Habitability Insights from Selected NASA Habitat Mockup Testing Campaigns

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In 2004, President Bush announced his Vision for Space Exploration, causing NASA to look beyond Low Earth Orbit. While the resulting Constellation Program was cancelled, a focus on expanding beyond LEO has continued to this day. Since 2005, multiple habitat concepts have been developed for the Moon, Mars, or deep space. Some of these concepts were mocked up in virtual or physical form and used in habitability testing campaigns. This paper provides an understanding of the value of two decades of habitability testing and highlights key insights obtainable only through human interaction with a vehicle concept design. The focus of this paper will be limited to primarily habitation work conducted primarily at or by the Johnson Space Center in support of active space habitat development programs or studies and is further limited to fixed habitats and will not discuss mobile habitats such as pressurized rovers.

I. Introduction

The Constellation Program triggered the development of new forms of habitability testing within the Johnson Space Center's human factors community that continues to evolve to the present day. NASA has conducted various forms of human factors testing since the dawn of the Agency, but recent testing has attempted to influence vehicle design by assessing, early in the development cycle, the impact of a habitat's design and internal layout on the crew's ability to live and work during the intended space missions.

Much of this work has never been permanently documented and is at risk of being lost to time if not published. A frequent occurrence is for program funding to allocate sufficient dollars to construct mockups and perform the test, but too often funding terminates at this point or shortly thereafter. Internal quick look reports are generally, but not always produced, and where possible more extensive test reports are written. However, these reports are generally Agency internal documents that are only retained by the test team and the program management. If the program or study is cancelled, much of the program data is often lost with only the highest-level reports archived. Retirement or job transfers of human factors test personnel could lead to permanent loss of knowledge.

Numerous insights have been gained through NASA habitability and human factors testing using low and medium fidelity mockups over the past two decades. This paper is intended to archive the most important results of these tests in a publicly accessible medium, making them available to the emerging commercial industries that are developing human spaceflight systems either in partnership with, or independent from, NASA exploration programs.

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II. Scope of Testing Campaigns

The scope of this paper is limited to testing campaigns associated primarily with habitation work conducted at, or by, the Johnson Space Center. The focus is specifically limited to habitat mockups and analog facilities that were constructed and used as prototypes of active or proposed space vehicles. While there are other analog habitats that conduct generic research associated with human performance independent of specific spacecraft architectures, these mockups and analogs were specifically developed and tested to evaluate a spacecraft design that was under active NASA consideration.

It is known that some level of habitat mockup work was conducted at other NASA centers, including Marshall Space Flight Center and Langley Research Center. At Marshall, a mockup of the Skylab II habitat was constructed by Marshall personnel including human factors engineers and members of the Advanced Concepts Office. Marshall also constructed the Exploration Augmentation Module (EAM) in the same facility. At Langley Research Center, an inflatable habitat was developed in the early days of the Constellation Program and a mid-expandable habitat was an additional concept briefly studied.

This paper does not include habitat work not associated with a specific spacecraft and mission. Multiple short and long-duration analog habitats at Johnson Space Center fall into this category. The Human Exploration Research Analog (HERA) transitioned from its role as a mockup of the Deep Space Habitat to the Human Research Program shortly after the end of the Constellation Program and is no longer connected to a specific vehicle design. Similarly, the 20-Foot Vacuum Chamber has been outfitted as a habitat for exploration atmosphere studies but does not reflect a specific space vehicle. (It is being used to validate cabin pressure and oxygen concentrations for lunar surface missions.) Finally, the Crew Health and Performance Exploration Analog (CHAPEA) is a 3D printed habitat intended for one-year missions. It also is not connected to a current design.

III. Generational Loss of Knowledge Within Habitation Teams

The habitability testing triggered by the birth of the Constellation Program was initially faced with the challenge of a generational loss of knowledge within the human factors and habitability team. Further, no process existed at that time to conduct a habitability evaluation and there was no clear feedback loop to iterate designs based on evaluation results.

To date, NASA has only flown two long-duration space habitats – Skylab and the International Space Station (ISS). No members of Johnson Space Center's Center for Design and Space Architecture (known then as the Habitability Design Center) were employees at the time when either habitat was at the conceptual design stage, and in the case of Skylab, most had not even been born. There are few, if any, employees left in the Agency who were present during Skylab's development and while there are still many who were part of the development of ISS, an increasing number have or are beginning to retire.

It is obvious from even a casual read that many lessons learned from Skylab and ISS were embedded in NASA-STD-3000, which has been superseded by NASA-STD-3001. However, many unknowns remain that are not captured in NASA standards.

As an example, NASA-STD-3001 indicates in section 7.9 Sleep, that, "The system shall provide volume, restraint, accommodations, environmental control (e.g., vibration, lighting, noise, and temperature), and degree of privacy for sleep for each crewmember, to support overall crew health and performance." It also states, "For long duration missions (>30 days), individual privacy facilities shall be provided." [1]

This leaves the door open to a great many questions. How is the volume for sleep determined? Is it a coffin-like contour of body dimensions? Should there be room to sit up? Does environmental control mean the crew can adjust the various environmental factors or does it mean that the system controls it to a designed bandwidth that the crew member must accept? What constitutes a degree of privacy?

With respect to privacy facilities, the rationale suggests that privacy facilities are intended to accommodate sleep and social retreat [1] But what constitutes privacy facilities? Is it a curtain or a wall? Is there a dedicated private facility for each crew member or is it something they have to take turns using? Should there be a window? What forms of individual work should be accommodated? What types of personal recreation? What forms of audio or video communication? Is there trash accommodation? Any forms of personal hygiene? Should they provide dedicated radiation protection? How large should a "private facility" be?

Even the duration is unclear. What happens if the mission is greater than 30 days but the time in an individual spacecraft is less? For instance, 5 days in Orion, followed by 4 days on Gateway, followed by 3 days in the Human Landing System (HLS), followed by 12 days in the Pressurized Rover, followed by 2 days in HLS, followed by 4 days on Gateway and another 3 days in Orion – a 33-day mission with less than half that time spent in any one vehicle. Do all four of these spacecraft have to have private facilities or do none of them? Additionally, what should exist for missions less than 30 days? These is some indication from field testing of the pressurized rover prototypes that deployable private quarters were highly valued by the crew in 3-day, 7-day, and 14-day missions. By comparison, the Orion spacecraft is intended for missions up to 21-days but offers no private quarters at all. There is nothing in NASA standards that can inform a spacecraft developer of the impacts of these unanswered questions.

Given the limited guidance in NASA standards, it is not surprising that there are few specific details regarding habitability for many of the exploration concept studies performed during the decades between Apollo and Constellation – LUNOX, First Lunar Outpost, various Mars Design Reference Missions, etc. It further does not appear that any of these studies developed full scale mockups or conducted human-in-the-loop (HITL) evaluations or any other habitability assessments.

It is known from informal conversations with former Apollo engineers and astronauts that mockup evaluations were used extensively during the Apollo program, but limited documentation can be readily found. Only a small collection of Apollo-era evaluation reports was ever located by the team. One interesting evaluation that was located concerned an airlock rather than a habitat.

In a 1966 Honeywell pressurized rover airlock incapacitated crew member evaluation the 1.86 m^3 airlock pressurized volume was too confining and it led to the rescuer crew member tripping over the incapacitated crew member, resulting in the two becoming trapped, wedged halfway in and halfway out of the airlock. [2] In an actual flight scenario, this would have resulted in the deaths of both crew members as there would have been no one to rescue them from their predicament.

Evaluations such as this airlock evaluation are vitally important and provided key lessons learned, but most of the engineers who learned these lessons are no longer employed by NASA or its contractors. The current generation largely is unaware of most of the work that has been done before and in many ways are learning for the first time.

IV. Lunar Habitat Mockups Project

A. Study Origin

The Lunar Habitat Mockups Project was established shortly before the official establishment of the Constellation Program. It was intended to help inform the Agency of needs surrounding surface habitation. The Constellation human lunar missions were expected to undertake far more ambitious activities than those of the Apollo program with the possibility of later missions lasting up to six months or more. Such extended missions would require the use of large-size lunar outposts to accommodate work area for research as well as living space, the actual outpost habitat will need to integrate many areas of science, engineering, technology, and operations. Areas requiring consideration include system environment and architecture, food stowage and preparation, waste management, surface dust handling, and human performance. [3] Therefore, careful consideration needed to be taken as to the layout of such a habitat. For example, in addition to private living and hygiene areas, there also would be a need for a communal galley and exercise space. Since these would be long-duration missions, planning had to be made for medical facilities and for dust mitigation. Separate laboratory areas would be needed for geological and biological studies, as well as facilities for maintenance and habitat operations. The project considered all of these factors in an attempt to evaluate architecture and placement for these areas. This project appears to have conducted the first known evaluation of an entire habitat spacecraft, as opposed to the part-task evaluations of individual workstations that were typical of ISS human factors support.

B. Horizontal Axis Lunar Habitat Mockup (HALHM)

It was acknowledged that the ISS had a Habitation Module that was designed and built but was never launched due to budget cuts. In the early days of the Constellation Program, the Lunar Habitat Mockups Project team asked the question what could we do with this module if we landed it on the Moon as a habitat? To explore the question, another piece of hardware was used. At the Johnson Space Center, a collection of horizontal modules had been used in the former Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex) life support project, each of which were comparable in size to the manufactured but unflown ISS Habitation Module. One of these modules was repurposed to contain a lunar habitat mockup. This was the first known habitat evaluation performed in the Agency. None of the team members were aware of or had participated in habitat evaluations of the International Space Station or Skylab. (Some evaluations of individual ISS elements, such as a crew quarters or a waste containment system, had been conducted, but none of an entire habitable environment.) As such, it paved the way for future habitat evaluations conducted under Constellation, Gateway, and Artemis.

In 2005, the former BIO-Plex module was laid out as a two-deck habitat and devoted considerable attention to comparing different crew quarters designs. Walkthrough evaluations of the habitat mockup were conducted using subject matter experts (SMEs) from a variety of disciplines, with each evaluation organized by subsystem SME disciplines. An evaluation of the wardroom area is shown in Figure 1. A challenge with walkthrough evaluations, particularly with low-fidelity mockups, is it can be difficult to know what is in or out of scope for the evaluation. For instance, does the absence of environmental control and life support system (ECLSS) ducting mean that it was too low fidelity to include and should not be evaluated, or that the mockup designers forgot to account for air flow, indicating likely volume/layout deficiencies?

Fig. 1 Evaluation of the Wardroom Area in the Horizontal Axis Lunar Habitat Mockup

An issue noted with this habitat that reoccurs periodically is adverse effects from the co-location of dissimilar functions. In the case of this habitat, emergency medical care was co-located with exercise. Several evaluators noted that if a medical emergency occurs while a crew member is exercising, the exercise system must be stowed before the medical emergency can be addressed. It is tempting for designers to "be efficient" with volume by co-locating as many systems as feasible. HITL evaluations are critical for discovering how these co-locations can induce unanticipated problems. Additionally, medical appeared to have been sized with regard to storing medical supplies and appeared to lack sufficient volume for actual patient treatment. Evaluators also questioned exercise volumes and the number of crew to simultaneously exercise.

The habitat also revealed a needed shift in design philosophy from the International Space Station or other microgravity spacecraft. Stowage on the ISS relies overwhelmingly on Cargo Transfer Bags (CTBs), which are box-shaped, fabric bags that zip open and closed. In a gravity environment, these are inferior stowage solutions to drawers or cabinets.

Spacecraft design fidelity is also important. Evaluators raised concerns about whether or not the stowage volume was sufficient, but at the point in time when the mockup had been constructed, lunar surface logistics studies had been not conducted and there were no stowage volume targets or requirements. Similarly, there were no established expectations for the food system and evaluators had no target needs for volume, types of functionality, etc.

Evaluators also noted another reoccurring issue in the form of insufficient head clearance for crew exercise. In the case of this habitat, there was insufficient clearance when using the treadmill. Another reoccurring habitat design issue noted by evaluators is0 that there was no place for sweaty or otherwise wet garments.

Discrepancies between the mockup and other emerging elements were also noted. The airlock assumed waist-entry suits similar to those used on the Space Shuttle and ISS. However, the developing Constellation Program was shifting to rear entry suits in order to utilize Small Pressurized Rovers (SPRs) equipped with suitports. The two types of suits have different volume requirements, and the habitat airlock would not have accommodated the rear entry suits in development.

As has been observed in several early concept habitats, entire functional areas were noted as missing or grossly inadequate. Evaluators were unable to identify a toolbox, repair station, or space for developmental testing. Similarly, no location was apparent for intravehicular activity (IVA) monitoring of extravehicular activity (EVA). Evaluators also noted that no volume was allocated for life science and that the process for removing trash from the habitat did not seem to have been thought through. They also noted that there was no indication that attention had been given to power and data comm ports throughout the habitat. Similar concerns were raised for vent locations and caution and warning panels.

Because the HALHM was low fidelity and the evaluation could only be performed as a walkthrough evaluation, many of the evaluator comments were speculative in nature. These opinion-based comments cannot be truly assessed without a higher fidelity analog mission where the crew can physically operate hardware and conduct realistic crew activities. That being said, it did establish that even a walkthrough evaluation of a physical mockup was superior to merely reviewing images of CAD models.

A key comment was observed by evaluators that it was time to "start thinking about habitat as interwoven tasks and stations and activities, rather than distinctly separate tasks and events. Everything here is connected." This represented a shift in human factors thinking from ISS. Due to the modular nature and assembly sequence for ISS, individual crew stations were evaluated as standalone items (e.g., galley, crew quarters, treadmill, etc.) rather than as an integrated habitation system.

Unfortunately, the Lunar Habitat Mockups Project was very limited in funding and was forced to adopt such a fast pace of activity that the project did not fund the analysis and dissemination of test data. The human factors team attempted to compile a test report but was forced to move to other priorities due to lack of resources. Despite the test having been conducted in 2004, this is the first internal or public release of any test data. Nonetheless, the HALHM evaluation triggered a major shift in operations for the JSC human factors community.

While mockups have been used by human factors practitioners to evaluate user interfaces while design are still "on paper", those mockups had up to this point been more limited in scope, ranging from individual controls to an entire control station. To the authors' knowledge, low-fidelity habitat mockups had not been widely used in the field (as attested by the lack of literature). As such, methods to conduct these evaluations were not well established and the experience of evaluating an entire habitat, with multiple systems and associated task areas proved to be more challenging than smaller scoped mockup evaluation. Consequently, the human factors test conductors gained the following insights:

The entire team needs to agree on goals of evaluation – This includes the engineering team as well as the test conductors. While the engineers may be familiar with human factors methodology, the methods for collecting feedback on large scale, low fidelity mockups tend to differ from other, more experimental methods. As such, stakeholder buy-in should be obtained prior to evaluation conduction.

Increase scenario development/explanation – SMEs should be exposed to a more detailed mission definition and "day in the life" scenario. This way test conductors can more explicitly define what is out of scope for system walkthroughs and what should be considered. This more complete scenario should be developed by the entire team (designers, engineering, and test conductors) in order for everyone to be cognizant of design constraints, assumptions, and rationale.

Coordinate walkthrough evaluations as interdisciplinary groups rather than solely by system. This would be especially beneficial during the focus group portion of the evaluation session as some SME groups proposed design solutions (or highlighted design issues) that impacted other SME groups.

C. Vertical Access Lunar Habitat Mockup (VALHM)

A vertical mockup followed immediately after the horizontal habitat evaluation, based on using the large diameter of the Ares V rocket to accommodate a 7.5-meter-diameter habitat with two decks. Shown in Figure 2, the structure appears to be three decks, but the lowermost section notionally represents a descent engine and propellant tanks with only the upper two levels intended as habitable volumes. Work began in 2005 and continued until 2006. Incorporating lessons learned from the horizontal habitat, separate volumes were allocated to biological science, physical science, EVA repair, and maintenance. Unfortunately, the project was defunded as the Constellation Program became further organized, with funding being terminated as soon as the empty shell of the mockup was completed. The mockup shell sat idle until 2008.

Fig. 2 Vertical Axis Lunar Habitat Mockup

However, the human factors team was later able to utilize student interns to outfit the habitat with notional architectural layout, in which a crew habitat was located on the bottom level and laboratory deck on the top. (The actual mockup build placed the habitat on the upper level and laboratory on the lower level due to pre-existing structural constraints.) The mockup consisted of low-fidelity volumetric conceptual displays and controls, stowage lockers, sensor and navigating instruments, controllers, food stowage, waste containment system (WCS), EVA suit equipment, food and utensils, maintenance supplies, and physical/biological gloveboxes.

Functional areas of the mockup were built using cardboard and approximated workstation functional volumes as per architectural designs. These areas provided enough strength to support actual or mockup equipment such as tools and laptops. The habitat (HAB) deck contained crew quarters, a waste containment system (WCS), exercise area, and medical bay. The crew quarters can be seen in Figure 3 and the medical bay in Figure 4. The laboratory (LAB) deck contained the galley, a WCS, biological and physical science station, general maintenance and EVA suit maintenance areas, several of which are visible in Figure 5.

Fig. 3 Cardboard Outfitting in Crew Quarters

Fig. 4 Low Fidelity Medical Bay

Fig. 5 VALHM EVA Suit Repair, Maintenance, and Physical Science Stations

Under funding provided by the Constellation Lunar Surface Systems Project, the human factors team conducted a quick walkthrough evaluation of the VALHM. The objective of this evaluation was to obtain human factors data on the layout of the lunar outpost architectural design. Collaboration between the Habitability Design Center (HDC, since renamed the Center for Design and Space Architecture) and Usability Testing and Analysis Facility (UTAF, since renamed the Human Factors Engineering Laboratory) was engaged in evaluating this design configuration. With the Lunar Surface Systems Project still in the early stages of concept development, it was the optimal time for usability and human factors data to be gathered so that the results could be leveraged for future designs.

Additional equipment used for conducting the evaluation included lipstick and digital video cameras, digital video recorders, multi-format monitors, wireless microphones, and a still digital camera. The video equipment was used primarily to record participant movement within the habitat with cameras being positioned at various locations around the habitat. Lighting inside the mockup was not considered representative of any type of lighting conditions expected to be in a flight vehicle.

The architectural layout was used to stimulate feedback by participants on issues and needed modifications. Divided in eleven crews of four, forty-four participants conducted a "day-in-the-life" lunar task scenario. that included personal tasks such as sleeping or grooming, as well as group tasks like eating and recreation. Each of these tasks was performed in different locations throughout the outpost. Once a sequence of tasks was complete, the participants then rated the acceptability of those areas (Scale 1 = low to 5 = High). Participant ratings and subjective comments were intended to be used to lead to a better understanding of the necessary functional arrangement of the habitat. These results in turn could be leveraged in future architectural designs in order to mitigate the risks associated with ill-conceived human factors models. Test sessions in the habitat took approximately four hours with task questionnaires being used during the test. An architectural sorting task and post-evaluation questionnaires were given to each participant at the end of the test.

Participants rated the overall acceptability of the HAB and LAB of the outpost on a number of features, habitable layout, comfort, and geometric layout as indicated in Figure 6. On average, both the habitat and lab were rated moderately acceptable with the habitat being rated slightly higher. Numerous comments indicated a need for a clear separation of "home" and "work" environments. Additionally, participants wanted a redesign that could release more space for a common area where crew could relax and socialize during off-duty hours.

Descriptive Statistics for Overall Acceptability

	Average	*SD*
Rate the overall *habitable layout* of the LAB deck	3.42	0.70
Rate the overall *habitable layout* of the HAB deck	3.77	0.78
Rate the overall *comfort acceptability* of the LAB deck	3.81	0.76
Rate the overall *comfort acceptability* of the HAB deck	4.05	0.69
Rate the overall *acceptability of the current geometric layout* of the LAB deck	3.53	0.70
Rate the overall *acceptability of the current geometric layout* of the HAB deck	3.86	0.74

Fig. 6 Overall Acceptability of the VALHM

The majority of the participants agreed that the current VALHM configuration was roomy, large, and had sufficient volume for a 180-day mission, shown in Figure 7. For a 500-day Martian mission, participants' comments were varied. Some indicated the current configuration provided a comfortable and efficient living space, while others suggested more volume. Reasons given by participants for increased volume were more privacy and a reduced feeling of confinement that may cause undue stress.

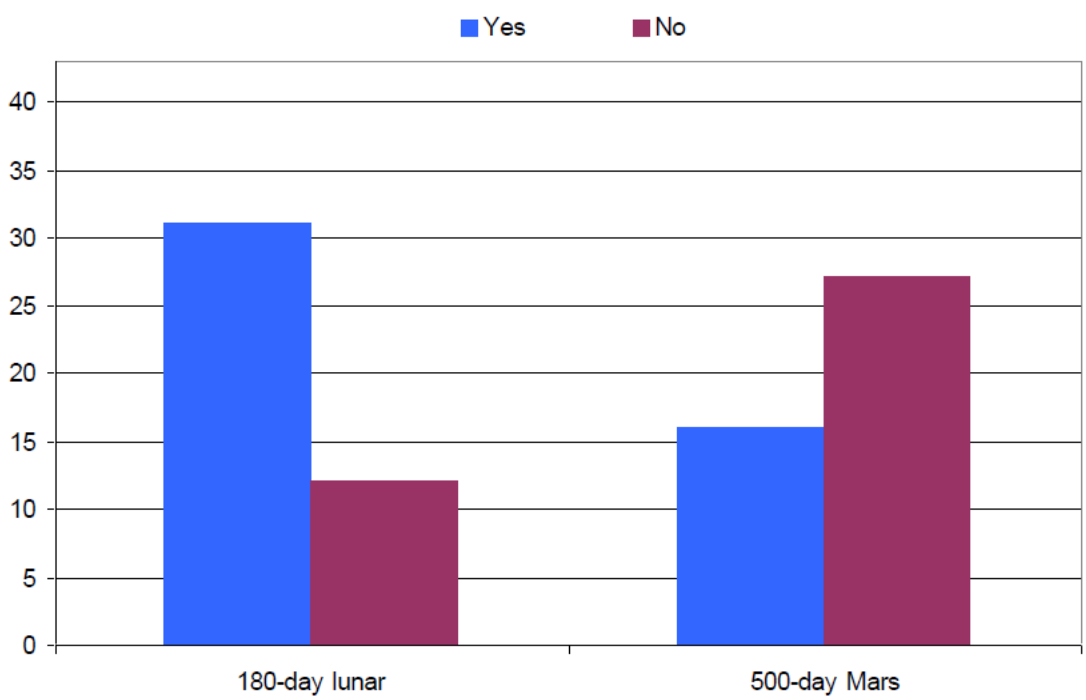

Fig. 7 Persons That Recommend the Configuration for Moon or Mars Missions

Overall, participants indicated that they would accept the functionality of the architectural design for a 180-day lunar mission with recommendations for improvements, many of which are suggested in Figure 8. A major issue was the location of the decks themselves, in which participants would rather have the crew quarters located on the top of the habitat rather than the bottom. Placing crew quarters on the lower level had been a design consideration driven primarily by radiation protection. In addition, this would then allow entry into the outpost directly from the lab level, which would decrease the amount of dust contaminating the crew living areas. Other rearrangements included the relocation and volume reduction of the medical bay from the habitat deck to the laboratory deck with suggestions of combining it with the biological station currently located on the lab deck. (The latter would be contradicted in a future mission operations test with crew overnights.) Reasoning behind this was (a) to place the medical area where hazards were most likely to occur and (b) keep all work-related functions on one deck. In the current evaluation the exercise area was located on the habitat deck. It was suggested this be moved to the laboratory deck to reduce noise impacts to the crew quarters and have the facility close to the relocated medical area for physiological monitoring. The galley and crew meeting area were originally located on the laboratory deck, but participants wanted this located on the habitat deck to reduce dust contamination of food and provide a social area near the living quarters. On the laboratory deck, most of the workstations were judged as having insufficient table surface space, insufficient stowage areas, and insufficient dividers between work areas for dust and noise mitigation. Other comments included suggestions for cleaning, trash management, and better translation methods between decks.

Area of Interest	Move From HAB to LAB	Move From LAB to HAB	HAB Relocate	LAB Relocate	Add Space	Delete Space
Treadmill/Exercise Area	15		2			
Crew Quarters			2			
Medical Station	19		2			
HAB WCS	2		1			
Stairway to LAB			5	1		1
Exit Hatches	10		1	2		
General Stowage				1	6	
Biological Station	1			4		
General Maintenance				2	1	
Geology Station				3		
Flight Station		1		1		
Food Stowage/Refrigerator		15		5		
Stairway to HAB				8		1
Galley Table		13		4		
Galley Counter		12				
Galley Area		17				
Food Stowage Shelf		12				
LAB WCS		3				2
Maintenance Shelf				1		1
Washer/Dryer		21				1
Totals	**47**	**94**	**13**	**32**	**7**	**6**

Fig. 8 Frequency of Comments for Relocating Areas within the VALHM

V. Lunar Lander Preparatory Study

The Lunar Lander Preparatory Study was established in 2006 to help NASA determine possibilities to help scope the emerging lunar lander project that would become the Altair Project Office. It was a large-scale, in-house NASA effort in 2006 to challenge NASA center teams to develop multiple innovative design concepts that fulfilled the human lunar lander requirements of the Constellation Program. The effort consisted of two eight-week phases, from March to May and from June to mid-September. [4]

It may on the surface seem odd that a lunar outpost would emerge from a lunar lander study. However, the Johnson Space Center team had the idea that the capability for long-term human presence could be developed very quickly, and they also wanted to embed the flexibility to build alternate outpost sites, compared to what would be required if deploying an entirely new habitat and infrastructure. The concept also allowed for easy expansion of the outpost's habitable volume and made maximum use of all lander elements. [4] Thus, was born the HabiTank.

The HabiTank, shown in Figure 9, was a lander spacecraft that was converted post-landing into a habitat module, such that four landers were combined to form a surface outpost, as seen in Figure 10 and Figure 11. This is what is sometimes referred to as a "wet tank" conversion, where a rocket propellant tank is used as such, but after the propellant is exhausted and the rocket has reached its destination, the tank is converted into a habitable environment.

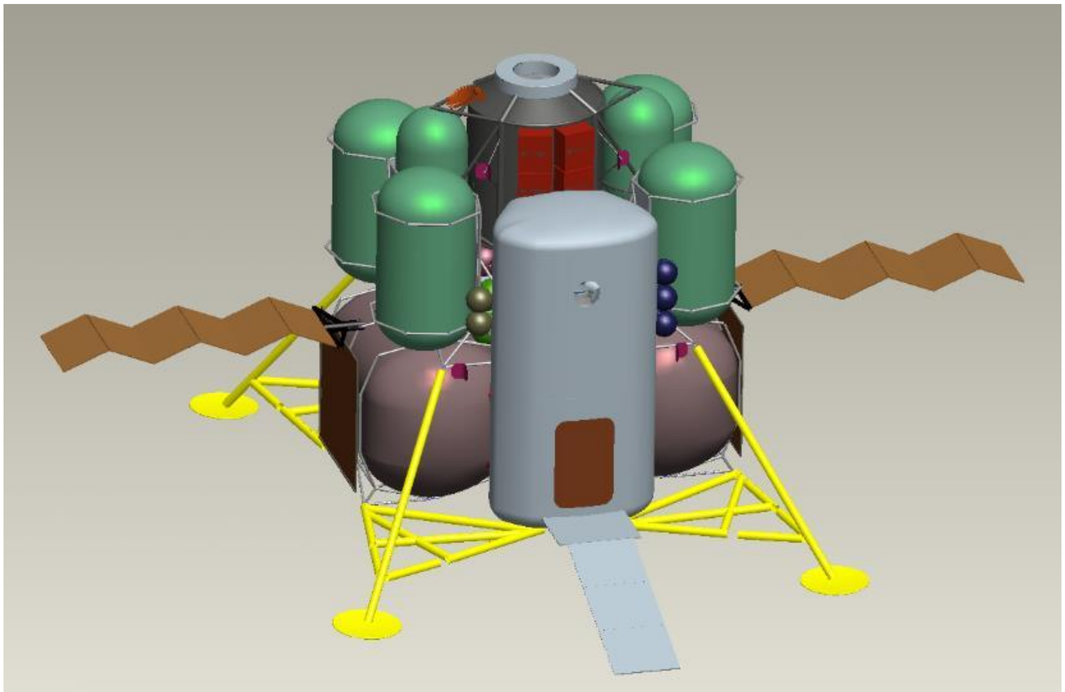

Fig. 9 HabiTank Lander

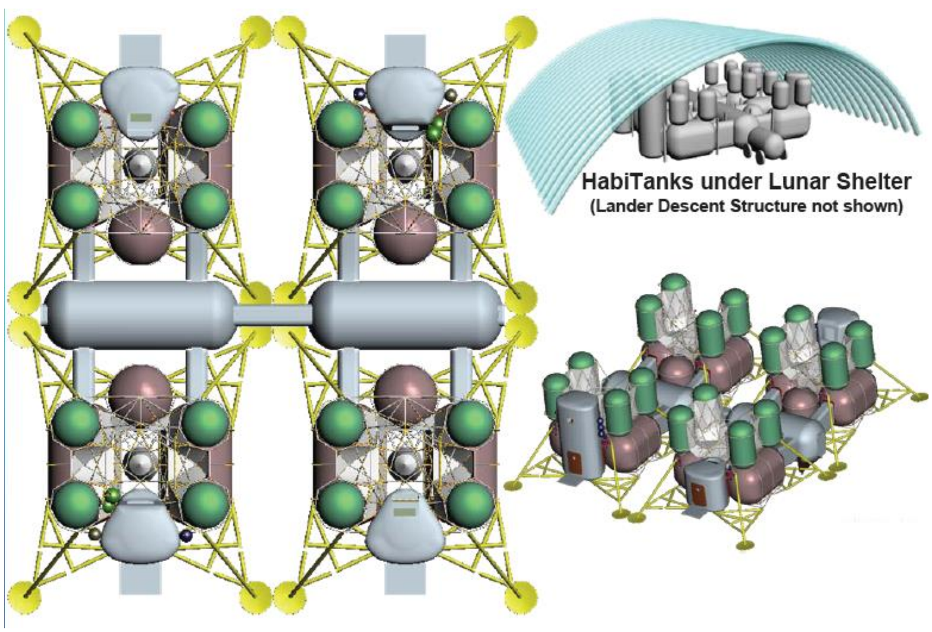

Fig. 10 Lunar Outpost from HabiTank Landers

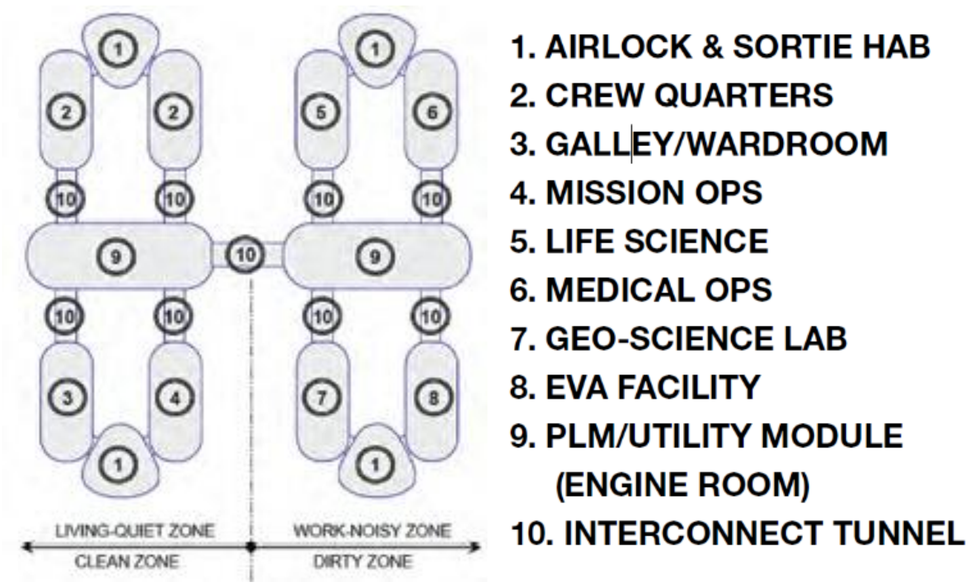

Fig. 11 HabiTank Lunar Outpost Layout

As previously noted, LLPS was a short-duration study. The detailed design work and mockup construction did not occur until Phase 2, which was only eight weeks in duration. This did not allow for the entire HabiTank lunar outpost to be mocked up. A low fidelity mockup of the ascent vehicle cabin was completed, shown in Figure 12, and a pressurized suit test was conducted – primarily an anthropometric analysis of ranges of motion in two different types of spacesuits.

Ascent cabin testing utilized a pressurized Mark III spacesuit and an Advanced Crew Escape Space Suit System (ACES) suit. The smaller ACES suit, shown in Figure 12, experienced no significant issues. The ACES subject was able to easily maneuver from front to back across the engine, conduct umbilical operations, operate flight controls, and translate through the rear hatch.

Fig. 12 Ascent Cabin Mockup (left), Subject in ACES Suit Accesses Ascent Cabin Rock Box Stowage Area (right)

Operations were more difficult for the larger Mark III suit, shown in Figure 13. Collisions between the suit and vehicle structure or equipment was noted when translating from front to back across the engine and when accessing the rock box. The test subject chose to not attempt to translate through the rear hatch. The subject maintained that no issues existed with operation of flight controls even with the addition of a person wearing a mockup Mark III suit. However, this was a low fidelity mockup, and no manipulation of controls were possible. Given the image showing physical contact between the two crew members, it likely would not have been possible to conduct dynamic flight controller operation with the other crew member present, but this level of assessment requires a higher fidelity mockup than was available. Arguably, a motion base platform may also be important to verify minimum volume acceptability.

This is a potentially significant omission in test data as this is an issue that potentially drives the pressure vessel size but could not be conclusively resolved in low fidelity mockup testing. There is an inherent error bar in any testing, but at the low fidelity level, certain impressions could be experienced that may be misleading relative to human performance in an actual flight vehicle.

Fig. 13 Subject in Mark III Suit Evaluates Operation of Controls Next to Person Wearing Mockup Mark III Suit

A partial mockup of one of the propellant tanks had been constructed, shown in Figure 14, in a fast turnaround time of less than three weeks [3], but was not fully outfitted at the point when the Lunar Lander Preparatory Study ended and thus no HITL evaluation was conducted for the propellant tank, which was to have been outfitted as a crew quarters.

Fig. 14 HabiTank Crew Quarters Module (right) Mockups

Soft goods were to have been used extensively in the conversion of the propellant tank to a crew quarters module as a mass and volume saving strategy. Rough sketches of the envisioned outfitting are shown in Figure 15. This form of outfitting has been discussed on many occasions, but no HITL testing had been conducted and thus it remains unclear if the quality of outfitting achievable with fabric solutions has a sufficient level of crew acceptability. Because both "wet tank" and inflatable habitats require in-space outfitting, it is possible that had further development of the HabiTank concept been conducted, the design and evaluation experience gained may have enhanced current industry efforts to develop inflatable habitats.

A complex series of conversion activities is required to transform the propellant tank into a habitable module. [5] Unanswered questions concerning these activities include task durations, number of crew required, installation tools and procedures required, and environmental considerations including lighting. And as was previously mentioned, the acceptability of a soft goods-based outfitting has yet to be determined. It is not clear how crew will process or tolerate the intended fabric structures.

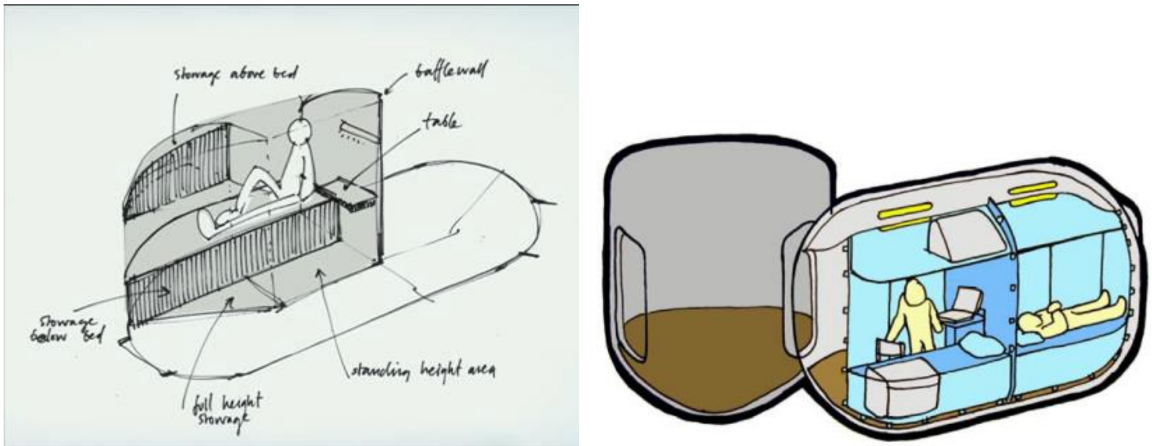

Fig. 15 HabiTank Crew Quarters Concept Sketches

VI. Constellation Program

A. 3 vs 3.5 m diameter Hab

Under the Constellation Lunar Surface Systems Project, several mockups were tested. The first lunar habitat concept considered, shown in Figure 16, was a modular lunar outpost with the outpost assembled by docking a number of habitable modules together, similar to the ISS architecture. [6] It was known that these modules would be a smaller diameter, but it was not clear what diameter should be targeted. This question needed to be answered prior to the development of the Reference Scenario 1 (RS-1) lunar outpost configuration.

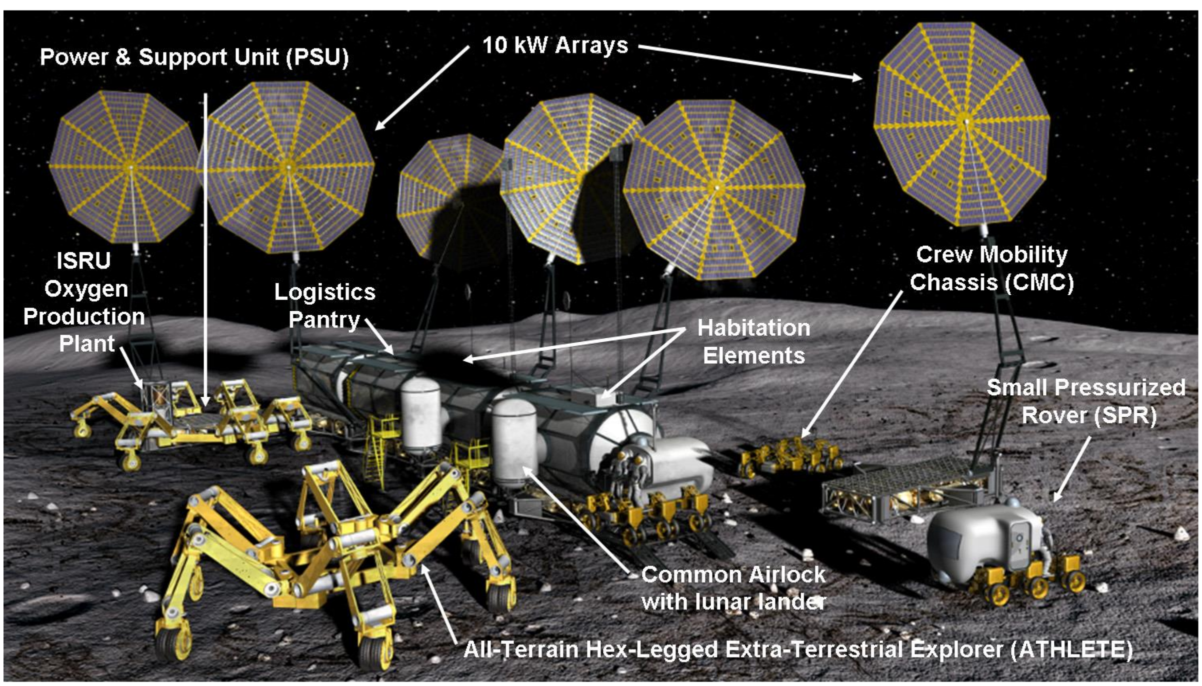

Fig. 16 Constellation Reference Scenario 1 (RS-1) Outpost Configuration

Consequently, a diameter test was conducted using 3-meter and 3.5-meter-diameter low fidelity mockups, pictured in Figure 17. Functional areas of the mockup were built using foam core and represented accurate measurements as per architectural designs

Fig. 17 3.0-meter and 3.5-meter Habitat Mockups

However, only a single module of each diameter was constructed and therefore did not represent all of the functionality needed on the lunar surface. Outfitting was limited to four sleep bunks, clothing storage, a system monitoring station, and waste containment system (WCS), representing a crew quarters module, as shown in Figure 18 and Figure 19. This outfitting provided enough strength to support equipment such as mockup tools and laptops.

Fig. 18 Crew Bunks

Fig. 19 Waste Containment System

The Net Habitable Volume (NHV) was calculated for each mockup. NHV is defined as the total remaining volume available to crew after accounting for the loss of volume due to equipment, stowage, and any other structural inefficiency (nooks and crannies) which decrease functional volume. Given that the mockups represent a lunar outpost (thus in a gravity field), the height of the module interiors impacted the NHV calculations. Because the Moon has a gravity field, all volume in the vertical dimension cannot be considered habitable. For purposes of this evaluation, volume above a height of 90.4”/229.62 cm (or the maximum reachable height of the 99^{th} percentile male) was treated as non-habitable volume.

Sixteen participants were divided into crews of four to conduct a “day-in-the-life task” scenario that included personal tasks such as sleeping, grooming, daily planning and reporting, telecom with Mission Control and family/friends, and emergency situations. Each of these tasks was performed in different locations about the module. Once a sequence of tasks was complete, the participants then rated the acceptability of those areas. Test sessions in each module took approximately two hours with task questionnaires being used during the test. An architectural sorting task and post-evaluation questionnaires were given to each participant at the end of the test, the results of which are compiled in Figure 20 and Figure 21.

Participants rated the 3.5m module as more acceptable than the 3.0 m in 8 out of 9 crew quarter tasks, 6 out of 7 waste containment (bathroom) tasks, 9 out of 13 operations tasks, and 4 out of 5 medical tasks when functionality was considered. However, very few of these were statistically significant. In an overall functional assessment of the four areas, the 3.5 m module was judged more acceptable than the 3.0 m, but only the crew quarters and bathroom area comparisons were statistically significant. The 3.5 m module was also perceived to be more habitable and comfortable than the 3.0. Finally, when asked if they would recommend the module diameter for a 180-day lunar mission, participants were almost evenly split as to whether or not they would recommend the 3.0 m module; however, 14 out of 16 participants recommended the 3.5 m when asked the same question. Nevertheless, other factors should be taken into consideration such as coupling to other modules, actual mission length, and mental/physical well-being of the crew before a final decision is determined.

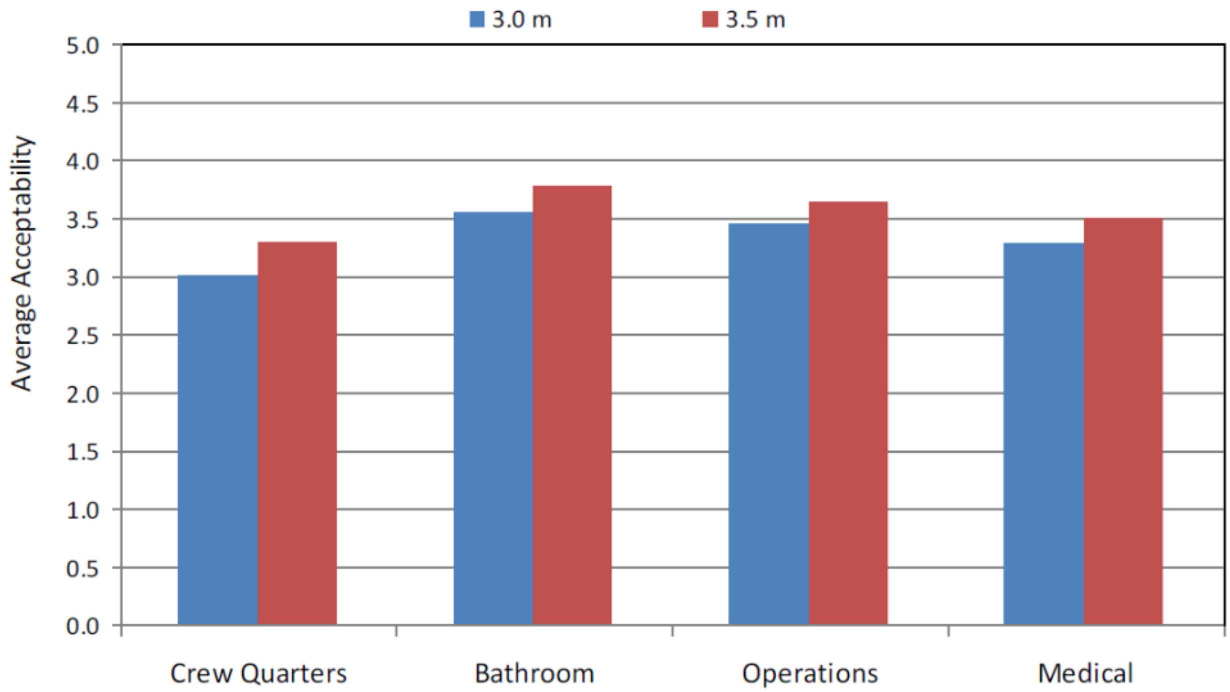

Fig. 20 Acceptability Ratings for all Functional Areas Averaged Over Tasks

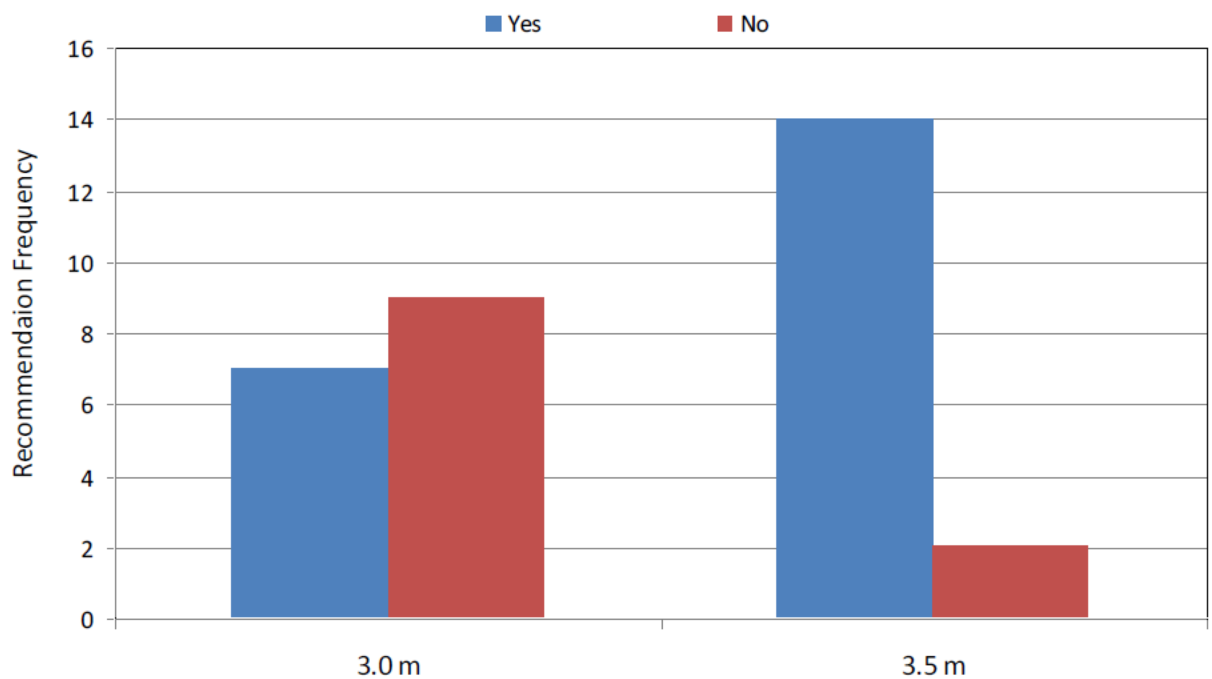

Fig. 21 Recommend Module for 180-Day Lunar Mission

Additional results of this evaluation included a redesign of the bunk layout in both modules would allow for more comfort, privacy, workspace, and stowage; and a reconfiguration to eliminate the all-in-one bathroom area. Future assessments of the displays and controls in the operations area is recommended with increased fidelity.

A key insight gained by the human factors team is that the mockup must match the goals of the evaluation. As previously stated, the intent of the evaluation was to help the Lunar Surface Systems Project decide between 3.0 and

3.5-meter module diameters. While the RS-1 Outpost shown in Figure 22 did initially utilize a diameter of 3.5 meters [6], the volume associated with the majority of the workstations and crew stations in the outpost were never evaluated, only those associated with the sleep bunks, clothing storage, systems monitoring station, and waste containment system . Thus, there was never any conclusive evidence that the 3.5-meter decision was any better or worse than 3.0 meters for the majority of the integrated outpost.

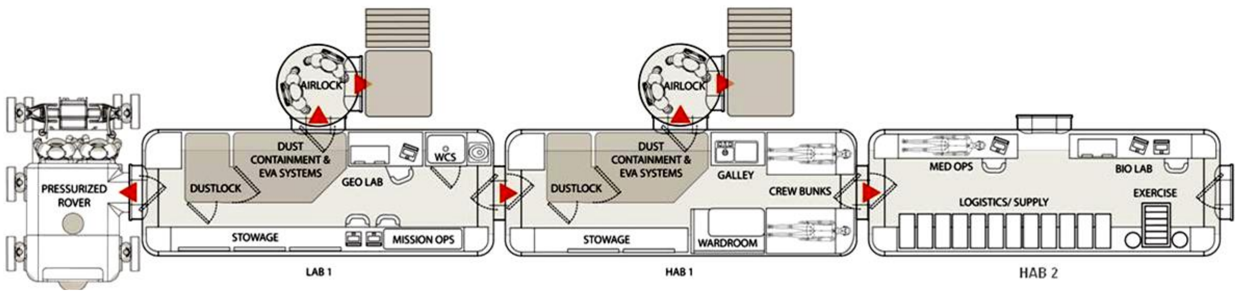

Fig. 22 RS-1 Outpost Hard-Shell Habitation Connection Topology

Shortly after the development of RS-1, Lunar Surface Systems Project revised surface outpost concepts with the RS-2 and RS-3 configurations shown in Figure 23 and Figure 24, both of which used a diameter of 3.0 meters. [6] The 3.0-meter diameter became the de facto standard for Constellation-era horizontally oriented habitat modules for the remainder of the program's life, despite only a small subset of outpost habitability ever having been tested. It remains unknown if any aspects of the RS-2 / RS-3 habitats would have experienced any limitations due to the 3.0-meter-diameter that would not have been present in the RS-1 habitats.

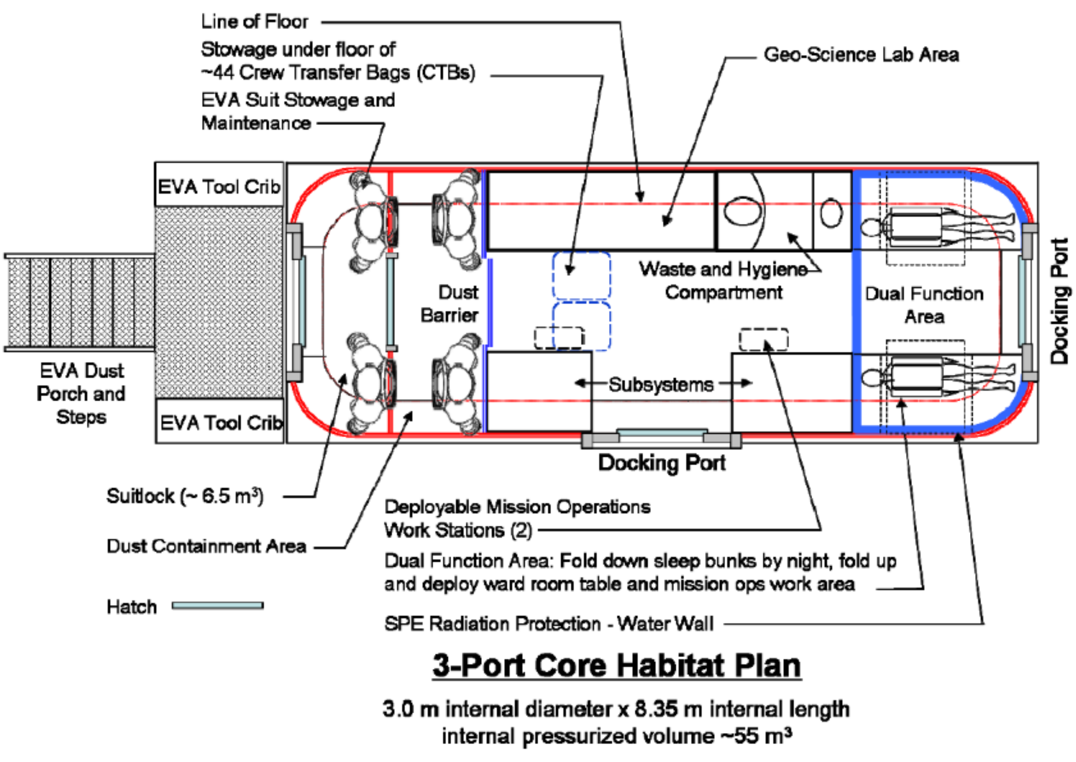

Fig. 23 RS-2 and RS-3 Core Habitat Plan

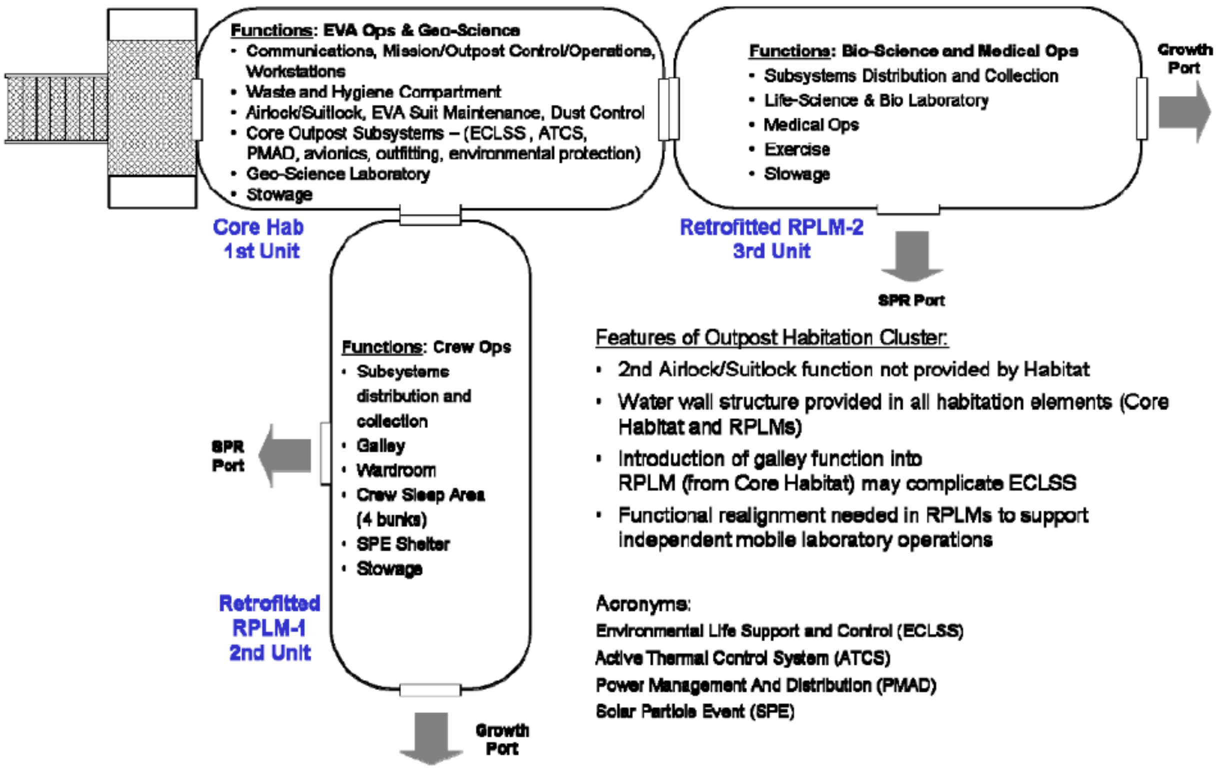

Fig. 24 RS-2 and RS-3 Outpost Complete Habitation Functions

B. Wet Bath

The second mockup test was a part task test of waste and hygiene functions, driven in part by test subject responses in the 3 vs. 3.5 m habitat test. This “Wet Bath” test examined whether full body hygiene could be co-located with waste management as had been done in both the 3 m and 3.5 m crew quarters module mockups.

Several designs were conceptualized based on analysis of analog systems such as (a) spacecraft waste and hygiene systems, (b) terrestrial wet-bath systems, and (c) characterization of desired wet bath attributes. A meeting with subject matter experts narrowed down the design parameters. A minimum volume and shape assessment of humans performing wet bath tasks generated an initial body motion envelope and internal volume dimensions

Five different concepts, shown in Figure 25, were then developed based on this information, each consisting of a toilet, sink, stowage (toilet paper, tissues, wipes, cleaning agents), mirror, personal hygiene kit attachment points, and a vent fan.

Each of the five designs was created so that various aspects of the wet bath were more prominent than others. For example, concept E was low on internal stowage, but high on internal usable volume, while concept D was high on internal stowage, but low on internal usable volume. Doing so, allowed the participants to rate the stowage and usable volume based on comparison. In addition, some of the concepts allowed for limited maintenance access based on their interior design. Thus, ratings for maintenance access were collected. One feature that was not incorporated was the external doors. Participants were told where the doors would be located and asked not to extend outside the interior wet-bath volume. The decision not to include external doors was based on the ability to view and communicate with the participants during the evaluation.

Fig. 25 Wet-Bath Concepts

Ten waste and hygiene subject matter experts (SMEs) from various facilities at JSC (e.g., the crew office, ECLSS system engineers, etc.) participated in the evaluation (3 males and 7 females). Each participant was asked to step into the mockup and enact a typical bathroom task, such as shaving, grooming, or maintenance, and rate that task according to the volume afforded. These tasks are indicated in Figure 26.

Task	Definition
Shaving	Simulated use of razor and shaving accessories
Grooming	Trimming, and combing or brushing hair
Oral Hygiene	Simulated use of toothbrush and toothpaste
Hand/Face Wash	Washing using the sink area
Shower	Simulated activities for cleaning body
Drying Off	Using a towel to dry off after shower
Changing Clothes	Ability to change clothes in wet bath
Maintenance Access	Ability to reach and perform maintenance
WCS Activities	Simulated toilet activities
Cleaning from Shower	Hand drying the wet bath area
Stowage Activities	Examining stowage of wet/dry towels and clothing, and hygiene items

Fig. 26 Wet Bath Task List

Volume adequacy ratings in Figure 27 were derived from the Cooper-Harper Handling Qualities Scale. The participant follows a flowchart to obtain a rating based on the answers to a series of questions. As shown, there was a greater frequency of desirable ratings for concept C versus the other four concepts. In fact, all of the ratings for concept C fell into the desirable range on the VAS and is the only concept for which this is the case.

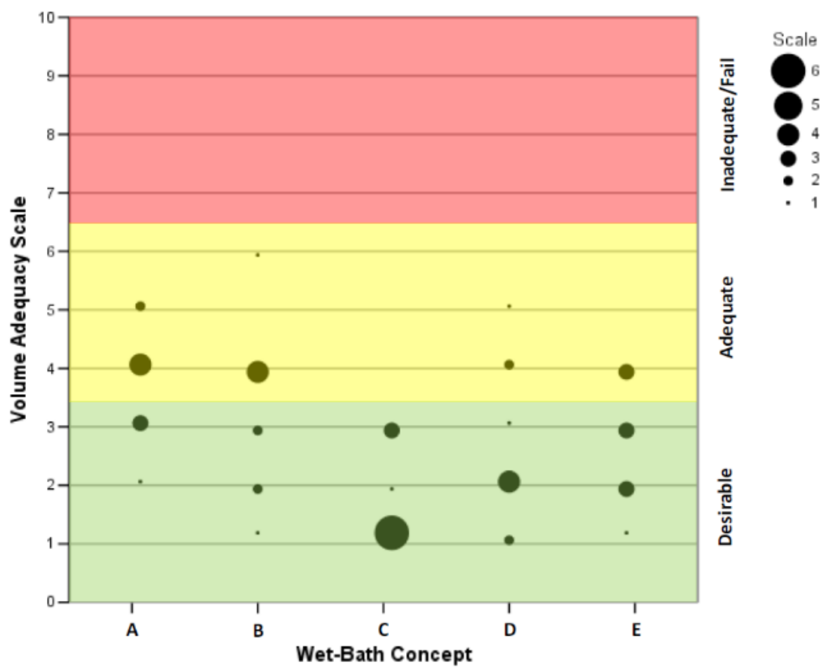

Fig. 27 Volume Adequacy Scale Ratings for the Five Wet-Bath Concepts

Once all tasks were completed, participants were asked to rate the concept just tested in terms of their ability to maneuver within the volume provided. The scale in Figure 28 was developed to assess a participants' effort to move in any direction, at a desired pace, ranging from "little to no effort" to "severely limited." Once again, concept C was rated the most maneuverable of all the concepts evaluated. Concepts D and E followed a close second, revealing the indecision on part of the participants to chose between stowage (concept D) and useable volume (concepts C and E).

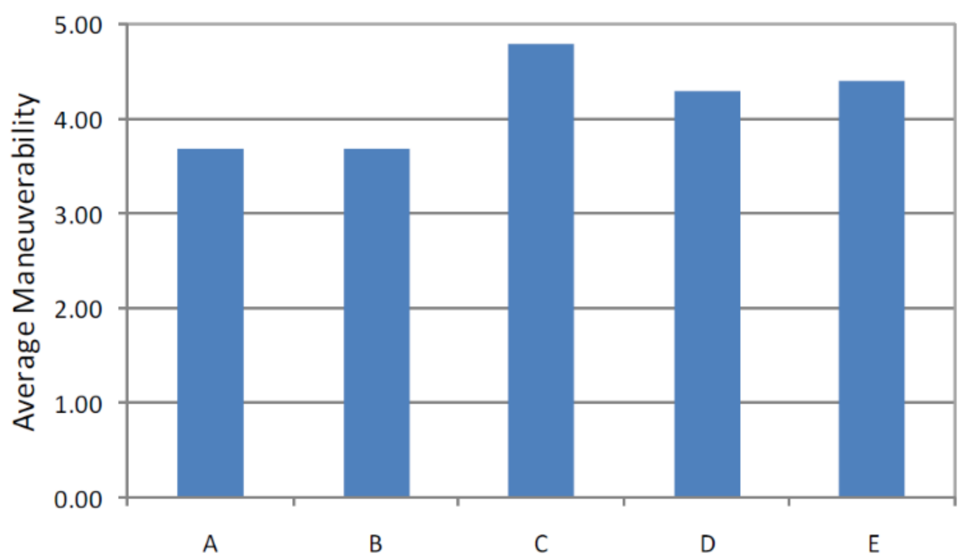

Fig. 28 Maneuverability Assessment Scale Ratings

Once all the concepts were evaluated, the participants were asked to rank them in terms of preference from best to worst. As shown in Figure 29, concept C had the greatest frequency of high rankings. Even though, concept D and E were rated high with stowage and usable volume, respectively, they were ranked worse than any of the other concepts. Based on participant comments, the same characteristics that caused them to be rated high, also caused them to be ranked low. With concept D, participants did not like sacrificing usable volume for more stowage – especially, when needed items could be easily bagged and brought into the wet bath. For concept E, participants did not like all the "wasted" volume afforded by less stowage. Participants felt that the increased volume was "luxurious" and not needed to perform the necessary activities.

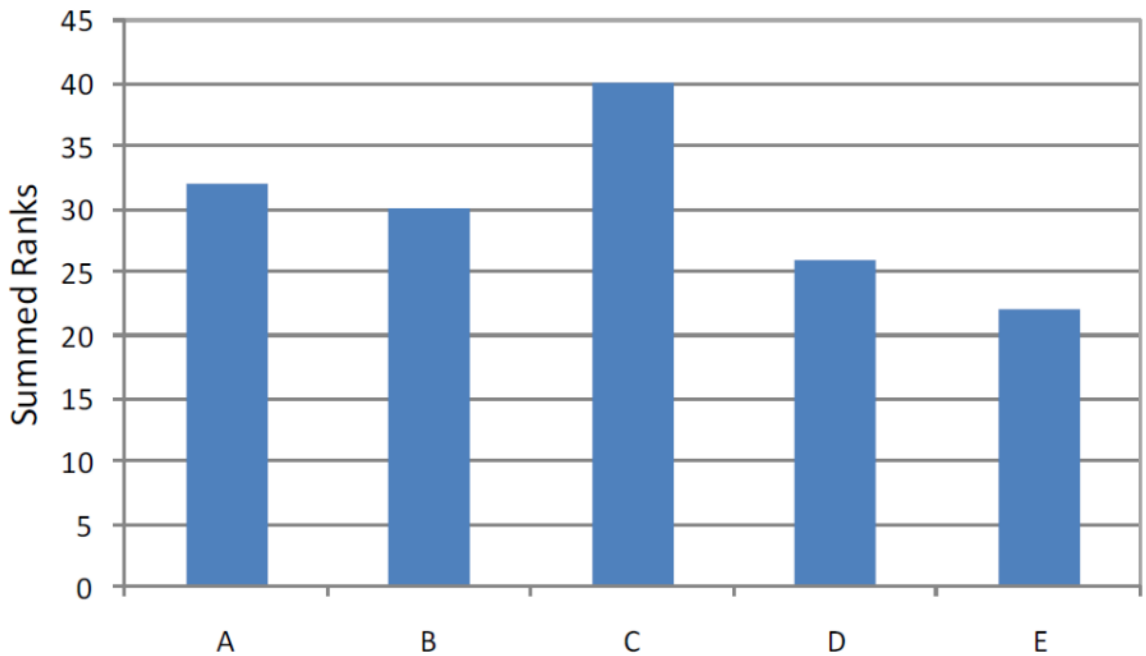

Fig. 29 Summed Ranking of Wet Bath Concepts

A net habitable volume (NHV) was calculated for each wet-bath concept. Net Habitable Volume is defined as the total remaining volume available to the crew after accounting for the loss of volume due to equipment, stowage, and any other structural inefficiencies (nooks and crannies) that decrease the overall functional volume. The NHV for each of the concepts are listed in Figure 30. Concept A, while having a high overall NHV, consists of two separate NHV values – one for the toilet area and one for the sink/shower area. Concepts C and E had the highest and most similar NHV values. Concept B had the lowest NHV.

Net Habitable Volume for each Concept

Concept	NHV (m^3)
A	1.70*
B	1.28
C	1.75
D	1.46
E	1.76

* Shower/sink half = 0.906; toilet half = 0.791.

Fig. 30 Wet Bath Concepts Net Habitable Volumes

An important note is that a correlation analysis found no significant relationship between the averaged task ratings and NHV. However, there were significant correlations found between the averaged ratings and scores of the VAS.

As task ratings became more positive, the volume was found to be more desirable, and less effort was needed to maneuver. While the relationship between the rating and scores on the VAS and the MAS seem logical, the more important result is that there was no relationship found with NHV and the averaged ratings, as well as scores on the VAS and MAS. This highlights the fact that the overall NHV cannot be used as a sole determiner of whether a volume is sufficient or not, but that the configuration of that volume and how it relates to the functional task is most important.

At the end of the evaluation, participants were asked if they would accept a wet-bath concept or not, and if not, would they prefer the compartments to be separated as (a) toilet separate from shower and sink, (b) shower separate from toilet and sink, or (c) all three separate. Overall, participants were split on the wet bath as a viable habitat concept in general, half the participants disliked it and half liked it. Of those that did not like it, most wanted the shower separate from the toilet and sink as found with terrestrial bathrooms. Some participants voiced concerns about germ migration between the toilet and other parts of the wet bath given their close proximity to one another.

Overall, a concept in which an equal attention was placed on stowage and usable space was preferred. Referred to as concept C in the test plan, this volume was rated high amongst the five concepts with most activities. An overall rating of the wet bath was calculated by averaging all task ratings for volume acceptability, in which, concept C was rated among the highest. In addition, concept C also had the greatest number high rankings, as well as more positive scores in terms of volume adequacy and maneuverability.

In terms of design, participants suggested that with concept C the toilet should be rotated 90° to where the front is facing the sink, rather than the outside wall. This redesign, illustrated in Figure 31, would allow for more foot-space and elbow room, while sitting on the WCS, and would increase the distance between the toilet and sink, which was desirable. In addition, by rotating the toilet, there could possibly be enough space to add a curtain between the shower/sink area and the WCS. This would help mitigate the amount of water to clean-up after showering within the compartment

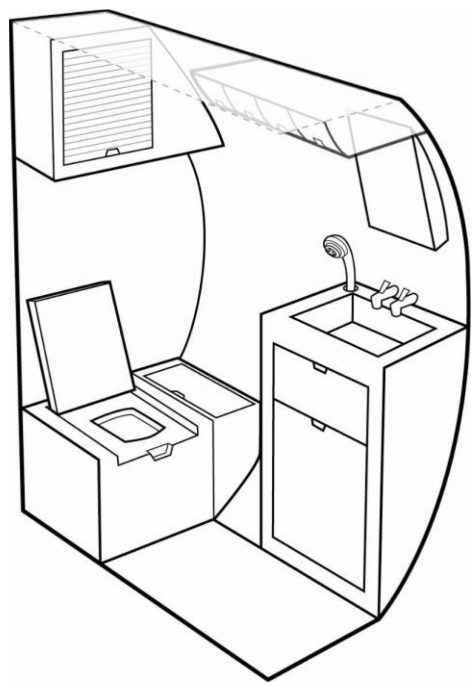

Fig. 31 Suggested Wet Bath Redesign

While these results suggest that a particular concept for a wet-bath could be chosen and was viable, participants were split as to whether they would accept an all-in-one-concept at all. Major concerns were the co-location of the shower/sink area and toilet. The toilet is a potentially dirty area, and the sink should always be clean.

C. Habitat Demonstration Unit

The final mockup constructed and evaluated under Constellation was the Habitat Demonstration Unit (HDU). This mockup was used in multiple habitat evaluations between 2010 and 2012, simulating different human spaceflight architectures. The Habitat Demonstration Unit (HDU) Project was conceived in the spring of 2009 as a means to develop medium-fidelity, functional habitat modules via a rapid-prototyping process for the purpose of supporting planetary surface and deep space analog testing scenarios. It was envisioned that these habitat modules could be used to assess not only habitability aspects of future space exploration habitats but operational aspects as well. [7]

1. 2010 Field Test

The HDU first participated in the 2010 Desert Research and Testing Studies (Desert RATS or DRATS) analog mission. The test environment for the Desert RATS analog missions was the Black Point Lava Flow test site; approximately 65.4-kilometer (km) (40 miles) north of Flagstaff, Arizona. This test site has a wide variety of geologically relevant surface features that present many opportunities to evaluate human performance with both the Intravehicular Activities (IVA) and Extravehicular Activities (EVA) science/exploration capabilities of both habitats and rovers. Surface characteristics included slopes with an approximate 6° of vertical from top to bottom, soil mechanics ranging from lose grain to hard-packed, surface properties ranging from flat/smooth to rocky, and some minimal vegetation.

The 2010 field test as conducted as an analog mission of an excerpt of Lunar Surface Scenario 12.1 informally known as the “Lunabago” Mode, shown in Figure 32. In this scenario, the multi-module lunar surface outpost includes a separable module called the Pressurized Excursion Module (PEM). This module and an attached external airlock are undocked from the outpost and carried by an All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE). It, along with two pressurized rovers, can depart the base camp and traverse away from the outpost for up to 30 days, conducting remote exploration. [8]

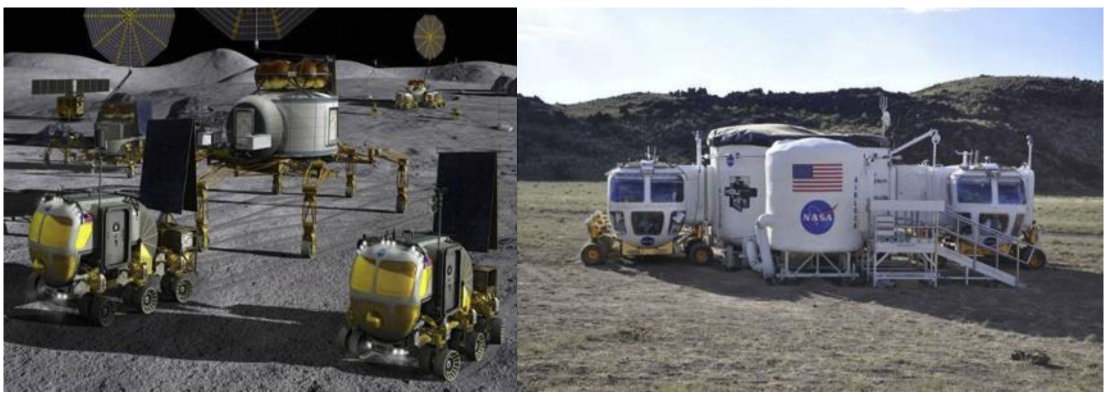

Fig. 32 Lunar Scenario 12.1 with PEM in Lunabago Mode Along with Two Rovers (left); Field Test Showing Both Rover Prototypes Docked to the HDU/PEM on Mission Day 6 (right)

This approach was intended to augment the mobility capabilities of the rover with the laboratory capabilities of the habitat. In this scenario, planners account for a crew of four living and working in the habitat for 14-days with two rovers and one PEM. It assumes the outpost already exists with the PEM being reconfigured into the excursion mode and the crew living in the rovers. Planners also assume the crew starts the mission from the PEM. However, during this field trial, the crew started as if they are already into a mission. On the 7th and 14th day, the two rover crews switched out via the PEM and resupply both rovers as well as bring samples to the habitat. [8]

The HDU was mocked up to represent the PEM at the 2010 DRATS, shown in the Arizona desert in Figure 33. As shown in Figure 34, the PEM includes only laboratory facilities and has no crew habitation facilities. In Lunabago mode, all crew habitation occurs within the rovers and the PEM provides laboratory, medical. The PEM has a diameter of 5 meters and a total height of 3.3 meters, with 2.0 meters constituting the height of the barrel section.

Fig. 33 HDU at the 2010 Desert RATS

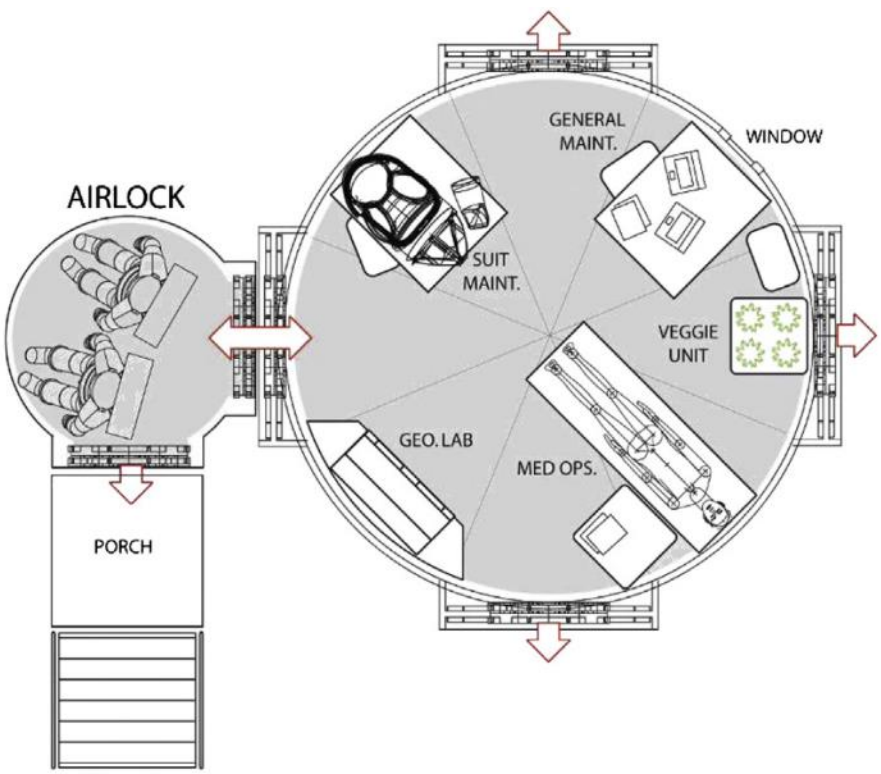

Fig. 34 Airlock and Pressurized Excursion Module

NASA Human factors engineers recorded approximately 96 hours of crew task performance with two different operations (vehicle setup and resupply) and four workstations (medical, general maintenance, suit maintenance, and geology lab science) while in the field by using standard human factors measures collecting data on volume acceptability, workload, and 89 functional design elements. Figure 35 shows the crew performing tasks inside the PEM.

Fig. 35 DRATS Crew Performing Workstation Tasks Inside the PEM

Results in Figure 36 and Figure 37 indicate the habitat's individual workstation volume was constrained when setting up the vehicle for operation, medical operations, and suit maintenance. General maintenance, logistical resupply, and geology science were considered acceptable. Overall, the vehicle's volume was considered acceptable by the crew for both a 14 and 30-day mission.

Crew workload for each station indicated resupply as being the lowest workload, with medical operations, general maintenance, and geology science tasks as light, while suit maintenance was considered moderate and general vehicle setup was rated the highest. Table surfaces among the workstation were reported by the crews as acceptable. For improvement, crew suggested table height adjustability and small containers for bolts and fasteners. Stowage was an issue around the PEM with the Space Exploration Vehicle (SEV) resupply stowage located in the center of the habitat as interfering with some workstation volumes and activities. Suggestions for redesign of other workstation stowage included hanging common tools on the wall, using small containers, and good labeling. Ergonomics of the geology science station was considered a major issue, especially with the overhead touch screens. The 2010 DRATS was the first analog mission simulation of dual rover resupply operations and it went well, with the crew using the horizontal surfaces inside the habitat as workspace for unpacking and repacking crew and rover supplies. Hatch size was rated as good, with the crew stating smaller hatches would hamper resupply operations; however, procedures for resupply need a vast improvement.

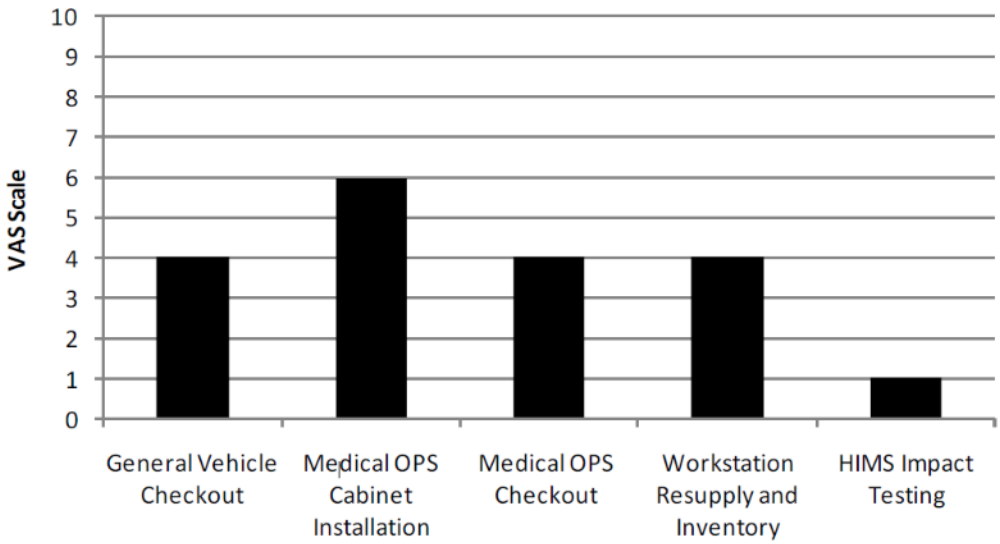

Fig. 36 VAS Scores by Task for General Habitation

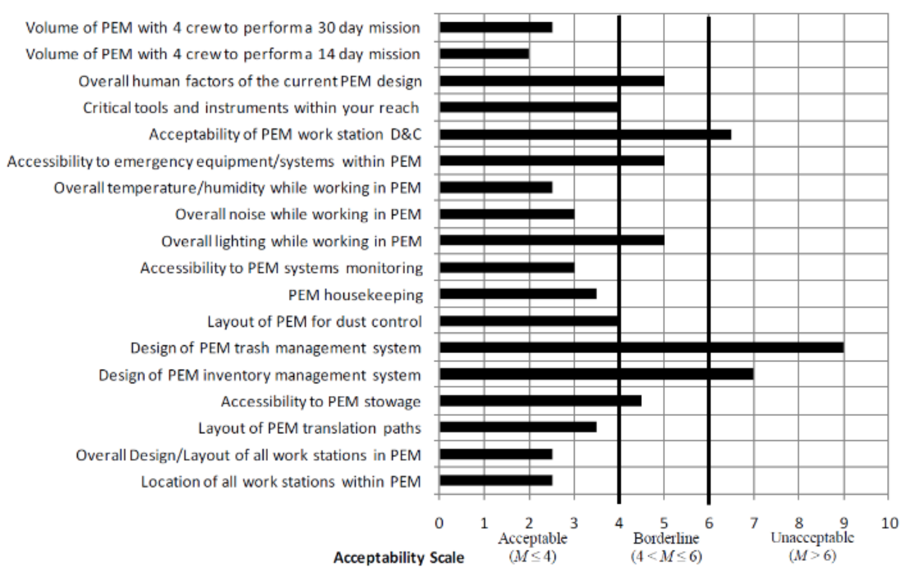

Fig. 37 PEM Acceptability Scale Ratings

Based on the human factors data collected, the following conclusions and recommendations can be drawn:

General Vehicle Assembly and Habitation

- The PEM trash management needs to be redesigned according to the crews' unacceptable rating.
- The PEM inventory management needs to be redesigned before returning to field trials.
- Workload for assembling the PEM was considered borderline.
- The current overall volume of the PEM was considered acceptable for a 14 t30-day mission by the crews.
- Overall lighting and accessibility to emergency equipment needs some improvement.

Medical Operations Workstation

- Crew members failed to deploy the surgical table when issuing care ta patient. This could be a training issue and further study will be needed.
- Horizontal work surface was adequate; however, there needs to be a specific work surface for staging medical supplies and instruments which are being used on the patient would reduce search time giving more time to the patient.

- Stowage requires further study. The overhead stowage was useful; however, the stowage did present the opportunity of falling on the patient while they were on the table if the table had not been properly deployed.
- The surgical table, when not in use, should be more compact for more efficient use of the station's volume.
- Currently no privacy curtain exists in the habitat for patient privacy. Adding a deployable curtain, much like the sleep station curtains on the SEVs, to provide some privacy was recommended.
- Replace the fixed seat with a wheeled seat.

General Maintenance Workstation

- The fold-out table was deemed worthy; however, improvement on the mechanical design to make the operation of folding or unfolding the worktable less cumbersome is needed.
- The table height was not adjustable. It was recommended adding the capability of adjustability to the table for more flexibility of the work surface.
- A better selection of tools for the station was recommended.
- Locating tools in the stowage lockers were difficult when others are working at the station. It was recommended hanging the more common tools on the wall and stow only the specialty tools to reduce the time needed to access the stowage lockers.
- Reexamine options for height adjustable user seating.

Suit Maintenance Workstation

- The station's worktable height was good but adjustability to the tabletop for more flexibility for working with suit systems is required.
- The stowage system needs improvement. It was difficult to find the correct tools due to the stowage lockers being labeled incorrectly or unlabeled.
- Reduction of about 50% of the suit maintenance tools was recommended but needs to be assessed against a more accurate estimation of suit maintenance activity.
- To improve the stowage, adding small containers to either the wall or on the table to house small parts was recommended.
- The support system for the computer blocked half of the station's working volume from a crew member who is trying to work on the suit. Relocating the support arm to the upper HDU rib section above the station to move the laptop up and out of the way as needed to clear the workspace was recommended.
- Space around the station for suit repair was a concern. Everything surrounding the workstation is in the way when the PLSS is mounted in the Marmon rig. More space around the station was suggested when the PLSS is mounted to the Marmon rig.
- Crews had difficulty in attaching the PLSS to the mounting rig due to the securing clamps. Clamps are friction lock and looked to be designed in the wrong direction facing downward instead of upward. A redesign of the clamp system was recommended.
- Stability of the mounting rig with an attached PLSS was very unstable due to the cantilevered nature of the mounting device. A redesign for robustness was recommended.
- Reexamine options for height adjustable user seating.

Geo Science Workstation

- Awkward accessing tools within the glove box via the glove port. Instruments were difficult to grasp on the smooth bottom surface of the glove box.
- Reaching the back sample ports was difficult especially for shorter subjects.
- Ergonomics of the workstation was inadequate.
- Difficult to do two-handed operations at either side of the station due tits size and depth. Height of the glove box was also an issue.
- Taller subjects stated the glove box height was too low for standing operations while shorter subjects stated it was too high.
- Crews tried a seated position and noticed some neck discomfort when looking at the displays.
- When standing, they observed their body posture was always is a sort of hunched position to accomplish the tasks.
- Reaching the touch screens over the glove box was considered awkward, tiring, and difficult. While trying to access the displays crews would accidently bump the microscope and cameras out of alignment. Typing or making fine adjustments was also difficult with the overhead displays.

Vehicle Logistic Resupply Operations

- Crews used the horizontal surfaces of the HDU workstations to stack their gear and either take items out of the soft lockers or pack the gear for the other crews.
- Hatch size for the transfer was very good. Crews stated this operation could be hampered if the hatch size was any smaller than the current size.
- The overall concept of logistical transfer was simple enough; however, more detailed guidance on the inventory list, more rigors towards the organizational efforts and consideration of time to houseclean the rovers.
- Suggestions for procedural improvements consisted of transferring the rover contents to the PEM, clean the rovers, systematically restock, and inventory each CTB, then returned restocked items to the rovers. Crews recommended looking into the current ISS process for development guidance.

Continuing a human-centered design approach and collaborating with designers to capture information to enhance human performance will lend confidence to both future space exploration habitat designs, as well as overall planetary vehicle designs.

2. Airlock Operations and Incapacitated Crew Member Test

An airlock operations and incapacitated crew member test was conducted at JSC as the final test under the Constellation Program. Using the HDU airlock within the context of the PEM configuration, investigators conducted an Extravehicular Activity (EVA) suit donning/doffing evaluation and an EVA crew medical emergency simulation to obtain preliminary human-in-the-loop performance data to apply to further enhance the habitat's capabilities for forward designs. Shown in Figure 38, the airlock connected to the HDU is 2.21 m (7.21 ft) in diameter with a cylinder height of 2.06 m (6.75 ft) and the end dome being 0.39 m (1.3 ft) (total height is 2.45 m (8.04 ft)). The approximate volume of the airlock is 8.64 m^3 (305 ft^3). Placed within the airlock were two non-flight like suit stands constructed of 80/20 aluminum with overhead and side grab bars. Also used for the study was a hoist/cable device with wired remote control with the ability to lift 680.4 kg (1500 lbs.). Mannequins were used to simulate the incapacitated crew member as shown in Figure 39. The objectives for the evaluation were:

1. To evaluate the volumetric acceptability of the HDU airlock for two crew members to don and doff the Global Effects MK-III Mockup planetary EVA suits while using suit stands, seats, side grab bars, and overhead grab bars.
2. To evaluate the volumetric acceptability of the airlock for assisting a suited incapacitated crew member into the airlock from outside the habitat; positioning them into a suit stand; or transferring the incapacitated crew member into the habitat's medical operations station.
3. To evaluate the feasibility of transferring an incapacitated crew member by using a litter into the HDU's airlock without damaging either the airlock hatch seals or the EVA suit.

Fig. 38 HDU Airlock Operations and Incapacitated Crew Member Evaluation

Fig. 39 Laceration Repair (left), Eye Exam (center), and AED Assist with CPR

The testing generated copious amounts of preliminary qualitative and quantitative data on human performance under simulated emergency conditions as well as nominal EVA conditions. Data collected was examined for any developing trends that may need to be addressed and brought forward to improve the HDU habitat. Investigators examined the volumetric acceptability of the airlock for crew donning and doffing of space suits; translation paths and volumetric acceptability during incapacitated crew situations; translation paths of incapacitated crew into the habitat; and volume within the medical operations station to conduct off-nominal procedures for an injured crew member. This was the first comparison of airlock usability under both nominal and contingency conditions, giving the vehicle designer insights into early system acceptability, usability, and functionality.

Results in Figure 40, Figure 41, and Figure 42 indicate that the volume of the airlock was considered borderline for both tasks due to interior hardware configuration and the airlock's hatch configuration (inward swing), which made mobility of suited crew members difficult and made maneuvering the incapacitated crew member difficult. Perceived exertion scores for the don/doff task indicated "light" to "somewhat hard" due to body twisting to gain access to the pull up bar. For the incapacitated crew member task, the perceived exertion scores ranged from "hard" to "very hard" for translating both the litter and injured crew member into the airlock and positioning them to close the hatch. For translating the litter and injured crew member up to the airlock, exertion was considered "light." Subjective acceptability ratings indicated the airlock was borderline for the don/doff task while for the incapacitated crew member the majority of the elements were considered acceptable. Suggestions for improving the HDU airlock volume include rearrangement of the internal hardware to reduce interference with the suit, to design foldable suit stands, and to study other hatch designs and configurations to increase workable volume. Other suggestions from the subjects to improve the system include adding a block to assist guiding the hoist cable, improving the controller button size and spacing, making the hoist controller cable longer or wireless to improve visibility of the injured crew member while translating them to the airlock, and relocating the hoist controller. For the medical station, designing pull out trays to reduce surgical table clutter, adding wheels to the surgical table for easier deployment, and redesigning the upper stowage drawers were suggested by subjects.

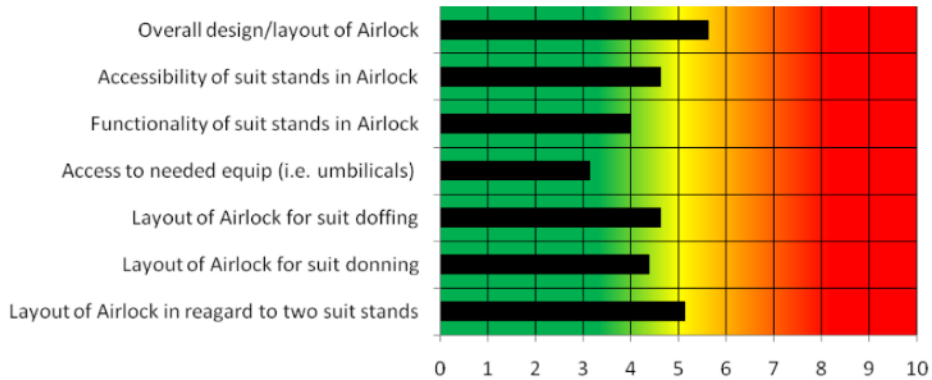

Fig. 40 Acceptability Ratings for HDU (PEM) Airlock

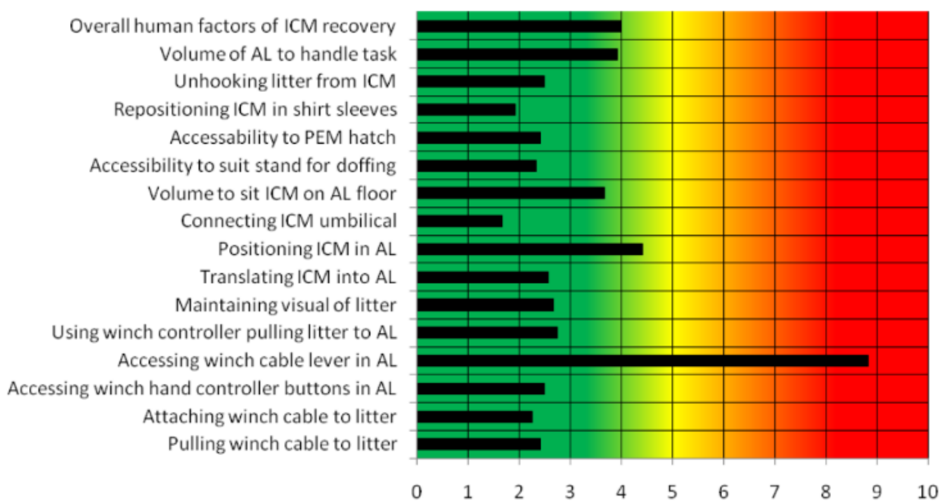

Fig. 41 Acceptability Ratings for Recovery of Incapacitated Crew Member into Airlock

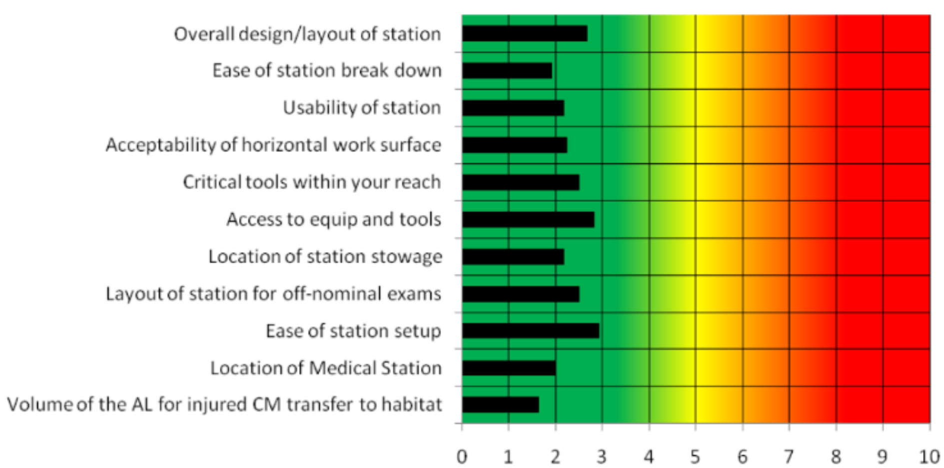

Fig. 42 Acceptability Ratings for Medical Operations Workstation

3. 2011 Field Test

Post-Constellation, the HDU was repurposed as a Deep Space Habitat (DSH) with additional elements added and tested at Desert RATS 2011 to simulate a mission to a Near Earth Asteroid. This was the first habitat test involving crews living in the habitat over multiple days. Two different four-person crews conducted operations inside the DSH, one for four days and three nights and the other for three days and two nights, with the second mission having been cut short due to hazardous weather. The HDU was modified as shown in Figure 43 to serve as a DSH by the addition of an inflatable section shown in Figure 44 that included a habitation (or HAB) deck with crew bunks, exercise, and galley, and the addition of a hygiene module containing waste and hygiene facilities. The lower deck (what had been the PEM under Constellation) became known as the LAB deck, which saw the former suit maintenance workstation replaced with a tele-robotic workstation. A combination ladder / elevator was added to the center of the habitat to enable translation between the HAB and LAB decks.

Fig. 43 HDU in the Deep Space Habitat Configuration

Human factors measures used included subjective questionnaires, workload and fatigue measures, task performance measures (i.e. accuracy, productivity, and confidence), crew debriefs, and video analysis to develop a complete picture of the DSH's habitable functions while the crews worked and lived in the habitat. Human factors objectives for the evaluation were:

1. To assess the effectiveness of the architectural design, crew performance, and functional volume for all LAB module workstations within the habitat (i.e., suit/general maintenance, GeoLab, Medical Ops, Tele-Robotics)
2. To assess the effectiveness of the architectural design, crew performance, and functional volume for all HAB module areas within the habitat (i.e., galley, exercise, crew quarters, communications, etc.)
3. To assess the effectiveness of the architectural design, crew performance, and functional volume of the habitat's Airlock and Hygiene Module
4. To assess the effectiveness of the architectural design, crew performance, and functional volume of the habitat's translation paths
5. To evaluate the overall net habitable volume (NHV) within all the habitats modules to identify maturity gaps in habitat Intravehicular Activities (IVA) operational concepts
6. To evaluate the effectiveness of the architectural design of the habitat on crews' team performance under different exploration mission conditions
7. To assess the effectiveness of the architectural design, crew performance, and functional volume of the habitat's stowage system using the Space Exploration Vehicle's (SEV) 14-day manifest for an exploration mission

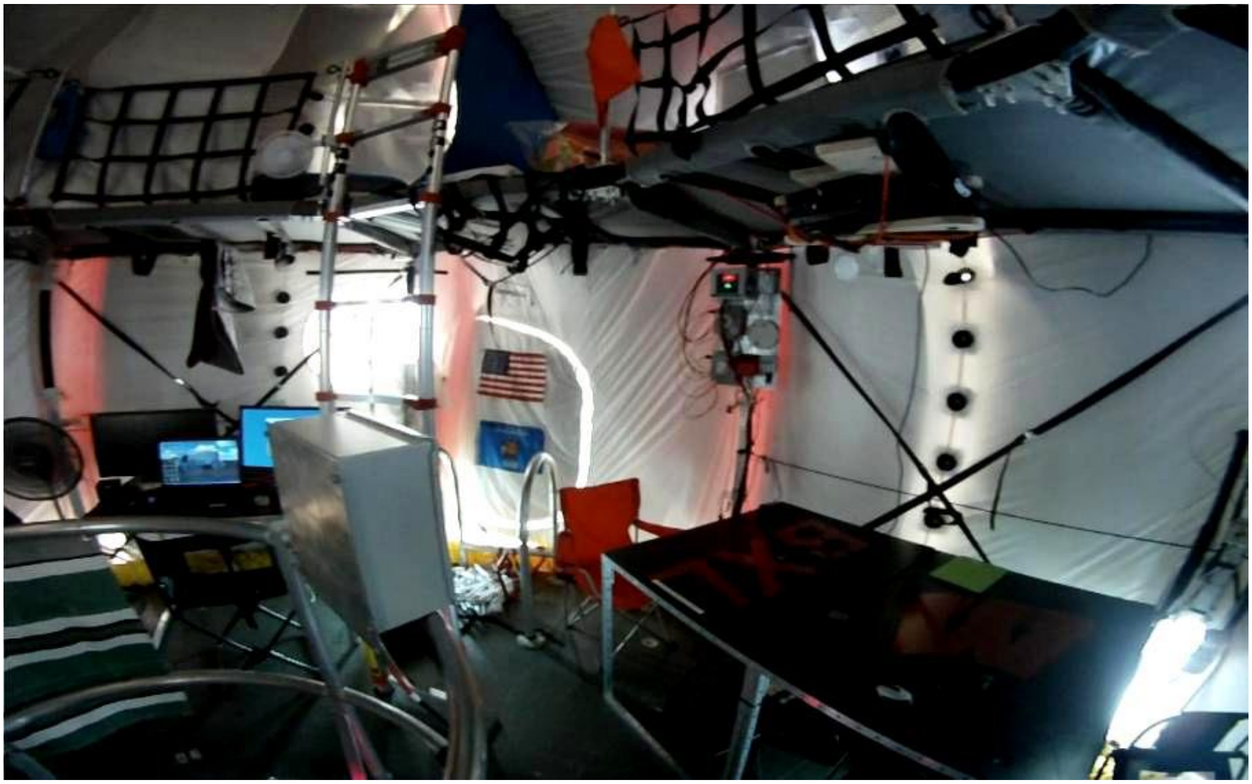

Fig. 44 HDU - Deep Space Habitat HAB Deck at the 2011 Desert RATS

Human factors data was collected on two separate crews of four while working and living in the habitat, the following conclusions and recommendations drawn are valid design concerns which should be taken into consideration for future vehicle designs:

HAB Deck:

- General design and layout of HAB deck was considered acceptable by crews. Crews thought deck was well protected from dust.
- Ladder positioned between the IVA workstation and the dining table caused a perceived separation between crew members when they sat down for a meal.
- Stowage on lower level could be more efficient. Crew suggested omitting open shelving and replace with more Shuttle-like mid deck lockers.
- Trash can on the HAB deck was considered too small.
- Lights on HAB deck were easily blocked and need to be repositioned from the floor to the walls. Crews also noted more light was needed on both the lower and upper lofts of the HAB deck.
- Temperatures on the HAB deck were considered uncomfortable, especially in the afternoon. However, majority of HAB deck falls within the temperature ranges of HSIR requirements (CQ 77%, Exercise 84% and Galley 88% within HSIR range).
- To improve inventory management, crew suggested having links to procedures and manifested items. They also suggested investigating current inventory procedures from ISS.
- Emergency equipment needs a more defined area that is clearly labeled. Crews also suggested a set of solid stairs instead of a rope ladder for the emergency exit out of the HAB deck.
- HAB deck floor space was limited due to the center lift railing, upper loft ladders, and exercise equipment. Crews suggested designing the lift to add support for the crews when using the CQ ladders. Crews also suggested designing the ergometer for easier disassembly and stowage.
- Structure of the CQ sleep station was an issue with crews. They felt like they were sleeping on a trampoline.
- Soft partitions used for CQ sleep station privacy were hard to stow and tended to pile up on one of the open shelves. Crews suggested designing a continuous curtain around individual sleep stations for easier stowage.

- Access to galley stowage was difficult due to the lift gate. Location of galley was considered good; however, crews wanted more horizontal workspace for meal preparation and the addition of a small sink with water source to clean up after the meal and to hydrate food.
- Crews noted that for the size of the habitat, they would only assemble the exercise equipment once and keep it assemble for the entire mission much like Shuttle and ISS.
- Floor space and volume for exercising was considered too limiting and crews suggested the exercise equipment needed a dedicated area on the HAB deck. Crews did use the habitat's existing structure to aid in doing resistive exercise. These structures had not been designed for such a purpose or to take the associated loads. Fortunately, no structural failures occurred. The key lesson is that if the habitat's outfitting does not match the crews' needs, they will invent something to compensate, which may cause them to use hardware in ways for which it was never designed or certified, potentially introducing new risks by doing so.

<u>LAB Deck:</u>

- Overall, the LAB deck was considered acceptable by the crews. The major issues for the LAB deck were workstation layout and accessibility to emergency equipment.
- The overhead stowage bins on the LAB deck were considered too high for shorter crew members to reach (5 foot 4 inches and shorter). Though they liked the high ceilings of the LAB deck, crews did suggest adding a small ladder to aid shorter crew members in accessing the overhead bins. Also, inside the bins, there needs to be better protection for wiring and hardware.
- Dust was observed by the crew as a major factor for the LAB deck. They suggested a need for some type of dust control strategy, especially for egress and ingress.
- Communication connectivity problems were a major issue with all the workstations.
- Overall lighting on the LAB deck was good; however, the noise level was unacceptable. The noise was mainly due to other test activities being conducted at the same time as the integrated testing with the SEVs. This effect the DSH IV crew member's ability to hear EVA support communications while in the TRWS on the LAB deck.
- Overall temperature on the LAB deck was considered comfortable by the crew and fell within HISR requirement limits (LAB 94% within HSIR range).
- As with the HAB deck, the central lift and associated railing caused volume conflicts with several workstation on the LAB deck. The two main stations affected were the MOWS and GMWS when the deployable tables were in use. This tended to block hatchways and translation paths on the deck. Crews suggested adding another gate on the opposite of the current lift railing, so crews have two ways of accessing the lift instead on one. Crews also suggested relocation of the MOWS and GMWS workstations to where the GEO and TRWS workstations are currently.
- Lift controls were reported by the crews as easy to use with one hand instead of the required two-handed operation; however, the e-stop button was too easy to engage and bump.
- Volume of the lift was considered somewhat small which make it awkward for the crews when trying to transfer supplies between decks.
- Lift movement speed was considered by the crews as slow and costly on the crews' time.
- Generally, the crew stated the central lift "clobber" all the workstation translation paths in one way or another. They suggested that a well-designed, well-built ladder with a pulley system could replace the lift.
- Crews liked having plants onboard the habitat; however, the red/blue grow lamps were too bright and caused the crews color perception to be altered for other tasks.
- GMWS was considered acceptable by the crews. They liked the deployable worktable and mid deck locker stowage. Crews suggested for tools the mid deck locker drawers were too big and noted smaller tool drawers would make finding tools a lot quicker and more efficient.
- The layout of the GMWS was also considered acceptable. Crews were impressed this could have two simultaneous tasks going on at the same time in the station. They credit this flexible with the deployable table; however, to improve this station further, the crews suggested another computer station and communication loop.
- Considered borderline at the GMWS was the PLSS support rig. Crews thought the PLSS rig was too flimsy, and the support legs seemed to be mounted backwards. When rotating the rig from a vertical position to a horizontal position the legs pointed upward. Crews suggest a redesign of the PLSS rig, so the legs stay in one position when the rig position is changed.
- MOWS was considered workable for nominal operations. In full setup configuration with medical deployed against the lift railing and stowage lockers positioned, the CMO had easy access to all needed items and the

patient, especially during an emergency event. However, as acceptable as this configuration was to the CMO, it blocked translation paths and access to the central lift.
- Crews suggested replacing the adjustable chairs at the MOWS with adjustable stools for a better fit under the MOWS desk, improved accessibility to the workstation's computer, and improved accessibility for the CMO to the patient.
- Crews suggested integrating an overhead light with the overhead camera above the medical table to better observe a patient.
- Privacy in the MOWS was noted by the crews as visual only and should include audible as well.
- MOWS stowage drawers for medical supplies were adequate; however, the crew noting accessing and reaching for medical supplies, especially during an emergency, was difficult. They suggested consolidating items based on emergency treatment versus basic treatment by using opposite sides of the stowage cabinet.
- The GEO station made some major improvements over the 2010 field test. Some issues the crews noted included needing a system to automatically launch all the software needed for the station's tasks; clearing the clutter around the station; increasing the horizontal work surface and improving the both the reach and clutter inside the glove box.
- Data recording at the GEO station was considered a two-handed operation since a single crew member would be consistently in and out of the gloves to access computer screens and photo capturing devices. A foot pedal was suggested as a way to decrease the task time and keep the crew member's hands in the gloves while capturing the data.
- The TRWS had the best location for dust control according to the crews. Stowage at the station was considered acceptable, especially for personal gear.
- Noise was the major issue surrounding the TRWS for DSH IV crew members who were supporting EVA missions with the SEVs. Crews stated the ambient noise was excessive and it was hard to hear EVA crew members in the field.
- Horizontal work surfaces were also needed at the TRWS. Crews suggested adding a deployable table to the station for notebooks, iPads, or laptop computers.

<u>Hygiene Module:</u>
- The hygiene module overall was considered acceptable, and the crew liked the compartmentalization of the module with the most private area being in the back of the module; however, the curtains used for this compartmentalization were unwieldy due to the material being too heavy and stiff making the curtains difficult and cumbersome to deploy or stow. Crews suggested using a more Shuttle like accordion screen made of lighter weight material for more efficient stowing.
- Air flow in the module was good with overall temperature being acceptable to the crews. They did note during the afternoon hours, the module tended to become warm. However, majority of module falls within the temperature ranges of HSIR requirements (Hygiene Entrance 84% and WCS 86% within HSIR range).
- Shower layout was considered unacceptable due to the baggy sides and tall drain making cleaning and drying the shower difficult and time consuming. Crews suggested a smaller water bag with a low flow rate so sponge-baths could be performed saving cleaning time.

<u>Airlock/Dust Mitigation Module:</u>
- Volume of the airlock was considered too small, especially while doing simultaneous tasks such as SPTM operations and suit storage. Translation paths in and out of the airlock also tended to be blocked when transferring equipment.

<u>Resupply Operations:</u>
- Depending on LAB deck activities, volume for doing a resupply operation could be tight and stowage difficult to access depending on the given workstation and number of crew.
- Crews stated there was a real need for a comprehensive concept of operations (ConOps) for this operation.

<u>Overall Crew Performance:</u>
- Fatigue and workload on the HAB deck was low which was to be expected.
- Fatigue on the LAB deck was also reported as low across the crews; however, workload across the workstations was slightly higher than HAB workload except for the TRWS. Crew workloads at the TRWS were moderate due to the excessive noise around the station.
- Task performance across three of the LAB workstations (MOWS, GMWS, and TRWS) generally fell in a favorable light. Mistakes made at these stations were considered rarely made by crew members during the planned tasks. Task productivity and confidence ranged between 70% to 100% task completed with a confidence level being just as high.

- Crew task performance at the GEO station was scored the highest among all the LAB workstations. Majority of the crews stated they were never told how many samples to process for a given time period; thus, affecting both their task accuracy and their self-confidence to do the task. Crews also stated it took the entire schedule time to do just one sample analysis which affected their productivity scores.

Vehicle Gravity Environments and Volume Assessments:

- The acceptability ratings for all gravity environments, from microgravity to lunar gravity to Mars gravity to Earth gravity, were all rated roughly rated the same, as indicated in Figure 45. As shown in Figure 46, for mission durations of 30 to 500 days, crews deemed the volume of the habitat as acceptable. For an 860-day mission, crews rated the volume of the habitat as borderline. The major issue with the habitat's volume, which has not been tested, is its ability to hold enough logistical supplies for missions lasting upwards of 180 to 860 days.

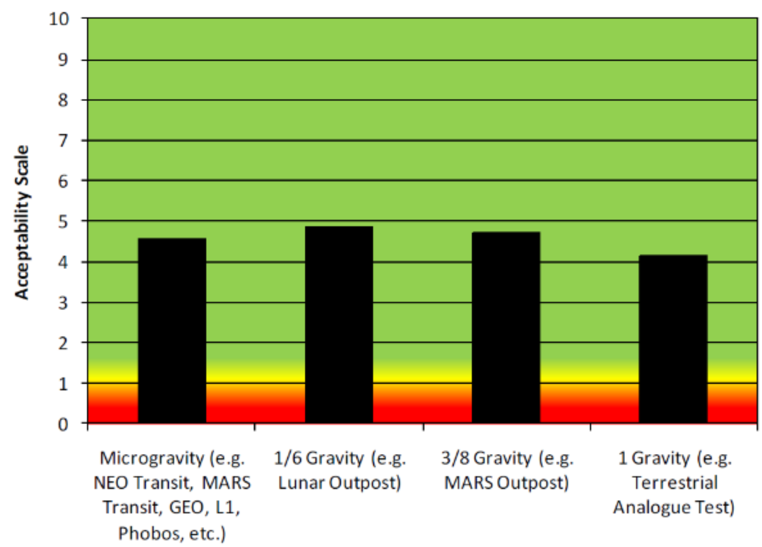

Fig. 45 Crew Ratings of DSH Layout Acceptability for Four Possible Gravity Environments

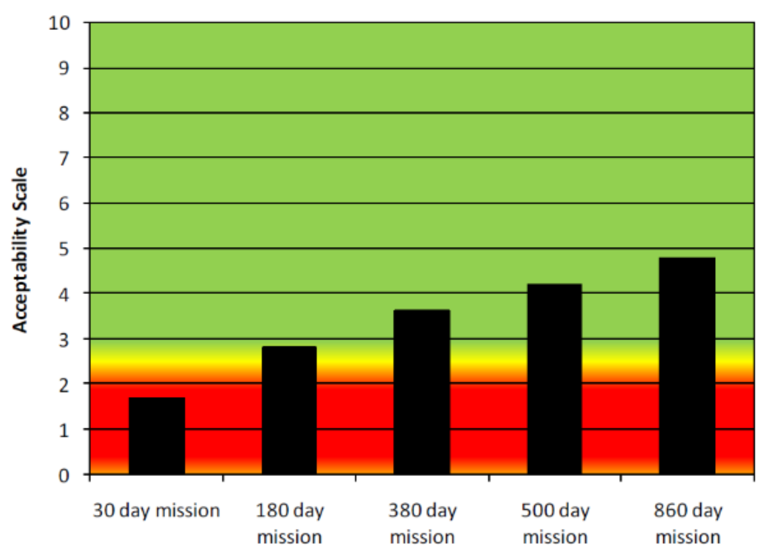

Fig. 46 DSH Volume Acceptability Ratings Over Five Mission Durations

For future research, it would be beneficial to evaluate the vehicle in both for longer duration missions with flight-like operational mission plans to help understand the interpersonal dynamics with both the crew and the vehicle.

4. 2012 Mission Operations Test

The following year, a final Mission Operations Test was conducted at JSC, with the HDU located in Building 220, shown in Figure 47, once again configured as the Deep Space Habitat. This ten-day test was the most sophisticated habitat test conducted up to that point, though all funding was terminated at the end of the test and the test habitability data was never compiled into a test report. The 2012 test simulated two portions of the timeline associated with a 400-day mission to a Near Earth Asteroid (NEA). The first five days simulated the mission phase where the DSH is in proximity to the NEA. The remainder of the test simulated five days near the end of the Earth inbound cruise, where the crew is preparing the DSH for their departure. The test was conducted only on weekdays, with the crew living in the habitat during the week but leaving the mockup to go home for the weekend after the first five-day sequence.

Fig. 47 2012 Mission Operations Test at NASA Johnson Space Center

The Hab Deck was completely rebuilt following the 2011 Desert RATS test, resulting in significant changes to the interior layout as can be seen in Figure 48, Figure 49, and Figure 50. The Hab Deck was more clearly divided into two levels, with Level 2 containing the galley, wardroom, aerobic and resistive exercise, and logistics and stowage, most of which are collectively visible in Figure 49 and Figure 50. Level 3 was dedicated to four private crew quarters, three of which are visible in Figure 49.

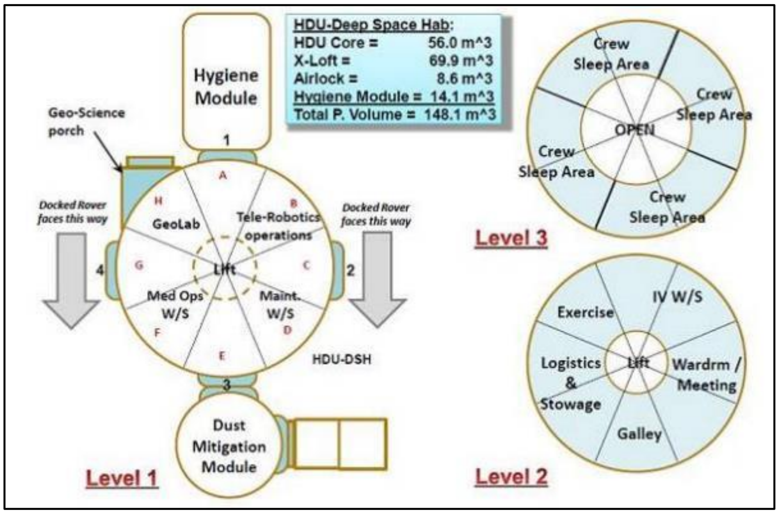

Fig. 48 HDU Configuration for the 2012 Mission Operations Test

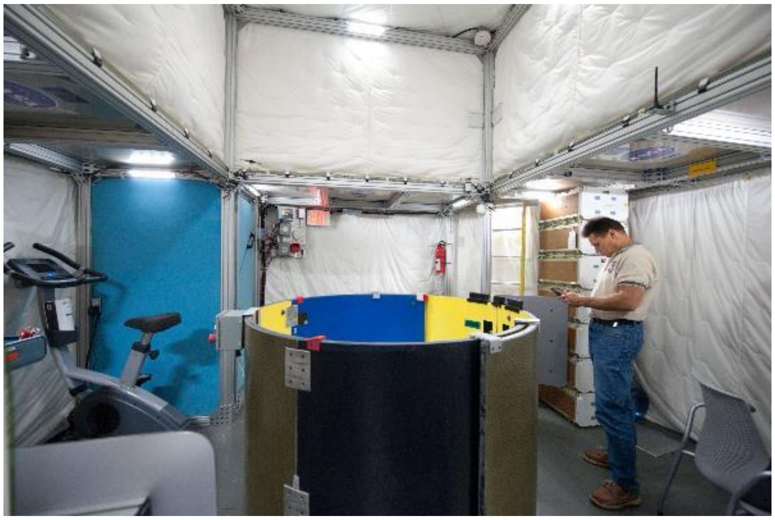

Fig. 49 Remodeled Hab Deck Showing Aerobic Exercise Device and Stowage on Level 2 with Walls of Three Level 3 Crew Quarters Visible

Fig. 50 Remodeled Hab Deck Showing Galley, Wardroom, Stowage, and Vertical Access

Effectively the 10-day mission was divided into two 5-day missions. As previously mentioned, the crew left the mockup at the end of the first five days. During the course of the missions, the crew conducted activities that both simulated the NEA mission and exercised the capabilities of the various workstations and crew stations inside the habitat. Figure 51 shows a crew member conducting one of several hardware fabrication activities in the General Maintenance Workstation and Figure 52 shows a crew member performing resistive exercise.

Fig. 51 Maintenance Activity in the HDU – Deep Space Habitat During the 2012 Mission Operations Test

Fig. 52 Crew Member Performing Resistive Exercise in the HDU During the 2012 Mission Operations Test

The aerobic and resistive exercises triggered an unexpected crew action that was observed by human factors personnel during the test but does not appear to have been captured in any crew comments. The crew had been provided Space Shuttle mid deck lockers (excessed at the end of the shuttle program and installed in the HDU) for stowage purposes, which was acceptable for clean clothing, but there had been no provision for how to treat clothing that had gotten wet during crew exercise. Stowing sweaty clothing in a mid-deck locker was undesirable and the crew quickly tired of having no way to dry their clothes out. This was the first habitat mockup where the crew had an active capability to fabricate new equipment of any kind and the crew took it upon themselves to build a clothesline and install it in the airlock. Due partly to the 2012 test taking place at JSC and due to the nature of the NEA mission segments simulated, there were EVAs from the DSH, causing the airlock volume to be largely unused during this test. This presumably made the airlock an ideal volume from a crew perspective to use for clothes drying.

This is a doubly important observation. First, the fact that the crew did not record this activity in their questionnaires indicates that habitability studies cannot rely entirely on data collection measures. Real-time observation is important, as is the ability to solicit in-mission feedback from the crew to explain the rationales behind their behavior. The second observation is that crew will invariably utilize the habitat in ways the designers did not intend. When forced to live in an analog facility, deficiencies will become evident in ways that cannot be seen in lower fidelity assessments and the crew will find a way to use the habitat that compensates, whether the habitat was intended to support that use or not.

(This was also seen in the Desert RATS analog missions involving the Small Pressurized Rovers. Human factors personnel learned after the fact that crews were urinating into water bottles instead of into the rover's toilet. They were not supposed to have had water bottles at all – the suit techs or other support personnel were apparently passing them to the crew, who should have been drinking from the rover's galley. Apparently, the toilet's desiccant waste bags were bunching up and not fully deploying, which caused the toilet to overflow when urinating. However, because this was not reported until after the end of the Constellation-era Desert RATS missions there was no opportunity to diagnose and correct the problem.)

The questionnaire data that was received did indicate some of the limitations of the Deep Space Habitat implementation of the HDU. The addition of the upper levels with a vertical translation path in the center of the habitat created problems for the crew, influencing acceptability ratings for both the Lab Deck and Hab Deck shown in Figure 53 and 54. Most of the crew commented on translation path issues. Crew felt that everything was on a major traffic route, that the lift was in the way and the source of translation problems, that paths were only wide enough for one-way traffic. It appears that for vertically oriented habitats of 5-meter or smaller diameters a central vertical passageway can cause interference with all outboard workstations. This, however, was not evident until the program performed a multi-day test in a medium fidelity mockup with operational workstations. The cost of moving the vertical translation path, however, would have been prohibitive so it is unlikely the HDU could have corrected this problem.

Had the NEA program continued, though, a number of minor improvements would have been implemented across virtually all of the DSH's internal architecture, following the areas indicated in Figure 53, Figure 54, and Figure 55.

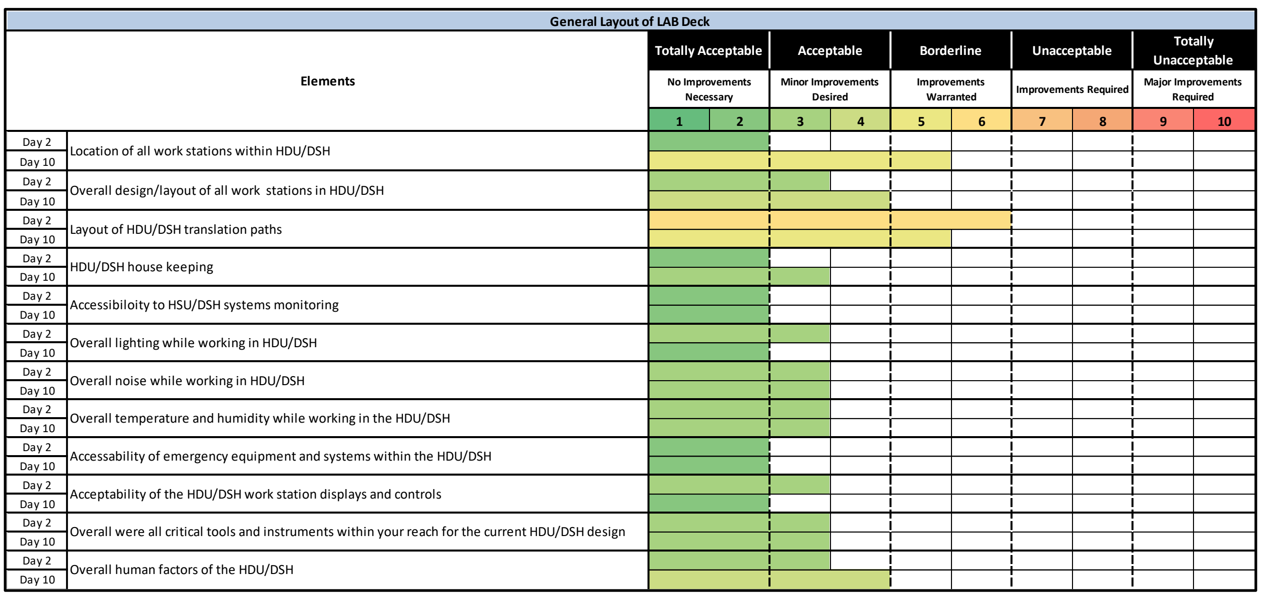

Fig. 53 2012 Lab Deck Acceptability Ratings

As shown in Figure 54, the DSH struck the crew as appropriate for a 30-day mission, such as the predicted Artemis lunar surface missions. But they did not feel it was sufficient for a six-month mission, let alone the at-the-time-planned 400-day asteroid mission. Crew commented that they felt like the volume was crammed and used past its capacity. While the questionnaire did not ask about Mars durations it is clear from the data collected that the size of the DSH is a nonstarter for human Mars transits, which can range up to 700 or more days.

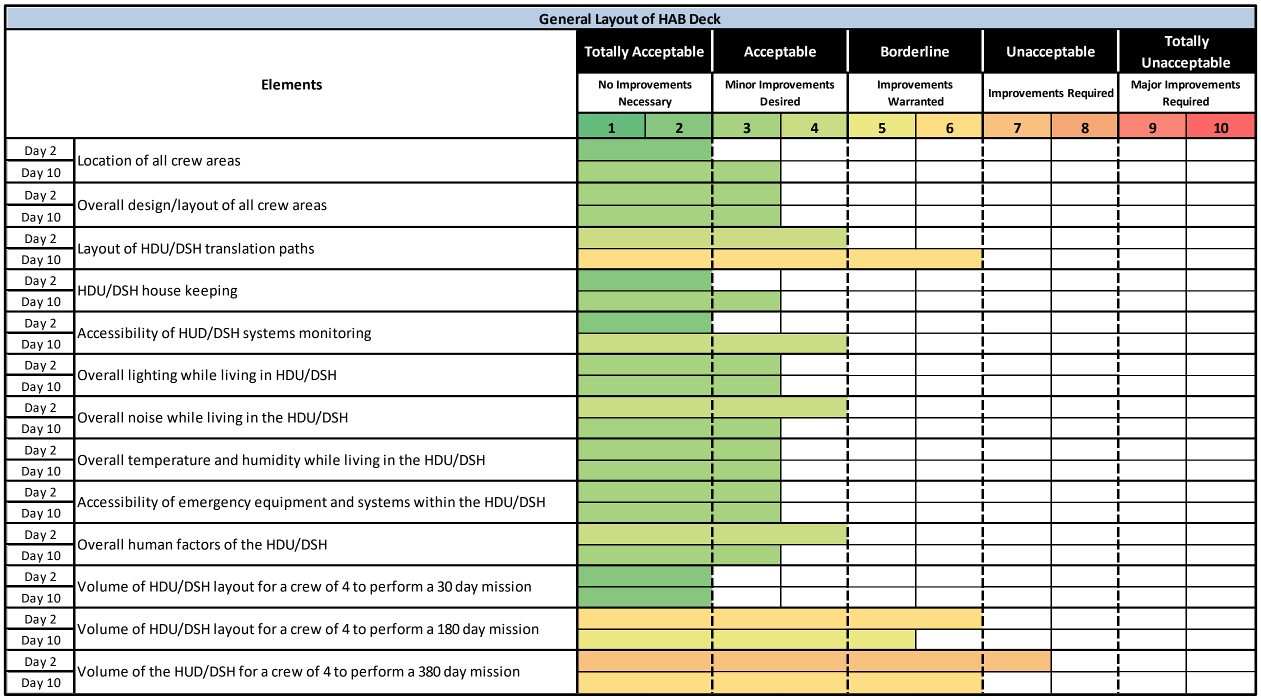

Fig. 54 2012 Hab Deck Acceptability Ratings

Logistics and stowage were by far some of the most challenging aspects of the DSH, as evidenced by the ratings in Figure 55. Crew indicated some stowage was too high or was difficult to access (due to other crew in the way). Crew also had challenges keeping up with where everything was located. Some crew were emphatic that stowage should be kept in a separate module, making the comparison that we don't live in warehouses on Earth and should not live in one in space.

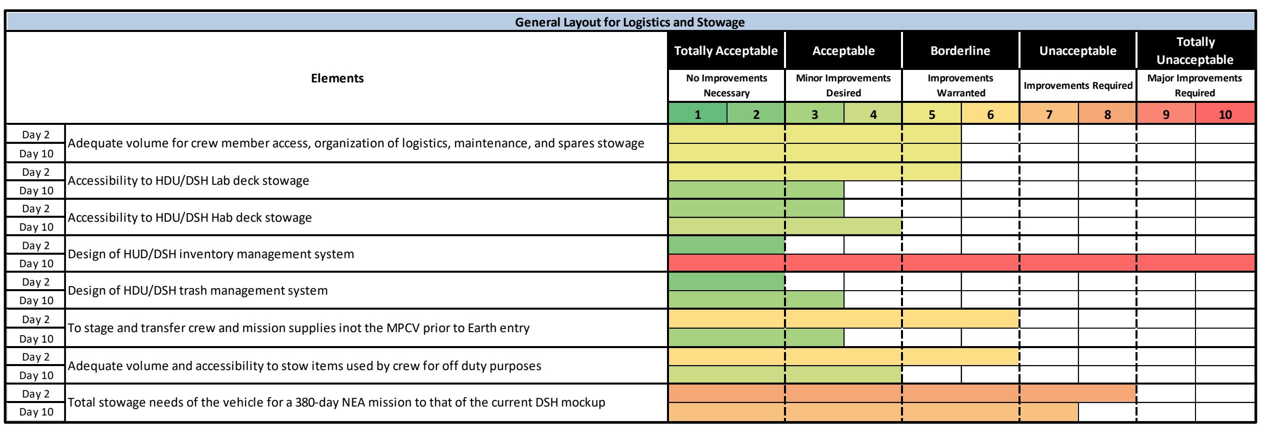

Fig. 55 2012 Logistics and Stowage Acceptability Ratings

After these studies were completed the HDU was transferred to the Human Research Program (HRP), where it was repurposed as the Human Exploration Research Analog (HERA). HRP continues to conduct analog missions in HERA, but unlike its use as the PEM and the DSH, the configuration of HERA is no longer directly tied to a specific spacecraft under program development.

D. Concepts Not Evaluated

The Lunar Surface Systems Project iterated through as many as 50 variant surface habitats during the Constellation Program's existence. Most of these concepts never progressed beyond a paper study stage. A few included notional floor plans in Adobe Illustrator and a smaller subset had partial CAD models completed. Because Virtual Reality was still a developing technology not yet available to the team, the types of Virtual Reality evaluations possible today could not be conducted on any of these concepts. These concepts included habitats such as the inflatable torus, an inflatable double torus, the previously mentioned Langley mid-expandable hybrid (which was actually built, but not evaluated), and a number of large-diameter habitats with various shapes and barrel section lengths that lent themselves to team-imposed, food-inspired nicknames such as the “egg-hab” and “hamburger hab.” Due to lack of resources these concepts were never evaluated through human-in-the-loop testing.

VII. Gateway NextSTEP Phase 2 US Habitat Studies

The Gateway Program conducted habitability walkthrough evaluations for the initially proposed US Habitat, which is no longer part of the program. NASA built first- and second-generation low fidelity mockups of its reference configuration prior to an industry competition where five companies built their own habitat variants. The NASA mockups were used to refine testing procedures and then the five industry habitats were tested in 2-3-day periods with no overnight stays.

The testing employed a methodology intended to ensure that the required level of rigor and consistency is applied before, during, and after the operational tests so that the data collected remains highly relevant to NASA’s strategic architecture and technology development goals, and provides data-driven, actionable recommendations. Key points of this methodology include:

- The definition of the strategic questions that need to be answered and rationale behind each
- An understanding of how results will be used and the decisions that need to be made
- The development of objectives and hypotheses (i.e., expected outcomes) related to the questions being tested
- The prospective definition of metrics that will be used to assess the objectives and accept/reject the hypotheses, including levels of practical significance
- The development of a study design that incorporates all necessary tasks to address the questions and objectives, and a plan to collect the quantitative and qualitative data
- The selection of test subjects that are representative of the target population (e.g., astronauts who have flown on space missions) and the provision of sufficient training, so that subjects understand the objectives and methods for collecting their input
- The execution of the study design with adequate fidelity of the operational environment and relevant technologies (hardware and software) to address the questions at hand
- The use of test subject consensus results to form a single set of data that reflect the agreed-upon results of any subjective input provided
- The mapping of the results to specific, actionable hardware, software, and/or procedural recommendations

In general, the Gateway evaluations were all walkthrough evaluations. The mockups were structural and permitted crew to enter and move around the habitat, but many of the workstations or components were nonfunctional mockups. Thus, the level of fidelity was insufficient for an analog mission with overnight crew stays such as the Mission Operations Test conducted by the Habitat Demonstration Unit. Additionally, some components and crew stations were designed exclusively for microgravity use and could not have been tested on Earth, regardless of the level of fidelity.

Company-specific test data was released to each company and remains proprietary. However, general trends were compiled to establish a series of 170 deep space habitat design guidelines, which were published as a NASA Technical Memorandum. [9] Additionally, the key capabilities were evaluated for the degree to which the crew perceived their importance in Gateway missions of less than or equal to 30 days and for a 60-day Gateway mission. These can be seen in Figure 56.

Essential/Enabling		Significantly Enhancing		Moderately Enhancing		Marginally Enhancing		Little / No Enhancement	
Impossible or highly inadvisable to perform mission without capability		Capabilities are likely to significantly enhance one or more aspects of the mission		Capabilities likely to moderately enhance one or more aspects of the mission or significantly enhance the mission on rare occasions		Capabilities are only marginally useful or useful only on very rare occasions		Capabilities are not useful under any reasonably foreseeable circumstances	
1	2	3	4	5	6	7	8	9	10

Capability	≤ 30 Day	60 Day
A hardwired multipurpose workstation for critical commanding	1	1
Trash removal capability on at least a per mission basis	1	1
A viewing window (not a virtual window)	2	1
An additional WCS separate from Orion	2	1
Private crew quarters	3	2
A dedicated hygiene area	3	3
An additional galley separate from Orion	4	2
Separate wet and dry trash stowage	4	3
Dedicated labeled stowage areas vs. bungees and CTBs	5	3
A permanently installed exercise station	5	3
A WCS on a different deck/module from the galley	5	4
Two or more multipurpose workstations	5	5
Exercise station separate from other volumes in habitat	6	5
A dedicated science area	6	5
Common secondary structure interface	6	5
Galley/ward room for 4 crewmembers	6	5
Circadian cycle lighting system	7	6
A dedicated medical area	7	7
Two exercise stations	8	5
Single (i.e., 30 days) missions worth of logistic stowage in the habitat	8	8

Fig. 56 Assimilated capability assessment ratings (not a rank order) from all contractor tests for missions ≤ 30 and 60 days; capabilities rated essential/enabling and significantly enhancing are boxed in red.

The Gateway tests also piloted the use of Virtual Reality. The NASA test team created a virtual copy of the second-generation NASA reference configuration of the Gateway US Habitat low fidelity mockup, shown in Figure 57 along with a photograph of the physical mockup. The team matched the fidelity of the two environments as closely as possible. Nonfunctional volumetric representations of subsystems and devices were accomplished in both mediums. Eight of fifteen areas of functionality represented in the mockups were tested by performing a walkthrough evaluation.

Fig. 57 Virtual Reality (left) and Physical (right) Low Fidelity Mockups of the Gateway US Hab NASA Reference Configuration

It is important to remember there was no functionality in either the physical or virtual mockups. They were only visual depictions of the Gateway habitat module. Thus, a walkthrough human-in-the-loop evaluation was performed to conduct visual inspection of eight functional areas.

In this study, results indicated that when testing an early design concept, there was a high correlation between the two environments, meaning SMEs found little to no difference when evaluating a design in either a physical or virtual environment. This correlation was strongest when test participants had no intention to physically interact with the environment.

There are advantages and limitations to both environments. The virtual world gave the experts a better sense of the microgravity space environment and the relationships of space and human presence that are difficult to simulate in a 1-g physical environment. Being non-static in nature, the virtual environment allows designers and evaluators a method that offers a consistency in transfer of knowledge between experts. However, the interaction between human and mechanics is better enhanced in the physical world compared to the virtual world.

This test did not show this level of low-fidelity walkthrough evaluation (in either physical or virtual environments) as sufficient to enable the design team to answer performance questions such as whether the habitable volume is sufficient, or whether required anthropometric ranges are accommodated, or operator effectiveness and efficiency with workstation tasks. However, it does enable a design team to make key preliminary design trades, such as refinement of initial architectural layouts as a precursor input to higher fidelity testing to answer the aforementioned performance questions.

Traditionally, the only option available to habitability designers was to use physical mockups to examine design configuration and volume allocations. However, with advancements in digital VR technology, a virtual mockup for early design phases could prove to be more beneficial than a physical mockup, particularly where the only test participant feedback needed can be obtained from visual inspection and does not require direct interaction with the habitable environment.

At no point can virtual reality testing substitute for multi-day, human-in-the-loop analog testing with crew living and working in the analog facility, but virtual reality shows great promise to support walkthrough evaluations for testing multiple, diverse, early design concepts, moving a program more swiftly through iterations to refine the design to an effective habitat that can then advance to those more elaborate physical mockups capable of addressing key performance questions.

VIII. Conclusions

With longer duration human exploration missions on the horizon, spacecraft habitability design has become increasingly important in the way design and configuration can affect a crew's physical and psychological outlook for everyday life onboard a space vehicle in a hostile environment.

Mockup fidelity has been an important consideration across all of these tests. Clearly, the earlier a habitat is in development the lower a fidelity will be possible. While even a low fidelity habitat is superior to a CAD model, some evaluation data cannot be obtained unless there is sufficient fidelity.

One caution does exist concerning fidelity. Over the past two decades, libraries of habitat CAD model components have been constructed and archived throughout the Agency. Often parts will be "borrowed" from old studies when quickly creating new concepts. This can give the illusion of fidelity because in some cases these are detailed models representing significant engineering work. But if those models are not compatible with the engineering associated with the current habitat effort, their dimensions and operational details may be suspect and ultimately fail to match those of their future counterparts for the habitat in question. Thus, if used in an evaluation, a participant may draw incorrect conclusions and provide inaccurate acceptability ratings.

Additionally, crew overnight testing is extremely valuable. In the known history of US spaceflight, there have only been two tests where overnights were conducted in a representative habitat design, in 2011 and 2012, both of which revealed habitat design insights never seen in other testing. Most notably, the 2012 Habitat Demonstration Unit Mission Operations Test uncovered complications associated with combining life science and medical functions that was not indicated by and contradicts recommendations of the 2008 VALHM low fidelity walkthrough evaluation. It was also interesting to note that the horizontal habitat evaluation raised the issue of crew needing a place to dry wet clothing, but this never led to any design changes in any of the Constellation-era habitats. But in the 2012 Mission Operations Test, the HDU crew became so fed up with a lack of such a place that they used the General Maintenance Workstation to build a clothes drying line. In a ten-day mission, a test crew took action. How much more motivated will a highly functional lunar or Mars crew be to scavenge whatever they need to in order to rectify any crew-perceived deficiencies in their habitable environments, whether designers or Mission Control intended for such usage or not?

As the Artemis program continues to develop, it will be valuable to develop and evaluate Artemis habitats via virtual and physical mockups prior to locking in commitments. Both the 2011 and 2012 tests of the Deep Space Habitat revealed ways in which the crew will use the habitat in ways it was not intended if their needs are not fully accommodated in the design. There is anecdotal evidence that this has occurred in spaceflight as well. The author learned from a Skylab flight controller that one of the Skylab crews had discovered a form of recreation that was saturating the station's control moment gyroscopes. Mission Control had to contact the crew to warn them to stop before they lost attitude control of the space station. Skylab did not include any recreational facilities in its design so in hindsight it is not surprising that the crew would innovate, but this possibility clearly escaped any controls in place during design and manufacturing. Habitability testing can reveal where limitations in the design will trigger the crew to act unexpectedly and allows time to examine the consequences and determine mitigations before the crew and spacecraft are far beyond any other human contact or assistance.

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