also be transferred to the PCTM. The Mission Control Center (MCC) will meanwhile be teleoperating the Pressurized Rovers (PRs) and cargo surface transportation systems from the Habitation Zone to the Landing Zone.

Once given a go by MCC, the crew will prepare the Crew and Logistics Lander for uncrewed operations, transfer to the PCTM, and close hatches. They will then command the PCTM Garage door open and command the crane system to deploy and lower the PCTM to the surface, where the PRs will dock with it, one at a time. Four crew will transfer over to the first rover, bringing their surface suits and any accompanying stowage items with them. Once loaded, it will undock, and the second rover will dock to repeat the process with the remaining four.

With the crew off the vehicle, MCC will remotely unload the logistics module(s). Once the cargo surface transportation systems are in place, MCC will command the logistics Garage door open and will command the crane system to deploy and lower the logistics module to the surface, where it will be received by the cargo surface transportation system and transported to the Common Habitat. If there is a second logistics module, the process will be repeated.

At the end of the surface expedition, the crew will depart the Common Habitat by ingressing the PRs with their surface suits and any payloads allocated for crew return. The overwhelming majority of payloads do not return with the crew but are launched separately.

(It is worth noting that there is a five-day overlap for lunar expeditions, where both the incoming and outgoing crews are on the surface at the same time. It is possible that either crew might choose to sleep in the PCTM during those five days, using the PRs to shuttle back and forth each day.)

The rovers will be driven by the crew to the Landing Zone, where they will dock one at a time with the PCTM. The crew will transfer shirtsleeve to the PCTM and stow their suits.

Once all eight crew have transferred over, they will seal the hatch and MCC will teleoperate the rovers away. The crew will the command the crane system to lift the PCTM and draw it back into the Starship until it has docked to the airlock. If this is completed late in the crew day, the crew may spend the night in the PCTM before preparing for launch. Once the crew has a go to prep for launch, the crew will leave their surface suits behind in the PCTM and ingress the airlock, ascending through the Transfer Tunnel to the Starship Ascent Module, along with any payloads returning with them. They will seal all hatches behind them as they ascend. Once in the Starship Ascent Module, they will don their pressure suits, complete launch preparation, and lift off.

Once in space, the crew will doff their pressure suits and configure for microgravity operations. They will complete the in-space cruise to rendezvous and dock with either Gateway or an Earth return spacecraft, at which point they will configure the Starship Ascent Module for disposal and close the hatch after egress.

The Starship Ascent Module is not reused. Its disposal operations will be commanded by MCC in line with its end-of-life plan, which may involve a commanded impact to the lunar surface, or an escape burn to depart Cislunar space (either a solar orbit or an eventual disposal in the Earth's atmosphere).

There are off-nominal surface operations that allow for a suited transfer from the surface to the Crew and Logistics Starship. In the event of PR failures where the crew must walk or use unpressurized rovers to reach the PCTM, the crew will travel four at a time and will dock to the PCTM suitports. They can remain in their suits or ingress the PCTM cabin. The PCTM will deliver four crew to the Starship Garage, where they will undock from the suitports and walk along the catwalks from the PCTM to the airlock, where they will ingress, repressurize, doff and stow their suits, and ascend to the Starship Ascent Module to await the other four crew, who will repeat the process.

In the event that the crane system fails during a PCTM ascent, the crew inside will don their surface suits and depressurize the cabin. They will then open the outboard side hatch and egress onto the PCTM outer deck, one at a time.

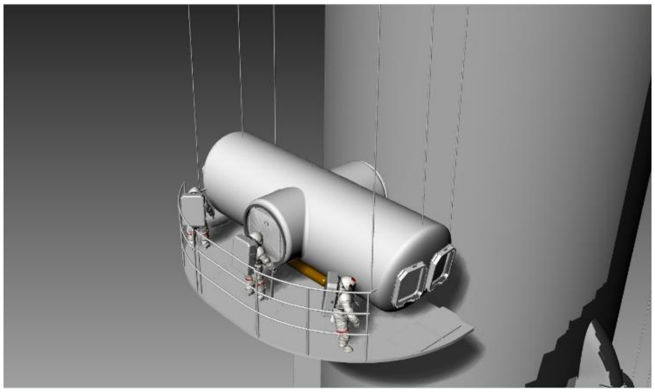

Figure 46. Crew Preparing Ascenders

They will each retrieve an ascender mechanism from external stowage and attach it to their suit, notionally indicated in Figure 46. The ascender mechanism includes an attachment to the suit and two attachments that can connect to cable or rail systems. They will connect the ascender to one of the two outboard lift cables. Using the ascender, they will climb the cable to just below the crane's extended arms as indicated in Figure 47. Each arm has a hanging rail that is low enough for the crew member to reach. They will connect their ascender to the rail and then detach from the cable. They will use the ascender to traverse horizontally along the rail until they are inside the Garage, shown in Figure 48. There, they will transfer the ascender to a second rail that will transfer them to the catwalk. They can walk the remainder of the distance to the airlock and ingress, shown in Figure 49.

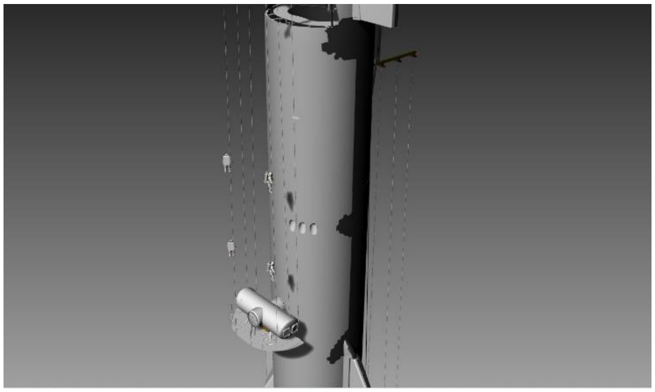

Figure 47. Using Ascenders to Traverse Lift Cables

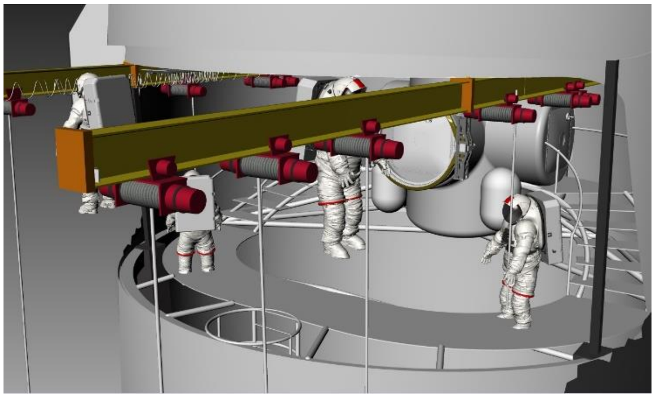

Figure 48. Traverse to Garage Interior

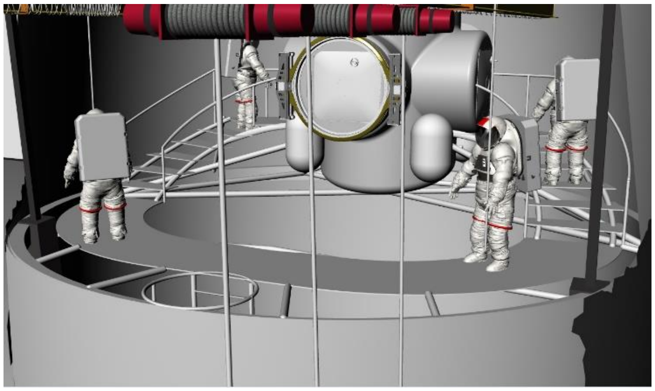

Figure 49. Traverse Catwalk to Airlock

If the PCTM crane system suffers a failure while there are still extravehicular activity (EVA) crew on the surface awaiting the PCTM, this will separate them from their nominal means of ingress, as suggested by Figure 50.

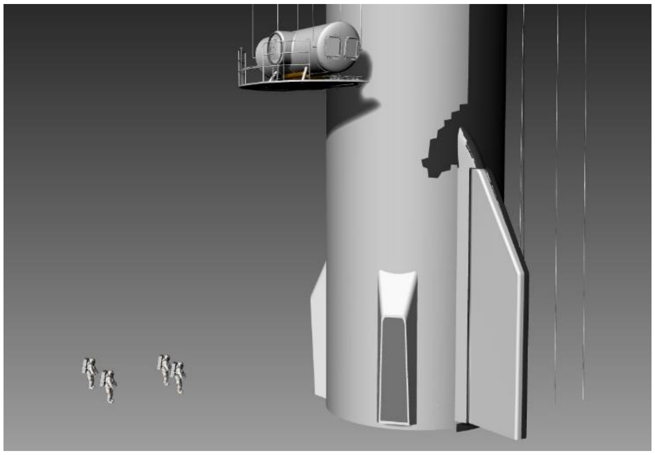

Figure 50. Surface Crew Separated from Airlock by Stuck PCTM

In such a case, the crew can ingress via the logistics crane. They will retrieve similar ascender mechanisms from the surface base camp or the Pressurized Rovers. Each crew member will attach their ascender to one of the six logistics module lift cables. If the logistics crane system is working, it can retract and draw the crew into the Garage, releasing them onto the Garage floor. If the crane system is not working, the crew will use the ascenders in an identical approach to that used from the PCTM, shown in Figure 51, with the exception that once inside the Garage, as indicated in Figure 52, there is no catwalk at the logistics module level.

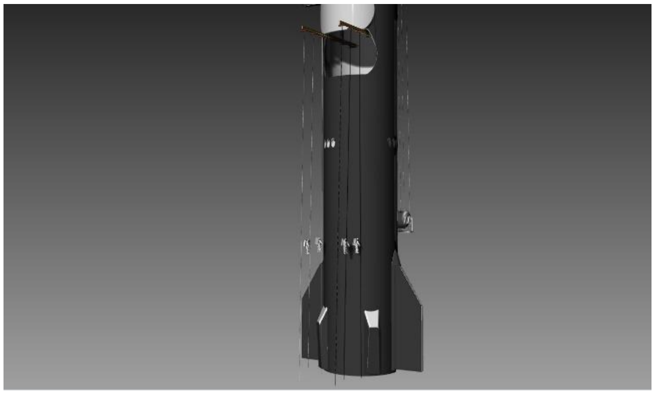

Figure 51. Crew Ascending Logistics Module Lift Cables

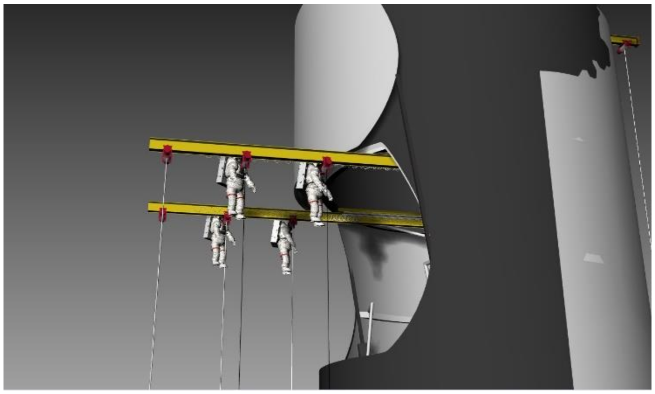

Figure 52. Traverse to Garage Interior

Instead, there is a secondary cable release on each crane arm that will lower a cable to the Garage floor. The crew will descend from the logistics crane arms to the Garage floor. There, they will walk over to the Garage ladder as indicated in Figure 53, which is directly opposite the logistics Garage door. They will climb the ladder to the PCTM level, as shown in Figure 54. If the PCTM is not present, they will traverse the catwalk to the airlock. If the PCTM is present, they will traverse through the PCTM to the airlock.

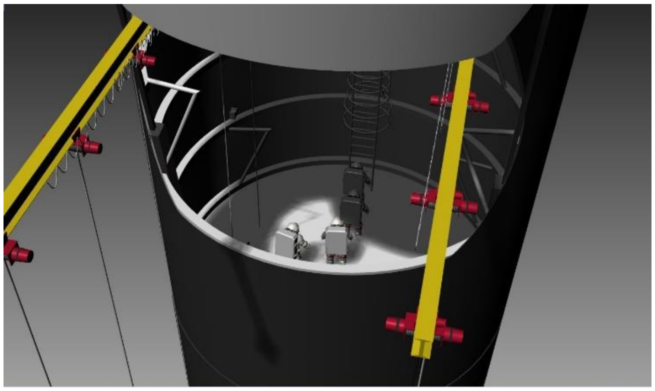

Figure 53. Descend to Garage Floor

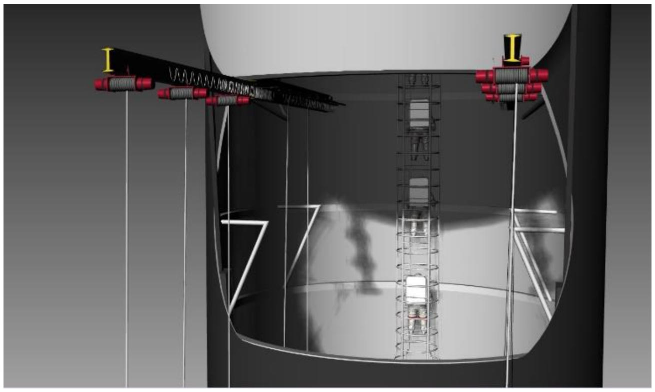

Figure 54. Climb Ladder to Catwalk

Key Differences for Mars Concept of Operations

The Crew and Logistics lander will depart LEO uncrewed and will perform a trans-Mars injection burn. It will capture into Mars orbit and will rendezvous with the DSEV in a 5-Sol Mars orbit. It will not dock with the DSEV. Instead, the crew will ingress one or both of the PRISMs and undock from the DSEV. They will fly to the lander and dock with the airlock.

The atmosphere on Mars is what drives the Crew and Logistics lander to have a heat shield and aerodynamic control surfaces. This results in a different entry profile than for the lunar landings.

Also because of the Martian atmosphere, there may be dust storms during the surface expedition. Identification of an appropriate means to protect the Garage from dust intrusion remains as forward work.

Unlike the lunar expeditions, there is no crew handover at Mars. Thus, at the end of the expedition there is no 5-day period where one crew might choose to sleep in the PCTM.

Following Mars ascent, the Starship Ascent Module will rendezvous with the DSEV in a 5-Sol orbit. It can there choose to dock directly with the DSEV, docking to the Two-Chamber Airlock Node (TCAN) or one or both of the PRISMs can undock from the DSEV and dock with it, one docking to the zenith port and the other to the nadir port.

Contingency Microgravity Maintenance Access

Nominally, the crew will not conduct EVAs inside the Garage. However, in addition to the contingency return scenarios, there is an option for contingency EVAs in the Garage in microgravity prior to landing. The crew can don surface suits and egress the airlock into the Garage should there be a need to inspect or make repairs to the Starship itself or any of the encapsulated elements.

6. CONCLUSIONS AND FORWARD WORK

This paper has demonstrated a volumetric configuration sufficient to enable crew and logistics transport to the surfaces of the Moon and Mars and crew ascent at the end of a surface mission, given a crew size of eight and surface mission durations ranging from 370 to 700 days. This approach includes both shirtsleeve transfer and suited transfer. Multiple paths of dissimilar redundancy ensure that the crew can transit from the surface to the Starship Ascent Module. Fourteen of these Starships enable ten lunar missions and four Mars missions within a single decade.

Trades and Forward Design Work

Mass estimation as well as mass optimization is a clearly needed effort, which was not possible under the current design cycle and will require a funded effort. Mass equipment lists (MEL) and power equipment lists (PEL) will be needed for the lander and its encapsulated elements.

SpaceX data on Starship performance also continues to evolve, which is to be expected as it is a rocket system still in development. Most literature cites a surface payload capacity of 100 tons, but these numbers were cited assuming no greater performance than that provided by the Raptor-2 engine. It is not yet clear how Raptor-3 engines will affect performance.

The 7.68-meter barrel elongation, encapsulated elements, key mechanisms, and internal structures described in this paper must fit within the 100-ton cargo delivery capability of Starship, or more precisely the cargo delivery capability that will exist once the Starship design has stabilized.

Interior and exterior lighting and camera placement will need to be assessed. Both will be needed to enable crew and MCC visibility and system monitoring.

Several propulsion system trades were outside of the scope of the current effort. A number of propellant tank configurations should be traded, including toroidal, cylindrical, spherical, and nested. Additionally, the current configuration has cylindrical tanks canted at an angle in an effort to reduce vehicle dimensions while also attempting to reduce the amount of propellant residuals. It will need to be assessed if this approach was necessary or successful.

Another trade concerns whether the ascent module propellant should be contained (from Earth launch) within the ascent module's tanks or if they should be filled in space (post-launch, in transit, or on the surface) with excess propellant from the Starship tanks. A similar question exists for the RCS thruster tanks – should they be pre-filled or filled immediately prior to Moon/Mars ascent with propellant from the ascent module tanks? Should there be cryocoolers, whether within the ascent module, aboard the Starship, or external? Currently, the RCS is a LOX-methane system, but a hypergolic RCS should also be traded. Additionally, the use or nonuse of cross feeding should be considered.

Power system trades are needed for both the lander and ascent module. While both can receive external power while on the surface, they both need power while in flight. Options include solar-battery, LOX-LH_2 fuel cells, and LOX-CH_4 fuel cells.

Thermal control system trades center primarily on the use of body mounted versus deployable radiators for both the Crew and Logistics Lander and the Starship Ascent Module. Also, for both spacecraft, there may be areas where passive thermal control can be applied.

The thermal protection system should trade heat shield sizing for Mars entry versus Earth entry. Presumably, a heat shield capable of protecting for Earth entry should be heavier than one sized for Mars entry, but there may be production cost advantages of maintaining commonality with Earth-entry Starships. Earth commonality also introduces a possible option for an Abort-to-Earth mode for the lunar outbound segment, especially if the crew transfer is performed in LEO. This might also give the Crew and Logistics Lander the ability to serve as a rescue vehicle to other spacecraft that may suffer from catastrophic events in LEO or Cislunar space.

The hatch and Garage door mechanisms are currently notional and require future design work. The Garage doors in particular may impose additional structural requirements on the Starship.

For Mars expeditions, a trade is also needed to address dust mitigation. The Garage interior can be protected against dust storms by retracting the PCTM as well as the logistics module cables into the Starship and closing the Garage doors. But this creates the risk that they may not redeploy at the end of the surface expedition, which could leave the crew stranded on Mars. But if they remain deployed, dust can get into the crane mechanisms.

Docking and crew ingress/egress involves a trade of one versus two docking ports on the Starship Ascent Module. At minimum, there must be a hatch at the bottom of the cabin for crew transition between the cabin and the PCTM. There must further be a vertical tunnel to clear the propellant tanks and main engines If this tunnel launches as part of the ascent module, then it can be used in space to facilitate docking. But traditionally, capsules such as Orion, Dragon, and the Apollo Command Module have placed a docking port at the top of the capsule. And from a redundancy/reliability perspective, should there be one or two means to dock the ascent module with another spacecraft?

Nominal and contingency habitation trades involve crew location in and utilization of systems in the Starship Ascent Module, transfer tunnel, airlock, and PCTM. Prior to ascent, all of these volumes are available. Post-ascent, only the Starship Ascent Module's cabin and vertical tunnel can be used.

The contingency ascender system is highly notional. Additional work is needed to estimate the design of an ascender, as well as the traverse path from the extended crane to the Garage catwalks.

Heavy Cargo Return System

Other forward work involves conceptual development of a cargo return capability. Given the amount of time that the crew will be on the surface, it is likely that an unprecedented quantity of return cargo mass will be generated, inclusive of geologic samples, ISRU products, human and other biological samples, spacecraft components, and other science payloads. The Starship Ascent Module is not intended to return cargo in these quantities.

Instead, a dedicated Heavy Cargo Return System (HCRS) is envisioned, derived from the Crew and Logistics Lander. The HRCS delivers itself to the Moon or Mars in advance of a crewed expedition. It could optionally be responsible for cargo return from a single expedition or could aggregate cargo over multiple expeditions before conducting a return.

The HCRS would deliver payload to Cislunar space in the case of a lunar mission, where it would await a standard orbital Starship to transport it to the surface of Earth. In the case of a Mars mission, it would deliver its payload to a 5-Sol Mars orbit where it would be retrieved by a DSEV for transport to LEO, where again a standard orbital Starship would rendezvous to provide Earth entry, descent, and landing.

The target capacity for the HCRS is 10,000 kg return payload, implying a capability comparable to that of the Starship Ascent Module's propulsion system. It is a forward trade as to whether or not this payload mass includes the mass of containment structures and any needed power or thermal management systems.

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BIOGRAPHY

Robert Howard *is the Habitability Domain Lead in the Habitability and Human Factors Branch and co-lead of the Center for Design and Space Architecture at Johnson Space Center in Houston, TX. He leads teams of architects, industrial designers, engineers, and usability experts to develop and evaluate concepts for spacecraft cabin and cockpit configurations. He has served on design teams for several NASA spacecraft programs, projects, and study teams including the Orion Multi-Purpose Crew Vehicle, Orion Capsule Parachute Assembly System, Altair Lunar Lander, Lunar Electric Rover / Multi-Mission Space Exploration Vehicle / Pressurized Rover, Lunar Terrain Vehicle, Deep Space Habitat, Waypoint Spacecraft, Exploration Augmentation Module, Asteroid Retrieval Utilization Mission, Mars Ascent Vehicle, Deep Space Gateway, Surface Habitat, Transit Habitat, Lunar Terrain Vehicle, and other human spaceflight studies mission studies. He received a B.S. in General Science from Morehouse College, a Bachelor of Aerospace Engineering from Georgia Tech, a Master of Science in Industrial Engineering with a focus in Human Factors from North Carolina A&T State University, and a Ph.D. in Aerospace Engineering with a focus in Spacecraft Engineering from the University of Tennessee Space Institute. He also holds a certificate in Human Systems Integration from the Naval Postgraduate School and is a graduate of the NASA Space Systems Engineering Development Program.*

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Felix Arwen *holds a B.F.A. in Industrial Design from the Rhode Island School of Design (RISD). During his time at RISD, he led the RISD Rover Club, serving as both technical advisor and president. He actively contributed to various NASA Artemis Design challenges, including the Micro-g Neutral Buoyancy Experiment Design Teams (Micro-g NExT) challenge, the NASA Spacesuit User Interface Technologies for Students (SUITS) design challenge, and the BIG Idea challenge. Additionally, he participated in the Human Exploration Rover Challenge (HERC), designing and racing a human-powered tandem vehicle that earned the featherweight award. Within the RISD community, he took on roles such as head shop monitor for Metal and Wood shops and the technology lab, and he was a teaching assistant in advanced fabrication and technical design classes. Recently, he finished an internship with the Center for Design and Space Architecture at NASA's Johnson Space Center, where he focused on designing for Common Habitat projects, as well as contributing to unpressurized rover logistics transfer and crew rescue efforts for the Ground Test Unit.*