A Multi-Functional, Two-Chamber Airlock Node for a Common Habitat Architecture

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An airlock is generally considered a necessity for any large, habitable spacecraft. While suitports, docked rovers, and external robotics can reduce the need for airlock operations, at some point it is necessary to move both crew and equipment from a habitat interior to the exterior environment. The Common Habitat is a large, long-duration habitat that uses the Space Launch System (SLS) Core Stage Liquid Oxygen tank as the primary structure (similar to Skylab) and has an internal architecture compatible with microgravity, lunar gravity, and Mars gravity, such that identical versions of the same design can be used in all three environments. It needs an airlock that is similarly appropriate for both surface and microgravity environments. After a brief survey of prior airlocks, the two-chamber node airlock concept applied to the Common Habitat architecture is described. This includes benefits of the dual chamber and node approaches, dimensions, hatches and docking ports, utilities connections, hatch covers, suit storage, EVA stowage, subsystems, and gravity-specific external attachments. Additionally, the functions of each chamber and reconfiguration capabilities are explained. Finally, conclusions and follow-on work are discussed.

I.Nomenclature

ATHLETE = All-Terrain Hex-Limbed Extra-Terrestrial Explorer
CBM = Common Berthing Mechanism
CHAPEA = Crew Health and Performance Exploration Analog
CTB = Cargo Transfer Bag
DCIS = Dual-Chamber Inflatable Suitlock
DIR = Docking Interface Ring
DRATS = Desert Research and Technology Studies
DSEV = Deep Space Exploration Vehicle
EVA = Extra-Vehicular Activity
EVR = Extra-Vehicular Robotics
HERA = Human Exploration Research Analog
HITL = Human-in-the-Loop
HUT = Hard Upper Torso
LCVG = Liquid Cooling Ventilation Garment
LER = Lunar Electric Rover
MDL = Mid Deck Locker
MDLE = Mid Deck Locker Equivalent
MGAAMA = Multi-Gravity Active-Active Mating Adapter
OGB = Overhead Grab Bar
PCM = Pressurized Core Module
PEM = Pressurized Excursion Module
PLM = Pressurized Logistics Module
PLSS = Portable Life Support System
PPE = Personal Protective Equipment
SIEB = Suit Ingress-Egress Bar

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SIP = Suitport Interface Plate
SLS = Space Launch System
TCAN = Two Chamber Airlock Node
UIP = Utility Interface Panel

II.Introduction

The Common Habitat is a conceptual long-duration habitat that uses the Space Launch System (SLS) Core Stage Liquid Oxygen Tank as its primary structure, in a manner similar to Skylab's use of the Saturn SIV-B stage. [1] The Common Habitat is not currently part of any active NASA reference mission or human spaceflight program. This paper is part of an ongoing a feasibility study to assess the viability of the Common Habitat and associated architectures, elements, and operations. Should such feasibility be determined, NASA would then be positioned to make a programmatic decision about whether to incorporate any aspects of these studies into current or future programs.

The Common Habitat is designed with a common layout, such that identical production units can be used as a lunar surface habitat (1/6g), a Mars surface habitat (3/8g), a deep space habitat (0g), and an Earth trainer or analog (1g). A design trade explored alternate configurations of the Common Habitat [2] and subsequent testing led to the adoption of a variant that is configured as a horizontal habitat, divided into lower, mid, and upper decks, as shown in Fig. 1 with the pressure vessel hidden to make the interior decks visible. The Common Habitat can accommodate crew sizes up to eight. Logistics sizing has been applied to the Common Habitat for crew habitation periods up to 1200 days in duration. [3]

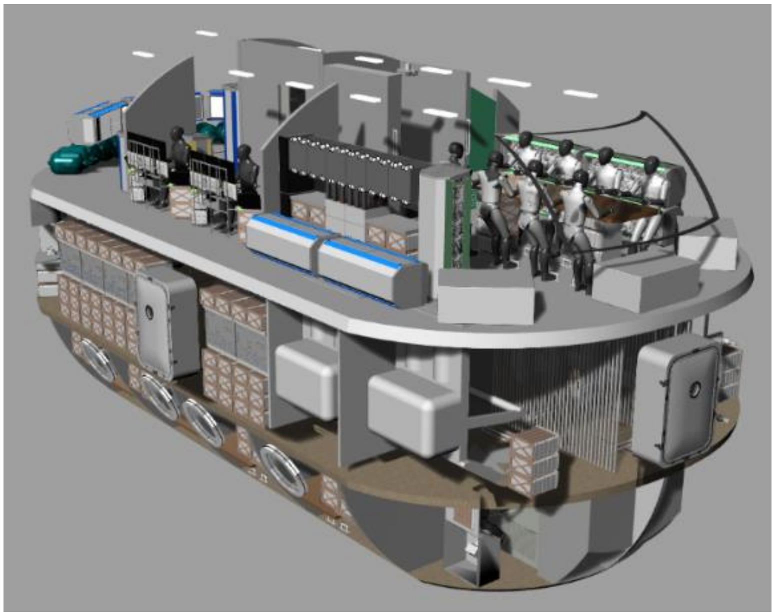

Fig. 1 Common Habitat, Pressure Vessel Interior

An architecture is being developed around the Common Habitat to serve as a basis to evaluate the performance of the Common Habitat in each of its potential missions. In this architecture, the Common Habitat is used for continuous lunar surface habitat, with overlapping crews experiencing 370.5-day surface missions. The Mars surface missions are not continuous, with durations varying as a function of orbital mechanics considerations. Surface durations considered in this architecture have ranged from 450-650 days. Transit missions also vary as a function of orbital mechanics considerations, with the total round-trip transit durations varying from 380-1200 days, with the longest one-way segment assessed to date on the order of 950 days. Earth-based analogs and trainers may of course be used for any duration needed to accomplish the intended training or analog mission purpose.

The Common Habitat does not include an internal airlock. The interior is devoted specifically to crew living and working functions and associated subsystems. Extra-Vehicular Activity (EVA) functionality is enabled through a docked, external system described in this paper. (EVA functions are also available through any docked spacecraft that has independent EVA systems.) In all Common Habitat missions, an external airlock is docked to the habitat at one of its four docking ports. This airlock provides for suit don/doff, ingress/egress, suit maintenance, and suit stowage. This paper will discuss the basis of the external airlock used in the Common Habitat architecture, considerations for its use in both microgravity and gravity environments, and how its features support the Common Habitat's missions.

III.Examples of Predecessor Airlocks

A. Quest Airlock

The Quest airlock on the International Space Station is the primary EVA system in the US Operational Segment. It primarily provides EVA access for US spacesuits but can also support Russian Orlan spacesuits. Quest is 5.5 meters in length and 4 meters in width, with a mass of 9923 kg. [4] It is berthed to Node 1. Quest consists of two compartments – a crew lock (purple in Fig. 2) and an equipment lock (green in Fig. 2). The crew lock, which is derived from the shuttle airlock, is the section that depressurizes to provide exit for EVAs. The equipment lock contains the systems and volume for suit maintenance and refurbishment. Suit stands mounted to the equipment lock walls, support suit donning and maintenance. Fig. 3 shows an astronaut crew member servicing a spacesuit Hard Upper Torso (HUT). [5] A high pressure gas assembly mounted on the exterior of the equipment lock provides breathing gases used to support EVA operations. [6]

The separation of functions into crew lock and equipment lock offers both safety and operational benefits to ISS. Should the Quest crew lock outer hatch fail upon return from EVA, the station crew can close the equipment lock hatch leading to Node 1 and depressurize the equipment lock. The EVA crew can then ingress the equipment lock and pressurize it, enabling a safe crew return. Operationally, nominal use of the crew lock for depressurization reduces the quantity of gas lost with each EVA, decreasing the logistics resupply requirement. The equipment lock also facilitates "camp outs," where the equipment lock is lowered from the station's nominal pressure of 14.7 psi down to 10.2 psi and the EVA crew spends the night in the airlock the night before a scheduled EVA. [7]

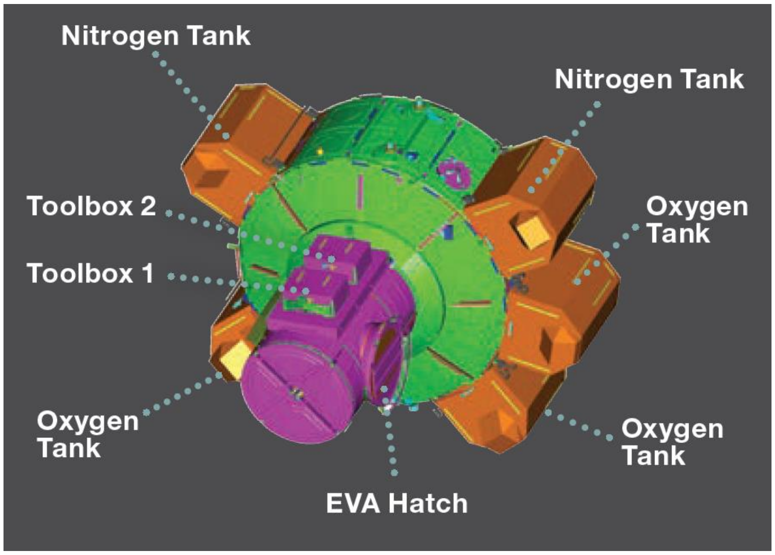

Fig. 2 Quest Airlock

Fig. 3 PLSS on Suit Stand in Quest Equipment Lock

B. Altair Airlock

The Constellation Altair Lunar Lander included a separate airlock as shown in Fig. 4. [8] For seven-day lunar sortie missions, the crew would launch, land, and live in the ascent module. The airlock module would be used to don/doff suits and ingress/egress the cabin for two-person EVAs. The Altair functioned somewhat as a hybrid between a dual chamber and single chamber airlock. The ascent module was used to store two of the four lunar surface spacesuits. During EVAs it would also store EVA-related stowage that could not go to vacuum (items stowed in the airlock when it is not depressurized). And in a contingency where the airlock could not repressurize, the crew in the ascent module could don suits and depressurize the airlock, allowing a returning EVA crew to ingress all the way into the ascent module prior to cabin repressurization.

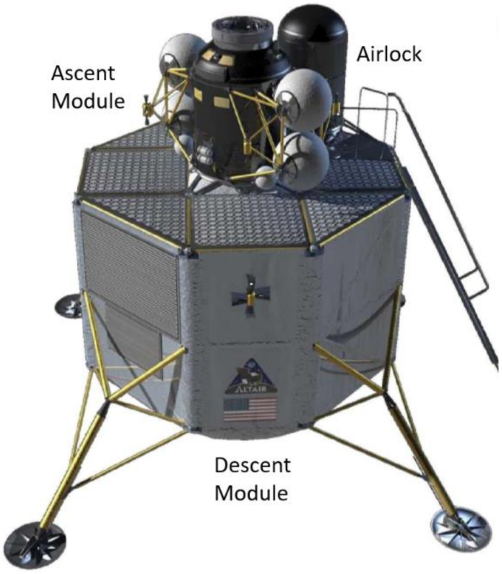

Fig. 4 Altair Lunar Lander

The Altair project attempted to define the minimum possible size for the Airlock (and Ascent Module), using a series of human-in-the-loop mockup tests to evaluate the interior configuration, make improvements to the layout, and test those improvements. A reconfigurable mockup, shown in Fig. 5, was used, featured flexible plastic walls that allowed the diameter and height of the ascent module and airlock to be changed. Donning stands were built into the airlock, shown in Fig. 6, to enable the test subjects to don and doff realistic spacesuit mockups. [9] At the time of the cancellation of the Constellation program, the Altair project had selected a diameter of 1.85 meters and a height of 2.3 meters for the airlock. [10]

Fig. 5 Variable Height and Diameter Altair Mockup

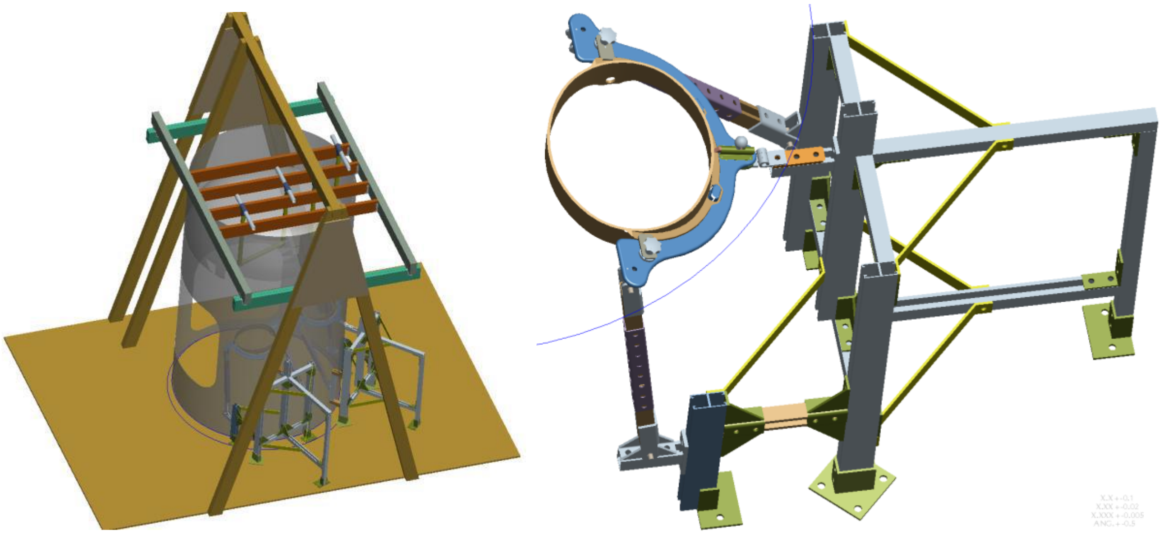

Fig. 6 Airlock Donning Stands

The Altair airlock used the volume beneath the floor to stow eight Cargo Transfer Bags (CTBs), shown in Fig. 7. [11] These CTBs are stowed in the airlock when it is pressurized as their contents cannot go to vacuum. Prior to EVA, these CTBs are transferred over to the ascent module and after the conclusion of an EVA they are returned.

Fig. 7 Under-Floor Stowage in the Altair Airlock Mockup

In addition to nominal IVA and EVA scenarios, the Altair project also tested a number of contingency scenarios with the Altair mockup, including an incapacitated crew member rescue. This test used a mockup of the Mark III spacesuit, stuffed with foam, at a mass of 36.29 kg, which was roughly equivalent to the average weight of a crew member in a spacesuit on the lunar surface. This scenario did require the three non-incapacitated crew working as a team to bring the incapacitated crew member inside and repressurize the spacecraft. [10] Fig. 8 shows two crew members carrying the incapacitated crew member to the airlock entrance. The third crew member is not visible in the photograph but is inside the airlock waiting to help receive the incapacitated crew member. While test subjects were able to complete the task, they did find it difficult to pass the incapacitated crew member through the tunnel (from airlock to ascent module) and to attach the incapacitated crew member to the donning stand. For the latter task in particular, test subjects commented it would have been extremely difficult to position the incapacitated crew member in a donning stand had they been in pressurized suits. (It is uncertain if the airlock would still need to be depressurized at this point in the rescue.)

Fig. 8 Two Crew Rescuing a Simulated Incapacitated Crew Member

C. Lunar Surface Scenario 12.1 Airlock

The Constellation Program's Lunar Surface Systems Project traded numerous lunar surface habitation scenarios prior to the program's cancellation. One of the more extensively developed was Lunar Surface Scenario (LSS) 12.1. This scenario included eight pressurized, habitable elements: Pressurized Excursion Module (PEM), Pressurized Core Module (PCM), Pressurized Logistics Module (PLM), Lunar Electric Rovers (LERs) 1-4, and the Airlock, shown in Fig. 9. [12]

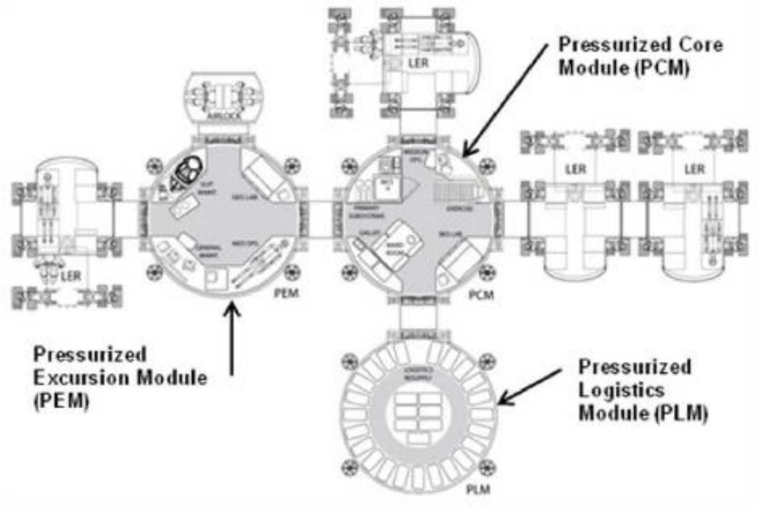

Fig. 9 Lunar Surface Scenario 12.1 Outpost Configuration

A notable feature of LSS 12.1 is its "Lunabago" Mode, shown in Fig. 10, where the PEM and Airlock can be detached from the outpost. Carried by an All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) robot, it can accompany two LERs on an excursion away from the Outpost to support field study of remote sites. [13]

Fig. 10 LSS 12.1 Lunabago Mode

LSS 12.1 is the only Constellation lunar architecture that was prototyped to sufficient fidelity to allow for a partial simulation in the Desert Research and Technology Studies (DRATS) field expeditions, taking part in the 2010 DRATS expeditions in Arizona. A repurposed version of the PEM and Airlock was upgraded and used in the 2011 DRATS and after additional upgrades was used in the JSC Near Earth Asteroid analog mission in 2012. It was repurposed yet once more to become the Human Research Program's Human Exploration Research Analog (HERA) facility. Fig. 11 shows the PEM and Airlock at the 2010 DRATS field test. [14]

Fig. 11 LSS 12.1 PEM and Airlock

It is worth noting that the airlock tested in the field at DRATS does not match the airlock in the conceptual floorplan shown in Fig. 9. The LSS 12.1 airlock was intended to be an inflatable airlock with a horizontal orientation. However, the LSS Lunar Surface Systems Habitation team did not have sufficient funding to develop a prototype of the inflatable airlock. Instead, the team repurposed a mockup that had previously been used for EVA testing by the JSC Crew and Thermal Systems Division, turning it into a prototype airlock for LSS 12.1. Thus, the size of the airlock mockup did not represent any design intent but was simply the size of the leftover asset the habitat team had acquired. It was initially believed to be larger than necessary because it was larger than the Altair airlock.

The prototype airlock tested at DRATS and at JSC measured 2.21 meters in diameter with a cylinder height of 2.06 meters with 0.39-meter tall end domes, yielding a total height of 2.45 meters. The airlock internal volume was 8.64 m^3. The interior included an aluminum skeleton structure for installing equipment and grated floor panels for dust removal. (It should be noted that the grated floor panels did not actually remove dust, but merely trapped dust and dropped small objects beneath the floor.) It included two load-bearing suit stand mockups constructed of 80/20 aluminum with overhead and side grab bars and removable donning seats. A hoist with a 680.4 kg lifting capacity was also mounted to the airlock interior. The airlock featured two 40-inch wide by 60-inch tall inward-opening hatches positioned at 90-degree angles – one leading to the PEM and the other to the lunar environment. Fig. 12 shows the prototype airlock. [15] This airlock used similar donning stands to those used for the Altair airlock mockup.

Fig. 12 LSS 12.1 Prototype Airlock

This prototype airlock differs from Quest in several ways. First, it was intended for use in lunar gravity. This substantially changes crew mobility and introduces considerations for lifting heavy masses such as the spacesuits themselves. The LSS 12.1 prototype airlock was also intended to accommodate suitport compatible spacesuits. The lunar pressurized rovers did not have airlocks, instead using suitports to enable the EVA crew to dock their suits to the aft bulkhead of the rover and ingress through hatches built into the aft bulkhead and rear of the suits. The LSS 12.1 prototype airlock was intended to receive these suits. This is one of the key reasons why the suit donning stands in the prototype face outwards, as shown in Fig. 13, [15] while the Quest suit stands face inward, as shown in Fig. 14. [16]

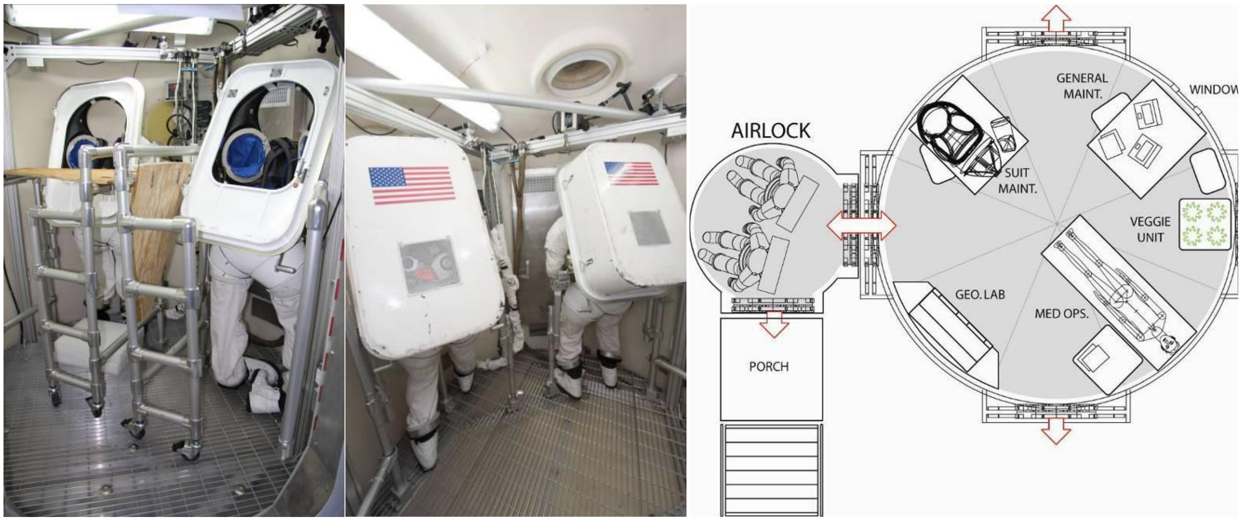

Fig. 13 Donning Stand Position in LSS 12.1 Prototype Airlock

Fig. 14 Suit Stands in ISS Quest Airlock

Human-in-the-Loop (HITL) testing of the airlock did indicate some areas of forward work needed to improve the design. In particular, an incapacitated crew member rescue scenario generated crew comments that the airlock volume was considered small. The test required using a hoist mounted in the airlock to bring an incapacitated crew member (represented by a mockup spacesuit stuffed with foam) on a sled into the airlock, shown in Fig. 15 and 16 and position it in the donning stand for crew member extraction, shown in Fig. 17.

Fig. 15 Attaching Hoist Cable to Incapacitated Crew Member on Litter

Fig. 16 Incapacitated Crew Member Being Hoisted Up the Airlock Ramp

Fig. 17 Maneuvering Incapacitated Crew Member Inside the Airlock

Unlike the Altair incapacitated crew member rescue, this test involved only a single rescuer. Even so, the airlock was barely large enough to complete the task. Some participants experienced difficulty maneuvering the incapacitated crew member (a mockup spacesuit filled with foam stuffing) sufficiently once inside the airlock to close the airlock hatches. Test subjects complained of bumping into airlock hardware, difficulty maneuvering in the airlock without stepping on the incapacitated crew member, and difficulty maneuvering the incapacitated crew member into position inside the airlock. [15] Some of this difficulty is illustrated in Fig. 18.

This was a surprise given that the Altair airlock had a 1.85-meter diameter compared to the PEM Airlock's 2.21-meter diameter. The difference was that because the HDU airlock hatch was intended for routine use it was hinged instead of removable and it opened inward. That hatch swing had a previously underappreciated driving impact on airlock diameter and the evaluation revealed a number of crew comments about the airlock being too tight due to collisions between the spacesuit Portable Life Support System (PLSS) backpack and the airlock hatch. [15]

Fig. 18 Difficulty Maneuvering Around Incapacitated Crew Member Inside Airlock

The LSS 12.1 airlock was initially envisioned as a single chamber airlock, which carries implications that were not fully assessed prior to the cancellation of Constellation. Aboard Quest, any equipment needed for refurbishment or servicing of suits, including stowage of such items, could be mounted in the Equipment Lock, near the suits. Some of this is visible in Fig. 2. In the LSS 12.1 airlock this is only possible for equipment that can be taken to vacuum and remain in an unpressurized state for hours. Additionally, the smaller size of the LSS 12.1 airlock makes it more difficult to place additional equipment. More significantly, should the airlock outer hatch fail to seal, the airlock will be unable to pressurize. If the pressurized rovers are docked to the outpost, the crew can perform an ingress through the rover suit ports, but if the rovers are not available the only remaining option would be to depressurize the Pressurized Excursion Module.

In recognition of the limitations of a single chamber and in order to enable higher frequency EVAs, a concept was introduced shortly after the cancellation of Constellation to replace the LSS 12.1 airlock with a Dual-Chamber Inflatable Suitlock, shown in Fig. 19. [14]

It is worth noting that there is confusion in NASA nomenclature with respect to the terms "suitport" and "suitlock." Two NASA Ames patents, filed in 1987 and 1996, refer to systems comparable to the suitport system on the aft bulkheads of the NASA pressurized rover concepts, with one patent describing the system as a "suitport" and the other as a "suitlock." [17], [18] During the Constellation Program, the term suitlock was used within the Lunar Surface Systems Project to denote an airlock subdivided into two chambers with two suitports on the bulkhead dividing the two chambers. [14] Currently in the Artemis program, the EVA Office uses the term suitlock to refer to a similar airlock system, but without suitports on the dividing bulkhead – instead a suit donning structure that does not form a pressurized seal. The JSC EVA Office describes the system that was called a suitlock during Constellation as a "Suitport-Airlock." Thus, when encountering the terms suitport, suitlock, and suitport-airlock in literature it is important to note the context and program heritage of the discussion. Further adding to the confusion, in some implementations of suitport-airlocks, the inner chamber is the actual habitat interior volume while in others it is part of a separate module, distinct from the habitat.

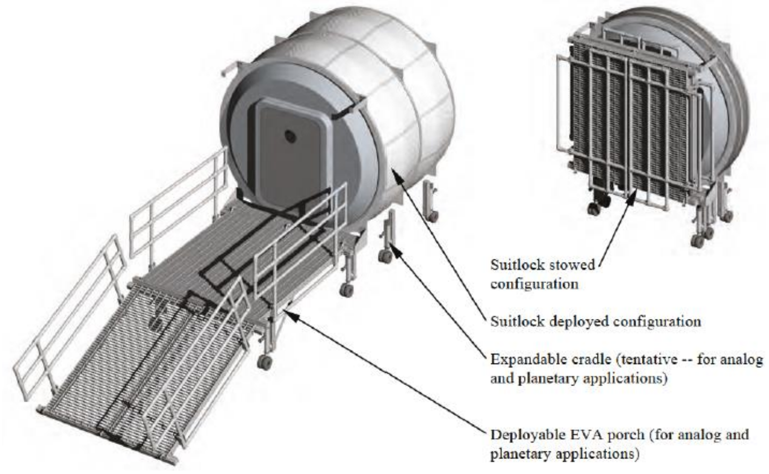

Fig. 19 Dual-Chamber Inflatable Suitlock

While the DCIS was named a "suitlock" when conceived in the immediate post-Constellation era, it meets the definition of what is described as a "suitport-airlock" today. The Dual-Chamber Inflatable Suitlock (DCIS) has a deployable center bulkhead, giving it two modes of operation: Suitport Mode and Large Volume Airlock Mode. In Suitport Mode, the inner chamber, which has a volume of 7.4 m^3, remains pressurized at either cabin pressure or at a reduced pressure as a transition from cabin to spacesuit pressure. The outer chamber, which has a volume of 5.9m^3, remains at vacuum. The outer chamber can be temporarily pressurized to enable shirtsleeve suit maintenance to be performed in the outer chamber. In Large Volume Airlock Mode, the dividing bulkhead is stowed, converting the DCIS into a single chamber with a volume of 13.3 m^3. This configuration enables the maintenance, assembly, or servicing of equipment too large for the outer chamber alone.

Other airlocks developed by NASA include those for Skylab and the Space Shuttle Orbiter. Currently, engineers at the Johnson Space Center are in the process of prototyping an inflatable airlock mockup as part of the Crew Health and Performance Exploration Analog (CHAPEA). As previously mentioned, the Pressurized Rovers do not use airlocks, but use suitports instead.

IV.Use of Airlock and Suitport within the Common Habitat Architecture

Both airlocks and suitports are used in the Common Habitat architecture. Therefore, it is important to understand which mission drivers lead to the selection of a suitport and which lead to selection of an airlock. By implication, this will also indicate why the Common Habitat architecture does not implement a suitlock / suitport-airlock. It is also a key design philosophy within the Common Habitat architecture to achieve maximum possible commonality across Moon, Mars, and microgravity domains, so any given airlock or suitport system is intended for use on the Moon, Mars, and in microgravity.

Suitports are used primarily in support of frequent and rapid EVA, leading to their use on the Pressurized Rovers. Even when the rovers are docked to the Common Habitat, they may still be prime for EVA when there is focused maintenance or repair activity that may require a series of back-to-back EVAs. ISS repairs have often required multiple EVAs and it is likely that external repairs for either the base camp or Deep Space Exploration Vehicle (DSEV) will require multiple EVAs as well. In such cases, those EVAs will begin and end from the rover suitports.

The suitports will also be used for surface remote excursions and for asteroid / small moon science exploration. Generally, this EVA activity will occur when the rovers have undocked from the Common Habitat and traveled to a remote site. This will occur with some level of regularity for the base camp, but for the DSEV this will only occur if the mission includes a low gravity or microgravity destination such as an asteroid, a Martian moon, or a servicing mission to a deep space probe or observatory. In such cases, one of the strengths of the rover is its ability to support multi-site EVAs, where over the course of a single crew day the rover may travel to multiple locations, enabling shorter survey-type EVAs. Where necessary, the rover can still support focused, lengthier EVAs. The advantage in both scenarios is that the suitport-enabled rovers facilitate numerous EVAs with low overhead.

By comparison, the airlock will be used for infrequent EVA activity. The airlock will be used to transfer suits between the rover suit ports and the airlock interior. To minimize suit exposure, suits will be kept inside the pressurized volume when rover-based EVAs are not anticipated. For surface base camps, the airlock may potentially be used for periodic external inspections of the base camp. If these occur while the Pressurized Rovers are docked the crew may choose between use of either suitports or airlock, but any inspections scheduled during rover excursions will require use of the airlock. Media or other public outreach events taking place in the immediate base camp vicinity may also require the use of the airlock.

The airlock is also used for transport of equipment to/from the external environment. This will include deployment or recovery of external science packages. These packages may arrive inside a pressurized logistics module and require assembly before deployment outside the Common Habitat. Previously deployed packages may also be retrieved through the airlock either for servicing or to remove samples. Other equipment transferred through the airlock may also include external subsystems, potentially those brought into the habitat through the airlock for servicing.

While it is true that the Suitport-Airlock has the advantage of reducing the EVA overhead in that it can conduct EVA egress and ingress operations more quickly than an Airlock can, this functionality is already achieved through the use of the Pressurized Rover suitports so there is no demand for this functionality on the Common Habitat. Additionally, the suitport-airlock requires volume in the outer chamber for suitport ingress/egress, which may compete with volume demands of transferring large equipment through the airlock. With no need for shorter habitat-based EVAs and volume complications associated with suitport-airlocks, they are not selected as a baseline element in the Common Habitat architecture. However, should a mission emerge needing suitport-airlock functionality, an external suitport-airlock could easily be docked to any available docking port.

V.Two-Chamber Airlock Node Concept

The Common Habitat architecture will employ a two-chamber airlock node (TCAN), shown in Fig. 20, to serve as the airlock system for base camp and DSEV purposes. A two-chamber system offers advantages to EVA operations, as has been seen with the ISS Quest airlock. A unique capability of the TCAN is that it features reversible chambers. The two chambers are identical, and their functions of equipment lock and crew lock can be reversed during a mission. There is a manufacturing benefit from using identical chambers – instead of designing two different chambers with different outfitting and different geometries (as was the case with Quest), a single design effort is applied to both chambers, reducing costs.

Fig. 20 Two-Chamber Airlock Node

The reversible system also offers operational benefits. In an airlock with dissimilar chambers, a hatch failure will render the chamber with the failed hatch unable to function properly. This will at best reduce the airlock to a single chamber airlock and for certain hatch failures could render the airlock nonfunctional. For the TCAN, no single hatch failure can render the airlock unusable and some hatch failures only result in a loss of redundancy or may have no long-term impacts at all. As an example, a failure to seal of the Quest outer hatch would result in an inability to pressurize resulting in a need to depressurize the equipment lock to conduct airlock operations. Should the TCAN experience the same failure, the airlock can be repositioned to dock the failed hatch to the Common Habitat and reverse crew lock and equipment lock assignment, such that the hatch that formerly led to the Common Habitat interior is now the outer egress hatch and vice versa. And because the failed hatch is now inside the cabin pressurized environment it is easier to access for repair. The reversible two-chamber system also aids in reconfiguring the base camp to a safe haven configuration, as is described in a separate paper. [19]

The TCAN's node functionality provides additional docking ports to receive visiting vehicles. While there are some constraints due to vehicle geometry impacting the sizes of docked elements, two visiting vehicles can generally dock without entirely preventing EVA operations. When neither chamber is scheduled to be used for EVA even more visiting vehicles can dock. In a safe haven scenario, the node functionality also enables the base camp to reconfigure its pressurized elements to provide a habitable volume while the crew repairs any habitat damage. [19]

Combining node and airlock functionality is deemed viable because both are infrequent use functions. Visiting vehicles will not be a constant presence at either the base camp or the DSEV. Thus, their activities can be scheduled to minimize interference.

VI.TCAN Chamber Description

The crew lock provides exit to exterior environment, suit donning and doffing, and suit resizing, checkout, and refurbishment. In a contingency it can also serve as a hyperbaric chamber. EVA science and maintenance tools that are not permanently stored in the space environment can be stored beneath the floor.

The equipment lock provides suit maintenance, long-term suit storage, EVA consumables storage, dust mitigation equipment storage, and facilitates crew access to docked elements. Depending on crew operations at any given time, hatches to docked elements may be open or closed

Due to the Node functionality of the TCAN, all airlock hatches are embedded within passive docking mechanisms. The largest such hatch in human spaceflight history is the 50-inch square hatch used in conjunction with the Common Berthing Mechanism (CBM). [20] However, the CBM hatch and all other flown hatches were designed exclusively for microgravity. By comparison, the TCAN must operate at 0g, 1/6g, 3/8g, and 1g in order to support the Common Habitat's design philosophy of a single design for all gravity environments. Based on Constellation-era suited human in the loop tests, [21] the TCAN hatch openings are all 40 inches wide and 60 inches tall, with a 16-inch stepover from the floor to the bottom of the hatch opening. This sizing enables EVA suited crew to pass through in both gravity and microgravity. It also enables incapacitated crew member rescue and transfer of relatively large equipment through the hatch. Fig. 21 shows a suited crew member translating across the 40-inch by 60-inch hatch of the PEM Airlock during a 2011 JSC evaluation. [15]

Fig. 21 Suited Crew Member Translation Through 40-inch by 60-inch Hatch

There are several options that describe the placement and translation of the hatch when opened. As shown in Fig. 22, on the ISS, hatches are tracked – they are mounted on rails that slide the hatch inward and to one side to move them away from the translation path when open. [22]

Fig. 22 Tracked Hatch on the International Space Station

Alternately, the hatch can be hinged, like an aircraft door. The side hatch of the Orion spacecraft is hinged to open outward, [23] while Orion’s docking hatch is removable. [24] The side hatch is visible in the open position on an Orion mockup in Fig. 23. The removable docking hatch is being placed in a protective hatch cover by the crew during the docking hatch evaluation shown in Fig. 24.

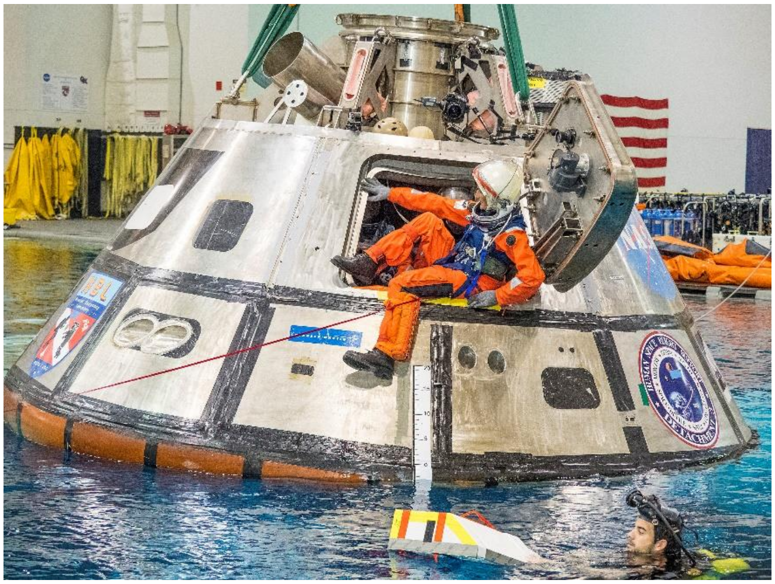

Fig. 23 Orion Mockup During Water Egress Testing

The swing or translation of a hatch when being opened or closed consumes a large amount of volume and the hatch itself occupies a significant amount of volume in the open position. For that reason, both internal and external spacecraft layouts can impact the decision of hatch translation. Also, there is a general preference for pressure assisted hatches – hatches that remain closed (due to internal cabin pressure acting as a sealing force) in the event of a latching mechanism failure.

If the TCAN hatch opened outward there would be potential interference with the Multi-Gravity Active-Active Mating Adapter (MGAAMA), [25] including both the docking tunnel and the MGAAMA hatch. There is insufficient room inside the airlock chamber for the hatch to be mounted on rails. Various obstacles are in the way above, below, or to either side. However, there is sufficient room for the hatches to all be hinged to open inward. (Future design trades may explore reconfigurations of the TCAN interior to allow for rails.)

Fig. 24 Docking Hatch Evaluation in Orion Cabin Mockup

The docking ports are designed to be compatible with the MGAAMA. A 2.24-meter diameter circular docking port surrounds each hatch. The docking port terminates in a Docking Interface Ring (DIR) shown in Fig. 25, an aluminum blade-like structure comparable to the Suitport Interface Plate (SIP) on a suitport-compatible spacesuit. Located between the DIR and hatch are various utilities connections, also shown in Fig. 25. These allow gases, fluids, data, and power to be passed between the TCAN and the MGAAMA. [25] The utilities can be used by the airlock for its operation and can be passed through the airlock to/from any docked element on an as-needed basis.

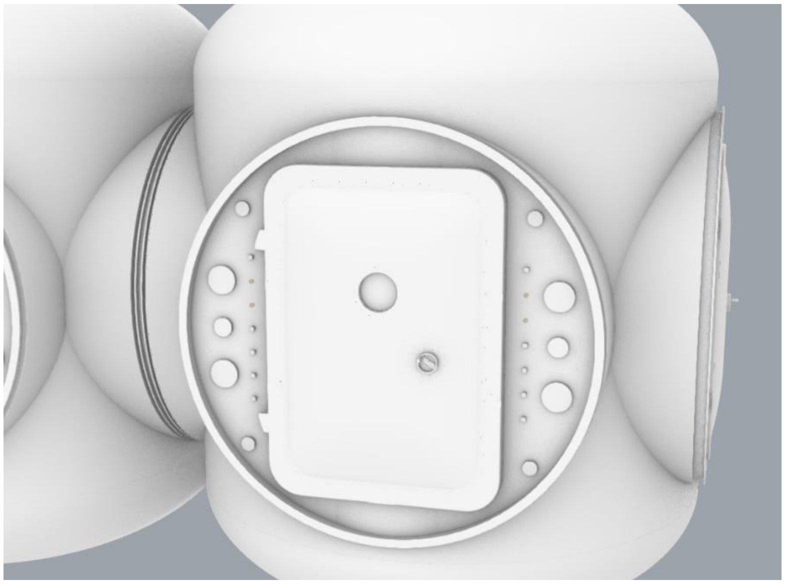

Fig. 25 Docking Interface Rings Surrounding Each Hatch

The airlock size is primarily driven by the four-hatch configuration and the placement of suits within the airlock volume. Each chamber has a diameter of 3.15 meters. Chamber height is 4.08 meters, with a 2.5-meter tall barrel and 0.79-meter tall upper and lower domes.

Because the hatches are exposed to the space environment, they do require environmental protection. And because they are exposed to the cabin interior when opened, they must also comply with NASA-STD-3001 standards regarding touch temperatures and other hazards. [26] This solution is forward work and will be identical to the protection scheme applied to the MGAAMA. [25]

The airlock has a maximum capacity of eight spacesuits. The crew lock can accommodate four suits in a configuration ready for donning. These suits are shown in Fig. 26, positioned at the "corners" of the crew lock, one between each hatch.

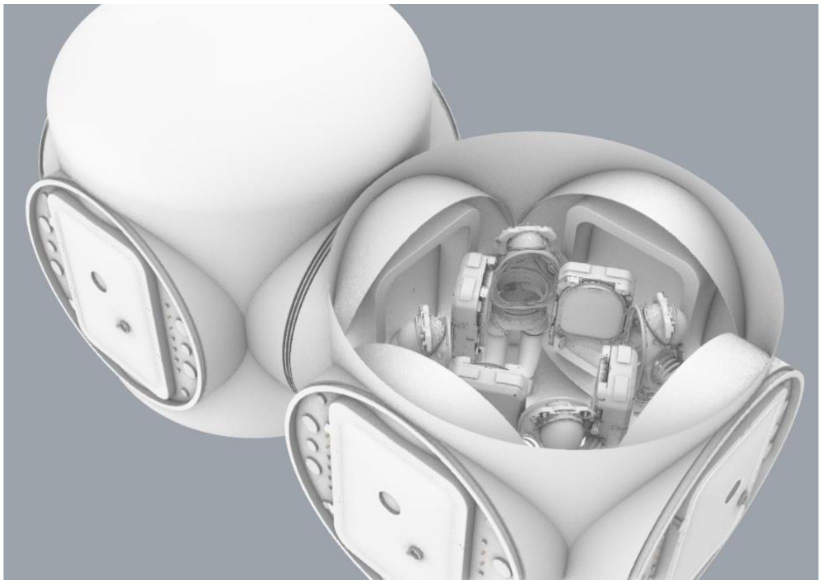

Fig. 26 Suits Positioned for Donning in the TCAN Crew Lock

An additional four suits can be stowed disassembled in the equipment lock as shown in Fig. 27. When four suits are on the Pressurized Rover suitports, flight rules will dictate whether the suits in the airlock are stowed in the crew lock or equipment lock. Suit stowage bags are used to protect the disassembled suit components and mitigate dust transfer when stowed in the equipment lock. The equipment lock includes ceiling-mounted attach points where four bagged PLSSs can be stored and under-floor stowage bays where the remainder of the suit components can be stowed.

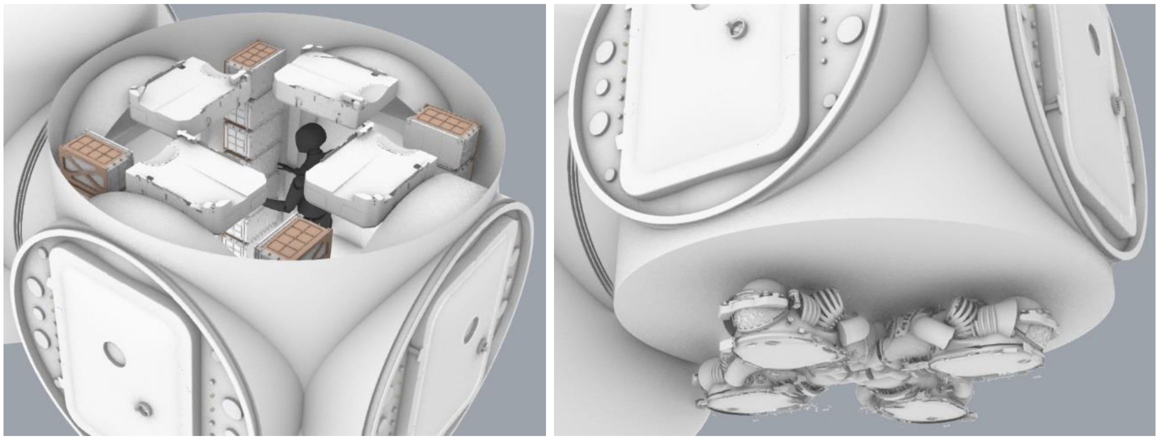

Fig. 27 Suit Stowage in the TCAN Equipment Lock

The equipment lock also accommodates limited quantities of EVA support items including suit maintenance tools, suit consumables (e.g. drink bags, diapers), material handling equipment, and frequent replacement spares (e.g. gloves, boots). These items are resupplied from the Logistics Module as needed.

These items are stowed in the equipment lock in four stowage towers, visible in Fig. 27. Each tower contains a four-mid deck locker equivalent (MDLE) stowage volume in a form factor consistent with half-depth mid deck lockers (MDLs). A mixture of half-height, standard height, and double-height lockers are used. One tower is at each corner of the equipment lock, occupying the space occupied by the donning-ready suits in the crew lock. These towers can each disassemble into two 4-MDL-equivalent height units for transfer across the hatch when needed, particularly when swapping crew lock and equipment lock functionality across the two airlock chambers.

The equipment lock also includes a deployable Suit Maintenance Worktable, which provides a suit mounting surface and tool work surfaces. It is stowed in the equipment lock in pieces and can be assembled for use when needed.

Both the crew lock and equipment lock stow dust mitigation tools, mounted on the walls and other crew-accessible locations.

TCAN ECLSS is an open-loop system derived heavily from PLSS and Pressurized Rover ECLSS components. ECLSS hardware is located in the upper dome with oxygen and nitrogen tanks externally mounted on the lower dome exterior as shown in Fig. 28. These tanks are recharged from the Common Habitat's ECLSS through high pressure oxygen and nitrogen supply lines via the MGAAMA. [25] The ECLSS can maintain the TCAN internal atmosphere, provide airlock depressurization and repressurization, and supply oxygen and water to the EVA subsystem for suit consumables recharge.

Fig. 28 TCAN Nitrogen and Oxygen Tanks

The TCAN Power subsystem does not include power generation, instead relying on docked elements to provide power. A 12-kWh battery energy storage system provides a limited contingency capability. Power management and distribution shares common hardware with the Pressurized Rover. The Power subsystem is also located in the TCAN upper dome.

The TCAN thermal subsystem includes a primary and redundant internal thermal control fluid loop that captures waste heat from TCAN subsystems. It also includes primary and redundant thermal transfer loops that link the docking ports, enabling heat transfer to move between the TCAN and other docked elements. A heat exchanger can transfer heat from the internal thermal control loop to the thermal transfer loop.

TCAN avionics include cabin lighting, external lighting, cameras, networked computer systems, and communications. Communications includes wired and wireless network connectivity and an intercom allowing for audio communication over the DSEV network.

The EVA subsystem is somewhat unique in that it is a relocatable subsystem and unlike most of the other subsystems it is not located in the upper dome. The EVA subsystem consists primarily of a relocatable Utility Interface Panel (UIP), Suit Ingress-Egress Bar (SIEB), and Overhead Grab Bar (OGB).

The UIP is designed specifically for the TCAN and includes a blind mate connection to a wall-mounted interface. This interface provides a structural mounting and allows the UIP to connect to power, data, oxygen and water. The UIP performs suit and PLSS consumables charging and can perform suit diagnostics. The UIP can fill suit drink bags directly, eliminating the need to fill them from the galley or a hygiene compartment inside the Common Habitat or Pressurized Rover. It includes a short umbilical to connect it to the suit. Finally, it includes a donning ring that attaches to the suit waist ring, providing the structural support for the suit during donning, doffing, and when the suit is unoccupied.

The SIEB is a spring-loaded, three segment bar that mounts to a receptacle on the UIP and wraps around the suit to the right, terminating in a seat behind the suit rear entry hatch. Springs within the SIEB cause its nominal position to be folded, stowed vertically along the right side of the UIP. A crew member can manually pull the bar down and lock it into place for use. Upon ingressing a suit, the suited crew member will stow the SIEB before closing the suit rear entry hatch and for egressing will deploy the SIEB after opening the rear entry hatch.

The OGB is a load bearing, horizontal bar mounted to the ceiling directly above the suit rear entry hatch. It is used by a crew member to lift him or herself between the SIEB and the suit interior. The OGB can be raised or lowered to accommodate differences in crew member stature and arm length. The UIP, OGB, and SIEB can be installed and removed without the use of tools. A small personal protective equipment (PPE) kit is stowed in the ceiling adjacent to the OGB, containing a protective garment, filtering mask, and eyewear.

The Moon and Mars base camps will require leveling legs to support the weight of the TCAN, position its docking ports at the proper height relative to the Common Habitat, and to compensate for variations in the surface terrain beneath it. These legs attach at the Y-frame intersection of barrel and lower dome of each chamber and have an autonomous self-leveling capability. This allows the base camps to be assembled prior to crew arrival and with minimized ground interaction.

As a microgravity spacecraft, the DSEV will require EVA handrails that are not needed on the base camp variants. Installed prior to launch, these handrails enable translation access to all hatches and lower and upper dome surfaces. If needed, handrails can be removed and replaced by EVA or extra-vehicular robotic (EVR) activity.

Both the base camps and DSEV require some physical structure immediately outside the airlock exit. In the case of the base camps, an access ramp or stairs are needed to access the local surface. A ramp is preferred over stairs because a ramp will better facilitate large equipment transfer or incapacitated crew member rescue. The initial point of departure concept is to use 3D printing technology to print an access ramp with local resources, thus eliminating most of the associated Earth launch mass. This includes guard rails and may include printing structural access points for lifting and transport of the ramp by surface robotic and material handling elements. The ramp must be repositionable even beyond the initial deployment because the base camp can relocate the airlock to other Common Habitat docking ports when warranted, and the external hatch used for EVA can be changed as needed. However, it remains forward work to confirm this point of departure solution. The DSEV needs some form of work platform immediately outside the airlock for the EVA crew to access tools stored permanently in the space environment. This work platform will have to be launched from Earth and is therefore a structure that must be developed and acquired. If a common structure could serve as both a microgravity work platform and surface access ramp a common solution might be employed for all TCANs.

VII.TCAN Operations

A. Crew Lock and Equipment Lock Reconfiguration Process

The two chambers of the TCAN can be referred to as the outer chamber and inner chamber, with the inner chamber being the one that is docked to the Common Habitat. As previously mentioned, either chamber can serve as crew lock or equipment lock. Fig. 29 shows the crew lock on the left and the equipment lock on the right.

The process to reconfigure chambers is described below. At the initial state the outer chamber is the crew lock and the inner chamber is the equipment lock. At the end state the outer chamber is the equipment lock and the inner chamber is the crew lock. This example will assume suits are present in both the crew lock donning rings and the equipment lock under-floor stowage bays.

1. In the inner chamber (equipment lock), detach upper unit of stowage tower 1 from the lower unit.
2. Destack stowage tower 1 and move the upper and lower units out of the way, clearing their former location to receive spacesuit 1.
3. In the outer chamber (crew lock), detach suit 1 from the UIP 1 donning ring and place suit out of the way.
4. Detach UIP 1 from the chamber wall, along with its SIEB and OGB. Move them to the inner chamber (equipment lock) and attach them at the former location of stowage tower 1.
5. Move suit 1 to the inner chamber (equipment lock) and attach to the donning ring of UIP 1.
6. Move stowage tower 1 into the outer chamber (crew lock) and reassemble at the former location for UIP 1.
7. Repeat process to swap the remaining stowage towers, UIPs, and EVA-ready suits.
8. Relocate the four stowed PLSS from the inner chamber (equipment lock) to the ceiling attach points in the outer chamber (crew lock)
9. Swap the under-floor stowed suits from the inner chamber (equipment lock) with the under-floor stowed EVA science and maintenance tools in the outer chamber (crew lock)
10. The process is completed – the inner chamber is now the crew lock and the outer chamber is now the equipment lock.

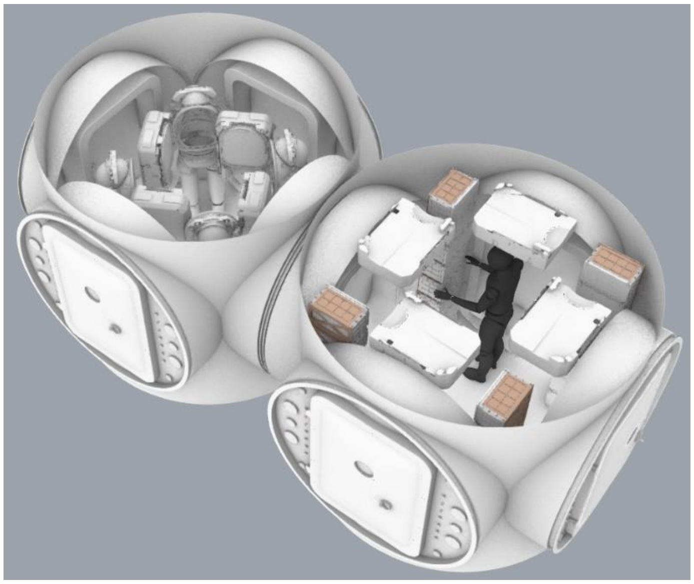

Fig. 29 TCAN Configured as Crew Lock (left) and Equipment Lock (right)

This process is used when transitioning the base camp from nominal to Safe Haven mode. It can also be used as part of the recovery from certain hatch failures, where as part of the recovery the airlock is undocked, rotated 180-degrees, and redocked such that what was the outer chamber is now the inner chamber. When this reconfiguration is performed in a gravity environment, a series of pulleys and cables stowed in the airlock can be anchored to the ceiling to assist in lifting and transporting heavier items.

B. Airlock EVA Egress and Ingress Operations

When EVAs are to be conducted from the TCAN, a modified version of the generic EVA ConOps is performed. [27] The suits are inspected, and any needed resizing is performed. PLSS consumables are recharged if needed. The day before the EVA, if the habitat is operating at 14.7 psi, the EVA crew may ingress the TCAN and seal the equipment lock hatch, isolating the TCAN from the habitat. They may then reduce TCAN pressure to 10.2 or 8.2 psi and spend the night prior to the EVA in the equipment lock, sleeping in deployable hammocks. If protocols dictate, they may also prebreathe pure oxygen in masks to purge nitrogen from their blood. [28]

On EVA day, the EVA crew will seal the hatch connecting the equipment lock to the Common Habitat if not already done the day before. They will then retrieve drink bags from the EVA storage, fill the bags via the UIP, and install them in the suits. Next, they will don liquid cooling ventilation garments (LCVGs), medical sensors, and communications equipment and stow their clothing in the stowage towers. The crew will ingress the crew lock and seal the hatches between the equipment lock and crew lock. In the crew lock, the crew will don their spacesuits and perform the necessary checks, including leak checks and communications checks.

Once the suits are confirmed ready for EVA and approval to depressurize is given, the crew will depressurize the crew lock. When depressurization is complete, the crew will transition from umbilical to PLSS operations and detach the UIP umbilical from their suits. They will then undock from their donning rings and open the crew lock outer hatch that has been designated for EVA. Finally, the crew will egress the airlock and conduct EVA tasks.

At the conclusion of an EVA the crew will perform dust mitigation to the extent possible outside the airlock, then ingress and close the hatch. They will then dock to their donning rings and connect the UIP umbilicals, transitioning from PLSS to umbilical operations. At this point the crew will repressurize the crew lock.

Next, the crew will open the suit rear entry hatches and egress the suits. While perched on the SIEB, the crew will retrieve and don their PPE before completing their egress. Once on the floor of the crew lock, the returning EVA crew will retrieve dust mitigation tools and conduct a deeper cleaning of the spacesuits, as well as the crew lock interior surfaces.

Once the crew lock has been cleaned, the crew will doff their dust mitigation equipment and open the hatch to the equipment lock. They will then retrieve their clothing and doff their LCVGs, medical sensors, and communications equipment. Items that can be returned directly to their stowage locations will be stowed, while those requiring further cleaning or maintenance inside the habitat will be bagged appropriately. Finally, with all airlock tasks complete, the crew will open the hatches from the equipment lock to the Common Habitat and ingress the habitat interior.

VIII.Conclusions

An airlock capability is necessary for either the surface base camp or the DSEV to effectively perform their full range of functions. The TCAN concept complements the functions provided by the Common Habitat, Logistics Modules, and Pressurized Rovers, completing the pressurized infrastructure of a Common Habitat-based architecture.

The TCAN enables visiting vehicles to dock to the base camp, shown in Fig. 30, or DSEV without compromising airlock functionality. Its nodes allow flexibility in determining which ports are available to visiting vehicles. Working in concert with the Pressurized Rovers, the TCAN enables an eight-crew EVA capability where needed, facilitates habitat-based EVA when the rovers are not present, and provides large item airlock operations not possible with rover suitports.

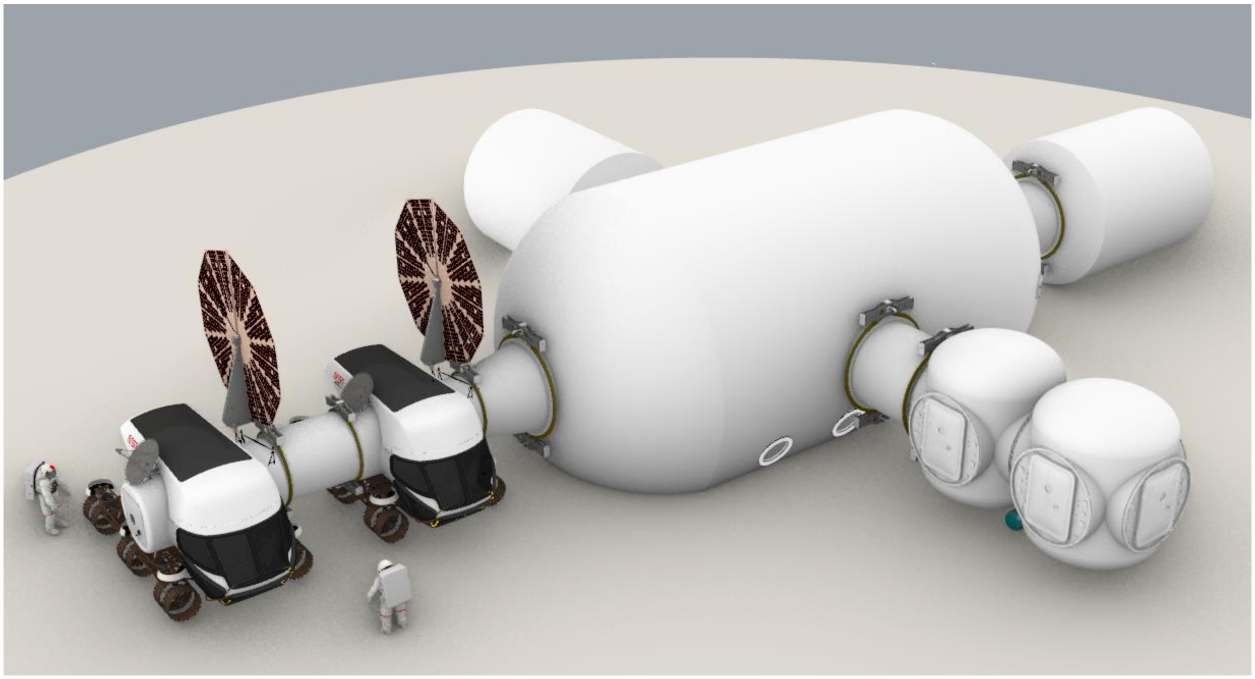

Fig. 30 Surface Base camp with TCAN

Forward work includes three key trade studies needed to resolve several open design issues. A hatch opening trade study is needed to down select options for hatch direction of travel. A hatch cover trade study is needed to resolve the issue of thermal management for hatches across the Common Habitat architecture. A ramp trade study is needed to trade the two competing options of a deployable, prefabricated ramp versus the initial 3D printed ramp concept.

A stowage analysis is also needed to determine the appropriate number and sizes of stowage lockers. These have been notionally assumed to be based on half depth mid deck locker equivalent volumes, but whether these are half, standard, double, or quad height needs to be determined. Also, forward work is needed to design the upper dome suit stowage volumes.

Initial design work is needed to prepare first order designs for the suit maintenance worktable, suit stowage bags, individual suit UIPs, SIEB, OGB, PLSS stowage interface, leveling legs, and EVA handrails. Mass and volume sizing, and layout studies are needed to place TCAN subsystems within the element. Finally, an initial configuration is needed for the node utilities routing concept.

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