Internal Layout of a Lunar Surface Habitat

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NASA is currently developing concepts for sustained crewed missions to the lunar surface. Sustained missions will occur on annual basis for durations of 30 days or more. To house and support the crew, NASA is exploring the use of a lunar Surface Habitat. NASA relies on conceptual spacecraft design to assist in planning and mission analysis. A crucial component of this habitation design is the internal layout: the interior location of systems, workstations, crew quarters, etc.

The purpose of this paper is to describe the process and resulting layout of a specific Surface Habitat design. This paper describes the SH's hybrid inflatable structure then details the habitat's interior layout. The proposed SH's internal layout is depicted inside a hybrid inflatable structure using a low-fidelity CAD model. Multiple NASA references were consulted to determine the SH's required functionality, minimal Net Habitable Volume, and minimal functional dimensions. These functions and volumes contribute to the placement and location of systems and spaces inside the habitat. In addition to functional volume, the layout includes systems and logistics placement. The resulting design will aid NASA in mission planning and further systems analysis.

I. Introduction

NASA is currently developing concepts for sustained crew missions to the lunar surface. A crucial component of these concepts is the need for elements to house and support the crew for durations of 30 days or more. A lunar surface habitat is one option for crew habitation. The Surface Habitat (SH) would support 2 to 4 crew with adequate space for logistics storage, systems, and crew living and work functions. One important aspect of habitation design is the internal layout, where systems, workstations, crew quarters, etc. are placed within the habitat.

The purpose of this paper is to describe the process and resulting layout of a specific SH design. Developing a conceptual internal layout in conjunction with a structural design can lead to greater understanding of the capabilities and constraints of the proposed structure. An internal layout can also be used to determine net habitable volume, validate required functionality, and establish allocations for science and utilization capabilities. Lastly, internal layout designs provide habitability guidance and lessons learned that can be applied to habitat designs under the current or future architectures.

This paper provides NextSTEP companies, future habitation partners, space architecture programs, and other space exploration professionals with insight into the current NASA reference configuration for the internal layout of the Artemis lunar Surface Habitat.

II. Surface Habitat Overview

The Surface Habitat is the core habitation capability for the Artemis Base Camp. As a non-mobile, habitable element, it effectively anchors long-term, human-lead exploration at the South Pole of the Moon. The habitat is self-

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sufficient: it is capable of providing its own communications, power, thermal control, radiation shielding, environmental control, life support, waste management, and science utilization [1]. The Surface Habitat serves as a home base for lunar astronauts, a hub for communications, a science facility, an extravehicular activity (EVA) equipment repair site, a waste processing facility, a supply hub, a surface operations base, and a test bed for sustained surface presence and preparation for Mars missions.

It will be used to test out operations for Mars surface habitation and will offer additional safety to lunar surface crews during simulated operations. The Surface Habitat is required to accommodate a nominal crew of two, with the ability to temporarily accommodate up to four during nominal swap-out periods and safe haven contingency operations of up to seven days [2]. The nominal surface mission is thirty days in duration.

The Surface Habitat houses an environmental control and life support system (ECLSS) with assumed regenerative capability including water processing, urine and condensate processing, CO_2 reduction and recovery, and high pressure oxygen generation for both itself and the Pressurized Rover. It has the capability to operate at atmospheric pressures of 8.2 psi with 34% oxygen concentration and 10.2 psi with 26.5% oxygen.

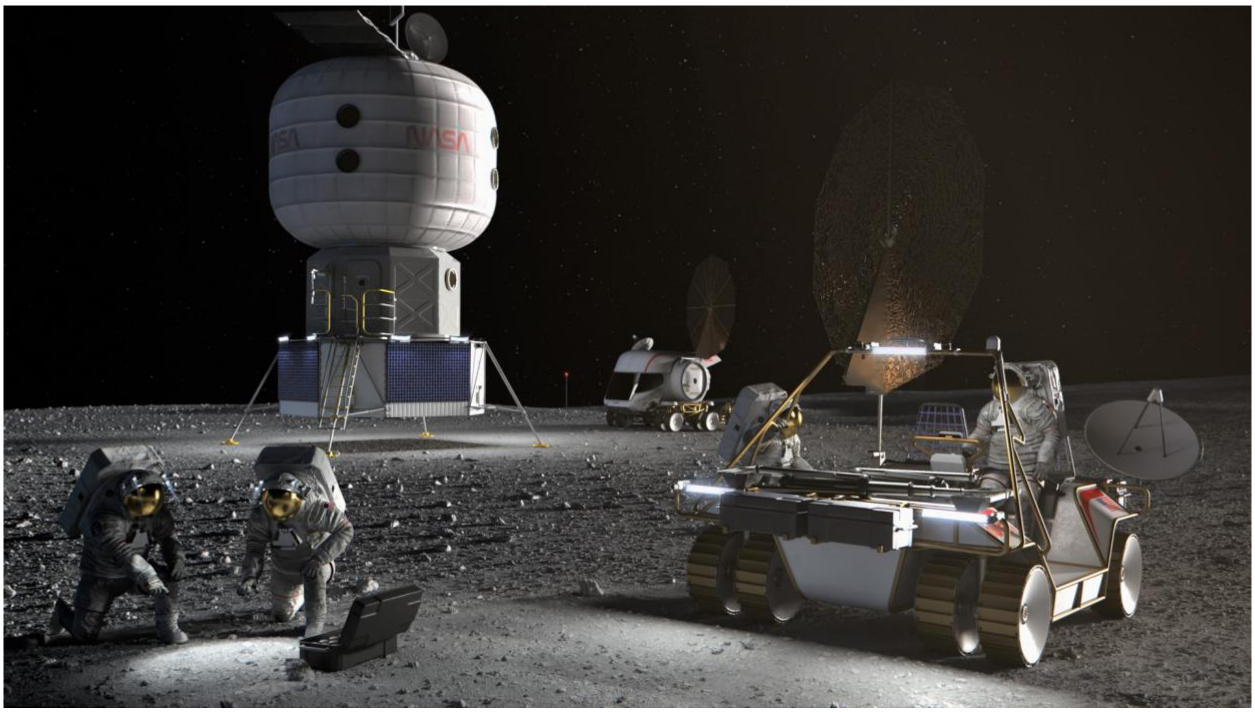

Fig. 1 An artist's concept of the Artemis Base Camp with the three proposed primary mission elements – the Lunar Terrain Vehicle (unpressurized rover), the Pressurized Rover, and the Surface Habitat

The NASA reference design for the Surface Habitat is not the actual vehicle that will be manufactured and launched to the Moon. It is instead a proof of concept, derived from a set of Ground Rules and Assumptions (GR&As), geared toward making NASA a smart buyer and to identify risk reduction activities required. The reference concept can help ensure consistency and sufficiency of the GR&As before requirements are drafted and levied on a commercial partner for the build.

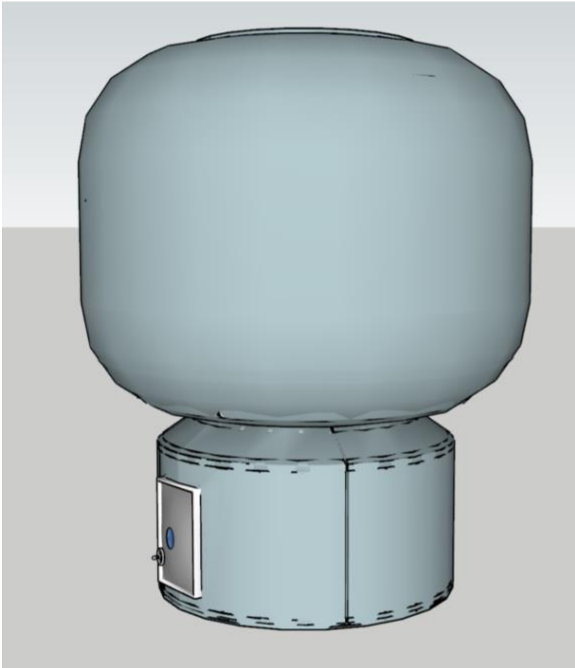

Fig. 2 NASA Reference Design for the Surface Habitat

The NASA Reference design is a hybrid inflatable where the lower deck is an aluminum pressure vessel, and the upper two decks are contained within an inflatable. The inflatable portion of the habitat is approximately 6.5 meters in outer diameter and 5.2 meters in height with an inner core of 3.3 meters in diameter. The metallic portion is 2.6 meters in height and 4.4 meters in diameter. The layout was performed on the fully deployed vehicle given the dimensions above including hatchways, EVA airlock, and core structure used to house systems.

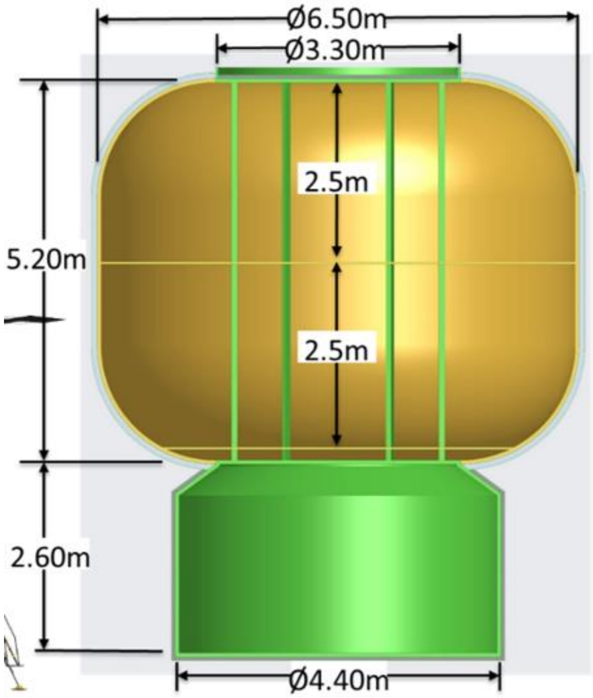

Fig. 3 Surface Habitat Dimensions

III. Surface Habitat Ground Rules and Assumptions Impacting Layout

NASA has developed a set of Ground Rules and Assumptions (GR&As) that can be applied to Surface Habitat concepts. Ground rules are relatively unlikely to change throughout the development process while assumptions are less rigid and either represent constraints that require further assessment or features that are desired. Assumptions are thus more likely to undergo updates as NASA's Moon to Mars architecture is refined [2]. The following sections summarize descriptions of those GR&As in effect at the time of this study that most directly impact Surface Habitat layout. Each GR&A includes a description and rationale.

A. Key Ground Rules Impacting Layout [2]

1. *Crew Size/ Habitable Duration*
   Description: At delivery, the SH will support a crew of two for approximately 30 days. Additionally, in a contingency it will be capable of providing a safe haven for four crew for seven days.
2. *Allowable Mass*
   Description: The SH allowable landed mass will be 12 metric tons.
3. *Habitability Functions*
   Description: The SH will provide the following habitability functions as a minimum: dust mitigation, suit and habitat maintenance provisions, solar particle event (SPE) radiation protection, micrometeoroid and orbital debris (MMOD) protection, exercise, medical, galley, private habitation/sleep areas, private hygiene, private waste management, group socialization and recreation, external direct viewing (at least 1-2 windows), logistics/stowage/inventory management, and subsystems monitoring and commanding. The habitat will provide for meaningful IVA crew work including physical and life sciences. The habitat design will enable crew awareness of surroundings and interaction with the environment and others; provide the means for customization and adaptability to changing resources, mission, and environmental dynamics; promote productive and responsible resource utilization; maximize completion of mission objectives; facilitate purposeful, personal, and social actions and activities; and provide for effective transition, flow, and sequencing of actions. Chapter 8 of the Human Integration Design Handbook (NASA/SP-2010-3407) may be consulted for guidance.
4. *Habitable Volume and Functional Volume Layout Process*
   Description: The SH will be capable of independent spacecraft operation and supporting crew needs with all required spacecraft subsystems, crew support equipment, logistics, and spares appropriate for long-duration missions. A functional volume layout will be performed to verify the volume provided is adequate to accommodate all required equipment, storage, and crew functions.
5. *Logistics Storage*
   Description: The SH will be capable of stowing required Cargo Transfer Bag Equivalents (CTBE) of logistics at the start of a mission. Re-supply logistics will be delivered to the surface of the Moon and must be transferred to the SH.
6. *Ancillary systems and elements*
   Description: Any mass or volume needed for crew access, habitat offloading, and any other ancillary systems or elements needed for the initial crew mission must be manifested with SH delivery.
7. *Supportability*
   Description: SH systems must be reliable and maintainable over approximately 30-day mission without resupply from Earth. Systems must have demonstrated a sufficient level of reliability based on flight heritage and ground testing.

B. Key Assumptions Impacting Layout [2]

1. *Expanded Habitation Considerations*
   Description: NASA is interested in options for expanding the SH to support four crew for approximately 30 days and four crew for approximately 60 days.
2. *Assumed Delivery and Operational Timeline*
   Description: The SH will be delivered within the next decade. The SH will be delivered on either a large cargo lander or a cargo variant of a crewed lander. It is assumed that the lander will provide the avionics and propulsion to deliver the habitat to the surface. Habitat offloading to the surface is not required in the current NASA reference ConOps. Optional habitat offloading equipment is not included in the lander mass.
3. *Crew Operational Periods*
   Description: Assume the crew will be present only during mostly illuminated periods.

4. *EVA Capability*
   Description: The total EVA time per crew will not exceed 24 hours per week. The SH will support a maximum surge rate of one two-person eight-hour EVA in a 24-hour period. The SH will provide egress/ingress capability to enable EVA. The SH will enable EVA suit maintenance.
5. *Utilization*
   Description: The SH will house a minimum of TBD kg of science and utilization payloads. Volume and resources required by these systems are TBD.
6. *Trash and Waste Disposal*
   Description: Surface logistics containers will be used to store trash and waste in a safe state on the lunar surface for TBD years.

IV. Surface Habitat Functionality

The layout's required functionality, minimum Net Habitable Volume, and minimum functional dimensions were derived from an internal NASA study called "Foundational Surface Habitat Net Habitable Volume Recommendations" [3]. This reference guide defines recommended functional capabilities of a Surface Habitat for the lunar surface and lists corresponding habitable volume and area recommendations for each function. The guide also defines three recommended relationships between functional volumes: possible overlaps among functional volumes, suggestions for colocations of functional volumes, and identification of functional volumes that should have physical separation. The approach for defining these functional volumes and overlaps was adapted from NASA's established process for measuring the Net Habitable Volume of a spacecraft, outlined in Net Habitable Volume Verification Method (JSC-63557) [3] and a corresponding study that applies this process to long-duration missions outlined in "Defining the Net Habitable Volume for Long-Duration Exploration Missions" [4].

The study estimated the habitable volume needed for 2 Crew (4 Crew in transfer & contingency situations). Because the Surface Habitat will operate in a low-gravity environment, habitable volume is generally determined by estimating a surface area and multiplying by a standard height to yield a volume. Volumes are defined based on anthropometric data from the 99th percentile male and female bodies and account for additional space based on safety standards. Based on these conditions, the standard height for most functional volumes is 2.4 meters. There are three exceptions: Sleep Accommodation (1 meter), Temporary EVA Items Stowage (1 meter), and Airlock Functions (2.6 meters). Sleep Accommodation necessitates enough height above the sleeping platform for a crewmember to sit up comfortably, this would allow for the possibility of bunkbeds, however individual crew quarters is highly recommended. Temporary EVA Items Stowage represents a volume that can accommodate stowage for items that need to be removed from the airlock when it is depressurized, thus does not require the full height recommended for a standing crewmember. Airlock Functions, on the other hand, include EVA Don/Doff functionality, which is estimated at a height of at least 2.6 meters to give adequate headroom to crewmembers when they're donning and doffing their suits.

The recommended minimum volume and dimensions were applied to the Surface Habitat to ensure that habitable volumes are adequate for each function. For ECLSS hardware, volumes representing the Collins Aerospace ECLSS pallets were used. In addition to the recommended functions, extensive utilization [1] was incorporated to demonstrate potential for full science capability. Table 1 lists the functional volumes that were defined in the NASA reference guide. These volumes outline the foundation for designing the subsequent internal layout.

Table 1 Surface Habitat Functional Categories

Function	Volume (m^3)	Area (m^2)
Crew Habitation		
Access to Personal Stowage	2.60	1.08
Changing Clothes	2.40	1.00
Sleep Accommodation	3.64	1.82
Stretching	3.36	1.40
EVA Support		
Computer Display and Control Interface	2.24	1.12
Suit Component Testing and Repair	3.28	1.37
Temporary EVA Items Stowage	0.25	0.25
Exercise		
Exercise on a Resistive Device	3.60	1.50
Group Socialization and Recreation		
Group Movie Viewing	5.04	2.10
Group Tabletop Games	3.89	1.62
Personal Recreation	3.89	1.62
Human Waste Collection		
Emesis Waste Collection	2.18	0.91
Menses Waste Collection	2.18	0.91
Liquid Waste Collection	2.18	0.91
Solid Waste Collection	2.18	0.91
WMS Maintenance and Repair	2.18	0.91

Function	Volume (m^3)	Area (m^2)
Hygiene		
Appearance Viewing and Body Inspection	2.54	1.06
Facial Cleaning	2. 54	1.06
Fingernail/Toenail Clipping	2.11	0.88
Full Body Cleaning	2.54	1.06
Hair Styling/Grooming	2.54	1.06
Hand Cleaning	2.54	1.06
Oral Hygiene	2.11	0.88
Shaving	2.11	0.88
Skin Care	2.11	0.88
Towel and Clothes Drying	2.11	0.88
Logistics		
Logistics Packing and Inventory Management	3.28	1.37
Maintenance and Repair		
Maintenance Workstation for Equipment Diagnostics	3.28	1.37
System Component and Electronics Repair	3.28	1.37
Meal Preparation		
Food Item Sorting	1.35	0.56
Food Preparation	1.35	0.56

Function	Volume (m^3)	Area (m^2)
Meal Consumption		
Full Crew Dining	3.89	1.62
Medical Operations		
Autonomous Ambulatory Care	2.68	1.12
Basic Medical Care (Space Motion Sickness, First Aid, etc.)	4.49	1.87
Computer Interface for Telemedicine and Data Entry	2.69	1.12
Mission Planning		
Mission Planning Computer Display and Control Interface Access	4.37	1.82
Mission Planning Work Surface Access	3.89	1.62
Team Meetings	4.37	1.82
Spacecraft Monitoring and Commanding		
Computer Interface for Teleoperation & Communication	4.37	1.82
Direct Window Viewing	1.35	0.56
Spacecraft Command and Control Interface	4.37	1.82
Translation Paths		
Crew Translation Paths	---	1.00m wide
Trash Management		
Trash Packing for Disposal	2.73	1.59
Utilization		
Internal Utilization Accommodation	---	---

Most identified functions do not require dedicated volumes or floor areas, allowing several functions to share a common space. Individual spaces can accommodate multiple functions, as long as the execution of those functions are separated in time and are operationally compatible. Potential overlaps were referenced from the internal NASA guidance [3] and used to create combined functional spaces. As indicated in Figure 6 and Figure 7, the size of each combined functional space is listed in terms of area. These areas are based on the standard heights listed above, however, the deck heights in the structural design are, in most cases, greater than the recommended standard heights, resulting in slightly larger volumes than the recommended minimums.

Table 2 Combined Functional Capabilities

Combined Functional Space	Area (m²)	Functional Category	ID*	Function
Stretching x 2 (one per crewmember)	1.40	Crew Habitation	1.1	Access to Personal Stowage
		Crew Habitation	1.4	Stretching
		Crew Habitation	1.2	Changing Clothes
Sleep x 2 (one per crewmember)	1.82	Crew Habitation	1.3	Sleep Accommodation
Medical Care	1.87	Medical Operations	11.1	Autonomous Ambulatory Care
		Medical Operations	11.2	Basic Medical Care
Exercise	1.50	Exercise	3.1	Exercise on a Resistive Device
Hygiene Station	1.06	Hygiene	6.1	Appearance Viewing and Body Inspection
		Hygiene	6.2	Facial Cleaning
		Hygiene	6.3	Fingernail/Toenail Clipping
		Hygiene	6.4	Full Body Cleaning
		Hygiene	6.5	Hair Styling/Grooming
		Hygiene	6.6	Hand Cleaning
		Hygiene	6.7	Oral Hygiene
		Hygiene	6.8	Shaving
		Hygiene	6.9	Skin Care
		Hygiene	6.10	Towel and Clothes Drying
Universal Waste Management System (UWMS)	0.91	Human Waste Collection	5.1	Emesis Waste Collection
		Human Waste Collection	5.2	Menses Waste Collection
		Human Waste Collection	5.3	Liquid Waste Collection
		Human Waste Collection	5.4	Solid Waste Collection
		Human Waste Collection	5.5	WMS Maintenance and Repair

Stretching and sleep combined multiple functions to establish the volume of each crew quarters. It is important to note that the individual minimum areas must be correctly mapped to a gravity environment. The reason for this is that crew sleeping in gravity requires a crew member to lie horizontally, unlike microgravity spacecraft that can minimize volume by sleeping in a vertical orientation. Generally, a crewmember needs slightly under two cubic meters for sleep volume, with a length driven by body stature. This stature length is generally a little less than floor to ceiling height, thus the minimum sleep volume is achieved when sleep is in the vertical orientation, something only possible in microgravity. In microgravity, sleeping and changing clothes – also done in the vertical orientation – can share the same volume, as is done in the ISS crew quarters. But in a gravity environment, the preferred orientation for changing clothes is perpendicular to sleeping. Also, because humans psychologically prefer sleeping on an elevated platform (when in gravity), changing clothes cannot easily overlap with sleeping, but must instead be adjacent to the sleep volume. Consequently, changing clothes and sleeping functions cannot overlap, a minimum volume crew quarters in gravity will generally be larger than a functionally equivalent crew quarters in microgravity.

Medical Care includes both basic medical and autonomous ambulatory care. These functions should be compared against more recent medical guidance. Basic Medical Care and Autonomous Ambulatory Care were derived from descriptions of Medical Level of Care standards in NASA-STD-3001 [4], but the Revision C update [5] to the standard no longer uses this terminology. Instead, new and developing tools such as the Integrated Medical Model (IMM) [5] and the Informing Mission Planning via Analysis of Complex Tradespaces (IMPACT) [6] are now being used to drive minimum medical capabilities.

The Hygiene Station combines numerous hygiene functions. Collectively, these functions enable both whole body and facial hygiene activities. It is important to note that both "wet" and "dry" activities are combined in this same volume, which should be flagged as an important design attribute when developing human-in-the-loop evaluations.

The Universal Waste Management System (UWMS) similarly combines multiple functions related to human waste collection – emesis waste collection, menses waste collection, liquid waste collection, and solid waste collection. Additionally, any maintenance and repair of the UWMS is intended to be conducted within its compartment.

Table 3 Combined Functional Capabilities cont.

Combined Functional Space	Area (m^2)	Functional Category	ID*	Function
Wardroom Table	2.10	Group Socialization and Recreation	4.1	Group Movie Viewing
		Group Socialization and Recreation	4.2	Group Tabletop Games and Creative Recreation
		Group Socialization and Recreation	4.3	Personal Recreation
		Meal Consumption	10.1	Full Crew Dining
		Mission Planning	12.2	Mission Planning Work Surface Access
		Mission Planning	12.3	Team Meetings
		Spacecraft Monitoring and Commanding	13.2	Direct Window Viewing
Work Surface (Maintenance, Logistics, etc.)	1.37	Logistics	7.1	Logistics Packing and Inventory Management
		Maintenance and Repair	8.1	Maintenance Workstation for Equipment Diagnostics
		Maintenance and Repair	8.2	System Component and Electronics Repair
		EVA Support	2.2	Suit Component Testing and Repair
		EVA Support	2.3	Temporary EVA Items Stowage
		Trash Management	15.1	Trash Packing for Disposal
EVA Computer Station	1.82	EVA Support	2.1	EVA Computer Display and Control Interface
General Computer Station	1.82	Mission Planning	12.1	Mission Planning Computer Display and Control Interface
		Spacecraft Monitoring and Commanding	13.1	Computer Interface for Teleoperation, Communication and Tracking
		Spacecraft Monitoring and Commanding	13.3	Spacecraft Command and Control Interface
		Medical Operations	11.3	Computer Interface for Private Telemedicine and Data Entry
Galley-Food Item Sorting	0.57	Meal Preparation	9.1	Food Item Sorting
Galley-Food Prep	0.57	Meal Preparation	9.2	Food Preparation
Utilization	---	Utilization	16.1	Internal Utilization Accommodation
Translation Paths	---	Crew Translation	14.1	Crew Translation Paths
Systems & Storage Access	---	Maintenance and Repair	8.3	Sub-Systems Access

As has been done in many habitat designs, the Wardroom Table is the sole volume for non-private social activity. It is intended to support movie watching, tabletop games, dining, or any non-private personal recreational activity. Recreation is essentially limited to seated activities – there is no option for physical activities such as sports in the Surface Habitat. Physical activity requirements are satisfied by exercise and a high frequency of EVAs. A window is also potentially located near the table, adding both operational and recreational external viewing to the combined functional capabilities associated with the table. In addition, the table is also used for team meetings and as a horizontal work surface for mission planning.

The Work Surface on Level One primarily supports maintenance and repair, specifically equipment diagnostics and electronics repair. It also supports EVA suit component testing and repair and temporary EVA items stowage. When not needed for maintenance or EVA support, it can be used for logistics purposes such as packing and inventory management. It can also be used for packing trash prior to disposal.

The General Computer Station primarily serves the function of spacecraft monitoring and commanding. In addition, mission planning is supported by this computer station in conjunction with the Wardroom Table. Because the General Computer Station is adjacent to the medical area, it also serves as the Medical Operations computer. This necessitates the ability for computing stations to accommodate multiple functions and have the ability to quickly switch between those capabilities in certain cases (e.g. medical emergencies).

The Galley only minimally combines functional capabilities. It has a deployable horizontal surface that provides surface area to support food item sorting. The Galley's primary purpose, of course, is meal preparation, including both rehydration and food warming.

After placing the functional spaces inside of the Surface Habitat structural design, the functional volumes and areas in the final layout were typically greater than the recommended minimum. Table 4 lists both the recommended minimums and the final allotted areas for each combined functional space.

Table 4 Recommended vs. Final Areas in SH Internal Layout

Combined Functional Space	Recommended Min. Area (m^2)	Area in Layout (m^2)
Stretching	1.40	2.68 (1.34/crewmember)
Sleeping	1.82	3.70 (1.85/crewmember)
Medical	1.87	3.43
Exercise	1.5	2.09
UWMS	0.91	1.04
Hygiene	1.06	1.04
Ward Table	1.62	2.23
Work Surface	1.37	1.30
EVA Computer Station	----	0.97
General Computer Station	1.82	2.10
Galley – Work Surface	0.56	0.95
Galley – Meal Prep	0.56	1.17
Utilization	----	5.07
Translation Paths, Ladder Access & Airlock/Suitport Access	-----	8.65
Systems & Storage Access	-----	5.79
Total	14.6	42.63
Total per Crewmember	7.3	21.31
Airlock	5.00	5.18

V. Surface Habitat Structure and Layout

The proposed Surface Habitat's internal layout is depicted inside the hybrid inflatable structure using a low-fidelity CAD model. The habitat enclosure provides approximately 127 m^3 habitable volume. For two crew, this is nearly 64 m^3 of habitable volume per crewmember. The internal layout accommodates all the functions listed in the previously mentioned Net Habitable Volume study and includes added functionality for science and utilization tasks.

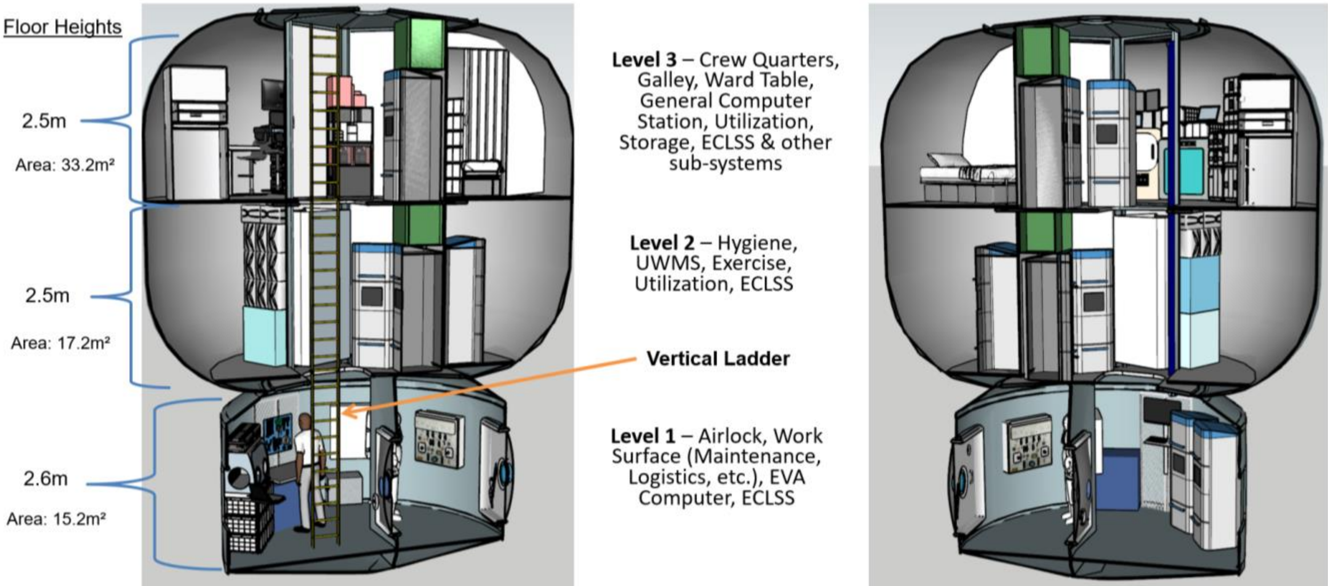

Fig. 4 Surface Habitat – Interior Layout

The Surface Habitat is made up of three separate levels: a metallic base level with an internal Suitport-Airlock and two additional levels in the inflatable portion. Each level is accessed by a ladder that runs through the center of the hab. The habitat layout includes locations for 10 Collins Airspace Universal Pallets dedicated to environmental control systems spread throughout the habitat. The ECLSS is a closed-loop system that provides cabin atmosphere and potable water. Collins Pallets are currently designed with a common pallet structure with a nominal length of 72" and a maximum allowable cross-section of 30.19" so as to translate through a NASA Standard Hatch. [7] Additional system volume is allocated throughout the habitat for sub-systems dedicated to power, avionics, food processing, and thermal. Logistics are stowed on board and stowage is located primarily on the third level in middeck lockers.

The first level is confined within the metallic portion of the habitat. This level contains a work bench with functionality for maintenance, logistics, and trash packaging. It has a Utilization workstation for geology (located on the first level for the possibility of a sample transfer port) and a Computer Station dedicated primarily to extravehicular activity (EVA) Support. There is also access to a Cargo Suitport for pressurized logistics transfer and two Collins Pallets for High Pressure Oxygen Generation Assembly. The other half of the first level is dedicated to a Suitport-Airlock with both an exterior-facing and interior-facing hatch and two suitports. Incorporating the suitports into the airlock enables more rapid EVAs than a traditional airlock. The center of the first level is open volume reserved for access to the Suitport-Airlock as well as for vertical translation to the second level.

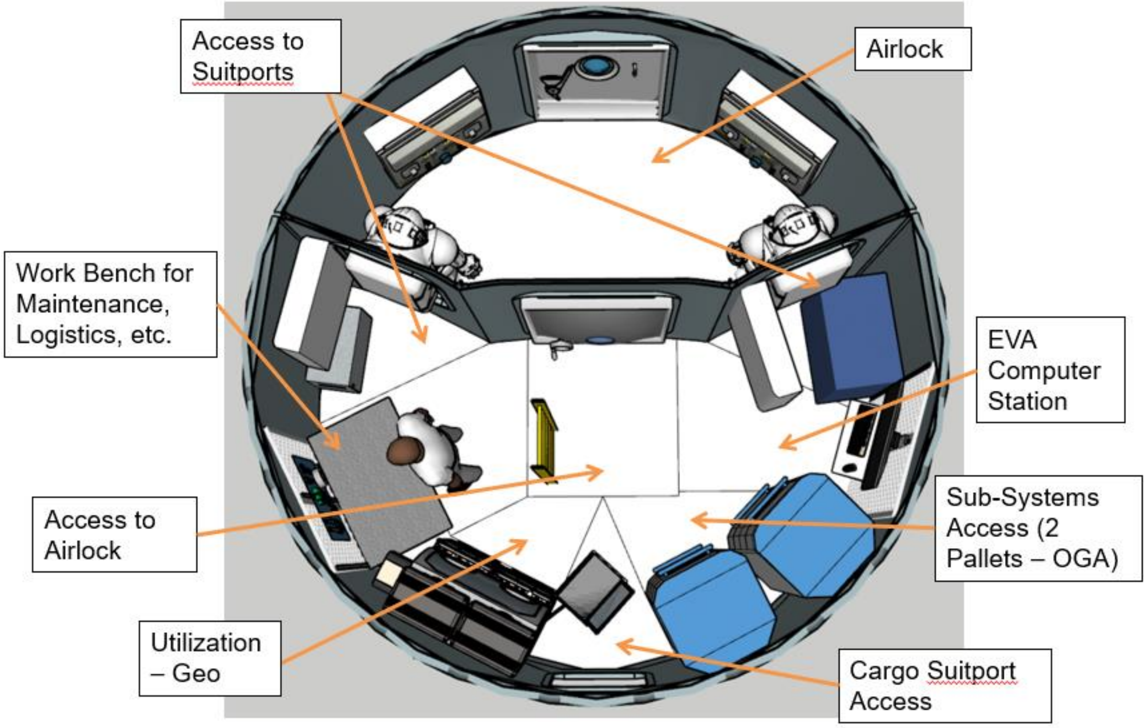

Fig. 5 Surface Habitat First Level

The second level contains a private hygiene station, a Universal Waste Management System in a separate private compartment, and an exercise station with one exercise machine similar to an E4D. There is also a Utilization workstation for Biology. The second level has access to multiple Sub-Systems, including two Collins Pallets for a Urine Processor and Brine Processor and three Collins Pallets for the Water Processor Assembly. Lastly, there is sufficient space to access the water tanks and the crew passageway.

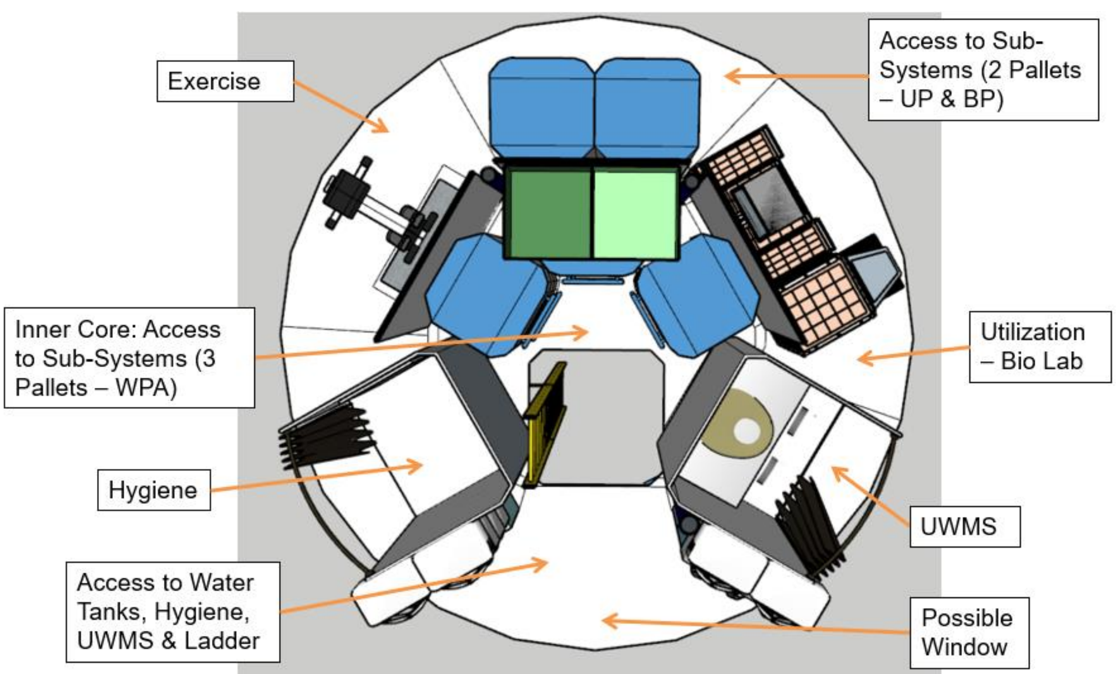

Fig. 6 Surface Habitat Second Level

The third level provides space for two private crew quarters, each with volume for sleeping, stretching, and access to a personal desk. It is not yet determined if this is a seated or standing desk. The exact placement of the desk is also forward work and is not shown in the figure. Storage is located primarily on the third level deck in Middeck Lockers that line the outer perimeter. There is a medical station with a stowable stretcher that can possibly be made private using privacy curtains. However, one of the crew quarters can only be accessed by traversing through the medical station. There is a general computer station for command and control and other functions. A station for food preparation and meal sorting is co-located next to the wardroom table, which can be used for eating, recreation, and team meetings. Three additional Collins Pallets are located in the core for the Air Revitalization System. Lastly, there is space for two more Utilization workstations: a Physics Lab and a Human Research Lab both currently based on ISS systems.

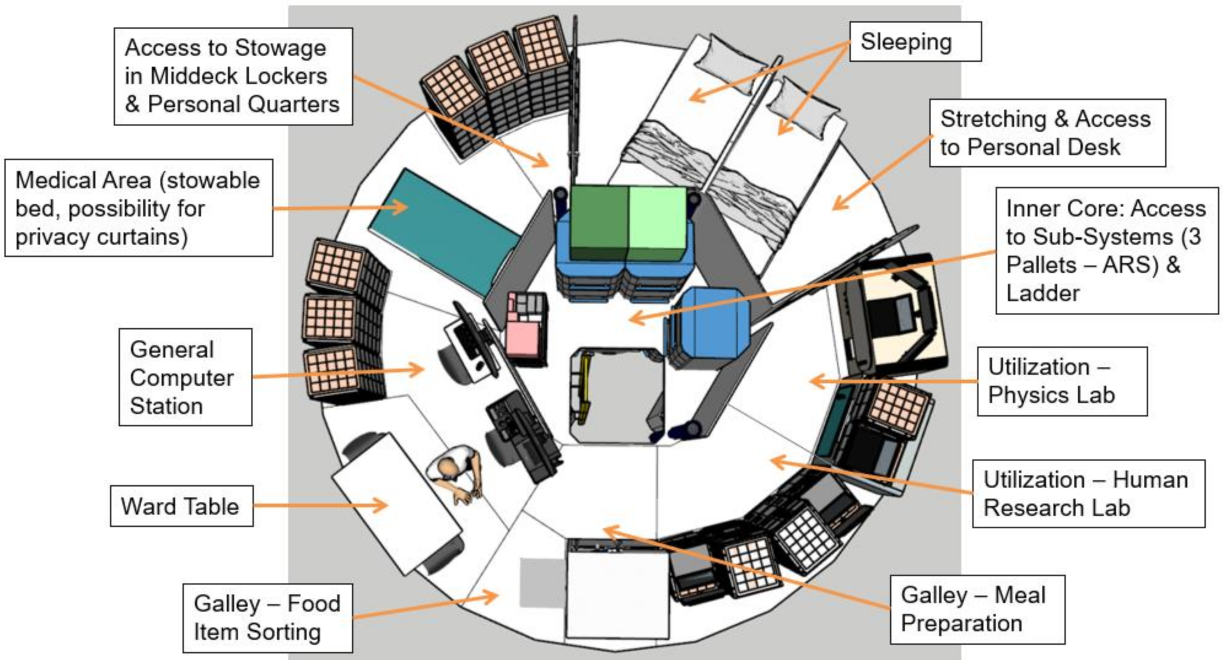

Fig. 7 Surface Habitat Third Level

VI. Functional Changes Related to Mass Constraints

The interior layout meets most of the required functionality that will be expected of a lunar-based habitat. The volume of each functional area was also measured and validated against the recommended functional volumes. Most of these volumes met or exceed the recommended minimums. However, for a habitat to be a viable option, volume and functionality must be considered alongside mass. Mass is a major factor for element decisions. Mass limits may require a deferred delivery of certain interior components and sub-systems.

The Surface Habitat has a ground rule limiting its landed mass to 12 metric tons [2]. This is intended to constrain the mass to within the capacity of the anticipated range of HLS-class landers [2]. Thus, irrespective of the layout indicated in this paper, only 12 tons of capability can be landed in the habitat delivery flight.

The Master Equipment List (MEL), based on the May 2022 update, indicates a predicted mass of 12,517 kg for the Surface Habitat, roughly 517 kg over the mass limit. However, this MEL is not synchronized with the internal layout. It is beyond the scope of this paper to perform mass estimates for each component in the CAD model, but it will be identified where entire functional areas are present in the CAD model but not in the MEL. If an element is present in the CAD model it will be assumed that there is agreement between the mass allocation in the MEL and the actual mass of the modeled components. On Level 1, the Geology Lab, EVA Computer Station, and OGA do not appear in the MEL. On Level 2, the Biology Lab, UP, BP, and WPA does not appear. On Level 3, the Human Research Lab and Physics Lab do not appear.

The labs included in the layout represent ISS systems and are not optimized for lunar surface operations. The masses of each are as follows: Biology Lab - 890 kg, the Human Research Lab - 724 kg, the Physics Lab - 1172 kg, and the Geology Lab - 835 kg. There is also a General-Purpose Station not modeled in the CAD with a mass estimate of 3760 kg. The subsystems not included in the MEL total up to 2234 kg. All of this mass is in excess of the 12.517 metric tons already contained within the Surface Habitat MEL and consequently none of these components can be landed with the Surface Habitat. Additionally, the additional upsizing of the power and thermal systems to support these assets is not included in the MEL.

The first option to meet the control mass limit is to eliminate components and delivered functionality from the Surface Habitat and scar for future outfitting. This would mean that the regenerative ECLSS and science utilization are not included in the habitat at delivery. The subsystems excluded result in an open-loop life support system with the expectation of either accepting the additional logistics resupply mass required or scarring for outfitting regenerative ECLSS on the surface. While open-loop life support provides lower cost and risk to habitation, it does prevent the ability to decrease the logistic resupply mass. It is currently assumed that “Logistics resupply of solid goods and water to the SH is provided through the transport of small logistics carriers through the airlock” [2]. These same carriers can be used on additional missions to deliver science lab instruments, payloads, and consumables. The buildup of the laboratory capabilities over time would therefore become a function of the flight rate(s) of the associated lander(s) delivering these logistics carriers and the available crew time in subsequent expeditions to perform installation and checkout operations.

Another option is to transfer some desired habitation functionality from the Surface Habitat to one or more other surface elements, potentially adding additional elements to the Artemis Base Camp. This could remove significant mass-driving components from the Surface Habitat and allow other elements to focus on those components and their associated functions. This option does, of course, have the complication of acquiring additional elements and landers and it adds complexity to surface operations as crew would now need to move back and forth between the elements. This option was explored by the Johnson Space Center’s innovation team, the Forge, in a rapid turnaround study [4]. The Forge team created two high-level, multi-module concepts: a stationary lab facility docked to the Surface Habitat, shown in Figure 12, and a mobile facility that can traverse the lunar surface, shown in Figure 13.

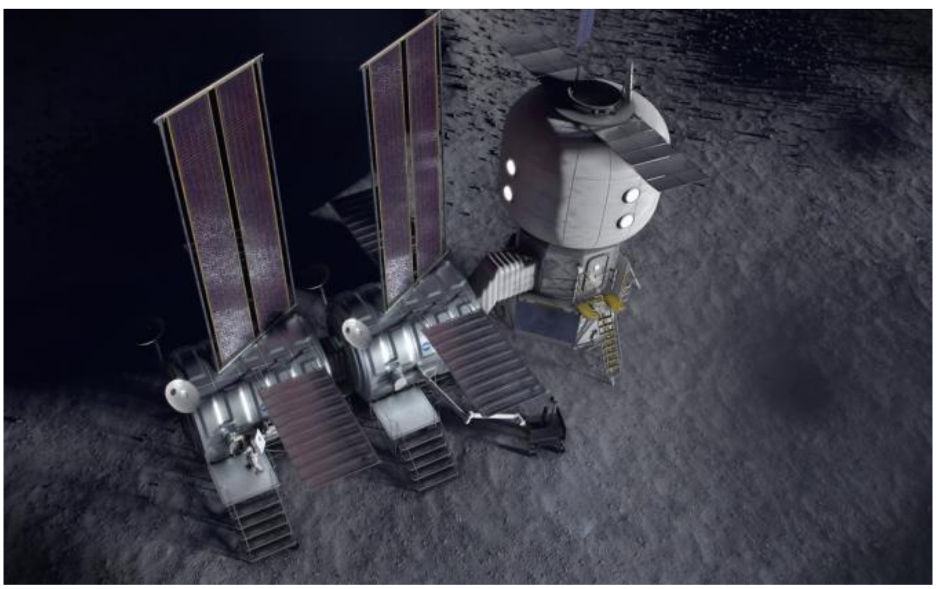

Fig. 8 Forge Study Multi-Module Stationary Lab

Fig. 9 Forge Study Multi-Module Mobile Lab

Besides options that reduce functionality or offload that functionality to other elements, the only other possibility is relaxing constraints on delivery mass. The Surface Habitat is specifically limited to 12 metric tons due to lunar lander constraints. If the habitat mass exceeds the performance envelope of the lander, then it cannot be placed on the surface at all. NASA is currently prioritizing maintaining a competition for lander providers above maximizing Surface Habitat performance, thus the driver is not accommodating all desired habitat functionality. Should the option to use more capable landers emerge, a logical follow-on action would be to increase the control mass allocation to the Surface Habitat.

Options aside from fully outfitting the habitat as assessed in this study would allow greater volume to those functions and would result in potentially more optimal layouts within the same volume. It is also likely that if less functionality is needed within the habitat, its size could be better optimized (reduced) or more modular approaches may be more beneficial. Mass constraints play an important role in determining final layout and should be considered in further iterations of a NASA Reference SH layout.

VII. Results

The NASA Reference Surface Habitat layout demonstrates an accommodation of habitat hardware and crew living and working spaces. This layout is a key initial step towards developing official habitat requirements and identifying paths for additional design and development. The resulting layout has uncovered the need for further analysis in several key areas. To improve the suitability of the Surface Habitat for crew usage continued study should be done on crew quarter expansion and dimensions, separating out additional combined functional spaces, systems and stowage access, and additional volume for utilization and maintenance and repair.

Interest has been repeatedly expressed in expanding the crew quarters to accommodate four crew. Current Artemis plans call for sending four crew to the lunar surface with two living in the Pressurized Rover and two living in the Surface Habitat. However, there are some mission advantages if it is possible to house all four crew in the Surface Habitat. If there is a failure of the Pressurized Rover that requires the crew to abandon the vehicle, there is currently insufficient accommodation in the Surface Habitat for them to reside for more than 7 contingency days. Unless those crew can live in the Human Landing System (HLS) for the remainder of the surface mission the entire crew will need to retreat to HLS and terminate the surface mission early. It would also be more challenging for a future crew to conduct a recovery mission to repair the PR, both from habitation and repair functionality perspectives, if only two can be accommodated in the SH during the surface mission.

There is also some interest in adjusting the dimension and layout of each crew quarters. Currently, the crew quarters have a triangular section at the foot of each bunk that is difficult to use efficiently. It is also preferable from a sound mitigation perspective for two bunks to not share the same wall. And the volume within each crew quarters limits the space available to provide a desk for private work activity.

Due to volume constraints, several functional areas exist that would ideally be separated instead of overlapping within the Surface Habitat. On the first level, the suitports open directly into the maintenance area and the EVA computer station. The maintenance and geology user work volumes also overlap. The geology station and Oxygen Generation Assembly (OGA) pallets overlap with cargo suitport access. The vertical ladder also intrudes into potential maintenance work areas.

On the second level, there is no direct access between the Urine Processor (UP) and Brine Processor (BP) pallets and the three Waste Processor Assembly (WPA) pallets. It is necessary to walk around either hygiene and exercise or around UWMS and biology to reach the UP and BP pallets. Additionally, the center WPA pallet is very tightly wedged in between the other two. It most likely cannot be removed for maintenance without first removing one of the others. The UP & BP pallets cannot be removed for maintenance without first disconnecting and removing all three WPA pallets.

On both the second and third levels, access to the thermal control subsystem is above the WPA and Air Revitalization System (ARS) pallets, making it difficult to physically reach. Also, on both levels, access to the subsystems adjacent to the vertical translation path intersects the path itself, such that there may be a risk of falling down the translation path for any subsystems access work.

On the third level, access to one of the crew quarters is only available by traversing through the medical area. The two crew quarters bunks are directly beside each other, with the only acoustic isolation being that which is available in the wall partition. A substantial amount of habitat stowage is also in medical. Stowage lockers in the Human Research Lab and Physics Lab are so tightly packed that it is not possible to simultaneously open two lockers that are side by side.

While the utilization allocation in the internal layout carries a wide variety of proposed scientific capabilities, there was insufficient volume in the Surface Habitat to include a general-purpose work surface, freezers, and additional stowage [3]. The ability to incorporate these components in the internal layout would have a significant impact on utilization productivity.

The volume allocated for maintenance and repair is limited to a small table and wall-mounted stowage. Additional volume for maintenance and repair tools could increase the number of hardware failures the Surface Habitat can respond to. This ideally should encompass both metal and plastic additive and non-additive manufacturing, thermoplastics, and textiles.

VIII. Forward Work

Several of the aforementioned limitations exist due to architectural, resource, volume, and mass constraints. In order to truly evaluate the feasibility of an internal layout, a combination of further analyses should be considered. These studies can include a tabletop evaluation, a VR evaluation, and/or a human-in-the-loop evaluation.

A tabletop evaluation can be conducted using two-dimensional images of the habitat CAD model. The test subject will view a series of such images that provide a pictorial walk-through of the habitat. An accompanying document with questionnaires will ask the subject to rate the acceptability of workstation design, the expected performance of tasks, and other human interactions with the spacecraft. A tabletop evaluation has as a key advantage its low cost. Tabletop evaluations can be performed without any support personnel beyond that of a CAD modeler to capture screen shots of the CAD model for use in the evaluation. This does come as a tradeoff because this evaluation is most appropriate at an early design stage where the CAD model is limited in detail. Some components may be sufficiently low in fidelity that only engineers intimately familiar with the associated component can recognize what they are. It may be impossible, for instance, for test subjects to differentiate between oxygen tanks, nitrogen tanks, potable water tanks, wastewater tanks, or propellant tanks making it difficult to assess the acceptability of their placement within the spacecraft.

Should funding be available to implement the Surface Habitat in Virtual Reality (VR), a VR evaluation can instead be conducted. A VR evaluation has the advantage that the three-dimensional immersion of the test subject makes it inherently easier for the test subject to perceive the habitat environment more fully. The subject is able to navigate through the interior of the habitat and visualize how a crew member would perform various tasks or take other actions inside an actual spacecraft. Additionally, it is possible to embed explanatory labels, text, or other information that cannot be conveyed in a two-dimensional tabletop evaluation. Questionnaires can also be imbedded inside the virtual environment, with the ability to capture not only multiple-choice responses, but freeform text, audio clips, and even snapshot images. As the use of VR for HITL evaluations grows, new capabilities are often added by human factors researchers.

Lastly, a human-in-the-loop (HITL) evaluation can both identify other areas of improvement that have escaped initial notice and can help prioritize the total set of needed improvements. The act of creating the layout described in this study does not establish whether or not it is acceptable for Artemis crew usage. It does, however, present a habitat that is ready for such an assessment. HITL evaluations are important tools to evaluate the feasibility of a design layout for human use. HITL evaluations should be performed as part of each design cycle as a way to identify areas where design changes are needed, or to measure the impacts of design changes performed in the preceding cycle. Various forms of HITL evaluations can be conducted. Early in the development of a habitable spacecraft, before physical prototypes are constructed, it is appropriate to perform walk-through evaluations. A walk-through evaluation is one where the test subject conducts a visual inspection of the habitat environment but does not operate or use any of the habitat components. This is used when the fidelity of the habitat representation is too low for any aspects of the habitat to be sufficiently functional to utilize. Walk-through evaluations are an efficient use of resources when trading early design concepts because these evaluations help to locate items that require resources that informs the overall design such as cable routing, cooling loops, and mechanical mounting interfaces. The evaluation can be conducted in several different ways, with a tabletop evaluation and virtual reality evaluation representing the extremes of the trade spac

IX. Conclusion

Designing an internal layout highlights important capabilities and constraints of the current structural SH architecture. The layout process can also give more insight into the --- of specific functional spaces and net habitable volume. Lastly, an internal layout, in conjunction with mass estimates, can supply planners with information about how to best meet mass limits. Three-dimensional CAD models go a long way in representing potential layout options, but to truly understand the full capabilities and limitations of an internal layout, further research utilizing multiple methods of analysis must be completed.

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