Down-Selection of Four Common Habitat Variants

Robert L. Howard, Jr.
NASA Johnson Space Center
2101 NASA Parkway
Houston, TX 77058
Robert.L.Howard@nasa.gov

Abstract— **The Common Habitat is a large habitat that uses the Space Launch System core stage liquid oxygen tank as its primary structure. It has a gravity-independent internal architecture, such that identical units can be used on the lunar surface, Mars surface, and in microgravity. In developing the habitat, two key architectural questions emerged. Should the internal layout use a vertical or horizontal orientation of the tank? Should the crew size be four or eight? This led to the design of four variants: a four-crew horizontal, four-crew vertical, eight-crew horizontal, and eight-crew vertical. The primary consideration applied for down-selection was the crew experience living and working in the habitat, inclusive of crew productivity, well-being, and survivability. Based on this consideration, a series of seven assessments was performed to compare the four variants. A stowage assessment developed a standard logistics module and then considered the amounts of water to be stored in each variant. It then estimated how much stowage could be carried onboard each Common Habitat and how many logistics modules are required by each variant for a given mission duration. A functional analysis identified and compared the living and working functions across the four habitat, ranking them relative to each other. A crew time assessment first estimated the total crew time, building a weekly crew timeline for both four and eight-person crews. It then allocated time to activities linked to living and working functions, comparing how much time was available for each function in each variant. A science productivity assessment developed a relative metric using crew time, science stowage, and assumed rates of experiment consumables use to analytically compare the four variants. It also comparatively ranked the habitats with respect to a number of subjective parameters and a workstation acceptability rating. A maintenance capacity assessment identified and compared eleven generic maintenance capabilities across the four variants and also ranked the variants for their predicted ability to complete twelve fabrication, maintenance, and repair scenarios. A contingency responsiveness analysis examined twelve serious in-flight contingencies. For each scenario, the number of crew needed to respond was predicted and acceptability of various aspects of contingency response was evaluated, comparing the four variants against each other. Finally, in a habitability assessment, 120 habitability characteristics reflecting 13 major categories were evaluated for each habitat. These results were compared to identify the most acceptable habitat in each category. Ultimately, the data was shown to favor the horizontal orientation over the vertical and an eight-person crew over four. Implications of selecting this variant are discussed, including specific architectural challenges that result from the use of the full SLS liquid oxygen tank.**

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1. INTRODUCTION

Common Habitat Overview

The Common Habitat is a conceptual spacecraft based on the repurposing of a manufactured (but not flown) propellant tank as a habitat primary structure. [1] It uses the Space Launch System (SLS) core stage liquid oxygen (LOX) tank. Figure 1 shows an exploded view of the SLS.

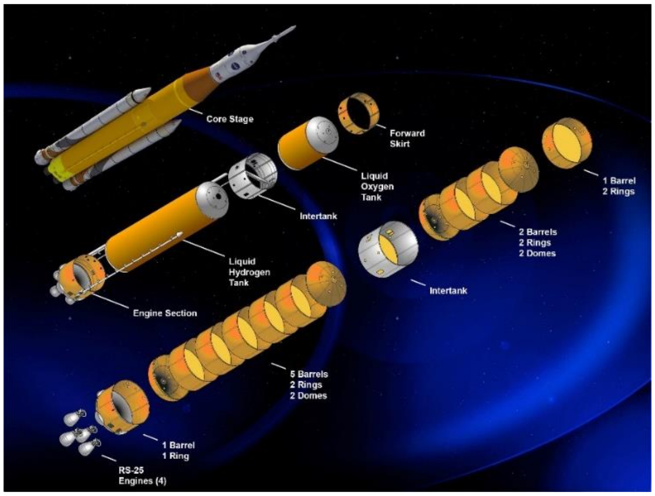


Figure 1. Exploded View of Space Launch System

Figure 1 also indicates that the LOX tank is composed of two dome segments, two barrel segments, and two rings. Repurposing a propellant tank as a habitat was first done in the 1970s, when NASA developed the Skylab space station by repurposing a Saturn S-IVB stage as the primary structure of Skylab.

Figure 2 shows a manufactured SLS LOX tank and indicates the relative size of the tank as compared with the people next to it on the ground.

Figure 2. SLS LOX Tank

The Common Habitat will have a gravity-independent architecture, such that identical copies can be used on the surface of the Moon, surface of Mars, in deep space, and on Earth as ground trainers and qualification units. [1] The Common Habitat is part of a conceptual study and is not currently part of any active NASA reference mission or human spaceflight program.

Origin of Trade Space

Early in the design of the Common Habitat two design questions emerged. Both questions held significant implications for the design of the habitat and lead to potentially very different spacecraft.

The first question is should the habitat have a vertical or horizontal internal orientation? An example of a vertical orientation is the NASA TransHab concept proposed by NASA in the 1990s, shown in Figure 3. [2] A vertical orientation is one such that the decks are parallel to a circular cross section of the pressure vessel.

Figure 3. Vertical Orientation of TransHab

By comparison, a horizontal orientation is one such that the decks are perpendicular to a circular cross section of the pressure vessel. The International Space Station (ISS), shown in Figure 4, has a horizontal orientation within its pressurized crew modules. An internal view of the ISS is shown in Figure 5 where the horizontal orientation can be clearly seen.

Figure 4. International Space Station

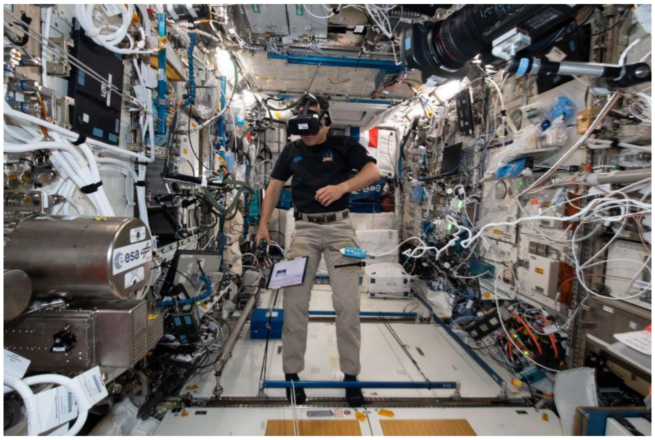


Figure 5. Horizontal Orientation within ISS Modules

The second question concerns crew size. Many of the Mars Design Reference Missions often featured six-person crews. [3] But more recent reference missions have featured four crew or fewer. The Constellation program also planned for a crew size of four for the Moon. However, personal observation during NASA Desert Research and Technology Studies (DRATS) field expeditions from 2008-2011 and the Research and Technology Studies (RATS) mission operations test held at Johnson Space Center in 2012 has raised the question whether this crew size is sufficient. During these tests, NASA evaluated prototypes of surface and in-space variants of small pressurized rovers and long-duration habitats. Figure 6 shows the prototypes evaluated in 2011.

Figure 6. 2011 DRATS Test Team with the Habitat and Both Rovers in the Background

The two-person rovers were found to be most effective when employed in pairs and the habitat fully engaged a four-person crew. It would be challenging to efficiently utilize a habitat and two rovers at the same time with only four people available. Thus, this study has imposed the question should the crew size be four or eight?

The two questions of orientation and crew size lead to a four-way decision point. Should the Common Habitat be a four-person horizontal habitat, four-person vertical habitat, eight-person horizontal habitat, or eight-person vertical habitat?

At the point in time when these questions emerged, the Common Habitat idea was only just beginning to take shape and one layout that reasonably captured all intended functions had been created by a Rhode Island School of Design (RISD) summer intern, shown in Figure 7. Only a horizontal layout was considered, based on the four-person crew size that dominated NASA architectures.

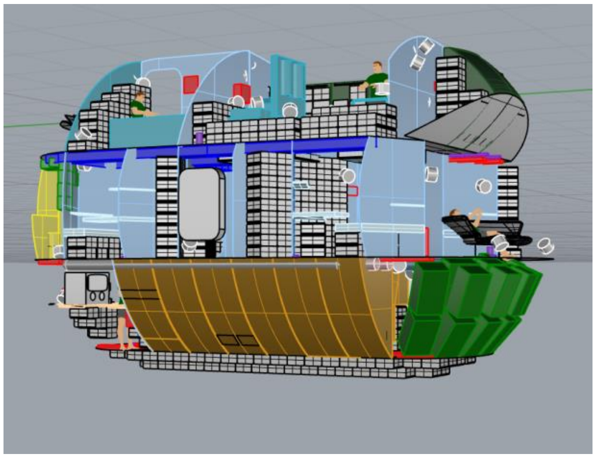


Figure 7. Horizontal Habitat Developed by Rhode Island School of Design Intern

In order to consider the possibility of a vertical orientation, the next summer intern, one from the University of Nevada, Las Vegas (UNLV), was asked to consider both orientations.

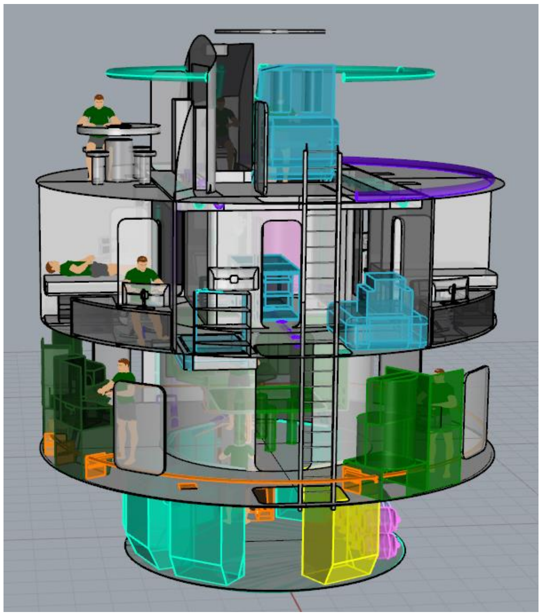


Figure 8. Vertical Habitat Developed by University of Nevada, Las Vegas Student

Only the vertical orientation was completed before the end of the summer tour, shown in Figure 8. Unfortunately, the RISD and UNLV concepts could not truly be compared because of functional differences between the two.

Development of the Four Variants

One team of Space Architecture graduate students from the University of Houston took on the Common Habitat as part of a design studio course and created initial layouts of all four variants, shown in Figures 9 - 12. [4] The eight-person habitats used the full SLS LOX tank, while the four-person habitats deleted one of the barrel sections, resulting in a significantly smaller volume. A single team was used to eliminate differences in architectural style as a source of bias. Each habitat was designed to be the most habitable environment possible. While each had to meet a core set of requirements, each design was uniquely shaped to take advantage of its respective volumes.

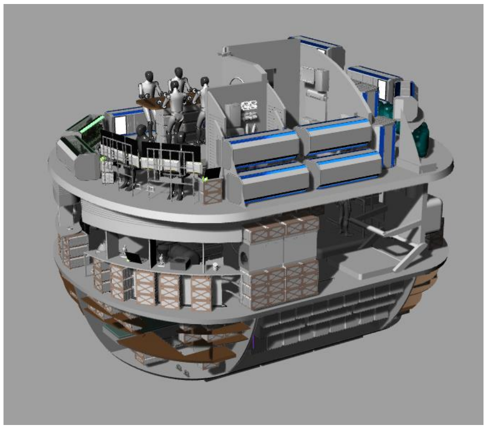


Figure 9. Four-Person Horizontal

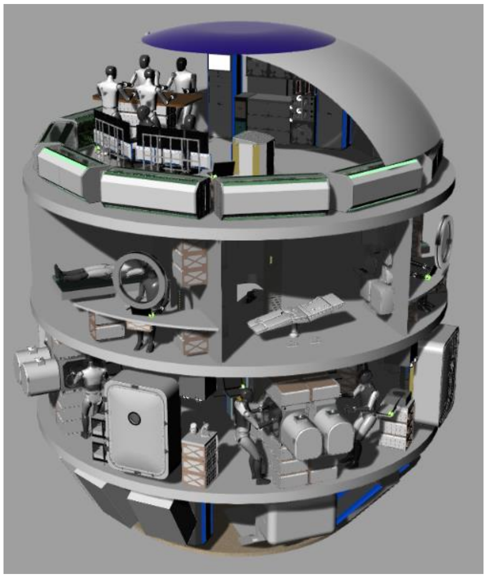


Figure 10. Four-Person Vertical

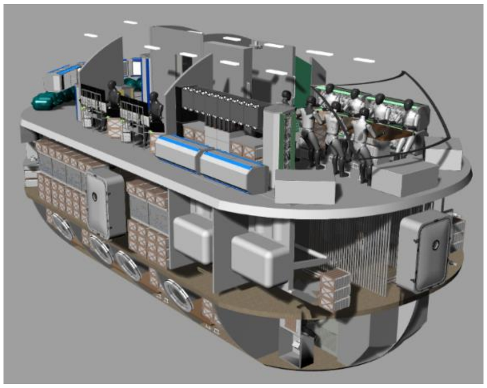


Figure 11. Eight-Person Horizontal

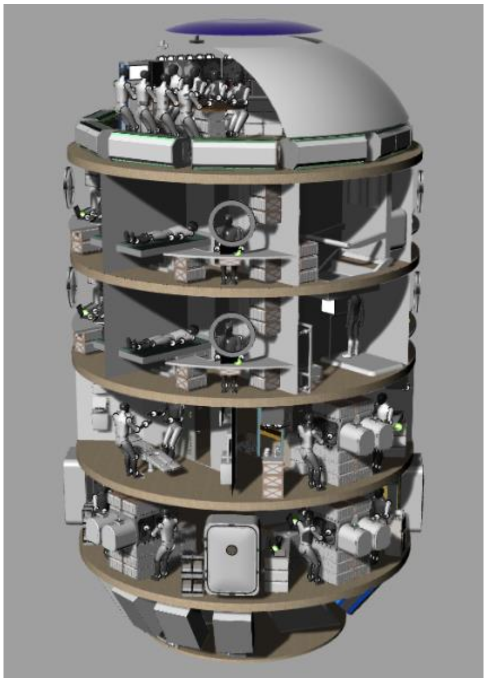


Figure 12. Eight-Person Vertical

Down-Selection Focus

In prior NASA habitat studies during the Constellation era and immediately after, there was often discussion surrounding a choice of vertical versus horizontal, but a decision was often made independent of any consideration of crew impacts. Crew size has similarly been driven by factors unrelated to the crew activities and operations. The Common Habitat study determined to use the crew experience living and working within the habitat as the sole decision-making factor to select a layout to advance for further study.

Seven assessments were conducted to drive the down-selection: Stowage Assessment, Functional Analysis, Crew Time Assessment, Science Productivity Assessment, Maintenance Capacity Assessment, Contingency Responsiveness Analysis, and Habitability Assessment.

Study Limitations

This analysis was performed as an unfunded, volunteer activity leveraging civil servants across multiple field centers, most with expertise working in various Artemis teams. However, volunteers participated on a time-available basis and generally were not all available to participate in each assessment. Additionally, the assessments were limited to the use of CAD models, images, and spreadsheet data, with no resources available for mockups or Virtual Reality.

2. STOWAGE ASSESSMENT

This stowage assessment will document and categorize the extent of variation in stowage capacities across the four Common Habitat variants. The assessment does not attempt to associate a level of "goodness" based solely on stowage capacities. Instead, these variations in capacities are inputs to other studies that assess the crew's ability to live and work in the Common Habitat. It does also inform stack configuration, as the stowage capacity of each Common Habitat has an impact on the number of logistics modules that must be associated with each. [5] Logistics modules are assumed to be required because the design philosophy was to prioritize habitability over stowage accommodation. Consistent with astronaut crew comments obtained during NextSTEP Gateway habitat testing, [6] habitats are for living and working. Logistics modules are for long-term stowage.

Stowage Estimation

Stowage sizing included all hardware, consumables, science payloads, and other items to be accommodated during a mission involving the Common Habitat. NASA stowage sizing tools from a variety of post-Constellation habitat studies were used for most estimates. However, custom estimates were used for science / utilization and maintenance, fabrication, and repair tools as the Common Habitat introduces performance goals for those functions not represented in prior NASA studies.

Water stowage was heavily impacted by habitat variant as the plant growth accommodation is one of the features that varied significantly across the four variants. Water stowage was also heavily driven by a water recovery contingency scenario requiring open-loop water during repair. All water is stowed within the Common Habitat.

Logistics Module Concept

A logistics module was roughly sized for the Common Habitat study, measuring 7 meters in length and 4.5 meters in diameter. [5] It has a limited open-loop life support capability as it has a secondary use as part of the Common Habitat architecture's Safe Haven. [7] Figure 13 shows the Logistics Module exterior and interior views. It has a capacity of 766 cargo transfer bag equivalent (CTBE).

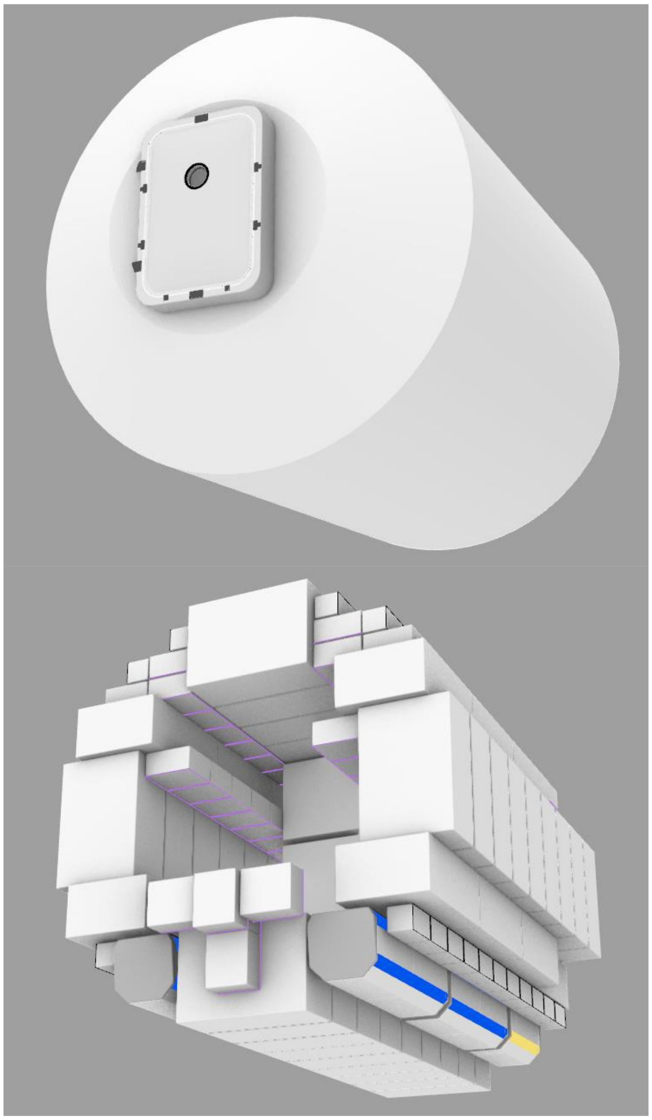


Figure 13. Logistics Module Exterior (upper image) and Configuration of Stowage and Subsystems (lower image)

Like the Common Habitat, the logistics module is gravity-independent and can be used on the lunar surface, in space, and on the Mars surface. It is docked to the Common Habitat by means of a docking tunnel. [8]

Logistics Modules Required

Table 1 provides an estimate of the stowage volume required (not including water) for a 1200-day mission. This, combined with the CTBE stowage capacity of each Common Habitat variant (332 – four-crew horizontal, 280 – four-crew vertical, 363 – eight-crew horizontal, 416 – eight-crew vertical) and the capacity of the logistics module determines the number of logistics modules needed. Table 2 indicates the logistics modules required as a function of both habitat variant and mission duration.

Table 1. Estimated Stowage Requirements for 1200 Days

	Mass (kg)		CTBE	
	4 Crew Baseline	8 Crew Baseline	4 Crew Baseline	8 Crew Baseline
Food	10,278.40	20,556.80	273.75	547.50
Wipes and Gloves	993.60	1,987.19	111.25	222.25
Health Care Consumables	546.13	1,092.27	61.25	122.25
Trash Bags	149.32	298.64	17.75	35.50
Waste Collection - Fecal Canisters	1,142.90	2,285.80	127.75	255.50
Waste Collection - Urine Prefilter	198.92	397.84	23.75	47.50
Operational Supplies	139.20	278.39	12.75	25.25
Recreation & Personal Stowage	278.39	556.78	25.25	50.25
Hygiene Kits	185.59	371.17	21.25	42.25
Clothing	873.05	1,746.10	19.00	37.75
Towels	537.13	1,074.27	60.25	120.25
Fecal/Urine Collection Bags	27.84	55.68	3.50	7.00
LiOH Canisters	292.31	584.62	11.25	22.50
EVA Maximum Absorbency Garments (MAGs)	130.56	130.56	22.00	22.00
Total Spares	5,145.01	5,145.01	192.25	192.25
Maintenance	1,600.00	1,600.00	60.00	60.00
Utilization Allocation	1,973.33	3,546.67	74.00	133.00
Total Stowage	24,491.68	41,707.79	1,117.00	1,943.00

Table 2. Logistics Modules Required as Function of Variant and Duration

	Number of Logistics Modules Required			
Habitation Duration (Days)	4-Crew Horizontal	4-Crew Vertical	8-Crew Horizontal	8-Crew Vertical
30	0.000	0.000	0.000	0.000
60	0.000	0.000	0.000	0.000
90	0.000	0.000	0.000	0.000
120	0.000	0.000	0.034	0.000
150	0.000	0.000	0.091	0.022
180	0.000	0.029	0.148	0.079
210	0.003	0.059	0.204	0.134
365	0.165	0.221	0.494	0.425
500	0.306	0.362	0.748	0.679
700	0.515	0.571	1.124	1.055
800	0.619	0.676	1.312	1.242
1200	1.037	1.093	2.063	1.993

This data indicates (1) the number of logistics modules that must accompany the Common Habitat and (2) how tightly each module is packed – impacting ease of removing stowage when needed. The image in Figure 13 represents a 100% full condition. Note that the aisle is partially blocked – the module is packed like a moving van, not like a pantry.

From Table 2 it can be seen that logistics modules are not needed for missions less than 90 days in duration, regardless of variant. On the other hand, missions above 210 days require logistics modules regardless of variant. For 1200-day missions, no more than two logistics modules are needed, though there is a minor overloading in case of the eight-crew horizontal habitat. This is the habitat that requires the most logistics module stowage, while the four-crew horizontal habitat requires the least.

3. FUNCTIONAL ANALYSIS

The Common Habitat is designed to support fifteen basic crew living and working functions. [9] Subject matter experts were asked to perform a relative ranking of the habitats. For each function, each habitat was ranked in order from best (score of 4) to worst (score of 1) with respect to how that function was accommodated within its layout. The results for each evaluation was averaged to produce an overall score for each function. The results of this analysis are captured in Table 3. Participants were provided with layout imagery of all four variants of the Common Habitat, including individual deck views and close-up images of each functional volume (e.g. crew quarters, galley, life science laboratory, etc.).

Table 3. Functional Analysis Results

		Summary			
		Averaged Results			
Function	Most Functional Habitat	4 Crew Horizontal	4 Crew Vertical	8 Crew Horizontal	8 Crew Vertical
Private Habitation	4 Crew Vertical	2.46	3.25	2.75	2.96
Hygiene	4 Crew Horizontal	3.57	3.07	2.39	2.39
Waste Management	4 Crew Horizontal	3.57	2.93	2.00	2.93
Meal Preparation	4 Crew Vertical	2.75	3.11	2.68	2.89
Meal Consumption	4 Crew Vertical	3.07	3.18	2.50	2.61
Group Socialization and Recreation	8 Crew Horizontal	2.79	3.04	3.11	2.50
Exercise	8 Crew Horizontal	3.43	2.57	3.57	1.86
Medical Operations	8 Crew Vertical	2.54	2.86	2.96	3.07
Scientific Research	8 Crew Horizontal	2.71	2.11	3.86	2.75
Robotics and Teleoperations	8 Crew Vertical	2.39	2.54	3.18	3.32
EVA Operations	8 Crew Horizontal	3.21	2.46	3.64	2.21
Spacecraft Monitoring and Commanding	8 Crew Horizontal	2.64	2.07	3.50	3.21
Mission Planning	8 Crew Horizontal	2.50	2.61	3.39	2.93
Maintenance and Fabrication	8 Crew Horizontal	2.39	2.61	3.82	2.61
Logistics	4 Crew Horizontal	3.46	2.32	2.89	2.75

Each habitat had at least a few functions that it performed better than any other. The four-crew horizontal habitat provided superior hygiene, waste management, and logistics. The four-crew vertical habitat provided superior private habitation, meal preparation, meal consumption. The eight-crew horizontal habitat provided superior group socialization & recreation, exercise, scientific research, extra-vehicular activity (EVA) operations, spacecraft monitoring and commanding, mission planning, and maintenance and fabrication. Finally, the eight-crew vertical habitat provided superior medical operations, and robotics and teleoperation.

Overall, in terms of ability to accommodate necessary living and working functions, the eight-crew horizontal provided the overall greatest accommodation of functions based on subject matter expert (SME) assessments.

4. CREW TIME ASSESSMENT

The approach used to compare the habitat variants for crew time was to estimate the crew time available in each habitat to perform general activities identified by high-level task analysis. Like the stowage assessment, this was an analytic assessment based on spreadsheet calculations, not SME responses. This assessment does not estimate crew times required, as that is both design and mission specific. The crew times used in this assessment are for relative comparisons between habitat variants. It is expected that actual mission timelines will vary.

The key difference in crew time is crew size. While the vertical and horizontal layouts will impose different translation times (with the vertical habitat performing the worst when in a gravity field) this difference is much less than the difference resulting from having additional crew members to share the workload. Thus, this assessment only tracks the difference between four and eight crew.

Crew times for twenty-four crew activities are considered in this analysis: Sleep, Post-Sleep, Breakfast, Daily Planning Conference, Remote Sensing Research, Life Science Research, Physical Science Research, Maintenance/Fabrication/Repair, Training, Day Off, Aerobic Exercise, Resistive Exercise, Public Outreach Event, Lunch, Private Medical Conference, Periodic Health Examination (Caregiver), Periodic Health Examination (Patient), Crew Planning Meeting, Dinner, Spacecraft Monitoring, Systems Inspection, Logistics, Housekeeping, and Pre-Sleep.

These activities are then mapped onto a typical crew week. In this assessment, Monday, Wednesday, and Friday crew schedules are identical. Tuesday and Thursday crew days are identical. Mondays and Tuesdays are shown in Figure 14. Saturday and Sunday are both unique and shown in Figure 15.

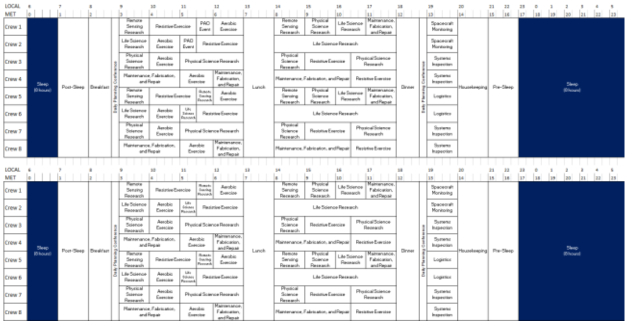


Figure 14. Monday and Tuesday Eight-Crew Schedules

Figure 15. Saturday and Sunday Eight-Crew Schedules

These crew schedules track crew time in 15-minute increments during the day and in 30-minute increments at night. All eight crew are tracked individually.

Similar schedules were constructed for four crew. In constructing the schedule, some activities are mandatory for each crew member (e.g. 8 hours of sleep daily). Other activities are mandatory for the spacecraft (e.g. 56 hours of spacecraft monitoring per week). Once all mandatory hours are accounted for, the remaining time is filled with mission-specific utilization activities (e.g. life science research, etc.).

The four-crew and eight-crew weekly schedules are then extrapolated across various mission durations, ranging from 4 weeks to 172 weeks (1204 days). Each crew-hour performed for each of the 24 crew activities is tabulated.

As might be expected, the eight-person crew has roughly twice as many hours available for most utilization activities. In a few cases the eight-person crew had slightly more than twice as many hours available – in the case of life science, 2.05 times as many and in the case of remote sensing 2.14 times as many. The greatest difference was in the area of logistics operations, where the eight-person crew has 3.75 times as many available hours. The maximum contingency response capability (the available hours if the crew stops all possible activity to respond to a vehicle emergency) is 2.02 times greater.

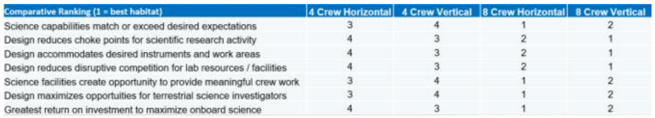
The bottom line is one eight-crew mission can accomplish slightly more than two four-crew missions of the same length. And from a safety perspective, an eight-crew mission has roughly twice as much margin (from a crew time perspective) to respond to in-flight contingencies.

Given that the results favor the eight-crew habitats and cannot distinguish between horizontal and vertical, the earlier statement regarding translation paths will be taken into consideration without actual analysis. It is believed to be a safe assumption that in a gravity environment translations will be faster in the three-deck eight-crew horizontal than in the six-deck eight-crew vertical.

5. SCIENCE PRODUCTIVITY ASSESSMENT

Several different techniques are used to compare the habitats with respect to science productivity, including both spreadsheet analytic assessments and SME assessments. It is inherently challenging to quantify science productivity given that science objectives for these classes of missions (long-duration lunar and Mars surface and deep space interplanetary transit) have not yet been developed. Consequently, several approaches were used to assess the potential of each habitat. SME participants in these assessments were given 2D imagery of the Common Habitat floor plans and close-up images of the science work areas. A science general productivity assessment comparing seven parameters subjectively estimates highest science productivity in eight-crew horizontal, shown in Table 4. .

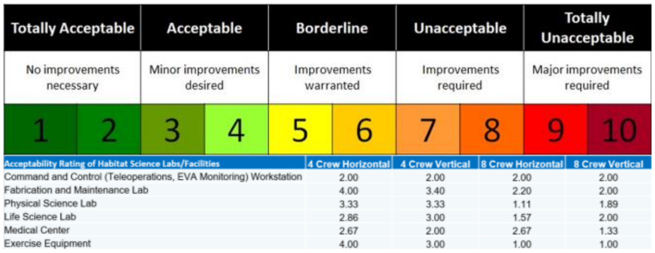
Table 4. Comparative Ranking of Habitat Variants



Comparative Ranking (1 = best habitat)	4 Crew Horizontal	4 Crew Vertical	8 Crew Horizontal	8 Crew Vertical
Science capabilities match or exceed desired expectations	3	4	1	2
Design reduces choke points for scientific research activity	4	3	2	1
Design accommodates desired instruments and work areas	4	3	2	1
Design reduces disruptive competition for lab resources / facilities	4	3	2	1
Science facilities create opportunity to provide meaningful crew work	3	4	1	2
Design maximizes opportuities for terrestrial science investigators	3	4	1	2
Greatest return on investment to maximize onboard science	4	3	1	2

Science, depending on the specific discipline, can be conducted from six different locations in the Common Habitat: Command and Control Workstation, Fabrication and Maintenance Lab, Physical Science Lab, Life Science Lab, Medical Center, and Exercise Equipment. An acceptability scale, shown in Table 5, is used to judge the acceptability of each workstation in each habitat. The eight-crew vertical habitat is slightly superior to the eight-crew horizontal habitat.

Table 5. Acceptability of Habitat Science Labs and Facilities



Totally Acceptable	Acceptable	Borderline	Unacceptable	Totally Unacceptable
No improvements necessary	Minor improvements desired	Improvements warranted	Improvements required	Major improvements required
1 2	3 4	5 6	7 8	9 10

Acceptability Rating of Habitat Science Labs/Facilities	4 Crew Horizontal	4 Crew Vertical	8 Crew Horizontal	8 Crew Vertical
Command and Control (Teleoperations, EVA Monitoring) Workstation	2.00	2.00	2.00	2.00
Fabrication and Maintenance Lab	4.00	3.40	2.20	2.00
Physical Science Lab	3.33	3.33	1.11	1.89
Life Science Lab	2.86	3.00	1.57	2.00
Medical Center	2.67	2.00	2.67	1.33
Exercise Equipment	4.00	3.00	1.00	1.00

Finally, an objective comparison is performed based on physical workspace, glove box count, and mid deck locker equivalent (MDLE) science payload slots. The eight-crew horizontal has the greatest horizontal work surface area and greatest number of MDLE payload slots. Both eight-crew variants have twice as many glove boxes as the four-crew variants.

6. MAINTENANCE CAPACITY ASSESSMENT

The mission durations, reusability, distance from Earth, and scope of exploration activities associated with the Common Habitat architectures suggests a possibility of mission scenarios where traditional ORU swap is not sufficient to maintain spacecraft viability.

Because the Common Habitat is the core habitation system in each potential mission application (surface outpost, deep space transit vehicle) it also carries the responsibility for in-flight repair of the entire system. Attached rovers, airlocks, power systems, propulsion systems, thermal systems, communications systems, and more will contain their own fault management systems, but will ultimately rely on the Common Habitat for scenarios that exceed their capacity. It is not realistic, for instance, to expect an airlock or pressurized rover to manifest an in-flight repair capability equal to that of the Common Habitat. It is not possible to carry spares for every possible failure in a surface outpost or deep space vehicle. Consequently, the Common Habitat is designed to include capabilities for a wide variety of maintenance, fabrication, and repair tasks.

SMEs were asked to perform two comparative ratings of each habitat. Rather than an absolute rating, it only asks which habitat is better than the others in a given area. Participants were provided with layout imagery of all four variants of the Common Habitat, including individual deck views and close-up images of each fabrication, maintenance, and repair work areas.

The first rating is of the habitat's ability to provide various fabrication and maintenance capabilities. The capabilities considered in the assessment are: additive manufacturing, subtractive manufacturing, electronics manufacturing, thermoforming, textile manufacturing, welding / brazing / bonding, computational systems (computer-aided design, computer-aided manufacturing, computational fluid dynamics, programming, etc.), inspection and analysis, material handling, item holding and positioning, and dust/particle/fume mitigation.

The second rating compares each habitat according to the SME's perception of its predicted ability to complete repair tasks in twelve different maintenance and repair scenarios, which are as follows:

Maintenance and Repair Scenarios

1) *All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) limb structural and mechanical failures (Moon/Mars surface)*
   The ATHLETE has significant damage requiring repair and the damaged components have been brought into the habitat for repair. Side paneling between the knee and ankle has torn loose and replacement paneling must be fabricated and attached. A hip pitch joint actuator has been contaminated with regolith. The entire actuator must be disassembled, cleaned, and lubricated. There is abrasion damage to the gears in the planetary gearbox and replacements must be fabricated and installed. The actuator can then be reassembled.

2) *Fabricate replacement for Human Landing System (HLS) broken crew restraint (Moon/Mars surface)*
   A bracket in the cabin used to anchor crew restraints was broken and knocked loose. No damage was done to the pressure vessel, but the restraint will not secure the crew member during ascent. Fabricate a new bracket that can be installed in the cabin.

3) *Perform Pressurized Rover transmission repair (Moon/Mars surface)*
   Two of the pressurized rover's transmission gearboxes have seized up and stopped working. They have been brought inside the habitat for inspection and repair.

The repair action required begins with disassembling them, where it will be discovered that they are full of lunar regolith and some erosion has occurred among the smaller gears. Clean the gearboxes and fabricate replacements for the eroded gears, then reassemble the gearbox and perform benchtop tests to verify their functionality.

4) *Clean debris-clogged Mars Ascent Vehicle (MAV) Reaction Control System (RCS) thruster (Mars surface)*

   During a systems checkout, all of the upward firing hypergolic thrusters on the MAV failed a vehicle health test and indicated a stuck-on condition, prompting an immediate shut down of propellant feed lines. The repair action will involve disassembling and inspecting each offending thruster quad once they have been removed from the MAV and brought into the maintenance area. The cause of the stuck-on condition will be determined to be an accumulation of dust particles that has clogged valves in each upward firing engine and lesser degrees of contamination in all of the others. In many cases the dust is now a muddy mixture of dust and hydrazine. The maintenance activity is completed by cleaning the debris to restore the thrusters to full functionality then reassembling each thruster quad.

5) *Fabricate replacements for Axel damaged components (Moon/Mars surface)*

   The Axel rover has severe structural damage to one wheel and dust intrusion has also failed the drive motor. Disassemble the rover and clean out the dust. Fabricate a replacement wheel. Fabricate replacement gears for the planetary gear. Reassemble the rover.

6) *Repair Lunar Terrain Vehicle (LTV) damaged fender (Moon/Mars surface)*

   An LTV fender broke off during a traverse. Fabricate a replacement fender and the necessary connectors to attach it to the LTV.

7) *Repair surface Extra-vehicular Mobility Unit (EMU) lower leg rip (Moon/Mars surface)*

   An accident led to an EVA crew member tearing several layers of the spacesuit lower leg, penetrating from the outer layers all the way to and including the bladder layer. Fabricate and apply appropriate thermoplastic, fabric, and mylar patches to each layer.

8) *Fabricate replacements for Mars Propulsion Element avionics box (in-space transit)*

   An avionics box from the Mars Propulsion Element has suffered structural and electrical failures due to an debris strike. Roughly a fourth of the box will have to be rebuilt. This includes fabricating a dozen printed circuit boards, fabricating eight electrical connectors, soldering power and data cables, fabricating an aluminum housing, disassembling the damaged box, installing all surviving and new components into the new box, and performing power and data testing on the new box.

9) *Fabricate replacements for Treadmill broken slats (in-space transit)*

   Several slats on the treadmill have cracked during use. Remove the failed slats. Conduct analyses on failed slats in conjunction with the ground to determine cause of failure. Machine redesigned slats. Install replacement slats.

10) *Rebuild solar alpha rotary joint trundle bearing assembly (in-space transit)*

    A debris strike has damaged the preload arm of the number six trundle bearing assembly. The trundle bearing assembly must be disassembled, a replacement preload arm fabricated, and the trundle bearing assembly reassembled.

11) *Repair failed ammonia thermal fluid pump (in-space transit)*

    The pump module has experienced multiple failures requiring repair. Four pump outlets have debris clogs and must be cleaned out. Two of the valve/flowmeter controllers have suffered electronics failures and will need soldering and wiring repairs. The accumulator structure has been damaged and a new one must be fabricated.

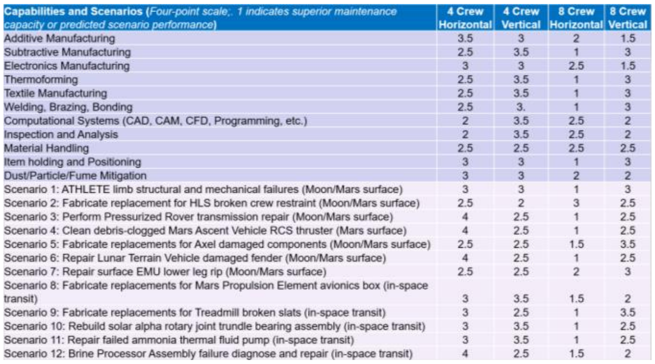
12) *Brine Processor Assembly failure diagnose and repair (in-space transit)*

    Virtually everything has failed in the Brine Processor Assembly: Leak in bladder due to puncture or seal failure; failure of electronics component; broken connector; broken bracket; crew interface control panel smashed due to collision with other object; housing damaged due to collision with other object.

Participants were asked to consider working volumes, internal volume, overall layout, and crew size. They were asked to not attempt to identify specific tools or machines, instead considering those visible in images as placeholders representing what pre-existing CAD models were available for preliminary layouts, not a design selection. In addition to the images of the Common Habitat, they were also provided with images of the items to be repaired, to help convey a "ballpark" scope of the task.

The results of both comparative ratings are shown below in Table 6. In eleven of twelve scenarios, SME assessments consistently identified the eight-crew horizontal as providing overall superior ability. The only exception was the HLS broken crew restraint, for which the four-crew vertical scored as superior.

Table 6. Maintenance Capacity Comparative Rating



Capabilities and Scenarios (*Four-point scale;. 1 indicates superior maintenance capacity or predicted scenario performance*)	4 Crew Horizontal	4 Crew Vertical	8 Crew Horizontal	8 Crew Vertical
Additive Manufacturing	3.5	3	2	1.5
Subtractive Manufacturing	2.5	3.5	1	3
Electronics Manufacturing	3	3	2.5	1.5
Thermoforming	2.5	3.5	1	3
Textile Manufacturing	2.5	3.5	1	3
Welding, Brazing, Bonding	2.5	3.	1	3
Computational Systems (CAD, CAM, CFD, Programming, etc.)	2	3.5	2.5	2
Inspection and Analysis	2	3.5	2.5	2
Material Handling	2.5	2.5	2.5	2.5
Item holding and Positioning	3	3	1	3
Dust/Particle/Fume Mitigation	3	3	2	2
Scenario 1: ATHLETE limb structural and mechanical failures (Moon/Mars surface)	3	3	1	3
Scenario 2: Fabricate replacement for HLS broken crew restraint (Moon/Mars surface)	2.5	2	3	2.5
Scenario 3: Perform Pressurized Rover transmission repair (Moon/Mars surface)	4	2.5	1	2.5
Scenario 4: Clean debris-clogged Mars Ascent Vehicle RCS thruster (Mars surface)	4	2.5	1	2.5
Scenario 5: Fabricate replacements for Axel damaged components (Moon/Mars surface)	2.5	2.5	1.5	3.5
Scenario 6: Repair Lunar Terrain Vehicle damaged fender (Moon/Mars surface)	4	2.5	1	2.5
Scenario 7: Repair surface EMU lower leg rip (Moon/Mars surface)	2.5	2.5	2	3
Scenario 8: Fabricate replacements for Mars Propulsion Element avionics box (in-space transit)	3	3.5	1.5	2
Scenario 9: Fabricate replacements for Treadmill broken slats (in-space transit)	3	2.5	1	3.5
Scenario 10: Rebuild solar alpha rotary joint trundle bearing assembly (in-space transit)	3	3.5	1	2.5
Scenario 11: Repair failed ammonia thermal fluid pump (in-space transit)	3	3.5	1	2.5
Scenario 12: Brine Processor Assembly failure diagnose and repair (in-space transit)	4	2.5	1.5	2

7. CONTINGENCY RESPONSIVENESS ANALYSIS

Contingency Discussion

The Contingency Responsiveness Analysis goes a step beyond the Maintenance Capacity Analysis. Where the Maintenance Capacity evaluates the ability of the habitat to support specific capabilities and to perform specific repairs, the Contingency Analysis takes a broader look at the entire impact of a serious vehicle or medical emergency.

Because the Common Habitat architecture would by definition result in multiple Common Habitats in continuous, parallel use for multiple decades in various locations throughout the inner solar system, low probability emergencies are considered for purposes of influencing the down-selection. The line of thought is that if we use the Common Habitat extensively enough, eventually – irrespective of probability – one or more of these emergencies will somewhere occur. Which Common Habitat has a better chance of weathering such a storm?

To explore this contingency space, twelve unique contingency scenarios were created for SME evaluation. Steps the crew will need to take to recover from the contingency were also listed. SMEs were given 2D images of all four Common Habitat variants and close-up images of each functional area within the habitats. SMEs were asked to perform two different evaluations to determine the resilience of each habitat to these serious, in-flight, life or mission-threatening emergencies.

In both evaluations, the SMEs were asked to perform absolute assessments – in other words scoring each habitat for its ability to respond, not scoring for its performance relative to the others. Because the habitats can be ranked according to their scores, a comparison can still be made, but the absolute rating also indicates whether the SMEs are of the opinion that each habitat can or cannot actually recover from the contingency.

The first evaluation concerned crew size. For each Contingency Response step, SMEs were asked to indicate the number of crew needed to successfully complete that action. They were specifically told to indicate the number of crew actually needed, even if it exceeds the total crew size. They were also told to not include incapacitated crew in their response. This was a single assessment for the scenario, not based on habitat variation.

The second evaluation was an acceptability rating. Participants were instructed to rate the acceptability of completing the contingency response within each habitat for each of the following assessment statements:

1) Degree to which this habitat reduces the need for crew to translate long distances across this habitat to respond or conduct repeated back and forth movement

2) Degree to which this habitat prevents discomfort or fatigue experienced by crew performing the response actions in this habitat

3) Degree to which this habitat enables the crew to respond without becoming overwhelmed / overloaded

4) Degree to which this habitat enables response without creating new hazards that may cause additional vehicle damage or crew injury

5) Degree to which the response in this habitat can be reasonably expected to prevent loss of life

6) Degree to which the response in this habitat can be reasonably expected to prevent long-term health impacts

7) Degree to which the response in this habitat can be reasonably expected to prevent loss of vehicle/element

8) Degree to which the response in this habitat can be reasonably expected to prevent loss of mission

9) Degree to which the crew and habitat can be expected to have recovered 2 days after the incident

10) Degree to which the crew and habitat can be expected to have recovered 20 days after the incident

11) Degree to which the crew and habitat can be expected to have recovered 200 days after the incident

12) Degree of functionality that can reasonably be expected to have been restored in this habitat after all response actions are complete (e.g. how close is the post-incident “new normal” to the previous normal)

13) Degree to which this habitat can be expected to enable / achieve a post-recovery status where there is no impact to future missions

14) Degree to which this habitat's design facilitates a successful response to this contingency

Contingency Scenarios

The twelve scenarios evaluated for this assessment and their associated crew steps are as follows:

1) An electrical fire has erupted within the galley food warmer. Crew response actions include:
    - Extinguish the fire
    - Inspect galley for heat damage
    - Remove the food warmer
    - Remove damaged components from the food warmer
    - Clean debris/melted plastic for salvageable food warmer components
    - Fabricate new food warmer plastic and metal components
    - Solder replacement food warmer electrical wiring
    - Reassemble the food warmer
    - Install the food warmer

2) A docking hatch has failed to seal during leak check prior to a logistics module undocking. The logistics module cannot be undocked until the hatch is repaired or it will expose a cabin leak to vacuum. Crew response actions include:
    - Inspect hatch and locate damaged metal mechanisms
    - Remove hatch and transport to maintenance and repair lab
    - Remove damaged mechanisms
    - Fabricate new mechanisms
    - Install mechanisms in hatch
    - Re-install hatch

3) A glove in a maintenance glovebox experienced a tear during repair of a failed MAV hydrazine thruster; the caution and warning (C&W) system has detected sufficient levels of hydrazine gas in the cabin to trigger an alarm. Crew response actions include:
    - Seal glovebox
    - Crew don PPE
    - Crew recover ambient atmosphere
    - Provide medical care for exposed crew members
    - Purge and clean glovebox
    - Remove and repair glove
    - Reinstall glove in glovebox

4) Components within a Carbon Dioxide Removal Assembly (CDRA), part of the Environmental Control and Life Support Subsystem (ECLSS) Air Revitalization System (ARS) have failed. While ECLSS continues to operate in a degraded performance mode, the CDRA must be restored to full capability. Crew response actions include:
    - Transport one ECLSS pallet (containing the failed CDRA) to the maintenance area
    - Disassemble and inspect CDRA
    - 3D print replacement metal components
    - Perform post-processing / finishing on 3D printed metal components
    - Assemble replacement valves
    - Install replacement wire meshes
    - Reassemble and inspect CDRA
    - Reinstall CDRA in ECLSS pallet
    - Transport ECLSS pallet back to subsystems area and reinstall pallet

5) The Pressurized Rover (PR) was abandoned 12 km from lunar habitat with three failed transmissions due to dust/regolith erosion of inner mechanisms. Crew response actions include:
    - Teleoperate ATHLETE robot to retrieve PR and bring to outpost
    - Conduct EVA to remove failed transmissions from PR and bring inside the Habitat
    - Provide intra-vehicular activity (IVA) remote monitoring of EVA
    - Clean and disassemble transmissions
    - Fabricate replacement components
    - Install replacement components, lubricate, and assemble transmissions
    - Conduct EVA to install repaired transmissions on the PR
    - Provide IVA remote monitoring of EVA

6) An intense SPE occurred during a Mars surface mission. The Common Habitat successfully weathered the SPE, but a post-event inspection has revealed avionics failures in the MAV, rendering it inoperable. Crew response actions include:
    - Conduct EVA to retrieve failed avionics units from MAV
    - Provide IVA remote monitoring of EVA
    - Inspection and testing of failed avionics units to identify damaged components
    - Disassemble failed avionics units to remove damaged components
    - Fabricate replacement components, including 3D printing, circuit board printing, and soldering activity
    - Install replacement components and reassemble avionics units
    - Conduct EVA to install repaired avionics units in MAV
    - Provide IVA remote monitoring of EVA

7) The Tri-ATHLETE robot suffered a failure in its payload grapple mechanism. Due to a misalignment and previously undetected metal fatigue, part of the grapple

mechanism has broken off and other portions of the metal have bent, rendering the Tri-ATHLETE unable to grapple payloads. Crew response actions include:

- Teleoperate Tri-ATHLETE robot to position its payload grapple device within reach of the airlock external platform
- Conduct EVA to remove the payload grapple from the Tri-ATHLETE
- Provide IVA remote monitoring of EVA
- Disassemble and clean payload grapple device, removing the broken and bent components
- Machine replacements for the broken and bent components
- Reassemble the payload grapple
- Conduct EVA to reinstall the payload grapple into the Tri-ATHLETE
- Provide IVA remote monitoring of EVA
- Teleoperate Tri-ATHLETE to its nominal position

8) While performing a repair EVA during the outbound cruise to Mars, a leak developed in one crew member's suit liquid cooling and ventilation garment (LCVG). Water is escaping the LCVG through several small slits and abrasions in the garment and is pooling in the helmet bubble, creating a safety hazard for the EVA crew member whose vision is obscured. Crew response actions include:
   - Terminate EVA and guide the at-risk EVA team member back inside the habitat
   - Provide IVA remote monitoring of EVA
   - Inspection of the suit and LCVG to locate and characterize each leak
   - Fabricate replacement segments for damaged sections of the LCVG
   - Cut away the damaged sections of the LCVG
   - Use a thermal or adhesive tool to fuse the replacement segments to the LCVG
   - Conduct a water leak test of the repaired LCVG

9) A crew member has a broken lower leg with severe bleeding and as part of treatment the following medical interventions will be performed:
   - Image the crew member's body (bones, vessels, organs, soft tissue) with at least one standard medical imaging modality
   - Control bleeding through direct pressure and tourniquet
   - Splint extremities
   - Wound closure
   - Measure, record, and trend vital signs
   - Perform full physical exam
   - Private audio and video consultation

10) An unconscious crew member is not breathing and as part of treatment the following medical interventions will be performed:
    - Image the crew member's body (bones, vessels, organs, soft tissue) with at least one standard medical imaging modality
    - Measure, record, and trend vital signs
    - Drain bladder (continuous/intermittent)
    - Clear obstructed airway with manual maneuvers and surgical airway management
    - Perform intubation
    - Suction airway and decompress stomach
    - Perform chest compressions
    - Provide breaths using manual and automated means
    - Provide and titrate oxygen via noninvasive/invasive means

11) A crew member has suffered an oral injury and as part of treatment the following medical interventions will be performed:
    - Image the crew member's jaw area (bones, vessels, organs, soft tissue) with at least one standard medical imaging modality
    - Control bleeding through direct pressure
    - Measure, record, and trend vital signs
    - Extract tooth
    - Replace lost filling or crown
    - Manage oral secretions

12) Contingency Triple Threat: A single debris strike has occurred on the pressure vessel hull near ECLSS subsystem pallets during a filter maintenance event causing three critical emergencies to occur all at the same time. The uninjured crew must respond to all three emergencies in parallel. They cannot focus on one at the exclusion of any other or complete one before starting the other.
    - Emergency 1: Pressure vessel penetration (cabin leak) from debris strike requiring immediate physical repair. Crew response actions include:
      - Locate pressure vessel penetration(s)
      - Retrieve leak repair kits
      - Move interior subsystems and other hardware blocking access to leak(s)
      - Conduct IVA patch / repair of leaks
      - Conduct EVA to external site of leaks
      - Provide IVA remote monitoring of EVA
      - Move exterior subsystems and other hardware blocking access to leak(s) and inspect damage
      - Coordinate external repair plan with Mission Control
      - Fabricate replacement components needed for EVA
      - Stage equipment for repair EVA
      - Conduct EVA to external site of leaks
      - Provide IVA remote monitoring of EVA

    - Remove exterior insulation and attached equipment to gain access to pressure vessel
    - Conduct permanent pressure vessel repair
    - Reattach exterior insulation and equipment
- Emergency 2: Shrapnel damage to ECLSS and Power subsystems pallets causing cascade damage to other subsystem components requiring immediate subsystems monitoring and commanding. Crew response actions include:
    - Command closed ECLSS and thermal valves that are causing consumables to be lost
    - Power down damaged systems
    - Reconfigure power distribution system
    - Reconfigure spacecraft systems to prevent additional damage (e.g. power down systems with no cooling, pumps with no fluid, etc.)
    - Bring back up critical systems that had lost power
    - Transport damaged pallets to the maintenance area
    - Disassemble and inspect damaged components
    - 3D print replacement plastic components
    - 3D print replacement metal components
    - Perform post-processing / finishing on 3D printed metal components
    - Machine replacement sheet metal and bar stock components
    - Assemble replacement components
    - Cut to size and solder replacement wiring
    - Reassemble and inspect pallets
    - Transport pallets back to subsystems area and reinstall
- Emergency 3: Life-threatening lacerations, concussion-induced unconsciousness, and electrocution to the crew member performing filter maintenance requiring immediate medical care. Crew response actions include:
    - Transport crew member to medical facility
    - Provide breaths using manual and automated means
    - Control bleeding through direct pressure and tourniquet
    - Wound closure
    - Treat electrical burns
    - Image the crew member's body (bones, vessels, organs, soft tissue) with at least one standard medical imaging modality
    - Measure, record, and trend vital signs

Crew Size Ratings

Table 7 indicates the average SME-recommended number of crew needed to respond to each contingency. The asterisk on the Contingency Triple Threat is to indicate a SME comment that an available number of crew of seven is only possible if no more than two crew are needed to transport an incapacitated crew member (including across vertical deck translations) with no assistance from other crew.

Clearly, scenarios that require more crew members than are onboard the habitat are a cause for concern as those could become loss of habitat or loss of life incidents. However, it is also worth noting if a scenario requires all or almost all of the onboard crew then there is little crew reserve. The response cannot tolerate an injury during the response that takes a crew member out of operation. It cannot tolerate any unexpected problems that require assistance. It cannot tolerate any unrelated actions that demand crew attention at the same time. In this regard, the four-crew variants do not perform well as a third of the scenarios overwhelm or threaten to overwhelm the crew.

Table 7. Average Number of Crew needed

	Average Number of Crew Needed
Fire	2
Cabin Leak	3
Toxic Atmosphere	2
Major Cabin Subsystems Failure	4
Wrecked Pressurized Rover Chassis	3
Inoperable Ascent Vehicle	2
Failed ATHLETE Robot	2
EVA Suit Failure	2
Broken Bone and Severe Bleeding	2
Breathing Event	2
Dental Event	2
Triple Threat	7*

The triple threat is an interesting scenario as it was created to intentionally break the system. It was actually conducted in a human-in-the-loop test in the wake of the cancellation of the Constellation program during the 2012 Habitat Demonstration Unit (HDU) Mission Operations Test (MOT). In that scenario, the HDU had been configured as a Deep Space Habitat (DSH) for a simulated mission to a Near Earth Asteroid (NEA).

The scenario was scripted in the MOT to occur during the simulated return cruise to Earth. In that architecture the Multi-Mission Space Exploration Vehicle (MMSEV – the in-space rover) had been left behind at the asteroid and the Orion capsule did not accompany the DSH. The only pressure vessels were the airlock – which was not large enough to serve as a safe haven – and the DSH cabin.

The MOT took the response a step further, allocating several test days for one crew member to use the General Maintenance Workstation to fabricate a replacement housing structure for a damaged electronics box using non-additive manufacturing and soldering capabilities.

That being said, the MOT also simplified several aspects of the scenario. The incapacitated crew member was injured within a few feet of the Medical Operations Workstation, virtually eliminating the incapacitated crew member transportation task and much of the medical response was very loosely simulated. The pressure vessel repair was also a very simple patch to a conveniently located place on the hull. And the fidelity of the HDU's computer systems and subsystem modeling and complete lack of physically mocked up subsystems limited the subsystem reconfiguration activity. Thus, while the MOT was able to complete this task with three operational crew it is a valid response from the SMEs to suggest a need for more crew members to respond.

The individual comments indicate some debate between SMEs as to number of crew needed and depending on assumptions it could have been as few as six or as many as nine. Several of the steps within each of the three emergencies were perceived as requiring either two or three crew and depending on the number that of course drove the total crew need. In no case did SMEs consider the triple threat survivable with a four-person crew and it is clear that the habitat will need to be designed to minimize the number of physical hands needed to respond to emergencies.

Acceptability Ratings

For each habitat, SMEs provided acceptability ratings for each of fourteen assessment statements for each habitat in each scenario. For each SME, the median acceptability values were computed to yield SME acceptability ratings for each habitat in each scenario. The ratings from each SME were then averaged to give the average median acceptability ratings in Table 8.

Table 8. Contingency Response Average Median Acceptability Rating

Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable	
No improvements necessary		Minor improvements desired		Improvements warranted		Improvements required		Major improvements required	
1	2	3	4	5	6	7	8	9	10

Contingency Scenario	Average Median Acceptability Rating			
	Four Crew Horizontal	Four Crew Vertical	Eight Crew Horizontal	Eight Crew Vertical
Fire	1.67	2.00	1.67	2.17
Cabin Leak	2.00	1.67	2.00	1.67
Toxic Atmosphere	1.00	1.00	1.00	1.00
Major Cabin Subsystems Failure	1.50	1.50	1.50	1.50
Wrecked Pressurized Rover Chassis	1.50	2.00	1.50	1.50
Inoperable Ascent Vehicle	1.50	1.50	1.50	1.50
Failed ATHLETE Robot	1.50	2.00	1.50	1.50
EVA Suit Failure	1.50	1.50	1.50	1.50
Broken Bone and Severe Bleeding	1.50	1.50	1.50	1.50
Breathing Event	1.50	1.50	1.50	1.50
Dental Event	1.50	1.50	1.50	1.50
Triple Threat	5.75	5.75	4.75	5.00

This table indicates in general how well each habitat performs in each contingency scenario. This table does not, however, confirm that the habitat definitively can respond to the contingency. For instance, the four-crew horizontal habitat has an average median acceptability rating of 5.75. This is a borderline response where improvements are clearly required, but when the individual assessment ratings are examined, there were ratings of 10, indicating that a specific aspect of the recovery could not be accomplished.

Table 9 is used to discern the presence of such instances where one or more individual assessments indicate problems responding to the contingency. For each SME, the maximum (or worst) acceptability value among the fourteen assessment statements was extracted to give a maximum acceptability rating for each habitat in each scenario. The ratings from each SME were again averaged to give the average maximum acceptability rating. This table indicates how bad the trouble spots are in each habitat's response to each contingency. Any rating below a three indicates that the habitat can comfortably respond to the scenario with no design modifications needed.

It should be noted that the acceptability ratings are driven by the design of the habitat. Thus, Table 7, Table 8, and Table 9 must be used in concert to determine the ability of each habitat to respond to contingency scenarios.

Table 9. Contingency Response Average Maximum Acceptability Rating

Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable	
No improvements necessary		Minor improvements desired		Improvements warranted		Improvements required		Major improvements required	
1	2	3	4	5	6	7	8	9	10

Contingency Scenario	Average Maximum Acceptability Rating			
	Four Crew Horizontal	Four Crew Vertical	Eight Crew Horizontal	Eight Crew Vertical
Fire	3.33	3.67	2.00	4.00
Cabin Leak	4.33	3.67	3.33	3.00
Toxic Atmosphere	3.00	3.00	3.00	3.00
Major Cabin Subsystems Failure	2.50	2.50	2.50	2.50
Wrecked Pressurized Rover Chassis	2.50	3.00	2.50	2.50
Inoperable Ascent Vehicle	1.50	1.50	1.50	1.50
Failed ATHLETE Robot	2.50	3.00	2.50	2.50
EVA Suit Failure	2.00	2.00	2.00	2.00
Broken Bone and Severe Bleeding	1.50	1.50	1.50	1.50
Breathing Event	1.50	1.50	1.50	1.50
Dental Event	1.50	1.50	1.50	1.50
Triple Threat	10.00	10.00	9.00	9.00

To rank the habitat variants, the maximum, minimum, and averages are computed for the data in each column in Table 8 and Table 9. With respect to average median acceptability ratings, the eight-crew horizontal habitat had the lowest (best) maximum and average values. All four habitats were tied for the lowest minimum values. With respect to average maximum acceptability, the eight-crew horizontal habitat had the lowest average value but was tied with the eight-crew vertical for maximum value. All four habitats were again tied for the lowest minimum values. In summary, the eight-crew horizontal is able to respond to contingencies better than the other three variants.

Additionally, SMEs commented that from a diversity of skills perspective (more expertise to respond to contingencies), a crew of eight is better than four.

8. HABITABILITY ASSESSMENT

The final assessment conducted to aid in the down-selection is habitability. Habitability is an assessment of working conditions and accommodations that are necessary to sustain the morale, safety, health, and comfort of the crew that contribute directly to astronaut effectiveness and mission accomplishment.

The Habitability Assessment conducted acceptability ratings in eleven major workstations and crew stations as well as in general stowage throughout the habitat and general layout. A total of 120 habitability characteristics were rated across the habitat in these areas. Participants were provided the same 2D imagery used by the other assessments, including both deck-by-deck views and views of individual working and living areas. Acceptability ratings are shown in Table 10.

Table 10. Habitability Assessment Ratings

Totally Acceptable	Acceptable	Borderline	Unacceptable	Totally Unacceptable
No improvements necessary	Minor improvements desired	Improvements warranted	Improvements required	Major improvements required
1 2	3 4	5 6	7 8	9 10

Habitability Category	4-Crew Horizontal	4-Crew Vertical	8-Crew Horizontal	8-Crew Vertical	Most Acceptable Habitat
Crew Quarters (CQ)	2.64	1.36	2.73	1.45	4-Crew Vertical
Waste Management Compartment	2.17	2.50	3.17	2.50	4-Crew Horizontal
Hygiene Compartment	1.88	1.88	3.75	1.88	4-Crew Horizontal (3-way tie with 4-Crew Vertical and 8-Crew Vertical)
Wardroom/Entertainment Area	2.86	1.71	3.00	2.29	4-Crew Vertical
Galley	2.83	1.67	1.83	1.67	4-Crew Vertical (2-way tie with 8-Crew Vertical)
Exercise	2.60	2.00	1.60	1.60	8-Crew Horizontal (2-way tie with 8-Crew Vertical)
Life Science	2.09	2.82	1.82	2.09	8-Crew Horizontal
Physical Science	2.09	2.91	2.00	2.18	8-Crew Horizontal
Maintenance Repair and Fabrication	3.83	2.83	2.50	2.83	8-Crew Horizontal
Spacecraft Monitoring and Commanding	3.17	2.83	2.00	2.00	8-Crew Horizontal (2-way tie with 8-Crew Vertical)
Medical	3.56	2.00	3.33	1.89	8-Crew Vertical
General Stowage - All Decks	3.67	2.33	2.33	2.50	4-Crew Vertical (2-way tie with 8-Crew Horizontal)
General Layout - All Decks	2.71	2.00	2.06	1.76	8-Crew Vertical

As a testament to the design of the individual variants, all habitation categories in all variants received average overall rating as acceptable with minor improvements or better. The four-crew horizontal received the most acceptable or tied for most acceptable in 2 of 13 habitation categories. The four-crew vertical received the most acceptable or tied for most acceptable in 5 of 13 habitation categories. The eight-crew horizontal received the most acceptable or tied for most acceptable in 6 of 13 habitation categories. Finally, the eight-crew vertical received the most acceptable or tied for most acceptable in 6 of 13 habitation categories.

Initially it might appear that the eight-crew horizontal and vertical are tied. When looking in detail at the data, differences do appear. The eight-crew vertical has a slightly lower average of acceptability scores, 2.05 versus 2.47. This is also true if looking at median, minimum, or maximum scores. However, the differences are not categorically different, with the exception of maximum. The maximum acceptability rating for the eight-crew vertical is 2.83, no improvements necessary. The maximum acceptability rating for the eight-crew horizontal is 3.75, minor improvements desired. Additionally, when looking only at the eight-crew habitats, the vertical is superior to the horizontal in seven categories; the horizontal is superior in four categories; and the two are tied in two categories. Crew quarters, hygiene, and medical were all clearly superior in the eight-crew vertical habitat. Thus, the eight-crew horizontal and vertical habitats are nearly equal in terms of habitability, with a slight edge going to the vertical.

9. CONCLUSIONS / RECOMMENDATIONS

Variant Selection

Based on these assessments a very clear rationale is present for selecting the eight-crew horizontal habitat to become the Common Habitat used in future studies.

There are a number of important insights gained from this analysis as well. Crew size was shown to have a more significant impact in these analyses than habitat orientation. Eight crew was clearly better than four crew. The eight-crew variants were more resilient to contingencies that threatened loss of mission or loss of crew. Additionally, missions in eight-crew variants were slightly more than twice as productive as two missions in four-crew variants.

Because habitat orientation scored relatively closely it is likely that orientation will be mission-specific, and the better orientation may change based on the specific needs of a given spacecraft. However, in the case of the Common Habitat, the vertical orientations proved slightly better for living functions and the horizontal orientations proved to be generally better for working functions. But overall, the majority of analyses favored a horizontal orientation for the Common Habitat.

Areas for Improvement or Monitoring

While the eight-crew horizontal habitat was identified as the best overall selection from among the four variants, there remain areas for improvement or monitoring. The other three variants all had areas where they demonstrated greater capability or acceptability. These analyses help identify areas of growth as the Common Habitat architecture is matured.

Stowage Assessment—For a 1200-day mission, the logistics modules are slightly overloaded at 102.5% capacity. Currently there are no identified missions in the Common Habitat architecture that require this duration, though one of the Mars mission opportunities comes close. It would be valuable to assess the habitability impacts of overfilling logistics modules and to examine the performance impacts of flying three logistics modules.

Functional Analysis—Improvements to the basic functionality of the Common Habitat will be beneficial in the areas of hygiene, waste management, logistics, private habitation, meal preparation, meal consumption, medical operations, and robotics and teleoperation.

Crew Time Assessment—The schedules used in the crew time assessment enabled a relative comparison, but there have been no NASA human-in-the-loop missions with an eight-person crew or in a habitat the size of the Common Habitat. A mission operations test in a medium fidelity or greater

Common Habitat mockup would be useful to validate the crew schedule.

Science Productivity Assessment—The outfitting of science hardware in the Common Habitat was notional at best for this assessment. As laboratory instruments are identified and placed, continuing studies should ensure that the lab configuration can be efficiently supported by the available crew.

Maintenance Capacity Assessment—At present, the tools and workspaces are only notionally represented. Potential interference with translation paths and options to contain generated dust and particulates are therefore difficult to assess. This will need to remain a watch area as the habitat is matured.

Contingency Responsiveness Analysis—SME comments in this assessment indicate a need to minimize obstructions or other inefficiencies in the maintenance workspaces. It is also important to be able to service both small and large components with a minimum of workstation reconfiguration.

Habitability Assessment—No aspect of the eight-crew horizontal scored higher (worse) than 3.75 (acceptable with minor improvements desired). Four areas did score between 3 and 3.75 and therefore will require minor improvements: waste management compartment, hygiene compartment, wardroom/entertainment area, and medical.

Implications for Common Habitat Architecture

Many key architectural questions could not be investigated while the Common Habitat's basic configuration was an unknown. These can be addressed now that the Common Habitat's basic configuration has been defined.

Launch Vehicle Shrouds—There are presently no launch vehicles that can deliver the Common Habitat to space without modification. From a mass performance perspective, both the NASA Space Launch System and the SpaceX Starship can launch the habitat to low Earth orbit, but neither have appropriately sized shrouds.

Lander Accommodation—While there has been Mars concept mission design work almost continually for decades and the Artemis program is currently competing lunar landers with private industry, no landers have been proposed with the specific intent of landing and offloading habitats the size and mass of the Common Habitat. In addition, the habitat will clearly have to be launched in a vertical orientation in the launch vehicle and it will have to be in a horizontal orientation once offloaded. Somehow, the lander will have to enable, perform, or not inhibit this change in orientation.

Surface Transportation—The lander will not land at the surface habitation site. Some system will be needed capable of transporting the Common Habitat from the landing site to its permanent location. The mass capacity of this transportation system may be the key driver that determines whether the Common Habitat can land fully outfitted or if multiple outfitting flights may be needed.

Surface Habitation Facility and Transit Spacecraft Incorporation—The Common Habitat is not a self-contained system. It requires external power, heat rejection, and communications. It must be attached to an external airlock. Logistics modules and visiting vehicles must dock to it. This is true for both surface and in-space configurations. These configurations can be designed to define how the Common Habitat fits into a broader architecture.

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This paper is dedicated to my aunt, Mrs. Joyce Marie Smith, who passed away at the age of 70 during the same period of time I was working on this paper. Aunt Joyce was a central presence in my childhood and while she might not have followed all of the technical details in this paper it would have thrilled her to no end to see it.

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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.