Functional Volume Assessment of an Early Version of the Mars Transit Habitat

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Abstract—**During the summer of 2020, the NASA Mars Architecture Team (MAT) assessed the Enhanced Habitation Capability (EHC), the transit spacecraft that was part of what was then the current Mars human exploration architecture, the Basis of Comparison (BOC). This assessment had six primary objectives: provide a sanity check to the BOC-derived EHC layout; understand if we can fit the hardware and functional tasks in the volume; provide a high-level assessment of how aggressive the layout is; generate a list of challenges or assumptions necessary to make it work; generate a list of future work to refine understanding; and identify proposed requirements. The results of this evaluation are discussed, including methodological challenges and rating challenges. Acceptability results are discussed for functions that the participants were able to rate and participant comments for functions that could not be evaluated are also described. Final conclusions are described, including challenges or assumptions needed to make the EHC design acceptable, future work needed to refine understanding of the EHC, and proposed habitat requirements based on test data. While NASA has since moved away from the BOC architecture, this assessment is still useful to inform the design of future Transit Habitats.**

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1. INTRODUCTION

In the summer of 2020, the NASA Mars Architecture Team conducted a functional volume assessment of the at-the-time current iteration of the NASA reference of the Transit Habitat (TH), which was then called the Enhanced Habitation Capability (EHC). The scope of the assessment was limited to the interior subsystems and crew stations within the EHC.

The goals of the assessment were as follows:

- Provide a sanity check to the Basis of Comparison (BOC)-derived EHC layout;
- Understand if we can fit the hardware and functional tasks in the volume;
- Conduct a high-level assessment of how aggressive the layout is;
- Generate a list of challenges or assumptions necessary to make it work;
- Generate a list of future work to refine understanding; and
- Generate a list proposed requirements.

The functional volume assessment conducted is a form of a human-in-the-loop (HITL) assessment. HITLs are needed throughout the design cycle for a spacecraft to inform the design team of the acceptability of the developing spacecraft concept for use by human crew.

The most advanced form of a HITL is a multi-day mission analog test, such as the dual rover habitation field study [1] conducted during the NASA Desert Research and Technology Studies (DRATS) in 2010. However, this type of assessment is inappropriate early in the design stage when the basic configuration is still undefined.

At the stage of development in 2020, the most effective form of HITL assessment is a Virtual Reality (VR) walk-through evaluation of a low fidelity CAD model. Unfortunately, this was not possible due to the coronavirus (COVID) pandemic. At the time of the assessment, NASA centers were closed with personnel teleworking from their homes. Mailing VR equipment to test subjects was considered but rejected as too time-consuming and involving costs that could not be supported by the test team.

Consequently, it was decided to conduct a table-top evaluation using .jpg images of the EHC low fidelity CAD model. This was the only alternative within the constraints of both test team budget and NASA COVID protocols.

The use of two-dimensional (2D) images was expected to result in a lower fidelity assessment than a corresponding VR evaluation. The evaluation was performed based on the EHC functional allocations in use at the time. Eleven civil servants participated, including six from Johnson Space Center, three from Langley Research Center, and one each from Goddard Space Flight Center and Marshall Space Flight Center. All participants are subject matter experts (SMEs) within the Moon to Mars enterprise with subsystem or vehicle-level expertise. SMEs were asked to provide ratings and comments for each functional allocation.

The Basis of Comparison was an internal NASA reference architecture for Mars, representing somewhat of an intermediate position between the public Design Reference Architectures (DRAs) and the current Moon to Mars architectures. It was based on a conjunction class mission with an EHC intended to support missions up to 1200 days.

The EHC used the BOC transit habitat as its starting point and was refined based on a Net Habitable Volume study [2] conducted by the Mars Architecture Team. The process used is summarized as follows:

- Classification of Crew Functional Tasks
- Organization of Functional Categories
- Estimation of Volumetric Requirements
- Identification of Functional Overlaps
- Identification of Cross-Category Overlaps
- Adjustment of BOC Design to Accommodate Functional Spaces

The Net Habitable Volumes in the EHC are depicted in Figure 1. The allocation of volumes between NHV, systems, storage volumes, and voids is tabulated in Table 1.

Table 1. EHC Volume Allocations

Area	Volume (m³)
Net Habitable Volume	147
Systems Volume	104
Storage Volume	52
Voids/Unreachable Areas	3
Pressurized Volume	306

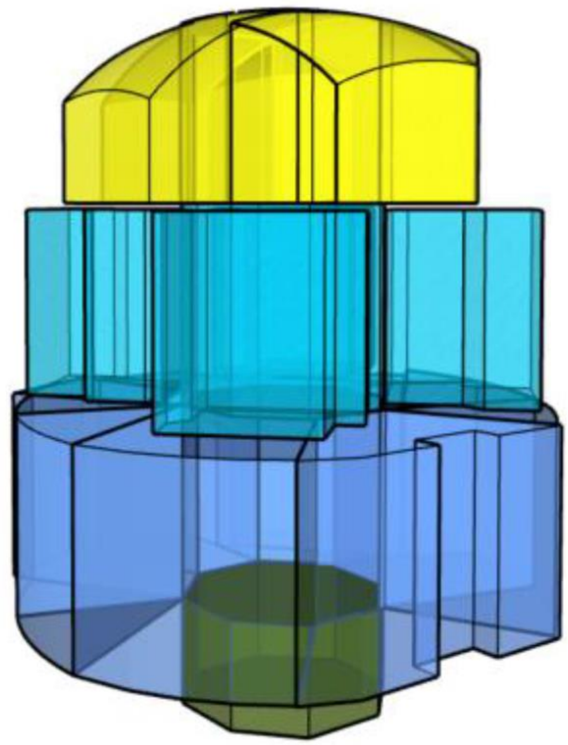

Figure 1. EHC Net Habitable Volumes

The BOC is no longer the current NASA reference architecture for human Mars missions. Some of the most relevant changes for the Transit Habitat are briefly mentioned here. The total flight time is reduced to approximately 760 to 850 days. Additionally, only two crew will descend to the surface of Mars for a roughly 30-day surface mission while the other two remain in orbit aboard the Transit Habitat.

While the current Mars architecture has changed since the BOC, this evaluation still provides useful guidance. The Earth to Mars transit durations are measured in the hundreds of days, regardless of whether an opposition or conjunction class trajectory is selected, regardless of whether the propulsion system is chemical, electric, nuclear, or a hybrid combination. In all cases, the readers can extract habitability guidance from the EHC evaluation and apply it to TH designs under the current or future architectures.

The EHC is a three-deck vertical habitat, shown in Figure 2. The lower deck (lab deck) includes the galley, command and control, a work/maintenance area, medical, waste management, hygiene, and an open area near the hatch for crew recreation or training. The mid deck (crew quarters deck) simply contains four private crew quarters. The upper deck (exercise deck) contains a Cycle Ergometer with Vibration Isolation System (CEVIS) and a second-generation treadmill (T2). Stowage is distributed throughout the habitat, filling in volumes between crew areas wherever possible. A single chamber, external airlock is mounted to the top of the habitat.

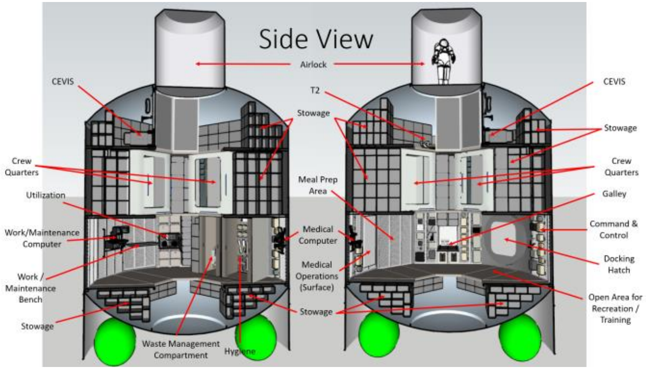

Figure 2. EHC Cutaway View

2. Functional Volumes

Nearly three dozen functions that consume habitat volume were identified for evaluation. The term "functions" was relatively loosely defined as a catch-all for anything that will take up space inside the habitat.

1. Mitigate Dust Ingress to Cabin
2. Solar Particle Event (SPE) Radiation Protection
3. Safe Haven
4. Suit Maintenance
5. Suit Don/Doff
6. Suit Storage
7. Extra-Vehicular Activity (EVA) Ingress / Egress
8. Maintenance Workstation
9. Exercise
10. Medical
11. Meal Preparation
12. Meal Consumption
13. Private Habitation / Sleep Areas
14. Private Hygiene
15. Private Waste Management
16. Group Socialization and Recreation Area
17. External Direct Viewing
18. Translation Paths
19. Stowage Accommodation / Locations / Access
20. Trash and Waste Accommodation / Locations
21. Total Stowage Quantity
22. Communication, Navigation, Command and Control, and Data Handling
23. Docking Operations
24. Physical Sciences Workstation
25. Life Sciences Workstation
26. Avionics Subsystems Volume
27. Power Subsystems Volume
28. Thermal Subsystems Volume
29. Environmental Control and Life Support Subsystem (ECLSS) Subsystems Volume
30. ECLSS Water Volume
31. ECLSS Oxygen and Nitrogen Volume
32. Overall Habitable Volume
33. Overall Layout: co-location / separation, dedicated / multipurpose / reconfigurable volumes, microgravity influence, and psychosocial issues

3. Evaluation Format and Plan

Participants were provided with a 31-page pdf file containing images forming a visual walk-through of the EHC. This included side cutaway views of the entire habitat, multiple views of each deck, and close-up deck views focused on individual crew stations or workstations. Participants were also given a data sheet to record ratings for simulation quality and acceptability for each of the evaluated functions.

The simulation quality scale is shown in Table 2. It is intended to allow the user to evaluate how closely the simulation (in this case the 2D images of the EHC) enables the functional volumes to be represented. The lower the simulation quality rating the better. The function is considered "unable to rate" if the simulation quality is greater than 6. It is reasonable to encounter high simulation quality ratings when evaluating low fidelity representations of spacecraft, whether with physical mockups, virtual reality, or 2D images.

Table 2. Simulation Quality

Sim Quality	How well is this functional volume represented in CAD?
1	No Limitations - Model quality (e.g. level of detail and fidelity in CAD model images) presented either zero problems or only minor ones that had no impact to the validity of test data
2	
3	Minor Limitations - Some limitations or anomalies encountered, but minimal impact to the validity of test data
4	
5	Marginal Limitations - Model limitations or anomalies made test data marginally adequate to provide meaningful evaluation of test objectives (please describe)
6	
7	Significant Limitations - Significant model limitations or anomalies precluded meaningful evaluation of major test objectives (please describe)
8	
9	Major Limitations - Major model limitations or anomalies precluded meaningful evaluation of all test objectives (please describe)
10	

The focus of the evaluation is the acceptability scale, shown in Table 3. Acceptability ratings are what indicate if the functional volumes provided in the EHC are appropriate for human crews during Mars missions.

Table 3. Acceptability Scale

Acceptability	How adequate is the volume and configuration of this function?
1	Totally Acceptable - No Improvements Necessary
2	
3	Acceptable - Minor Improvements Desired (please describe).
4	
5	Borderline - Improvements Warranted (please describe).
6	
7	Unacceptable - Improvements Required (please describe).
8	
9	Totally Unacceptable - Major Improvements Required (please describe).
10	

4. Model Walkthrough

Lab Deck

An overhead view of the Lab Deck is shown in Figure 3. This deck is the point of entry from docked spacecraft such as Orion, Gateway, Lunar Landers, and the Mars Ascent Vehicle. To the immediate left and right of the docking hatch from the perspective of an entering crew member are the Command and Control and Galley, respectively, shown in Figure 4. Moving in the direction of the Galley, Medical and Hygiene are the next areas, shown in Figure 5. The Waste Management Compartment is next to Hygiene but is not visible in this figure. Utilization and Work/Maintenance complete the deck layout, visible in Figure 6. There is a region of stowage beneath the Lab Deck. This can be barely seen in Figures 4 and 6 but is more evident in Figure 2.

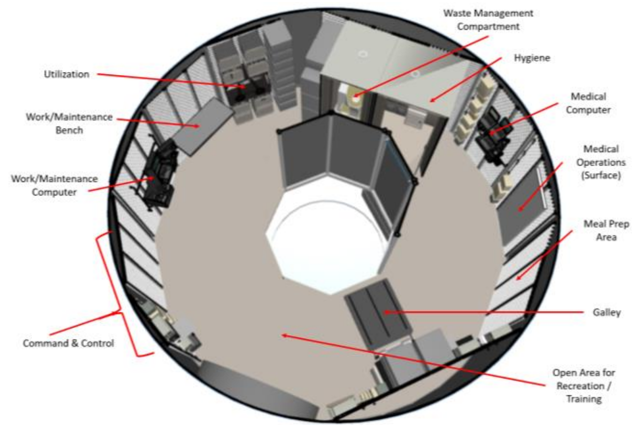

Figure 3. Lab Deck

Figure 4. Galley, Docking Hatch, and Command and Control

Figure 5. Lab Deck View of Hygiene and Medical

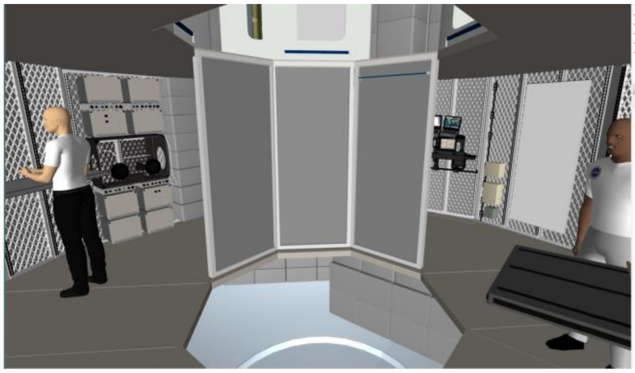

Figure 6. Lab Deck View of Maintenance Bench, Utilization, Medical, and Galley Table

Crew Quarters Deck

The Crew Quarters Deck is immediately above the Lab Deck and as shown in Figure 7 it consists of a vertical passageway, four identical crew quarters, and stowage. Figure 8 shows the interior of an individual crew quarters. The bunk is vertically mounted, but the remainder of the crew quarters is not defined. The entrance door is either a sliding, hinged, or accordion door.

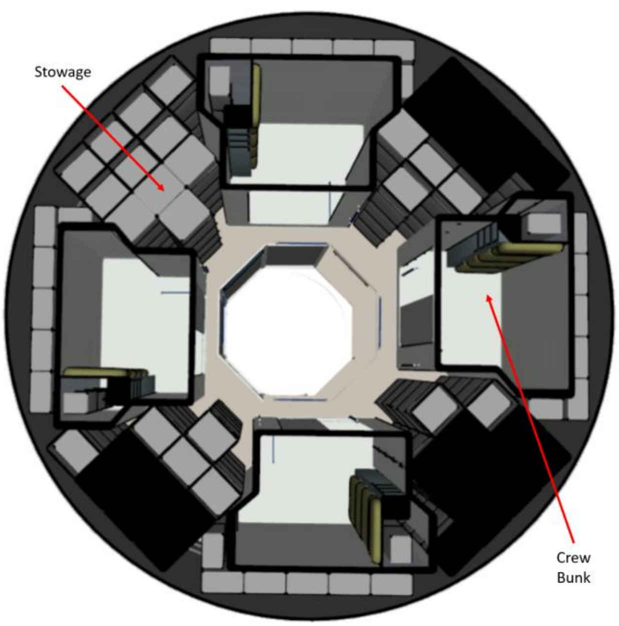

Figure 7. Crew Quarters Deck

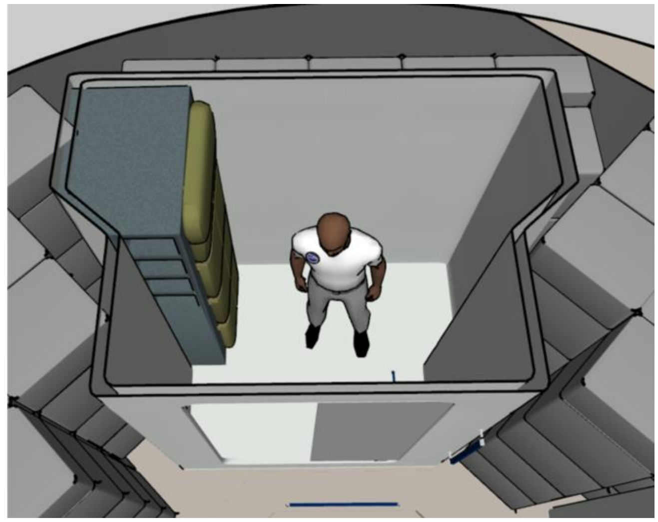

Figure 8. Individual Crew Quarters Overhead View

Exercise Deck

The Exercise Deck is the uppermost deck of the habitat's primary structure. As shown in Figure 9, it includes volume for a CEVIS aerobic exercise ergometer and a T2 treadmill.

The CEVIS location is shown in Figure 10. The CAD model does not include a human model using the device, but it is clear that access to the ergometer is rather tight.

Because the Exercise Deck is the top level of the EHC it extends into the spacecraft dome. There is therefore a transition in deck height from the center to the edge. Where the T2 is located, shown in Figure 11, a 99th percentile stature male, shown in Figure 11, has only four inches of clearance between the top of his head and the ceiling.

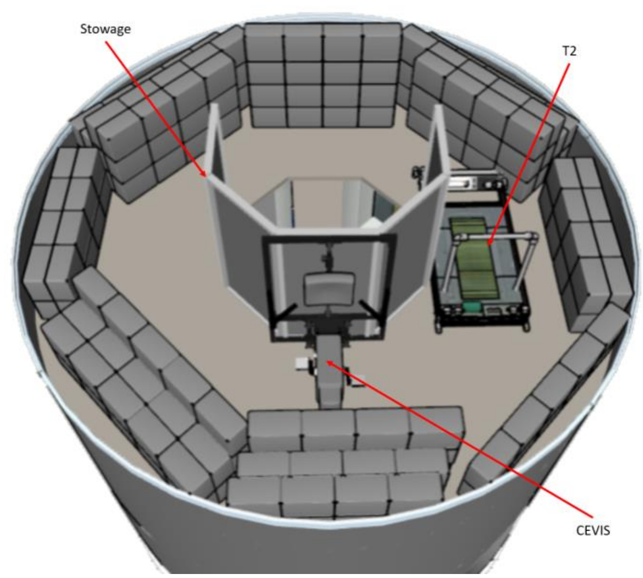

Figure 9. Exercise Deck

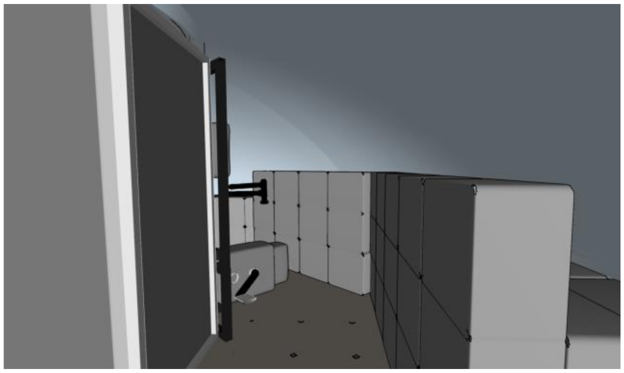

Figure 10. CEVIS Exercise Device

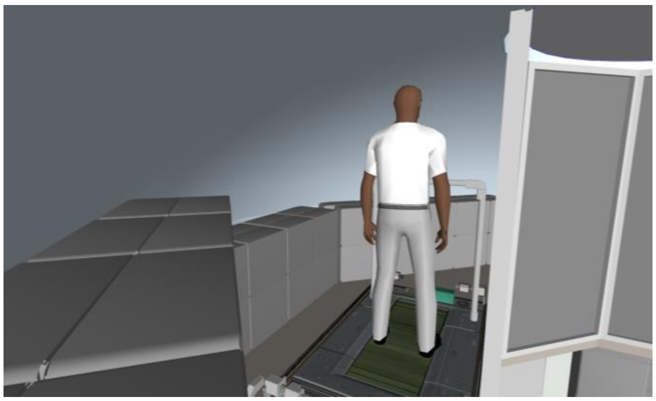

Figure 11. Crew Member on T2 Exercise Device

5. EVALUATION RESULTS

Methodological Challenges

Caution should be exercised when interpreting evaluation results. There are inherent limitations due to the type of evaluation selected.

The EHC CAD model is low fidelity, thus there are inherent differences between what is intended, what is perceived, and what a mature concept includes. The workstation designs are at best notional. Human models (where present) were limited to models available to CAD designers and were not in the neutral body postures associated with microgravity flight. The subsystems (where shown) were at a very low maturity and were not entirely synched to the MAT's mass equipment lists.

The 2D format also presents challenges. 2D imagery is difficult to accurately process (humans live in a three-dimensional world). Interactions between both adjacent and non-adjacent areas of habitat are difficult to conceptualize from 2D imagery. 2D visual evaluation cannot capture the impacts of mission operations or the multi-day effect of living in the spacecraft environment. Finally, 2D imagery cannot capture all interactions – some images may not show representative personnel or postures.

Finally, use of an evaluation modality that only engages one human sense (vision) has limitations. Auditory, olfactory, and tactile interactions do not exist in visual evaluations but have huge impacts on actual spacecraft.

Rating Challenges

As could be expected, not all functional volumes were able to be rated due to simulation quality. Additionally, there was variation among participants as to which functions they were able to evaluate.

Nine participants (82%) were unable to rate 3 out of 33 functions. Eight participants (73%) were unable to rate 4 out of 33 functions. Seven participants (64%) were unable to rate 8 out of 33 functions. Six participants (55%) were unable to rate 11 out of 33 functions. Five participants (45%) were unable to rate 14 out of 33 functions. Three participants (27%) were unable to rate 17 out of 33 functions. Two participants (18%) were unable to rate 20 out of 33 functions. One participant (9%) was unable to rate 26 out of 33 functions.

There are a number of reoccurring reasons that participants were unable to evaluate various aspects of the habitat. Some were unable to determine dimensions/sizes of various models. Several indicated they needed to see anthropometric reference persons in neutral body postures. Some were unable to recognize modeled items (e.g. subsystems, specific workstations, etc.). A significant issue was many modeled elements are too notional, missing design detail, or simply not modeled at all. Some were unable to differentiate between similar items (e.g. different stowage items). In some cases, participants felt the modeled area does not match descriptions of the area. Some felt there was missing context of the habitat in relation to rest of spacecraft (e.g. is the floor in the direction of thrust or is thrust in the direction of a wall or the ceiling). Some were unable to tell how crew would use the volume and/or equipment. In some cases, a rating was better suited for some other form of analysis (e.g. ray tracing for radiation, Excel calculations, etc.). Finally, some had difficulties with image quality (e.g. shading, textures, color).

Acceptability Results

Functions Rated by 11 of 11 Participants:

Exercise—Average Acceptability: 4, Acceptable - Minor Improvements Desired

Participant comments indicated concern that there is not enough headspace and range of motion. Vibration isolation systems can be as large as the equipment and was not depicted. A suggestion was made to consider locating exercise equipment at the bottom of the habitat, though this was based on an assumption that such a location would be closer to the vehicle stack CG and would therefore minimize integrated vibrational impacts to vehicle. Participants also raised the issue that only aerobic devices were depicted and that a resistive exercise device is also necessary.

Maintenance Workstation—Average Acceptability: 3, Acceptable - Minor Improvements Desired

Participants commented on a CAD fidelity issue where the model shows a rotational hand controller (RHC) in the maintenance area, but it would make more sense to place it in Command and Control They also commented that the maintenance workspace is small / challenged for opening even a small orbital replacement unit (ORU), there is no tools/equipment stowage near the work area, no ability to contain loose items, and no in-space fabrication. One suggested that perhaps the workspace could reconfigure and swing out to allow access from both sides.

Meal Consumption—Average Acceptability: 3, Acceptable - Minor Improvements Desired

Participants noted that only two crewmembers are shown at the table and wondered if all four would fit without forcing at least one to have to float over the tunnel / vertical translation path.

Medical—Average Acceptability: 3, Acceptable - Minor Improvements Desired

Participants were unclear as to whether the medical supplies were included in the volume or elsewhere, and that the visible stowage seemed beyond the reach of the caregiver when treating a patient. Concern was also raised that medical seemed very close to meal preparation and that cross-contamination might be an issue. It was also noted that there was no medical privacy in this layout.

Private Habitation / Sleep Areas—Average Acceptability: 2, Totally Acceptable - No Improvements Necessary

Participants felt that the crew quarters design was an odd shape that did not use the volume well and possibly had too much interior storage. Additional outfitting beyond the crew bunk should have also been included such as a personal workstation. The door swing (in the case of the hinged door) also should be reversed (to open inwards) to prevent door collisions with crew in the translation corridor outside the crew quarters.

Private Hygiene—Average Acceptability: 3, Acceptable - Minor Improvements Desired

Participants appreciated that the hygiene is separated from the toilet. However, they noted that the interior surfaces should be smooth for ease of cleanup and that as modeled there are too many interaction surfaces if doing full body hygiene. They also felt there should be a dedicated area for towel and clothes drying somewhere in vehicle and provision to keep clothes and other items from becoming wet. Some felt that one unit could be a bottleneck and requested a second unit.

Translation Paths—Average Acceptability: 4, Acceptable - Minor Improvements Desired

Participants were suspicious that the paths would not be as clear as depicted. They suggested racks, storage columns, cables, and mounting fixtures might stick out into the translation path. They noted translation paths seemed tight near hygiene, waste management, and wardroom.

Functions Rated by 10 of 11 Participants:

Overall Habitable Volume—Average Acceptability: 4, Acceptable - Minor Improvements Desired

Participants had contradictory opinions in this area. Some commented that the volume appears relatively large, while others stated that it seems pretty small for four crew for three years.

Overall Layout—Average Acceptability: 4, Acceptable - Minor Improvements Desired

Participants felt that the adjacencies were questionable, and it was unclear where equipment was reconfigurable. Others mentioned the lack of a safe haven and suggested multiple pressure vessels as a solution. Participants commented that some volumes are clearly represented while others are either not represented or unclear. They also felt that the stowage is not necessarily co-located near places of need and that both subsystem details and access to subsystems for repair was lacking. They noted that volume is tight in some areas (e.g. exercise), there are potentially awkward/difficult to use areas (odd shapes in crew quarters), and limited access in areas (e.g. science) - there is a lot of volume, but not necessarily for what a given crew member needs at a given time.

They felt the greatest frustration is likely to be a lack of utilization volume for multiple crew to work at the same time, causing frustration and competition over work areas. They noted a severe lack of privacy except when in crew quarters, the waste compartment, or the hygiene compartment. Because working and social volumes overlap, they felt the social activities will be less relaxing because it is in the working environment, thus making it difficult to truly unwind.

Meal Preparation—Average Acceptability: 3, Acceptable - Minor Improvements Desired

Participants noted that the meal preparation area appears to only support prepackaged food (no fresh food production is visible anywhere in habitat). Also, no trash stowage was evident. However, the volume was felt to be sufficient.

Life Sciences / Physical Sciences Workstation—Average Acceptability: 3, Acceptable - Minor Improvements Desired

It is worth noting that in the EHC CAD model, physical science and life science are combined into one station

(Utilization) that overlaps with maintenance. Participants felt the volume was too constrained with only room for one crew member to work at any given time. There also was very limited space for staging equipment and no computer access within the work area. Most participants felt this was a problem, but some felt that utilization was not as important as critical subsystems and felt it was acceptable to minimize utilization in favor of subsystems volume.

Private Waste Management—Average Acceptability: 3, Acceptable - Minor Improvements Desired

Participants liked having a dedicated space for waste management and noted that access to the toilet equipment for maintenance is important. The concern about one unit being a bottleneck was raised with a request for a second unit, but with a greater degree of concern than hygiene because if the sole toilet fails the crew will be forced to use diapers or Apollo bags until repaired. It was also noted that it is not clear if the volume in front of the toilet is sufficient to allow standing and disrobing.

Functions Rated by 9 of 11 Participants:

Communication, Navigation, Command and Control, and Data Handling—Average Acceptability: 3, Acceptable - Minor Improvements Desired

Participants commented that the workstation layout was severely lacking with insufficient display real estate and only a single laptop interface, which could cause the operator to be overwhelmed in the event of any serious system failure. It was also unclear how many crew members should be accommodated at the workstation.

Group Socialization and Recreation Area—Average Acceptability: 3, Acceptable - Minor Improvements Desired

Participants commented that this space would be very important but that it wasn't clear how the volume would be used or if it supports the types of recreation that would be desired.

Stowage Accommodation / Locations / Access—Average Acceptability: 5, Borderline - Improvements Warranted

Participants stated they needed to know if the urgent and frequent use items have stowage volume proximal to use (e.g. medical, maintenance, galley). They felt in general that a lot of stowage is not near its point of use. And a lot of the stowage is also difficult to access (blocked by other stowage). This was especially noted for the multi-layer-deep stowage found on the crew quarters deck. One comment was that it was "unclear if there is a stowage organizational strategy (except to just fit as many [stowage bags] as possible)."

Functions Rated by 8 of 11 Participants:

Docking Operations—Average Acceptability: 3, Acceptable - Minor Improvements Desired

Participants felt there is good volume for staging items near the hatch, but were not clear if any workstations, cameras, windows, etc. are associated with docking operations (or where they might be).

EVA Ingress / Egress—Average Acceptability: 3, Acceptable - Minor Improvements Desired

Participants had some difficulty estimating the volume required and recommended showing two suited crewmembers in the Airlock, along with any equipment also located there.

Total Stowage Quantity—Average Acceptability: 4, Acceptable - Minor Improvements Desired

Participants were unsure if the stowage was sufficient and did not like how it was configured. One evaluator commented that, "All decks except the Lab Deck feel like living in a warehouse. On the lab deck feels like nothing you need is within reach." Others said they were not sure if there was enough storage for a crew of this size and mission duration.

Functions Rated by 6 of 11 Participants:

External Direct Viewing—Average Acceptability: 4, Acceptable - Minor Improvements Desired

It must be noted that other than hatch windows in the docking hatch and airlock hatch there are no windows in the CAD model, though participants attempted to find one.

Participants commented that a habitat for this duration needs multiple windows where crew can sit as long as needed and that the "tiny hatch windows not useful for external viewing." Other windows are needed for observation, well-being, and potential science activities.

SPE Radiation Protection—Average Acceptability: 4, Acceptable - Minor Improvements Desired

It must be noted that the level of radiation protection cannot be measured by viewing an image. Actual measurement requires ray tracing analysis.

One participant commented that the crew quarters could probably serve as SPE shelters, but virtually everything the crew needs to do during an SPE is done somewhere else in the habitat. Another participant commented that there was no obvious radiation shelter and wondered if the exercise deck is intended to serve that function due to the amount of stowage surrounding the exercise devices.

Trash and Waste Accommodation / Locations—Average Acceptability: 5, Borderline - Improvements Warranted

Participants commented that there is no clearly indicated location for trash or waste, thus no indication of how much volume is associated with trash and waste accommodation. Participants commented that there will need to be accommodation for different types of trash and waste (e.g. medical biohazard, dry trash, etc.) It is also not clear how much trash or waste each container will need to accommodate before it is emptied. They did seem to think that there was sufficient space in the habitat.

6. Functions Unable to be Rated

The following functions were unable to be rated due to low simulation quality: (listed in order of increasing inability to rate)

- Mitigate Dust Ingress to Cabin
- Suit Don/Doff
- Suit Maintenance
- Avionics Subsystems Volume
- ECLSS Oxygen and Nitrogen Volume
- Safe Haven
- Suit Storage
- ECLSS Water Volume
- ECLSS Subsystems Volume
- Power Subsystems Volume
- Thermal Subsystems Volume

It is therefore impossible to draw any conclusions from this evaluation related to the acceptability of volume for these functions. Some comments are, however, useful for future habitat design.

Mitigate Dust Ingress to Cabin

It was evident from participant responses that potential sources of dust ingress were unclear. This will vary from architecture to architecture, but in the EHC's intended usage there were three potential sources of dust intrusion. It was planned to use the EHC in Cislunar space in conjunction with lunar surface missions prior to human Mars missions. Thus, any dust that is brought into the lunar lander cabin could potentially be transported into space and over to the EHC following docking. Similarly, when used for Mars missions, any dust that enters the Mars Ascent Vehicle could potentially be transferred over to the EHC. Finally, dust and other particulates can be generated onboard the EHC from both biological and non-biological sources.

Suit Don/Doff

It was not clear if suit don/doff was intended to be performed in the single-chamber airlock shown in the CAD model or in the EHC Exercise Deck. Both appeared to be large enough, but the model needed more detail to assess. Beyond the scope of this evaluation, it was also unclear if a suited crew member could translate between the different decks of the EHC.

Suit Maintenance

The scope of suit maintenance was not clear in the BOC architecture - wipe down a helmet visor, sew a torn fabric layer, or fabricate a new bearing ring could all be forms of suit maintenance, but each implies drastically different volume requirements. Further, details of how this function would be performed, such as suit storage position, workstation, tools placement, and isolation from rest of the habitat are not clearly shown. One participant suggested that since EVA itself is likely only a contingency function for the EHC there is no need for a dedicated suit maintenance volume – other areas could be repurposed as needed. Nonetheless, participants agreed that some indication of suit maintenance capability does need to be included in the EHC.

Avionics Subsystems Volume

Participants stated there is no location labeled for avionics nor any indication of the volume needed. Additionally, it is critical to show how the crew would access components for repairs and maintenance.

ECLSS Oxygen and Nitrogen Volume

Participants were not sure where to look to find these volumes. Two large, green tanks are shown in the model. One participant noted them but stated it was unclear what they are for. Another assumed they were oxygen and nitrogen tanks but pointed out there was no indication of the volume or storage capacity of either tank. Another participant thought they might be water storage but considered they might be propellant tanks. Another questioned whether they might be stored somewhere externally and plumbed in.

Safe Haven

It does need to be noted that safe haven was not a required functional space during the EHC update to the BOC design, but emerged in Mars Architecture Team discussions between the EHC update and this evaluation. The definition of safe haven was still in debate at the time of evaluation. It was unclear to participants if "safe haven" should be associated with radiation protection, loss of pressure, fire, or other such emergencies. Some participants felt it was very high risk to fly without some kind of safe haven and noted that the EHC does not appear to have that capability. Holding the opposite viewpoint, other participants felt safe haven provisions are debatable and need to be considered with all risks.

Suit Storage

Participants stated that they did not see where suit storage is supposed to be in the EHC CAD model. They also indicated that without suits and umbilicals shown in their storage locations it is hard to make a volume assessment. Some specifically recommended that if suit storage is in the Airlock, then four suits should be shown in that space (it was not clear at the time how many suits would be manifested), along with any equipment also located there. One participant felt that the EHC as shown could accommodate two suits, but not three or four. Another felt that the entire issue of suit storage was important, but that the location was not critical if EVA is only a contingency function.

ECLSS Water Volume

Participants were unsure where to look for water storage. Several asked if the previously mentioned green tanks were water storage and another asked if water could be stored externally and plumbed in. It was not clear if there was enough water for the mission.

ECLSS Subsystems Volume

Participants stated there needs to be more detail in the drawings to determine if volume is adequate. They assumed some ECLSS equipment can be accommodated but were concerned about shape factor and accessibility for maintenance. One participant stated there is no location labeled for ECLSS subsystems nor any indication of the volume needed. But they stated it is critical to show how the crew would access ECLSS for repairs and maintenance.

Power Subsystems Volume

There was no indication in the CAD where power subsystems are included in the layout. Some participants assumed it might be near command and control. They indicated crew access would be necessary for internal maintenance such as changing out switches or switching to redundant strings. They indicated cable routing and multiple modular power management and distribution locations should be provided.

Thermal Subsystems Volume

There were no specific volumes identified and participants were unable to evaluate the thermal subsystem. Participants indicated that thermal subsystem components and fluid loops should be shown.

7. RECOMMENDATIONS BASED ON RESULTS

Evaluation Conclusions

As expected, divergences in opinion were encountered throughout the evaluation. This was partially a limitation of tabletop fidelity, but it also reflects different experiences, priorities, etc. Additionally, some functional allocations require further definition – for instance, Safe Haven. Design implementations of the functional allocations that were unable to be rated all require additional design detail to provide “positive proof” of volume sufficiency. Subsystems must also be more fully identified and incorporated into the model.

Given the uncertainty in the functional volumes not fully represented and concerns identified with those sufficiently defined for evaluation in the model, there is a reasonable likelihood that the Basis of Comparison habitat does not provide sufficient volume for the Enhanced Habitation Capability habitat.

By extension, follow-on NASA or partner concepts with comparable total pressurized volumes may experience similar challenges. As one option for increasing volume, some participants recommended that the next design iteration should consider inflatable concepts, as has already been pursued by several partner companies in NextSTEP studies.

Assessment of Evaluation Goals

GOAL—Provide a sanity check to the BOC-derived EHC layout

The BOC-derived EHC layout moves in the right direction but lacks several key functions and capabilities that it may not have sufficient volume to accommodate. The functional space and volume process can be considered a “ballpark” solution but is not sufficient as a “sizing” solution. Placement of estimated functional volumes in a pressure vessel will drive pressure vessel size and will always lead to a greater total volume than the sum of the individual functional volumes. Beyond this, subsystems impose additional volume impacts due to both the equipment itself and crew access for maintenance and repairs.

GOAL—Understand if we can fit the hardware and functional tasks in the volume

The hardware is not sufficiently modeled to enable a conclusive answer. There is also too much uncertainty in functional tasks to enable a conclusive answer (yet). And there is credible concern that some of the hardware and functional tasks identified to date do not fit in the volume.

GOAL—Conduct a high-level assessment of how aggressive the layout is.

The level of aggressiveness in the layout is inconsistent. For instance, exercise lacks some of the required capabilities – there is no resistive exercise capability present. But on the other hand, the crew quarters include volumes not allocated (in the model) to any capabilities. In general, the layout has a mid-range level of aggressiveness.

GOAL—Generate a list of challenges or assumptions necessary to make design work.

Challenges:

- Increase fidelity of spacecraft subsystems and workstations / crew stations.
- More fully define capabilities of each function, including but not limited to: dust mitigation capability, safe haven, suit maintenance, maintenance, exercise, medical, food systems (cold storage, pantry storage, rehydration and heating,

plant growth), private habitation, group socialization and recreation, and science/utilization.
- The stowage philosophy is at odds with NextSTEP crew testing results [3] – the astronaut crews want stowage out of living areas and in a separate logistics module vs. the EHC design placed stowage in/around living areas wherever possible.
- Update human and EMU CAD models with anthropometrically correct models representing the range of astronaut populations and the geometries of expected suit designs.
- Intent to achieve radiation protection through the placement of stowage is obvious, but unclear if actual effect will match intent.

Assumptions Necessary to Make Design Work:

- Assume that restraints and mobility aids do not need to be considered at this point in the design life cycle.
- Assume that placeholder workstation / crew station models can be replaced with EHC-specific models within the same dimensional constraints.

GOAL—Generate a list of future work to refine understanding.

- Increase design maturity throughout EHC (use evaluation comments to start design discussions) including, but not limited to:
    - Suit don/doff
    - Suit storage
    - EVA ingress/egress
    - Meal consumption
    - Crew quarters
    - Hygiene
    - Waste management
    - Window
    - Trash and Waste
    - Communication, Navigation, Command and Control, and Data Handling
    - Utilization - physical science and life science
    - Subsystems hardware and utilities: ECLSS, Avionics, Power, Thermal
- Revisit architectural layout
    - Working / Living separation
    - Cross-Contamination
    - Behavioral Health
    - Individual workstation/crew station design
    - Reconcile design practices that contradict results of NextSTEP crew tests [3]
- Use "day in the life" scenarios to guide layout development
    - Nominal transit ops
    - Crew transfer at Mars
    - EHC restocking/servicing
    - Spacecraft contingencies
- Incorporate next layout in an inflatable spacecraft consistent with the point of departure architecture (or whichever architecture is current at the time).
- Comparative Evaluations. Several other long duration habitat concepts exist (to some extent) that could be compared against functional volumes to further refine understanding. Existing habitat concepts include:
    - Sierra Nevada LIFE Module (Physical mockup, may have virtual model; NextSTEP Phase A Gateway configuration; test crews suggested it was on the right track for an EHC-class habitat)
    - Bigelow Aerospace B-330 (Physical mockup, may have virtual model; NextSTEP Phase A Gateway configuration; test crews suggested it was on the right track for an EHC-class habitat); module may be inaccessible due to COVID-related Bigelow Aerospace closure.
    - NASA HERA (former Deep Space Habitat; JSC B220 physical mockup; virtual model may be out of date)
    - NASA CHAPEA (1-year food study, Mars analog habitat; JSC B220; physical mockup and virtual model; under construction as of FY2021; first analog mission: fall 2022)
    - NASA Exploration Atmospheres (11-day study, JSC B7 20-foot chamber, physical mockup and virtual model, first analog mission November 2021)
    - Common Habitat (long-duration, multi-destination, gravity-independent habitat; virtual model) [4]

GOAL—Generate a list of proposed requirements based on test results

Based on results of this test, it was determined that two new requirements are recommended to provide to habitat partners:

1. The EHC shall employ physical barriers to prevent cross-contamination with any functional volumes involving food, medical care, hygiene, waste management, exercise, and any other component or payload involving hazardous chemicals.
2. The EHC shall provide a means to mitigate dust entry from visiting vehicles or ingressing spacesuits.

It is reasonable to expect that additional requirements will be necessary, but these are the ones that were directly indicated by the results of this test. As an aside, the first requirement perhaps may trigger further discussion and gets at the limitations of a tabletop evaluation.

The participants were able to recognize the need for barriers to protect against the migration of chemicals. However, particulates can also be sources of contamination. All of the areas mentioned by the test subjects as well as the science and maintenance volumes can potentially generate particulates, some of which can be hazardous. This presumably was not evident to the participants from the visual imagery, which may be why they did not mention particulates at all. This could also be missed in a virtual reality or low fidelity mockup, or even a walkthrough of a medium fidelity mockup. It is not until a mission operations test is performed in a medium fidelity mockup that particulate-generating activities are actually performed in the spacecraft environment, and even there, because the mockup is on Earth at 1G, there can be differences in particulate behavior from that experienced in microgravity.

While designers can obtain tremendous amount of information from any level of HITL assessment it is always important to be cognizant of types of data that are not obtained from a given test.

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BIOGRAPHY

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