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Deep Space Habitability Design Guidelines Based on the NASA NextSTEP Phase 2 Ground Test Program

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Acronyms

AMCC	Analog Mission Control Center
BAA	Broad Agency Announcement
CAPCOM	Capsule Communicator
CDR	Commander
CO_2	Carbon Dioxide
CPR	Cardiopulmonary Resuscitation
CTB	Cargo Transfer Bag
DPC	Daily Planning Conference
EVA	Extravehicular Activity
FLIGHT	Flight Director
FY	Fiscal Year
GFE	Government Furnished Equipment
HALO	Habitation and Logistics Outpost
HEOMD	Human Exploration and Operations Mission Directorate
I-Hab	International Habitat
IFM	In-flight Maintenance
IRB	Institutional Review Board
ISS	International Space Station
JSC	Johnson Space Center
LLT	Low-Latency Teleoperations
MS	Mission Specialist
NASA	National Aeronautics and Space Administration
NextSTEP	Next Space Technologies for Exploration Partnerships
PAO	Public Affairs Office
PI	Principal Investigator
PWD	Potable Water Dispenser
RFID	Radio Frequency Identification
RMS	Remote Manipulator System
SME	Subject Matter Expert
SPE	Solar Particle Event
SRC	Sample Return Canister
TC	Test Coordinator
TCCS	Trace Contaminant Control System
TRR	Test Readiness Review
VIS	Vibration Isolation System
WCS	Waste Collection System

1 Introduction

This report summarizes habitation design guidelines for deep space habitats, which were derived from the NASA Next Space Technologies for Exploration Partnerships (NextSTEP) Phase 2 Habitat Ground Test Program. All data presented in this document have been contractor-deidentified and approved for public release. The report prioritizes capabilities and recommends allocating those capabilities to either the Habitation and Logistics Outpost (HALO) or the International Habitat (I-Hab). A review of the design guidelines is presented in the main body of the report, along with a list of the 170 specific design guidelines with references to the specific data sources from which they were derived.

Five government contractors each developed a ground-based prototype of the Gateway habitation system; the purpose of the NextSTEP Phase 2 Ground Test Program was to evaluate how the capabilities, layouts, and design features of these prototypes enhance the mission and crew performance. To accomplish this, astronaut test subjects conducted the same representative multiday core Gateway mission in each contractor's ground-based prototype habitat, while also performing unique tasks that highlighted various aspects of each habitat design, such as in-flight-maintenance tasks and tests of various new technologies.

The core mission timeline was developed with input from NASA subject matter experts (SMEs, Appendix A.1.1) and included exploration objectives from the Human Exploration and Operations Mission Directorate (HEOMD) and the International Space Station (ISS) Exploration Capability Study Team. The resulting ground test objectives were incorporated into functional tasks, which were then structured to represent a Gateway mission timeline. During each test, the core timeline was augmented with unique tasks that were conducted in a sequence that maximized crew performance in each contractor's unique layout. Each mission timeline was approved by the contractor before the testing began.

Four NASA astronauts evaluated each prototype. At least 2 of the astronauts overlapped between each test, ensuring a consistent evaluation. To increase the fidelity of the mission simulation, The NASA Flight Operations Directorate provided a flight director, a capsule communicator (CAPCOM), and a planner to support each test by providing flight-like communication and an operations tempo. All test subject crews were trained on the rationale and objectives of the testing, including familiarization with the equipment, methods, and metrics, and they participated in an in-house NASA dry run test (Appendix A.2.1).

Objective and subjective data were captured throughout each test. Objective metrics included the planned versus the actual time to complete objectives (Appendix A.3.8), and crewmember location frequency distribution within the habitats (Appendix A.3.9). The location frequency distribution data were collected using the AllTraq system, which was used to track the amount of time each crewmember spent in pre-defined functional zones of the habitat while executing the mission timeline. The resulting data provided insight into how the crew used the space and how efficiently they performed tasks in different areas of the habitat, as well as identified areas of the habitat that were under-utilized and could potentially be re-purposed or eliminated.

The astronaut test subjects provided subjective evaluations of the simulation quality and acceptability of each of the habitation elements (ranging from no improvements necessary to improvements desired, warranted, or required). Additionally, to prioritize the cost benefit of implementing the capabilities, the test subjects determined if the capabilities were essential or offered significant, moderate, marginal, or no enhancement for the mission. A pairwise comparison of capabilities was also performed to discriminate the relative importance for capabilities that received the same rating. The test subjects also evaluated the layout of each design and recommended the best location and quantity for each habitat system, including crew quarters, hygiene areas, waste collection system (WCS) areas, exercise areas, galley, galley table, trash management, multipurpose workstations, science workspaces and surfaces, gloveboxes, medical workspaces and surfaces, crew common areas, and logistics stowage.

The astronaut test subjects provided both individual and consensus ratings of simulation quality and acceptability. Individual ratings collected throughout each test provided contextual information and insightful comments; however, inferential statistics using individual ratings from an n of 4 is not meaningful, so the test subject crew also performed a consensus evaluation at the end of each test day. The consensus evaluation ensured that each test subject interpreted the questions consistently, and it allowed them to discuss and judge, using their prior experience, how microgravity might affect operations. The consensus evaluations were considered the actionable results.

Appendix A describes the details of the rigorous process by which the study objectives and mission timelines were generated, how the tests were executed, and how the data were collected and analyzed. The investigators assimilated the data from evaluations of each habitat, and a summary of the recommendations for the layout and the design of a deep space habitat are presented in this document, along with the priority for incorporating the capabilities, and the best location for allocating each function. These design guidelines were assessed in the context of a 30-day or a 60-day Gateway mission; however, some of the recommendations for general layout and specific features of habitation systems could apply to longer duration missions. All design guidelines recommended in this report were vetted by the astronaut test subjects and the NASA Astronaut Office. A summary of the design guidelines is provided in Appendix B Table 4.

2 Capability Assessment Prioritization

The primary objective of the NextSTEP Phase 2 Ground Test Program was to identify the capabilities that are required for exploration missions, the nonessential capabilities that might enhance exploration, and the capabilities that provide marginal or no meaningful enhancement and can therefore be excluded, resulting in cost savings without impact to mission success. The astronaut test crews used a 10-point Likert capability assessment scale that has been used extensively in the past to rate capabilities that might enable and enhance future exploration missions (Figure 1). The scale consists of 5 categories: essential/enabling (impossible or highly inadvisable to perform the mission without this capability); significantly enhancing (capability is likely to significantly enhance one or more aspects of the mission); moderately enhancing (capability is likely to moderately enhance one or more aspects of the mission or significantly enhance the mission on rare occasions); marginally enhancing (capability is only marginally useful or useful only on very rare occasion); and little to no enhancement. At the conclusion of each habitat test, the astronaut crew provided capability assessment ratings for 20 candidate Gateway capabilities for mission durations $\leq$ 30 days and up to 60 days. Figure 1 shows the assimilated capability assessment ratings from all evaluations for mission durations ≤ 30 days and up to 60 days; note these are not ranked in order. These evaluations provide a cost-effective approach to prioritize the capabilities that will provide the most impact to the mission; other less enhancing capabilities can be added as resources (e.g., time, money) allow.

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

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

Figure 1. Assimilated capability assessment ratings (not a rank order) from all contractor tests for missions ≤ 30 and 60 days; capabilities rated essential/enabling and significantly enhancing are boxed in red.

2.1 Capability Assessment Ratings for Missions ≤ 30 Days

Essential/Enabling: Four capabilities were rated essential and enabling for missions ≤ 30 days: *a hardwired multipurpose workstation for critical commanding*, a *trash removal capability on at least a per mission basis*, *a viewing window (not a virtual window)*, and *an additional WCS separate from Orion*. At least one *hardwired multipurpose workstation* was considered essential for flight safety because wireless critical commanding was not considered sufficiently reliable. *Trash removal on at least a per mission basis* was deemed essential because continually stowing trash on the Gateway for a year or more could result in both unfavorable living conditions and systems contamination. *A viewing window* was also considered an essential capability because it provides operational safety during dynamic events (e.g., robotics and docking situational awareness) through direct visual situational/spatial awareness, it also allows photography opportunities for science and public outreach, and it enhances crew morale. *An additional WCS separate from Orion* provides a backup should the Orion WCS malfunction; such a malfunction could result in termination of the mission depending on the timing of the WCS failure. Furthermore, the Orion WCS only has 5-liter tank for waste water, and if used as the primary WCS, would require at least daily waste water dumps in the direction of the stack and lander. A second WCS that is separate from Orion will provide flexibility for crew to perform simultaneous WCS operations, saving time and enhancing crew performance.

Significantly Enhancing: Four capabilities were rated significantly enhancing for missions ≤ 30 days: *private crew quarters*, *a dedicated hygiene area, an additional galley separate from Orion, and separate wet and dry trash stowage*. For shorter duration missions, e.g., early in the assembly of the Gateway, temporary sleep accommodations would be acceptable, assuming that permanent crew quarters would be provided later. However, daily deployment and stowing of sleep stations takes time and, depending on their location, they could interfere with ongoing tasks. *A dedicated hygiene area* (i.e., enclosed) was rated significantly enhancing even for short-duration missions because this will mitigate cross-contamination with other habitation and work areas and will provide privacy without interrupting nominal operations. It is much less desirable to perform hygiene activities in a common space or in other dedicated areas such as private crew quarters due to the risk of cross-contamination, and it is unacceptable to conduct hygiene-related tasks in the WCS compartment. *An additional galley separate from Orion* adds substantial efficiency over what can be provided by Orion, including the potential for additional food prep options (i.e., potable hot and cold water) and a common gathering area to eat together. *Separate wet and dry stowage* would be significantly enhancing because wet trash results in more odor and contamination risk than dry trash, and it requires a solution for ventilation and odor mitigation.

Moderately Enhancing: Eight capabilities were rated moderately enhancing. *Dedicated labeled stowage areas* were determined to be moderately enhancing and were preferred over *bungees and cargo transfer bags (CTBs)* because strapping CTBs to pallet fronts, or wherever space allows, has become untenable on the ISS. *A permanently installed exercise station* would limit the time needed to setup and stow exercise devices each time a crewmember exercises. *A WCS on a different deck/module from the galley* would limit cross-contamination between "dirty" areas (e.g., hygiene, WCS, exercise) and "clean" areas (e.g., galley, crew quarters, science, and medical). *Two or more multipurpose workstations* (with the assumption that both are hardwired) were rated as moderately enhancing because of the strong desire to have a backup to support critical commanding. This capability could also be implemented with a laptop or tablet computer for systems monitoring in wireless mode or could be plugged into a hardwired receptacle for critical commanding. An *exercise station separate from other volumes in the habitat* would limit cross-contamination of "clean" areas (e.g. science, galley, medical, crew quarters). *A dedicated science area* was rated moderately enhancing, but the necessity and dedicated space aspect is highly dependent on the specific science objectives of the mission. A *common secondary structure interface* may reduce the number of tools required for reconfiguration, payload installation, or in-flight maintenance (IFM). A *galley/ward room table for 4 crewmembers* is not essential; however a volume large enough for all crew to gather comfortably is important for crew productivity and morale.

Marginally Enhancing: Four capabilities were rated marginally enhancing. A *circadian cycle lighting system* may improve sleep and mood for some crewmembers. *A dedicated medical area* was rated only marginally enhancing, particularly for medical treatment, as long as there is multi-use space provided elsewhere that can accommodate medical tasks. *Two exercise stations* were deemed unnecessary because operations can be planned to accommodate all 4 crewmember's daily exercise without the need to have them exercise in parallel (and assuming a single exercise device could accommodate both cardiovascular and resistive exercise). A *single (i.e., 30-day) mission's worth of logistic stowage in the habitat* was deemed unnecessary because no more than a week's worth of logistics plus critical spares would be needed in the habitat; additional logistics can be retrieved from the logistics module. For conventional smaller habitats, the additional logistics volume could be used to improve layout and add additional capabilities such as permanent crew quarters and windows. The large inflatable habitats have sufficient volume for more than a week's worth of logistics without compromising layouts and capabilities; this extra volume could be useful to accommodate unutilized spares and utilization elements as logistics modules are changed out.

Little to No Enhancement: No capabilities were rated as having little to no enhancement.

2.2 Capability Assessment Ratings for 60-day Missions

A comparison of capabilities assessment ratings for ≤ 30 and 60 days are shown in Figure 1. Several of the habitation capabilities were rated as providing greater enhancement for 60-day missions than for 30-day missions. *Private crew quarters*, and *an additional galley separate from Orion* became **essential/enabling.** The following capabilities became **significantly enhancing:** *dedicated labeled stowage areas vs. bungees and CTBs, a permanently installed exercise station, a WCS on a different deck/module from the galley*. The following capabilities elevated to **moderately enhancing**: *a circadian cycle lighting system, two exercise stations*. The remaining **marginally enhancing** capabilities remained the same.

2.3 Pairwise Comparison of Capabilities

After the astronaut test subjects rated the capabilities, they conducted a pairwise comparison of these 20 capabilities. This pairwise comparison discriminates the relative importance of capabilities that received the same rating, and results in a rank order of most-to-least important capabilities; note, however, that just because a capability is ranked lower, it does not mean that it is not mission enhancing.

Overall, the top-ranking capability was a *hardwired multipurpose workstation for critical commanding* and the lowest ranking capability was *a single (i.e., 30-day) mission's worth of logistics stowage in the habitat*. Furthermore, the eleven highest ranked capabilities for missions of 60 days were all rated essential/enabling or significantly enhancing (highlighted in the red box in Figure 1).

3 Function Allocation Recommendations for the Habitation and Logistics Outpost and International Habitat

The capabilities defined in Table 1 were rated *essential* or *significantly enhancing* and represent the recommended minimum set of capabilities required for the Gateway mission. The crew provided their preference for the location and quantity of these capabilities within the dual habitat Gateway reference stack containing the Habitation and Logistics Outpost (HALO) and the International Habitat (I-Hab) (Table 2); additional capabilities, namely those with assessment ratings > 4 (as shown in Figure 1), were desirable if they could be implemented. Note that the astronauts test subjects recommended this function allocation be included if no limits exist with respect to time, resources, or money; it is recognized that in reality some limitations may exist that preclude the inclusion of all of these capabilities. A strong common theme across all 5 habitats was the desire to separate clean and dirty functions. For the HALO and I-Hab, this translates into a "clean" habitat and "dirty" habitat, where the dirty habitat contains the WCS, hygiene, and exercise areas.

Table 1. Definitions for Each Essential/Enabling and Significantly Enhancing Capability

Capability	Definition
A hardwired multipurpose workstation for critical commanding	A workstation for performing robotics, critical commanding, and subsystems checks
Trash removal capability on at least a per mission basis	A capability to remove trash from the Gateway at least once every 30 days rather than stowing it long-term
A viewing window (not a virtual window)	A window with a view of the Earth/Moon at some portion of the orbit; also able to support monitoring of robotic and visiting vehicle operations
An additional WCS separate from Orion	A separate, enclosed WCS area
Private crew quarters	Four private crew quarters that are ideally permanent vs. deployable
An additional galley separate from Orion	A galley area for rehydrating/warming meals
A dedicated hygiene area	An separate, enclosed hygiene area that is not co-located with the WCS
Separate wet and dry trash stowage	Separation of wet and dry trash stowage along with the ability to contain wet trash odors for the duration of their storage
Dedicated labeled stowage areas vs. bungees and CTBs	Dedicated volume solely for logistics storage of both high frequency use items (i.e., items used at least once per week) and low frequency use items (i.e. items used once or less per 30-day mission) along with a deterministic system for stowing and retrieving items.
A permanently installed exercise station	A permanently installed exercise station
A WCS on a different deck/module from galley	A separate, enclosed WCS area that is in a different deck/module than the galley
Multipurpose Payload/Work Surface Area	A reconfigurable work surface/area with available power/data/fluids connections to support a variety of payloads (e.g., medical and science tasks)

Table 2. Capability Allocation Recommendations for HALO and I-Hab

Capability	Quantity in HALO (“dirty hab”)	Quantity in I-Hab (“clean hab”)
A hardwired multipurpose workstation for critical commanding	1	1
Trash removal capability on at least a per mission basis	1	1
A viewing window (not a virtual window)	1[A]	1
An additional WCS separate from Orion	1	0
Private crew quarters	0[B]	4[C]
An additional galley separate from Orion	1[D]	1
A dedicated hygiene area	1	0
Separate wet and dry trash stowage	1	1
Dedicated labeled stowage areas vs. bungees and CTBs	1	1
A permanently installed exercise station	1[E]	0
A WCS on a different deck/module from galley	1[F]	0
Multipurpose Payload/Work Surface Area	1	2

[A] include if possible since rated as essential for a mission of any length
[B] include, if possible; for initial short missions, temporary deployable sleep quarters would be acceptable
[C] four permanent and private crew quarters
[D] minimal galley for short-duration missions (potable water dispenser and/or food warmer)
[E] can be deployable for HALO-only missions and permanent for HALO + I-Hab missions
[F] acceptable not to meet this for HALO only missions

4 Habitat Design Guidelines

Individual (proprietary) reports that included the detailed analyses of all objective and subjective data were provided to the contractors and NASA headquarters at the conclusion of each ground test. The habitat design guidelines presented below were derived from the assimilated data from all assessments. Data from the acceptable and unacceptable habitat elements have been mapped to corresponding design guidelines, with the unacceptable elements being as significant as the acceptable elements in informing design guidelines. Whereas existing design standards were followed by all contractors, those design standards are traditionally focused on individual crew tasks and workspaces. These tests offered the opportunity to evaluate contractor-provided integrated designs that represented a balance between human factor task and workspace design and engineering and operational constraints, and, as such, represent a unique set of integrated design guidelines and recommendations. The resulting guidelines are generally applicable to all deep space missions and specifically to Gateway missions of ≤ 30 days and up to 60 days; any guidelines that are specific to particular mission durations are stated explicitly (e.g., deployable versus permanent crew quarters and exercise stations). The habitat design guidelines presented below are provided in the order of general habitat layout followed by habitation systems (e.g., crew quarters, hygiene stations, etc.) and then work systems (e.g., multipurpose workstations, dedicated science workspaces, etc.).

4.1 General Layout

Habitat layout and volume are important factors in the acceptability of the habitat design. In general, the results of this test suggest that layout can be more important than volume; i.e., a smaller, properly laid out volume is generally more acceptable than a larger, poorly laid out volume. However, additional volume (provided it is properly laid out) can enable better separation of function to minimize interference between crewmembers, prevent cross-contamination, and provide more room for privacy and more separation for noise abatement. Additional volume also enables duplicate functional areas to be incorporated, which saves time, improves efficiency, and provides contingency options in the event of hardware or subsystem failures. Large habitat designs (e.g., with multiple decks) result in more open translation paths and less interference between crewmembers; their deck-to-deck translation paths for personnel and equipment are shorter and thus can be more efficient than translation through linked modules. However, multiple standard smaller habitat modules could also provide sufficient volume and might provide an additional redundancy advantage (although unless they are virtually identical with a full Environmental Control and Life Support System) and all the necessary functions to execute mission objectives, the loss of one smaller module could have mission-degrading impacts up to and including loss of mission (the same is true for loss of a single larger habitat).

Habitat layouts should separate "clean" and "dirty" functional areas. "Clean" areas include crew quarters, galley, and science and medical workspaces. "Dirty" areas include the WCS, hygiene, and exercise spaces. Locating "dirty" areas near one another (e.g., a hygiene station next to an exercise area) mitigates cross-contamination when crewmembers move between these areas. Cross-contamination can be further mitigated by strategically locating the floors, walls, pallets, and other barriers in the galleys, exercise, and medical areas. Smooth surfaces more easily facilitate cleaning. All areas of the habitat that must be cleaned should be easily accessible. Separate accommodations for wet and dry trash stowage with odor mitigation should be provided; if possible, wet trash and WCS waste should be vented directly into trace contaminants incinerators for odor control. Where practical, long-term trash stowage should be located in a separate module with a sealable hatch. Trash should be removed at least once every 30 days.

All habitation and work areas must have sufficient stability aids (e.g., handholds, foot restraints, and body restraints), mobility aids (including an adequate mounting structures), and temporary stowage accommodations (e.g., Velcro, bungees, nets, and caddies). The specifics of each should be dictated by the work functions to be performed in each area and the individual layout of the area (see Sections 4.2 through 4.17); for example, a large amount of appropriately sized temporary stowage accommodations should be provided near hatches for staging cargo during transfer of logistics between modules (e.g., between an arriving logistics vehicle and the primary habitat). The size and location of stability and mobility aids and temporary stowage should be adjustable to accommodate individual crewmembers working in the area in multiple orientations, and they should provide enhanced flexibility for microgravity operations.

The ability to reconfigure all habitat modules (i.e., the ability to move pallets, payloads, and/or entire functional areas within each module or between modules) allows for flexibility as the Gateway is assembled and as Gateway objectives and mission durations change. A common secondary structure (e.g., mounting points, tracks, interfaces, fasteners, pip pins) throughout the habitat module(s) reduces the number of different tools needed on board and overall crew overhead. In smaller habitats, deployable work surfaces can better utilize the available space, but they require mounting tracks, power and data ports, deployable task lighting, adjustable stability aids (e.g., foot and body restraints), and temporary stowage accommodations. The size and orientation of work surfaces should also be adjustable.

Dedicated, labeled storage areas for short-term and long-term stowage of high-frequency and low-frequency use items is needed to accommodate payloads, spare parts, wet and dry trash, waste from WCS, and personal items. A simple, clearly defined coding scheme that references the item's location should be implemented so crewmembers can quickly and reliably locate items.

A viewing window (not a virtual window) should enable viewing of the Earth, Moon, and rendezvous and robotic operations (because direct viewing increases safety); due to the expected orientation of Orion on the Gateway stack, the Orion windows will be insufficient. A window also provides photography opportunities for science and public outreach and enhances crew morale. An omni-directional viewing window is preferred over a planar view port, with additional benefits if it can be relocated to different ports based on operational drivers.

4.2 Crew Quarters

Private quarters should be provided for each crewmember. For missions ≤ 30 days, the crew quarters can be deployable; for missions > 30 days, crew quarters should be permanent. The crew quarters should be co-located with other "clean" areas of the habitat (e.g., galley, science workspaces, and medical workspaces); hygiene tasks should be performed in separate, dedicated spaces to limit cross-contamination (Section 4.3).

Each crew quarter should incorporate a rigid enclosure and door, light and sound proofing, adjustable ventilation (air flow speed and direction that is adjustable for personal preference and to mitigate CO_2 buildup), caution and warning indicators (audible and visual), power and data connections (for laptops, tablets, task lighting, general charging), peripheral mounts (for laptops and tablets), customizable mood and spot lighting (relocatable, adjustable color/brightness), flexible temporary stowage (e.g., Velcro, bungees, nets, caddies), adjustable sleeping bag positioning (both orientation and location within the crew quarter), and direct access to any additional personal crew stowage lockers from within the crew quarters. Adjustable aids for stability and translation should be provided to accommodate crew activities such as working on a laptop/tablet, changing clothes, reading, and watching entertainment. The dimensions of the crew quarters should be at least 30" wide x 30" deep and > 78" long to comfortably accommodate crewmembers, while accounting for on-orbit spinal elongation.

4.3 Hygiene Stations

At least one dedicated, enclosed hygiene station should be provided. This area should be separate from other functional areas, including the WCS and crew quarters, to prevent cross-contamination; the crew quarters should remain dry, and the WCS should be reserved for WCS operations. The hygiene station(s) should be co-located near other "dirty" areas in the habitat; locating one next to the exercise area minimizes the need for crewmembers to pass through the habitat after they exercise and reduces the risk of sweat contaminating other areas. Each hygiene station should be permanent, private, easy to clean, and sufficiently ventilated. The hygiene enclosure should have rigid walls and a door; all surfaces should be slick, smooth, and non-porous to repel water, facilitate easy cleaning, and prevent bacterial growth. To ensure privacy, the door should be securable to prevent it from inadvertently opening if bumped.

Adjustable stability aids for body, hands, and feet are required, as is temporary stowage accommodations (e.g., to include cleanable and removable caddies for stowage of shampoo, soap, etc.).

Long-term stowage of hygiene-related items should be available outside the hygiene station to prevent cross-contamination and to facilitate cleaning of the interior of the station.

Hygiene station dimensions should be a minimum of ~45” wide x 30” deep x 78” tall. An asymmetrical cross-section can provide a sufficient anthropometric work envelope for hygiene tasks (e.g., a 45” x 30” rectangle is more useful than a 37.5” x 37.5” square). The dimensions should accommodate taller crewmembers when they change and wash their hair, while also accounting for crewmembers’ on-orbit spinal elongation. The volume should provide adequate space to move the body and maintain positions required during showering and should be tall enough to accommodate crewmembers with long hair (note that long hair floats in 0g and should not contact the enclosure during washing). A portion of the hygiene station could be deployable, allowing it to expand as needed for crewmembers to change clothes or wash long hair.

4.4 Waste Collection System

At least one private, dedicated WCS separate from Orion should be provided. The WCS(s) should be co-located with areas where other “dirty” functions are performed. Each WCS should be permanent, private, easy-to-clean, well ventilated, and separate from the hygiene station. The WCS enclosure should have rigid walls and a door; all surfaces should be slick, smooth, and non-porous to repel water, facilitate easy cleaning, and prevent mold growth. To ensure privacy, the door should be securable to prevent it from inadvertently opening if bumped. The enclosure should provide sound abatement. The WCS itself should be appropriately located within the enclosure to enable adequate space to position the body while using the WCS and have sufficient space to access all sides when conducting maintenance.

Adjustable stability aids for hands and feet should be provided in front and to the sides of the WCS itself. Temporary stowage accommodations are needed for items such as toilet supplies and urine funnels and should be easily reachable while performing WCS operations. Separate, long-term storage of WCS related wet trash and waste should be provided within the WCS enclosure or in a temporary canister that is then combined with all wet trash and stowed elsewhere; this stowage should be vented directly into the trace contaminant control system (TCCS) to catalyze and absorb odors, rather than allowing odor to leak into the cabin atmosphere. The WCS enclosure should have task lighting that is adjustable to assist crewmembers during cleaning, maintaining, and servicing the WCS.

WCS compartment dimensions should be a minimum of ~40” wide x 30” deep x 78” tall to accommodate taller crewmembers while also accounting for on-orbit spinal elongation.

4.5 Exercise

Guidelines for exercise are dependent on the prescribed protocol for inflight exercise, including the type (e.g., cardio, resistive), frequency, and duration, as well as the specific hardware to be used. The exercise device may need be mounted on a vibration isolation system (VIS), therefore additional space to accommodate a VIS should be considered. The following recommendations are made based on evaluations using the Hopper (a NASA government furnished equipment [GFE] ground prototype resistive exercise device), a full range-of-motion volumetric assessments, and the assumption that all crewmembers will exercise daily for a minimum of 30 min. For missions

≤ 30 days, a deployable exercise device is acceptable, provided adequate volume is available to perform all required exercises and operation does not interfere with other crewmember activities. For missions > 30 days, the exercise equipment should be permanently installed in a dedicated area to avoid setup and stow before and after each use. The exercise station should be located in close proximity to other "dirty" areas of the habitat. Positioning the exercise station near a hygiene station limits the distance crewmembers need to translate to clean up after exercising, thereby reducing the risk of cross-contamination within the habitat. Power connections should be provided nearby for viewing laptops, tablets, or personal electronics, and temporary stowage accommodations and adjustable mounts should be within reach for exercise gear, water bags, and towels. A window near the exercise area could allow external viewing during exercise. Adequate ventilation should be provided to prevent CO_2 buildup and to allow for temperature and humidity control. The dimensions of the exercise area will be dependent on the flight exercise equipment and exercise protocol but should accommodate the tallest crewmembers while they perform a full range of motion for all exercises.

4.6 Galley and Galley Table

An additional galley separate from Orion should be provided for missions of any duration. The galley should be located near other "clean" areas of the habitat and be separated from "dirty" areas to prevent cross-contamination. For missions of ≤ 30 days, a minimal galley that includes a potable water dispenser (PWD) and possibly a food warmer is sufficient. For missions of > 30 days, additional galley features are desirable, such as hot and cold PWDs, food warmers, cold storage, local stowage for one week's worth of food, and a galley table large enough for all crew to gather together to eat a meal. Simple PWD interfaces should be used (e.g., the needle-captured septum used in previous spacecraft including the Space Shuttle and ISS, or others). Food warming systems should incorporate swing-open doors and not long pullout drawers, which require additional space and stability aids to access. Food should be stowed near the galley and readily accessible while the PWDs and food warmers are being used and while crewmembers are gathered at the table. The galley table should be no smaller than the table on the ISS (e.g., at least 22" wide x 50" long when fully extended), allowing all crewmembers to gather and eat together, and it should be located where it does not interfere with other critical workspaces (e.g., it should not inhibit access to a multipurpose workstation used for critical commanding). The table may be deployable.

Stability aids should be provided for use when operating the PWDs and food warmers and to enable all crew to "sit" at the table. Sufficient local temporary stowage should be provided to accommodate items required for meal preparation and consumption and should include the ability to stow multiple small items, such as condiments, food packets, and utensils. Separate wet and dry trash stowage should be provided in or near the galley; this could be implemented by attaching trash bags directly to the galley table (e.g., as is done to the handrails along the ISS galley table). The galley table could also be used as a common gathering area for crewmembers to perform work or for entertainment; therefore, easily accessibly power/data connections and mounts (e.g., for laptops, tablets, task lighting, etc.) should be provided; crewmembers should also be able to access the primary galley functions (e.g., PWD, food storage, etc.) while other crewmembers are working at the galley table. All galley surfaces should be easy to clean.

4.7 Trash Management

Weekly removal of trash is highly desirable; removing trash at least every 30 days is critical. Trash must be collected, stowed, isolated, and disposed of effectively to control odors and mitigate risk of cross-contamination. For effective trash management, wet and dry trash should be collected and stowed separately. Wet and dry trash containers should be provided near areas where trash is generated, eliminating the need to move it long distance. Routine planned trash management should include consolidating trash and moving it to long-term stowage locations. Dedicated areas are required for stowing biological waste (non-WCS) and sharps (e.g., needles, catheters) to prevent exposure to biohazards. If trash needs to be stowed long-term, it should be located outside of the main habitation areas (e.g., inside a rarely used logistics module compartment). Note that if trash is stowed inside the logistics module, odors will leak into the habitat every time the logistics hatch is opened. This could be mitigated by having a dedicated wet trash compartment that has a one-way, grommet-style door to seal the trash. Trash should be vented directly into the TCCS to absorb and catalyze odors rather than allowing odor to leak into the cabin atmosphere. A method should be provided to remove trash from the Gateway at least once every 30 days (e.g., via a trash ejection capability). If a trash ejection capability is available, the ejection velocity should ensure that the trash does not re-contact any element of the Gateway stack. A volume of approximately 36 ft^3 is needed to store the typical amount of wet and dry trash, excluding WCS waste, accumulated during a 30-day mission.

4.8 Multipurpose Workstations

At least one hardwired multipurpose workstation must be provided to ensure reliable critical commanding; a second hardwired multipurpose workstation can be provided as a backup and to accommodate parallel operations. Wireless workstations or tablets are not acceptable for critical commanding; they are acceptable for monitoring and status checks. Access to critical commanding workstations should not be blocked at any time. To help ensure that operators can provide precise inputs (e.g., stack commanding, robotic manipulator system operations), workstations should be positioned away from heavy traffic/high-use areas to avoid inadvertent interference from other crewmembers who are passing or are conducting other tasks nearby. If critical commanding and robotics operations need to occur in parallel, there should be sufficient space for 2 crewmembers to work in parallel.

Workstation monitors and hand controllers should be adjustable, in both the vertical and depth directions and in tilt, to accommodate variability in crew height and ergonomic preferences as well as right- and left-handedness; adjustments should be easy, quick, and require no tools. Adjustable foot restraints (that also require no tools to adjust) should be provided to enable the crewmember to position themselves effectively and comfortably in relation to displays, keyboards, and hand controllers. Handholds, adjustable arm rests, and body restraints may be needed for additional stability during delicate hand control movements. Separate hand controllers should be used for translation and rotation; each controller should have stick forces that enable precise inputs and an easily identifiable central detent that provides no input.

If touchscreen workstation displays are used, the touchscreen feature should have a lock feature; when this feature is unlocked, a firm touch input should be required to prevent inadvertent commands if a crewmember accidently brushes against the screen. Furthermore, critical functions accessed through a touchscreen should have a manual back-up method (e.g., bezel buttons, keyboard inputs, mouse inputs) in the event that the touchscreen capability malfunctions. Regardless of whether inputs are provided via touchscreen, bezel button, keyboard, or mouse, immediate feedback (e.g., visual, audible, and/or tactile indicators) should be given indicating that the input has been accepted to avoid inadvertently inputting multiple commands. Any lag between an input and execution of a command should be minimized.

Small work surfaces, mounts, and temporary stowage accommodations (e.g. Velcro, bungees, nets, pockets, etc.) should be provided near multipurpose workstations to accommodate checklists, notebooks, and tablets; corresponding power and data connections for laptops, tablets, and task lighting should also be provided.

4.9 Dedicated Science Workspaces and Surfaces

Depending on intended science tasks, dedicated science workspaces and surfaces might not be required as long as sufficient multipurpose workspaces and surfaces are provided; at least one multipurpose work area should be available for science during shorter missions. Multiple multipurpose work areas should be provided for longer duration missions to allow for parallel science and/or medical tasks. Workspaces and surfaces used for science should be grouped with other "clean" areas to mitigate the risk of cross-contamination from "dirty" areas. Note that some science tasks could be considered "dirty" (e.g., animal-based research experiments), and it should be possible to isolate these tasks within the science work area (e.g., inside a glovebox that can be thoroughly cleaned). Deployable workspaces are acceptable if proper interfaces to secure them are provided, including, for example, standoffs that accommodate vertical loads on the surface. These workspaces can be deployed into full, half, and quarter sizes to accommodate different needs.

Workspaces that accommodate science should have smooth, non-porous surfaces that repel liquids for ease of cleaning. Accommodations for temporary stowage of wet, dry, and biohazard trash should be provided (as applicable). Adjustable stability aids (i.e., foot restraints and handrails) should be provided to allow different sized crewmembers to appropriately position themselves in relation to the work area. Temporary stowage (e.g., Velcro, bungees, pockets, caddies) should be available at the workspaces to accommodate the science tools and instruments, including various small items. Power and data connections and adjustable mounts for laptops, tablets, task lights, and science equipment should also be provided.

4.10 Glovebox

If a glovebox is used for science and operations (e.g., maintenance) tasks it should be able to be thoroughly cleaned. A glovebox does not need to be permanently deployed unless it will be used regularly (e.g., at least once per week); it could be deployed in a multipurpose work area when needed and stored in a logistics module when not in use. The latter approach would allow the volume otherwise dedicated for a glovebox to be allocated to other, higher priority functions.

The area around an installed glovebox should allow access to all glove ports and nearby work surfaces, mounts, and data connections should be available for tablets, laptops, and notebooks. Adjustable stability aids (e.g., foot and body restraints) should be provided so that the installed height of the glovebox accommodates a range of crew heights and arm lengths. Access within the glovebox should accommodate the reach of all crewmembers; all locations inside the glovebox should be reachable, including the back and side walls, airlock access port, instruments (e.g., microscope), and tools. Furthermore, power/data connections, adjustable lighting and temporary stowage accommodations for tools, samples, equipment, etc., should be provided both inside and outside the glovebox. Other considerations include the potential need for an ultraviolet bulb to assist in sterilizing, viewing reagents, etc., and an ultra-pure water source could be built into the glovebox for molecular and/or biomedical work.

4.11 Dedicated Medical Workspaces and Surfaces

Dedicated medical workspaces and surfaces for crew medical diagnostics and treatment are not necessarily required if sufficient multipurpose work areas are provided; at least one multipurpose work surface should be available for medical use for missions of any duration. It is desirable to have audio privacy for medical conferences (e.g., private crew quarters). Multiple multipurpose work areas should be provided for longer duration missions to enable parallel science and/or medical tasks. Workspaces used for medical tasks should be grouped with other “clean” areas of the habitat to mitigate the risk of cross-contamination from “dirty” areas (e.g., exercise, WCS, hygiene). At least one multipurpose workspace should allow a patient to be restrained to a surface with enough space for at least one other crewmember to access the patient from all sides. Adjustable stability aids (e.g., foot restraints and handrails) should be provided around the patient to enable a non-patient crewmember to conduct medical care, including cardiopulmonary resuscitation (CPR). Workspaces that accommodate medical tasks should have smooth, non-porous surfaces that repel liquids for ease of cleaning. Temporary stowage (e.g., Velcro, bungees, pockets, caddies) should be available that accommodate all expected medical tools and instruments. Additionally, separate wet and dry trash receptacles, sharps containers, and biohazard bags need to be located near the patient. Power and data connections and adjustable mounts for laptops, tablets, task lights, and medical equipment should also be provided.

4.12 Crew Common Area

An area large enough for all crewmembers to gather provides positive morale benefits to the individual and to the team. This area could be integrated into other areas (e.g., the galley table) or could have its own dedicated volume if space is available. Large, high-resolution viewing screens in this area could be used for planning meetings, videoconferencing, public outreach, press conferences, displaying views from external Gateway cameras (which could provide a psychological benefit, but are not a substitute for windows), and entertainment (e.g., watching movies). Power/data connections and adjustable mounts (for screens, additional lighting, laptops, tablets, etc.) should be provided. Adjustable stability aids should be available that allow crewmembers to comfortably view the screens and to interact with each other. All lights in nearby areas should be adjustable (including an option to turn them off) to avoid glare and unwanted reflections.

4.13 Logistics Stowage and Location Referencing

Dedicated logistics stowage volume, as well as a logical, concise coding scheme that references the location of items should be incorporated into initial habitat designs. The habitat should have dedicated stowage for one week's worth of consumables (approximately 85-95 ft^3 for food and clothes), frequently used items, and critical spares; these items should be located close to the areas in which they will be used (e.g., food should be stored near the galley). The remaining items should be stored in the logistics module, thereby freeing up space in the main habitat. CTBs should be stored no more than one layer deep for easy identification and retrieval; if accessible from both sides, CTBs can be stored 2 layers deep. Transparent sides of CTBs would ensure that the contents are easily verified while stowed and upon retrieval. CTBs can be secured with crossover elastic straps or bungee cords that keep bags in place and allow individual bags to be removed to access specific items. Elastic straps or bungees are preferred over large cargo nets, which make it difficult to access individual bags without unstowing others.

A stowage tracking system (e.g., radio frequency identification [RFID], scanner, camera, etc.) as well as a clear and concise coding scheme should be implemented to assist crewmembers in locating items. The location reference scheme should include a definitive grid (i.e., radial, horizontal/vertical) that uses simple letters and/or numbers; colors or icons can also be included for simplicity. The same location reference scheme should apply to all equipment in all work and habitation areas. The reference scheme should be labeled throughout the habitat modules in multiple locations, so it is easy to see from any location within each module. Stowage bags and containers should have a clear, concise numbering scheme with labels that are visible on all sides when the bags are in their stowage location.

There should be a sufficient number of temporary stowage accommodations in all areas and surfaces of habitat (e.g., Velcro, bungees, tethers, caddies, etc.), as detailed in the other functional work and habitation area sections. Additionally, temporary stowage staging areas should be located near the hatches for cargo bags being transferred from and to visiting vehicles as they arrive and depart the Gateway.

4.14 Lighting

Both general and task (i.e., spot) lighting should be available throughout the habitat. Brighter overhead general lighting in each module and each functional area should help the crewmembers orient themselves with the workspace (i.e., in the heads-up/nadir-zenith direction). Simple on/off switches paired with brightness and possibly color control should be available in each module and also in areas with critical or overlapping tasks. Both fixed and mobile task lighting should be provided. Fixed task lights, with the same level of controllability as general lighting, should be installed in each compartment (e.g., WCS, hygiene, glovebox). Mobile, adjustable task lights (adjustable position, orientation, and brightness) that can be moved and installed wherever work is necessary (e.g., during maintenance tasks) should also be provided. When dedicated lighting is required in certain areas of the habitat for specific purposes (e.g., plant growth lights), protective eyeglasses or the ability to block, dim, or turn off the lights should be provided when crewmembers are required to work in close proximity. Private crew quarters should have an option to completely darken them inside. Automatic or manual circadian lighting to facilitate day/night cycles may benefit the health and performance of some crewmembers. Additional guidelines for lighting design for each functional area are described in their respective sections above.

Caution and warning lighting, paired with audible indicators, should be provided throughout the habitat. A "smart" subsystem caution and warning indicator lighting system would allow crewmembers to readily distinguish subsystem failures. In cases where an emergency evacuation is necessary, translation path lighting should lead the way to Orion.

4.15 In-flight Maintenance

Ground test evaluations included the assessment of representative IFM tasks; note that testing did not evaluate IFM of the habitat as a whole. Habitat designs should enable simple and efficient in-flight maintenance. All subsystems that may need IFM should have adequate physical and visual access to replace components, including for mating/demating power, data and fluids connectors. Where needed, systems that enable access to all sides of subsystems should be implemented (e.g., "drawers" that allow pallets to first be pulled out and then rotated for better access). Common tool kits, and/or interfaces that require no tools, would minimize the tools required on board and can make IFM more time efficient. Dedicated subsystem IFM kits will reduce the time needed to gather supplies; this is particularly important for time-sensitive maintenance tasks, such as pressure vessel leaks. The operator performing the maintenance task should be able to view and access all relevant fasteners and interfaces. Common relocatable multipurpose work surfaces with movable temporary stowage that can be affixed where needed during maintenance tasks should be provided. A multipurpose temporary stowage caddy with elastic pouches, Velcro, etc. could provide temporary movable storage that is independent of the work surface itself and could better accommodate tools, parts, and equipment. Mobile and adjustable stability aids (i.e., hand and foot restraints) and task lighting are also required; these should be able to be secured wherever maintenance is needed.

4.16 Radiation Protection

All crewmembers must have rapid access to adequate protection from solar particle events (SPEs). While SPE protection could be provided through a variety of different means (e.g., by the external shell of the habitat, individual radiation "suits" that crewmembers don during radiation events, or a dedicated radiation shelter within the habitat), the following guidelines are specific to isolated SPE shelters constructed within the habitat. Note that due to programmatic resource limitations, the ground test did not evaluate overall protection due to galactic cosmic radiation.

The shelter does not need to be permanently deployed within the habitat; the crew could construct it when needed. If the SPE shelter is constructed as needed, all necessary components (e.g., water tiles, compacted trash tiles) should be easily identifiable, and the crew should be provided with simple construction plans that clearly denote where each component is to be placed. Since SPEs may last for several days, the crew must have the ability to perform essential personal and operations functions within the shelter (e.g., the ability to eat, sleep, perform basic hygiene and WCS ops, and conduct critical commanding). However, if these functions cannot be performed inside the shelter, the radiation shelter should be constructed in close proximity to areas were the functions can be performed to limit the amount of time that crewmembers must be outside of the shelter (e.g., a single exit/entry point with direct access to the WCS). The shelter should also contain ventilation, power, and data connectivity (e.g., for lighting and laptops/tablets, including a hard-wired monitoring/commanding interface), and methods for securing sleeping bags, and accommodations for temporary stowage. Privacy barriers (e.g., curtain, door) within the shelter should be provided for privacy during activities such as changing clothes.

4.17 Multipurpose Airlocks

Modules can be designed to provide habitation functions (e.g., exercise and science) and to serve as an airlock for extravehicular activity (EVA). Airlocks for EVA generally have both an equipment lock (where EVA preparation and post EVA activities occur) and a crew lock (where suited crewmembers egress and ingress the spacecraft). Normally the equipment lock does not go to vacuum pressure, but a pressure vacuum could occur if the interior crew lock hatch fails to seal. Thus, any habitation-related equipment in the equipment lock that cannot tolerate a vacuum must be moved to other modules during EVA preparation activities. Sufficient volume and stability aids must be provided in the equipment lock to mount 2 EVA suits and to accommodate up to 4 crewmembers working on and around the suits simultaneously. The suits should be accessible for donning (upward through a hard upper torso or through a rear-entry hatch) and mounting of all necessary EVA tools and equipment on the suits. Stowage volume and accommodations (permanent and temporary) should accommodate all necessary EVA tools, equipment, suits, and umbilicals. Umbilicals must be long enough to reach from the interior of the crew lock to any location in the equipment lock. Any permanent (e.g., lockers) or temporary stowage (e.g., Velcro, bungees) accommodations must accommodate suit servicing kits, crew preference items, tools, etc., within the equipment lock during EVA prep and post operations. Crew lock umbilical interfaces and restraints currently used on ISS should be provided.

5 Conflicts of Interest

None of the investigators or stakeholders receive any research support from non-public sponsors of research. They do not perform any validation research of a drug or device. They do not receive any gifts or income from individuals associated with these research studies. They do not use their positions or proprietary or confidential information obtained in performing their duties, in any marketing, investing, or commercial ventures.

6 Funding

Funding for the project and associated testing has been provided by NASA's Advanced Exploration Systems via the NextSTEP Phase 2 program.

Appendix A: Ground Test Background and Methods

The NASA NextSTEP program is a public-private partnership model that seeks commercial development of deep space exploration capabilities to support human spaceflight missions around and beyond cislunar space [1]. The NextSTEP Phase 2 Broad Agency Announcement (BAA) invited 5 commercial companies to refine their cislunar habitation concepts and to develop ground-based prototypes for evaluation by NASA astronaut test subjects [2]. The NASA ground-test protocol covered all aspects of these evaluations, including the hypotheses, strategic questions, objectives, methods, and metrics by which the Phase 2 habitation concepts were consistently evaluated during integrated, multiday mission simulations [3]. In Fiscal Year (FY)18, 2 engineering test runs and 2 evaluations by astronaut test subjects were conducted at NASA Johnson Space Center (JSC) on 2 NASA-developed habitation configurations to train the astronaut crews and ground-test team, and to refine the data collection and evaluation methods. Additional 1-day evaluations by astronaut crew were conducted in early FY19 to increase the astronaut test subject pool. These evaluation dry runs were conducted to ensure informed and consistent assessment of the contractor deliverables in FY19.

The NextSTEP Phase 2 ground tests each involved 4 NASA astronauts performing a multiday mission timeline that integrated all habitation operations (e.g., eating, sleeping, WCS operations, exercise) and representative science and robotics tasks relevant to future Gateway missions (e.g., low-latency teleoperations [LLT] rover operations, life science tasks, medical evaluations); some tests included EVA tasks (e.g., airlock configuration, prep/post EVA operations). All mission timelines included a core set of NASA-defined tasks (Appendix A.2.3 Table 3) in addition to several tasks that were specific to each contractor's design and based on the contractor's unique design deliverables. Established objective and subjective metrics were collected and analyzed to provide data-drive actionable recommendations for Phase 3 of the NextSTEP program. The overall purpose of this assessment was not to select a single specific configuration, but to provide data and recommendations regarding how habitation, science, and EVA functions can be acceptably distributed across the elements of the Gateway. Data from these tests are also used to define the minimum acceptable configurations, as well as a variety of options for hybrid configurations that offer the highest levels of acceptability (though some of these may not be achievable due to practicalities). The resulting datasets obtained from the FY19 evaluations were assimilated and analyzed to define a range of acceptable Gateway habitation options, including elements and distributions of function across those elements (Sections, 2, 0, and 4). The following subsections provide a brief overview of the test methods, study design, and evaluation metrics used to generate these final recommendations for habitat design.

A.1 Study Design

Since 2008, the core ground test team for the NextSTEP Phase 2 habitation concepts evaluations has successfully conducted multiple evaluations of spaceflight analog missions using a consistent set of operational products, tools, methods, and metrics to enable the iterative development, testing, analysis, and validation of evolving exploration architectures, operations concepts, and vehicle designs. This has been achieved by ensuring that the required level of rigor and consistency is applied before, during, and after the operational tests so that the data collected remains highly relevant to NASA's strategic architecture and technology development goals, and provides data-driven, actionable recommendations. Key points of this methodology include:

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

A.1.1 Mission Timeline Development

The core Gateway mission timeline was derived from a rigorous process that is described in detail in the ground test and analysis protocol [3]. Briefly, ground test objectives were developed by mapping the HEOMD exploration objectives, the ISS Exploration Capability Study Team phase objectives, and the capability test objectives to representative functional requirements for the Gateway. Ground test objectives were then defined to evaluate how well different Gateway configurations address each of the representative functional requirements. These objectives were further refined using recommendations provided by NASA SMEs and stakeholders, and ultimately formed the common baseline used to consistently evaluate each contractor's concept for habitation. Figure 2 provides a flow diagram of this process.

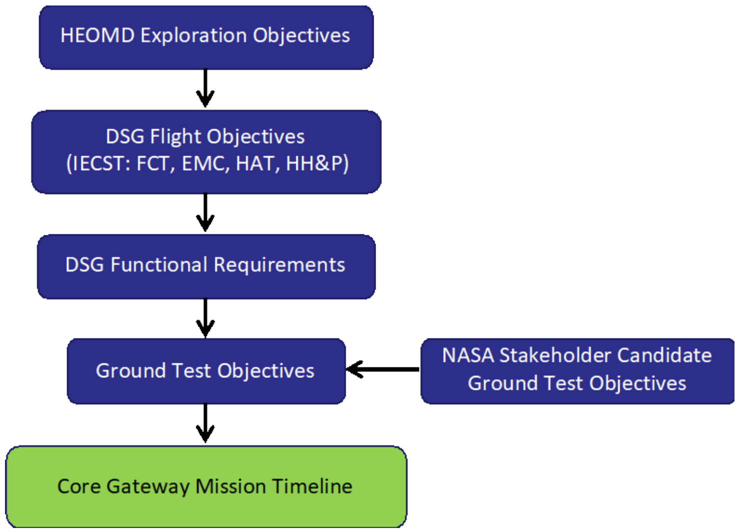

Figure 2. Flow diagram for developing the core Gateway mission-representative timeline.

The timeline for evaluating each habitation concept was developed by integrating multiple ground test objectives into functional tasks and structuring them into a representative mission (Figure 3). A core set of timeline tasks were completed across all contractor's designs to ensure consistency across all tests. Contractor-specific tasks were also included in the timelines if specific aspects of a contractor's unique habitat design and layout could not be evaluated with the core set of NASA tasks. Table 3 provides a high-level summary of the NASA-provided, core Gateway mission timeline tasks that were conducted consistently across the different contractor's habitat designs.

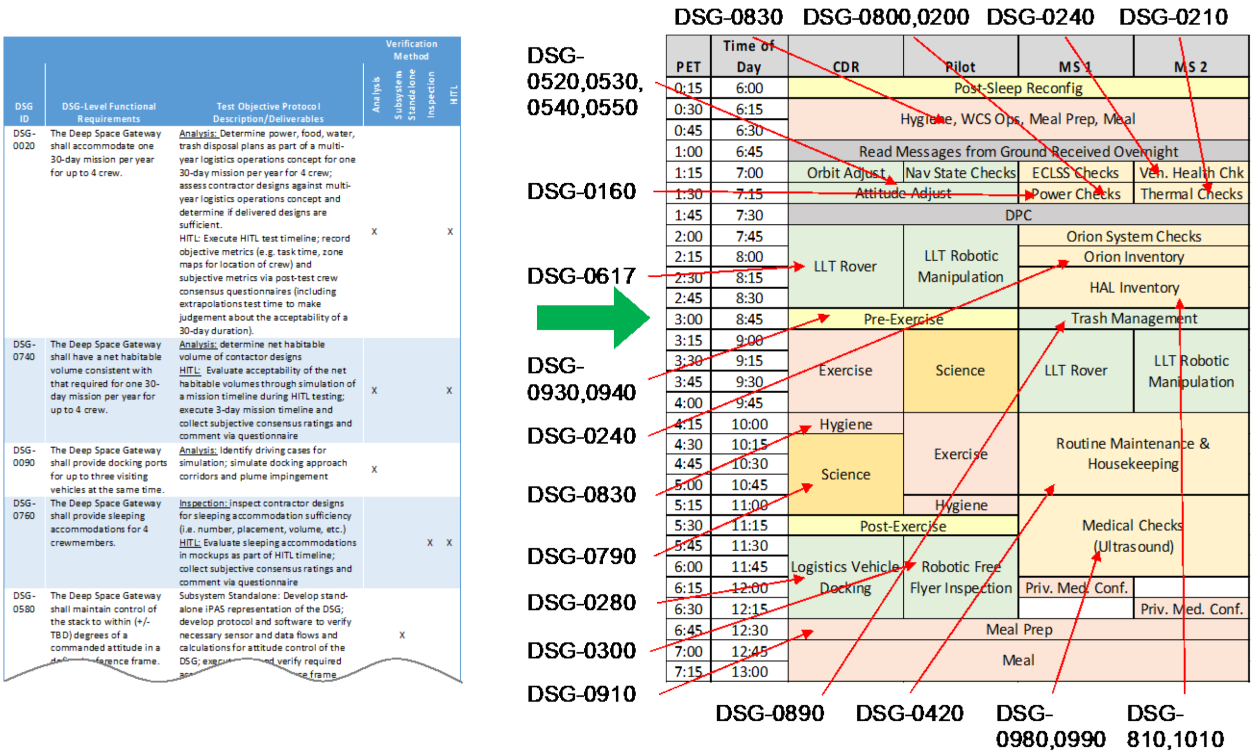

Figure 3. Mission timeline task derived from and mapped to draft Gateway functional requirements and objectives.

Table 3. NASA Core Timeline Tasks with High-level Task Summaries

Category	Task	Task Description
Habitation	Crew Quarters Operations	Perform pre- and post-sleep activities in the crew quarters, including getting dressed, working on a laptop or tablet, reading, and watching entertainment. Simulate sleep. Evaluate the number, location, layout, volume, and privacy of the available crew quarters for sleep and pre-/post-sleep activities.
	Waste Collection System (WCS) Operations	Simulate use, maintenance, and cleaning of the WCS. Evaluate the number, location, layout, volume, and privacy of each WCS.
	Personal Hygiene	Perform personal hygiene tasks including changing clothes, shaving, taking a shower, and washing hair. Evaluate the ability to conduct personal hygiene tasks in the habitat; include considerations for privacy. If a dedicated hygiene station is available, consider the quantity, location, layout, volume, and ability to clean the station.
	Exercise	Conduct volumetrically representative resistive exercises. Evaluate the ability to conduct exercise, including sufficient volume for the unstowed and stowed equipment.
	Meal Preparation & Consumption	Prepare and eat a meal. Evaluate the ability for multiple crewmembers to prepare food and eat simultaneously based on the available galley and galley table features.
	Housekeeping Tasks	Gather locally stowed trash and move it to the long-term stowage location. Conduct routine housekeeping tasks, such as cleaning walls, doors, enclosures, surfaces, etc. Evaluate trash management and the ability to conduct housekeeping tasks; include considerations for accessibility.
	Radiation Shelter	Construct a radiation shelter. Evaluate the radiation shelter location, volume, layout, accessibility, and usability to continue habitation and work operations from within the shelter.

Category	Task	Task Description
	Stability/Mobility Aids and Temporary Stowage	Evaluate the location, type, usability, and availability of stability aids, mobility/translation aids, and temporary stowage accommodations throughout the habitat.
Systems Checks	Habitat Consumables and Subsystems Checks	Check status of habitat consumables, power subsystem, and environmental control and life support system subsystem. Evaluate the quantity, location, layout, volume, and usability of the workstations for conducting these tasks.
Operations Planning	Daily Planning Conference (DPC)	Conduct a DPC with the Mission Control Center (MCC) team. Evaluate the location, volume, and elements needed (e.g., workspaces for taking notes, etc.) for all crewmembers to conduct this task together.
Robotic and Telerobotic Operations	Gateway Stack Attitude Adjustments	Simulate commanding the Gateway stack into a new attitude by navigating attitude telemetry, inputting a new state, and monitoring the progress of the adjustment on a multipurpose workstation. Evaluate the location, volume, layout, and usability of the workstation.
	Low-Latency Teleoperations (LLT) Rover Simulation	Perform a high-fidelity physics LLT simulation of a lunar rover moving through a congested rock field with the goal of reaching a sample return ascent vehicle. Evaluate the location, volume, layout and usability of the workstation including hand controllers for performing LLT.
	LLT Robotic Manipulation Simulation	Perform a high-fidelity physics LLT simulation of robotic manipulation that requires precise rotational and translational control. Evaluate the location, volume, layout and usability of the workstation, including hand controllers for performing LLT.
	Robotic Manipulator System (RMS) Transfer Simulation of Sample Return Canister (SRC) to Science Payload Airlock	Robotically retrieve a lunar sample container from an arriving SRC; grapple the sample return vehicle with the robotic arm and retrieve the SRC using the RMS. Evaluate the location, layout, volume, and usability of the workstation including hand controllers for performing robotics operations.
Science	SRC Processing Glovebox	Retrieve the SRC from the Science Payload Airlock, prepare the SRC for Earth-return inside the glovebox, and stow for return-to-Earth. Evaluate the location, layout, volume, and usability of the glovebox and associated areas for conducting the task.
	Lunar Traverse & Sample Collection Simulation	Navigate a lunar region of interest to find specific rocks within a boulder field that are desired by Earth-based scientists. Evaluate the location, layout, volume, and usability of the workstation including hand controllers for performing this task.
	Telescope Observations Simulation	Point an externally mounted Gateway telescope at specific targets on the Earth, Moon, and Sun and take pictures at specified times throughout the mission. Evaluate the location, layout, volume, and usability of the workstation for conducting telescope observations.
	BioMolecule Sequencer	Collect environmental samples and extract bacterial DNA using a mini-DNA sequencer. Evaluate the ability to conduct this lengthy, complicated science task while other crewmembers are performing other parallel tasks nearby.
	Muscle Ultrasound	Perform an SME-guided ultrasound scan of a crewmember's leg muscles. Evaluate the location, volume, layout, and usability of the workspace available to conduct this science research task.
	Vein Ultrasound	Perform an ultrasound-guided intravenous catheter insertion into a phantom arm. Evaluate the location, volume, layout, and usability of the workspace available to conduct this science research task.
Medical	Personal Health Checkout	Conduct a personal health checkout, including heart rate, blood pressure, temperature and pulse oximetry. Evaluate location, volume, layout, and usability of the workspace available to conduct this routine medical assessment.

Category	Task	Task Description
	Private Medical Conference	Conduct a conference call with a flight surgeon on the ground to review results from the personal health checkout. Evaluate the location and privacy available for this call.
Reconfiguration	Logistics Reconfiguration	Retrieve one week's worth of stowage from the logistics module and transfer it to contractor pre-defined locations within the habitat. Evaluate the location(s), volume(s), availability, accessibility, and organization of stowage areas within the habitat for both short-term and long-term stowage, as well as low-frequency use and high-frequency use stowage. Evaluate interference with other crewmembers performing activities during logistics transfers.
	Extravehicular Activity (EVA) Preparation and Post-EVA Operations	Reconfigure the airlock module from "habitation mode" to "EVA airlock mode." Evaluate the location, volume, layout, accessibility, and usability of this area for conducting EVA preparations and post-extravehicular activities.
PAO	Public Affairs Office (PAO) Event	Conduct a PAO event with the ground. Evaluate the location, volume, layout, and usability of the habitat to support this event while other crewmembers are conducting parallel tasks.

A.2 Ground Test Execution

A.2.1 Test Personnel Roles, Responsibilities, and Training

Each ground test was designed to provide a high-fidelity simulation of a cislunar mission, including the use of astronaut test subject crews and mission control personnel. All test subjects were recruited from the NASA Astronaut Office and included astronauts who have flown in space and astronaut candidates. These astronaut test subjects were assigned the roles of Commander (CDR), Mission Specialist-1 (MS1), Mission Specialist-2 (MS2), and Mission Specialist-3 (MS3). Timeline tasks were typically conducted by 2 crewmembers together: CDR and MS1 were paired, and MS2 and MS3 were paired. All subjects participated in training sessions at JSC that included the rationale and the objectives of the testing, and hands-on familiarization with the equipment, methods, and metrics. The crewmembers also participated in at least one engineering dry run of a Gateway-representative mission timeline that used NASA-developed habitation elements, and they completed individual and consensus questionnaires evaluating their experiences (see Appendix A.3). During the week before each test, the crew assigned to the test received a 1-hr briefing on the contractor's habitation concept and the unique timeline tasks, and the protocol principal investigator (PI) reviewed the proper process for completing the questionnaires. The day before the first Mission Day, the crew trained for approximately 6 hours on the contractor-unique timeline tasks inside the contractor's ground-based habitat.

The ground tests took place at either a NASA center or a contractor facility and were supported by NASA Flight Operations Directorate flight controllers and SMEs in the NASA JSC Analog Mission Control Center (AMCC) in JSC Building 30. The AMCC enables experts to coordinate, monitor and execute test activities within JSC and at remote locations, and consists of individual consoles with multi-monitor computer workstations. The consoles are linked by a high-speed data network, and each is identified by the call sign of the operator who uses it. During the mission days, the AMCC was staffed by a flight director (FLIGHT) who oversaw all activities during the test, a CAPCOM who communicated directly with the astronaut test subject crewmembers, a planner who supported the generation of timelines, and at least one SME who provided support for each task. The ground tests were further supported by a network of out-of-simulation personnel who ensured the test was running in accordance with the objectives outlined in the protocol and provided hardware, software, and network troubleshooting support if needed. The protocol principal investigator (PI) was responsible for ensuring tasks and questionnaires were completed according to the priorities of the protocol, and made real-time decisions if operations ran off-nominal. This individual coordinated with the test coordinator (TC) and relayed critical decisions directly to the Flight Director if needed. The TC was responsible for coordinating all out-of-simulation activities with the test architecture support personnel and for relaying relevant information to the PI; he or she assisted the PI with real-time decision making and managed the flight rules timer (described below). Test architecture support personnel were present at both the test site and in the AMCC to ensure crew workstations, AMCC consoles, and communication networks were functioning properly. All AMCC personnel and test execution and support personnel participated in the same JSC-based dry runs as the astronaut test subjects.

A.2.2 Communication

Two-way communication (including voice, text, video, and data) was exchanged between test subject crews and AMCC personnel. All audio, video, data, and text traffic traveled across the NASA Space Network Research Federation network and was managed by several out-of-simulation console support personnel to ensure connectivity. Communication protocols that mirrored ISS communication procedures were established between the astronaut crew test subjects and CAPCOM and between FLIGHT and SMEs. All in-simulation and out-of-simulation personnel were trained on communication "best practices" for use during each test. VCOM® software (IntraCom Systems, LLC) provided the communication loops that enabled conversations among the crew, AMCC, and test personnel:

- **Flight –** coordination loop between FLIGHT and SMEs (and Protocol PI when needed).
- **S/G-1, 2, 3, 4, 5 –** space-to-ground loops to communicate with the crew. CAPCOM was the nominal voice to the crew, and these conversations primarily occurred on S/G-1. SMEs listened to S/G-1 at all times. On a task-specific basis, FLIGHT could direct SMEs to talk directly to the crew (e.g., for complex procedures) on the S/G-2, 3, 4, 5 channels. S/G-2, 3, 4, 5 assigned specifically to individual crewmembers.
- **S/G-M1, M2 –** medical 1 and 2 loops dedicated to private medical conferences between individual crewmembers and the SURGEON.
- **Intercom Loop –**internal crew coordination loop inside the habitat only.
- **Plan Coord –** loop for communicating with the Planner.
- **SME Coord –** loops for SME teams to communicate with each other.
- **Test Loop –** out-of-sim coordination between TC and test team.

A.2.3 Timeline and Procedure Management

Playbook, a crew timeline management and execution tool [4], was used by each crewmember on each Mission Day. Execute notes and detailed procedures were developed for each task and linked into Playbook. Execute notes served as high-level reminders for the purpose of that particular task with respect to the study objective. Procedures were displayed through the procedure execution tool ProX so that crewmembers could step through each procedure step automatically and the MCC and SMEs could follow along in real-time with the crew as they completed the steps. Figure

4 shows a representation of the crew timeline with tasks organized for each crewmember, task execute notes, and corresponding ProX procedure.

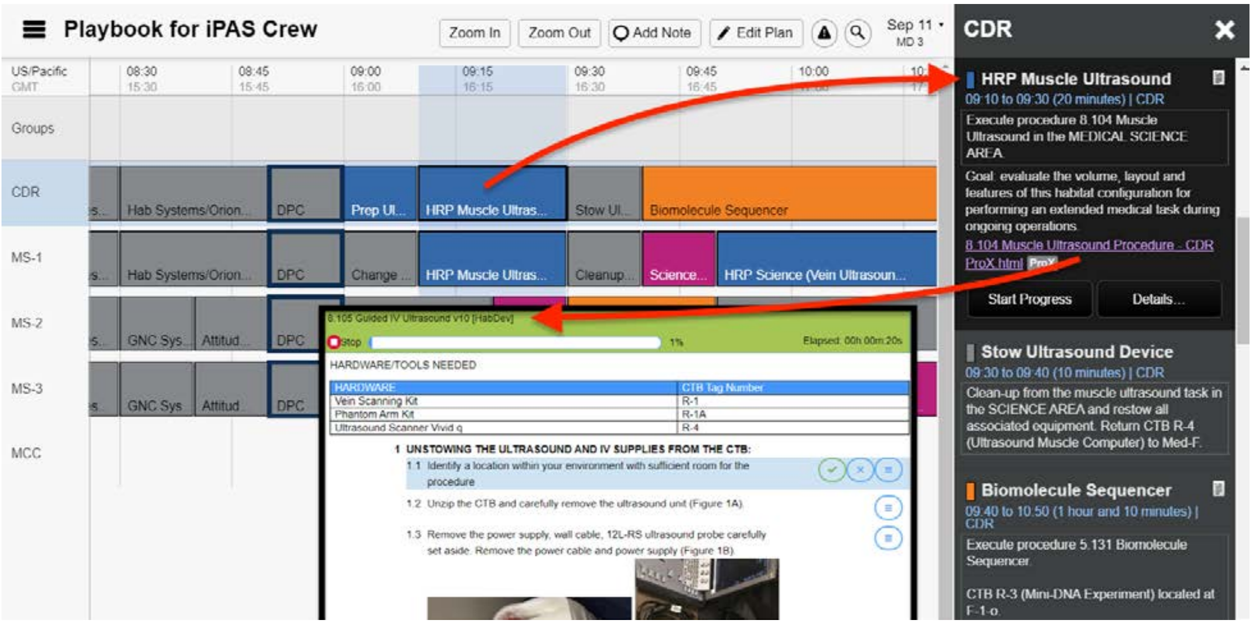

Figure 4. Playbook integration of crew timelines and procedures.

A.2.4 Test Execution Flight Rules

The following flight rules were implemented to troubleshoot issues with communication, hardware, and simulation:

1. Space-to-ground voice communication troubleshooting: The communication team can spend up to 10 min troubleshooting the communication network, while testing continues in parallel if possible. After 10 min, the following backups will be employed:
   - If Crew ←→ AMCC communication is down and the crew is not directly communicating with an SME: the backup local CAPCOM (at the test site) will temporarily communicate with the crew. Once communication is restored, the Protocol PI will provide a recap and handoff back to the JSC AMCC. If Crew ←→ backup local CAPCOM communication is down: backup local CAPCOM opens hatch and talks direct to crew.
   - If Crew ←→ AMCC communication is down and the crew is directly communicating with an SME: SME talks direct to crew via cell phone.
2. Physical hardware troubleshooting: Up to 2 individuals can enter the mock-up to conduct troubleshooting for up to 2 h (assuming minimal test interference during this time). If there is a complete hardware failure that takes more than 10 min to resolve, the crew will be instructed by CAPCOM (via Protocol PI) either to move to the next task or to wait.
3. Simulation troubleshooting: The simulation team can spend up to 10 min troubleshooting. If the sim cannot be fixed in 10 min, CAPCOM will direct the crew to standby until FLIGHT talks with the Protocol PI, who determines how to proceed.

A.2.5 Test Readiness Review and Institutional Review Board Approvals

A test readiness review (TRR) was completed and approved before to each test. The TRR included a detailed hazard analysis and safety inspection of all facilities and equipment used in that test. Members of the TRR board included safety and medical officers, facility managers, TCs, and the protocol PI. Furthermore, all testing was conducted in accordance with the pre-approved NASA JSC Institutional Review Board (IRB) protocol #STUDY00000040. Before to the start of each test, all astronaut test subjects were informed of the test termination criteria and means by which their privacy and the confidentiality of their data would be maintained. They provided informed, written consent to their participation in each study.

A.3 Metrics and Data Analysis Methodology

Subjective and objective data related to test crew performance, human factors, and habitability were collected throughout each test. Subjective metrics included capability assessment, pairwise comparison of capabilities, simulation quality, acceptability, and measures of fatigue and workload. These metrics have been developed, refined, and vetted by the core ground test team over the past decade and have been successfully used to evaluate habitability, human factors, and human performance aspects of candidate spaceflight vehicles [5-8] and other operations concepts for future human exploration-class missions [9-17] to derive actionable results and recommendations for future iterations and tests. Objective metrics include planned versus actual timeline data and crew location over time within each contractor’s mock-up. Objective data inform the subjective results (and vice versa).

The astronaut test subjects provided both individual and consensus ratings of capability assessment, simulation quality, and acceptability. Whereas individual ratings provide contextual information and insightful comments, the use of inferential statistics from individual ratings for an n = 4 is not meaningful, therefore test subjects also provided a crew consensus rating at the end of each test day. The consensus rating ensured each test subject interpreted the questions consistently, and allowed them to discuss and judge, using their prior experience, how microgravity might affect operations. The consensus evaluations were considered the actionable results.

A.3.1 Practical Significance

A 10-point Likert scale was used to obtain subjective ratings of capability assessment, acceptability, workload, and fatigue (described in detail in the following sections). Each scale is divided into 5 distinct categories with 2 numerical ratings within each category to discriminate preferences. For these ground tests, sample sizes were not large enough to use inferential statistics and hence we prospectively defined *practical significance* as a categorical difference on the Likert rating scales (Figure 5). For objective metrics, such as the planned versus the actual time to complete a task, we prospectively defined practical significance to be a 10% difference.

Categorical Difference

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

No Categorical Difference

Figure 5. Acceptability rating scale describing practically significant (i.e., categorical) differences.

A.3.2 <u>Capability Assessment Ratings</u>

The primary objective of the NextSTEP ground test program is to identify the capabilities that are required for exploration missions, the nonessential capabilities that might enhance exploration, and the capabilities that provide marginal or no meaningful enhancement and can therefore be excluded, resulting in cost savings without impact to mission success. The capability assessment scale is a 10-point scale used to rate the extent to which candidate capabilities might enable and enhance future exploration missions (Figure 6). The scale consists of 5 categories: essential/enabling (impossible or highly inadvisable to perform the mission without this capability), significantly enhancing (capability is likely to significantly enhance one or more aspects of the mission), moderately enhancing (capability is likely to moderately enhance one or more aspects of the mission or significantly enhance the mission on rare occasions), marginally enhancing (capability is only marginally useful or useful only on very rare occasion), and little to no enhancement.

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

Figure 6. Capability assessment rating scale.

The astronaut test subjects evaluated 20 candidate Gateway capabilities for each contractor's habitat. Although many of these capabilities related to general interior architecture, the crew evaluated the capabilities in the context of each contractor's habitat design. Evaluations were conducted twice: first for missions less than 30 days, and second for missions of 60 days. The 20 capabilities evaluated included:

- An additional WCS separate from Orion
- An additional galley separate from Orion
- Galley/ward room table for 4 crewmembers
- Trash removal capability on at least a per mission basis
- Separate wet and dry trash stowage
- Common secondary structure interface
- Two or more multipurpose workstations
- A dedicated medical area

- A dedicated science area
- A dedicated hygiene area
- A hardwired, multipurpose workstation for critical commanding
- Two exercise stations
- A permanently installed exercise station
- Exercise station in separate module from the main habitat
- Private crew quarters
- A dedicated labeled stowage area vs bungees and CTBs
- Single (i.e., 30 days) missions worth of logistic stowage in the habitat
- A WCS in a different module from the galley
- Circadian cycle lighting system
- A viewing window (not a virtual window)

After they completed their evaluation of the larger inflatable habitats, the crew was asked to provide a capability assessment rating of replacing the single standard habitat in a stack that also includes a multipurpose airlock, personal protective equipment (PPE), and logistics module with either one large inflatable habitat or two standard (smaller, non-inflatable) habitat modules. The level of mission enhancement was rated in reference to this baseline and while assuming each habitat would provide the same habitation functions.

A.3.3 <u>Pairwise Comparison of Capabilities</u>

After they completed the capability assessment ratings, the astronaut test subjects completed a pairwise comparison of the 20 different capabilities. This pairwise comparison discriminates the relative importance of capabilities that may have received the same rating, and results in a rank order of most-to-least important capabilities. For this assessment, the 20 capabilities were listed across the rows and columns of a matrix (Figure 7). Test subjects then compared the capability in each row to the capability in each column, one pair at a time. If the capability in the row was more important than the capability listed in the column, an X was placed in that cell. If the capability in the row was less important than the capability in the column, the cell was left blank. If the capabilities were equally important, a T (for tie) was placed in the cell. The relative weighting and rank order of each capability was then calculated using the analytical hierarchy process where X = 2, blank = 0.5, and T = 1. The test subjects completed this consensus pairwise comparison task twice: first for missions less than 30 days, and second for missions greater than 30 days.

Selection Criteria (x Indicates Row more Important Than Column; T indicates capabilities are equally important [silver bullet])	An additional WCS separate from Orion	An additional galley separate from Orion	Galley/ward room table for 4 crew	Trash Removal Capability	Separate wet and dry trash stowage	Common secondary structure interface	Two or more multi-purpose workstations	A dedicated medical area	A dedicated science area	A dedicated hygiene area	A hardwired multi-purpose workstation for critical commanding	Two exercise stations	A permanently installed exercise station	Exercise station in separate module from the main habitat	Private crew quarters	A dedicated labeled stowage areas vs bungees and CTBs	Single (ie 30 days) missions worth of logistic stowage in the habitat	A WCS in a different module from the galley	Circadian cycle lighting system	A viewing window
An additional WCS separate from Orion																				
An additional galley separate from Orion																				
Galley/ward room table for 4 crew																				
Trash Removal Capability																				
Separate wet and dry trash stowage																				
Common secondary structure interface																				
Two or more multi-purpose workstations																				
A dedicated medical area																				
A dedicated science area																				
A dedicated hygiene area																				
A hardwired multi-purpose workstation for critical commanding																				
Two exercise stations																				
A permanently installed exercise station																				
Exercise station in separate module from the main habitat																				
Private crew quarters																				
A dedicated labeled stowage areas vs bungees and CTBs																				
Single (ie 30 days) missions worth of logistic stowage in the habitat																				
A WCS in a different module from the galley																				
Circadian cycle lighting system																				
A viewing window																				

Figure 7. Pairwise comparison of candidate Gateway capabilities.

A.3.4 Simulation Quality Ratings

Simulation quality ratings reflect the extent to which the simulation allows meaningful evaluation of the aspects of Gateway habitation being assessed (Figure 8). Unplanned communication drop-outs, unresolved hardware failures, and low-fidelity mock-ups are examples of factors that could affect simulation quality ratings. Aspects of Gateway habitation that were not being assessed in this test, including 1-g test artifacts, were intentionally excluded from consideration when providing ratings of simulation quality.

Each acceptability rating (described next) was preceded by an evaluation of simulation quality because the same simulation may differ in quality depending on the types of operations or systems being assessed or the perspective from which it is being assessed (e.g., by different groups). When a simulation quality rating of 4 or 5 was given, comments were noted describing the simulation limitations but acceptability ratings were not collected because, by definition, significant simulation limitations or anomalies precluded meaningful evaluations. It was understood and expected that some habitation elements would not provide flight-like simulation qualities. Hence, simulation quality ratings enabled the study team to place the other ratings in context.

Rating	Criteria
1	Simulation quality presented either zero problems or only minor ones that had no impact to the validity of test data.
2	Some simulation limitations/anomalies encountered, but minimal impact to the validity of test data.
3	Simulation limitations/anomalies made test data marginally adequate to provide meaningful evaluation of test objectives.
4	Significant simulation limitations/anomalies precluded meaningful evaluation of major test objectives.
5	Major simulation limitations/anomalies precluded meaningful evaluation of all test objectives.

Figure 8. Simulation quality rating scale.

A.3.5 Acceptability Ratings

The acceptability rating scale (Figure 9) measures the acceptability of different prototype systems and operations concepts for future spaceflight missions, and it informs requirements for improvements when necessary [17]. The scale consists of 5 categories: totally acceptable with no improvements necessary, acceptable with minor improvements desired, borderline with improvements warranted, unacceptable with improvements required, and totally unacceptable with major improvements required. Any rating of 4 or lower is considered acceptable. Any rating of 3 or higher requires the evaluator to describe the specific desired, warranted, and/or required improvements.

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

Figure 9. Acceptability rating scale.

Test subjects completed individual and consensus acceptability questionnaires related to the following Gateway habitation systems and functions: general habitat layout, crew quarters, hygiene stations, WCS, exercise, galley and galley table, trash management, multipurpose workstations, science workspaces and surfaces, gloveboxes, medical workspaces and surfaces, crew common area, logistics stowage and location referencing, lighting, inflight maintenance, radiation protection, and (if applicable to the contractor) multipurpose airlocks. Individual questionnaires were completed after each test subject finished the associated task. Consensus questionnaires were completed at the end of each mission day by all 4 crewmembers together. The astronaut test crews also provided a consensus evaluation of the overall acceptability of the habitat configuration.

A.3.6 Fatigue Ratings

The fatigue rating scale (Figure 10) measures the level of underlying fatigue that each test subject experienced throughout the course of the testing [18]. Fatigue reflects multiple factors, including task workload and complexity, stress, sleep quality, and physical exertion. This scale consists of 5 fatigue categories: no, minor, moderate, significant, and extreme fatigue. Fatigue ratings were collected at the beginning, the middle, and the end of each mission day.

No Fatigue		Minor Fatigue		Moderate Fatigue		Significant Fatigue		Extreme Fatigue	
Performance not compromised		Performance not compromised		Performance will likely be compromised if continued		Performance is compromised		Unable to continue with adequate performance	
1	2	3	4	5	6	7	8	9	10

Figure 10. Fatigue rating scale.

A.3.7 Workload Ratings

Workload refers to the test subject's ability to maintain maximum task performance in a given environment or under a given test condition while accounting for task overlap and/or interference from other test subjects conducting their own tasks. Although this does not provide direct insight into the distribution of functions across the Gateway configuration, it does provide insight into the task and the overall habitation system design. For example, workload may be rated high during setup of exercise equipment if the habitat interfaces, accessibility, and procedures are complex.

The workload rating scale integrates mental, physical, and environmental factors and is used to identify peak and average workload per subject and across all subjects [18] (Figure 11). This scale consists of 5 workload categories: minimal, low, moderate, significant, and extreme. Workload ratings were collected at the beginning, the middle, and the end of each mission day.

Minimal Workload		Low Workload		Moderate Workload		Significant Workload		Extreme Workload	
Minimal operator effort required to maintain workload - All operations completed with maximum possible performance		Low operator effort required to maintain workload - All operations completed with maximum possible performance		Moderate operator effort required to maintain workload - Performance of some operations may decrease marginally due to workload		Significant operator effort required to maintain workload - Performance of some tasks is decreased due to workload		Extreme operator effort required to maintain workload - Unable to satisfactorily complete all tasks due to workload	
1	2	3	4	5	6	7	8	9	10

Figure 11. Workload rating scale.

A.3.8 Planned versus Actual Timeline Execution

Variance between the actual time required to complete a task and the planned time for that task provides a contextual understanding of other crew performance metrics. Each mission timeline was developed to provide a common structure to consistently evaluate the different Gateway habitation concepts, and it was designed to limit the number of crewmembers conducting a specific task at a given time, avoiding crewmember overlap and wait times for use of various cabin functions (e.g., WCS, galley, or exercise devices). The core mission timeline was baselined to be configuration-independent and representative of a cislunar Gateway mission. However, the timeline of the tasks was modified to serve each contractor's architecture, and unique tasks were integrated into the timeline to highlight specific design features and habitation elements.

Variances between the actual and planned time to complete tasks were compared with insight into to what may have caused the differences (such as conflicts for use of the same habitable volume, simulation quality effects, crew training nuances, etc.).

A.3.9 Crew Location Frequency Distribution

The amount of time that test subjects spent in different areas of each habitat were collected over time to evaluate the distribution of tasks and functions. To develop the frequency distribution of area usage, each habitat was divided into different functional zones. The time that each test subject spent in each zone on each test day was collected using the AllTraq system with the objective of assessing the efficacy of crew time/motion as they executed the timeline. These data provided insight into cabin layout, volume utilization, and efficiency of task/function distributions throughout the habitat to further inform functional requirements and habitation design refinements for NextSTEP Phase 3. For example, areas of the habitat that may be underutilized could potentially be repurposed or eliminated.

The AllTraq system is a real-time position tracking system that uses ultra-wideband frequency receivers, radio frequency identification (RFID) tags, and data security protocols for collecting data on human movement. The RFID tags worn by test subjects were small and non-intrusive and had an accuracy of ~6-8 inches between pre-determined zones. For each contractor habitat, a number of receivers were placed throughout the habitat and a geolocation center was calculated. To improve accuracy, stationary RFID tags were positioned within each habitat module. The "Stationary Tag Accuracy" is a metric that quantifies the error in the geolocation estimate of the stationary tag. Accuracy of the geolocations was calculated by first placing the stationary tag in the habitat with the other receivers and then calculating a probability or confidence level. Each functional zone was subdivided into a grid of 10-in x 10-in squares. The amount of time spent in each 10-in square was inferred from the density of the geolocations within that area. Heat maps were constructed to visualize the time each test subject spent in a particular area; the color gradation scale ranged from white (representing 0 minutes spent in that area) to dark red (representing 60 minutes spent in that area). Histograms were also generated to show the relative distribution of high-use and low-use zones; an equal distribution reference line was added to the histograms that represents the total amount of time that would be spent in each zone if the crew distributed their time evenly between zones.

A.3.10 Design Element Distribution

The test subject crew completed a consensus element distribution during which they designed the details of their preferred Gateway stack. This included defining which and how many different habitation and work elements they thought should be allocated to that contractor's habitat module(s)/decks and associated logistics module. These data were used to inform design guidelines for Gateway habitation modules.

A.4 Study Limitations

Several study limitations were present throughout the execution of the ground tests. The following list describes these limitations and explains how the effects of each limitation were mitigated.

1. Number, Type, and Fidelity of Contractor Habitats: Due to budget, schedule, and 1-g limitations, the number, type, and fidelity of various contractor habitation elements varied widely. For this reason, simulation quality ratings (Section A.3.3) were used to discriminate the data that could be reliably used for Gateway recommendations. Also due to budget and schedule, the ground tests did not include mock-ups of Orion. Hence, the contributions of Orion should be assessed through a combination of analyses, virtual reality, and standalone testing, rather than fully integrated human-in-the-loop astronaut testing.

2. 1-g Test Environment: The Gateway will be occupied in a microgravity environment, which cannot be fully simulated in on Earth. However, previous testing has shown that 1-g mock-ups that contain features required for microgravity operations (e.g., handholds, foot loops, Velcro, etc.) and are reviewed by experienced astronauts can still result in meaningful assessments. Virtual reality was also used to address some aspects of microgravity, such as full utilization of the habitation volume that is not always possible in a 1-g test (e.g., exercise on the ceiling versus floor).

3. Ground Test Study Design: The NextSTEP BAA Phase 2 resulted in 5 different habitation configurations. At the start the test program, the test team did not have the details of each individual contractor configuration with respect to the number and type of modules and the distribution of habitation, science, and EVA functions. Also, since each contractor provided their own designs, the test team did not have full control to systematically vary the independent and dependent variables, and they could not could not prospectively develop multiple specific hypotheses. Instead, 2 high-level hypotheses were proposed that provided the framework to guide the human-in-the-loop astronaut ground tests [19]. The results of each ground test were assimilated, analyzed, and used to inform the Gateway design guidelines presented above. In this type of human-in-the-loop testing using a targeted population of astronauts as test subjects, it is not possible to execute the studies with large numbers of subjects (due to limited number of astronauts, scheduling constraints, etc.). Therefore, although individual data was collected, the crew's consensus evaluation was used to test the hypotheses and to identify the actionable results.

4. Ground Test Timeline Limitations: The timeline used in each contractor evaluation was derived through the rigorous process of down-selecting tasks from high-level Gateway objectives and functional requirements. Due to programmatic and resource limitations, we could not practically test every possible timeline variant (including content and order).

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Appendix B: Summary Design Guidelines

Table 4 summarizes the design guidelines provided in Section 4 and also links to the data products from the individual contractors (de-identified as contractor A, B, C, D, and E) from which the design guidelines were derived. Descriptions of the data products are provided in Appendix A.3.

Table 4. Summary Design Guidelines

Design Guideline #	Design Guideline	Supporting Data References
General Layout		
1	Habitat layout can be more important than volume; i.e., a small volume that is properly laid out can be more acceptable than a large volume that is poorly laid out.	• Overall Acceptability → A, B, C, D, E • General Layout Acceptability → A, B, C, D, E • Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E
2	Additional volume (provided it is properly laid out) can enable better separation of functions to minimize interference between crewmembers, prevent cross-contamination, and provide more room for privacy and more separation for noise abatement.	• Overall Acceptability → A, B, D, E • General Layout Acceptability → A, D • Overall Capability Assessment → A, D • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, B, D, E • AllTraq → A, B, C, D, E
3	Additional volume also enables the incorporation of duplicate functional areas, which improves crew timeline efficiency and provides contingency options in the event of hardware or subsystem failures.	• Overall Acceptability → A, D, E • General Layout Acceptability → A, D • Overall Capability Assessment → A, D • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, D, E • AllTraq → A, B, C, D, E

Design Guideline #	Design Guideline	Supporting Data References
4	Habitat layouts should separate “clean” and “dirty” functional areas. “Clean” areas include crew quarters, galley, and science and medical workspaces; “dirty” areas include the WCS, hygiene, and exercise spaces.	• Overall Acceptability → A, B, C, D, E • General Layout Acceptability → A, B, C, D, E • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, B, C, D, E
5	Locating “dirty” areas near one another (e.g., a hygiene station next to an exercise area) mitigates cross-contamination when crewmembers need to translate between these areas.	• Overall Acceptability → A, B, C, D, E • General Layout Acceptability → A, B, C, D, E • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, B, C, D, E
6	Strategically located floors, walls, pallets, and other barriers in the galleys, exercise, and WCS, hygiene, and medical areas can further mitigate cross-contamination risks.	• Overall Acceptability → A • Galley Acceptability → A, B • Exercise Acceptability → A, B • WCS Acceptability → A, B, C, D, E • Hygiene Acceptability → A, B, C, D, E • Medical Acceptability → A, D • Element Distribution → A
7	All areas of the habitat that must be cleaned should be easily accessible and have smooth surfaces to facilitate easy cleaning.	• General Layout Acceptability → A, B, C, D • Hygiene Acceptability → A, C, • WCS Acceptability → C • Exercise Acceptability → A, B, C, D, E • Galley Acceptability → A, B, E • Science Acceptability → D
8	All habitation and work areas should have sufficient, adjustable stability aids (e.g., hand-holds, foot restraints, and body restraints) and mobility aids (including an adequate mounting structure) and temporary stowage accommodations (e.g., Velcro, bungees, nets, and caddies).	• General Layout Acceptability → A, B, C, E • Stowage Acceptability → A, B, C, E

Design Guideline #	Design Guideline	Supporting Data References
9	Specific stability/mobility aids and temporary stowage accommodations should be dictated by the work functions to be performed in each area as well as the individual layouts of those areas.	• General Layout Acceptability → A, B, C, E • Stowage Acceptability → A, B, C, D. E • Crew Quarters Acceptability → A, B, C, D, E • Hygiene Acceptability → A, B, C, D, E • WCS Acceptability → A, B, C, D, E • Exercise Acceptability → A, B, C, D, E • Galley Acceptability → A, B, C, D, E • MPWS Acceptability → A, B, C, D, E • Science Acceptability → A, B, C, E • Medical Acceptability → A, B, D, E • Common Area Acceptability → A, D • IFM Acceptability → A, B, C, E • Radiation Shelter Acceptability → A, B • Multipurpose Airlock Acceptability → C
10	The size and location of stability/mobility aids and temporary stowage accommodations should be customizable by individual crewmembers to accommodate individual anthropometrics.	• General Layout Acceptability → A, B, C, E • Stowage Acceptability → A, B, C, D. E • Crew Quarters Acceptability → A, B, C, D, E • Hygiene Acceptability → A, B, C, D, E • WCS Acceptability → A, B, C, D, E • Exercise Acceptability → A, B, C, D, E • Galley Acceptability → A, B, C, D, E • MPWS Acceptability → A, B, C, D, E • Science Acceptability → A, B, C, D, E • Medical Acceptability → A, B, D, E • Common Area Acceptability → A, D • IFM Acceptability → A, B, C, E • Radiation Shelter Acceptability → A, B • Multipurpose Airlock Acceptability → C
11	Habitat layouts should support reconfigurability (i.e., the ability to move pallets, payloads, and/or entire functional areas within each module or between modules) to provide flexibility as the Gateway is assembled and as Gateway objectives and mission durations change.	• Overall Acceptability → A, C • Reconfiguration Acceptability→ E • Capability Assessment (≤ 30 day) → B, C, E • Capability Assessment (> 30 day) → B, C, E
12	A common secondary structure (e.g., mounting points, tracks, interfaces, fasteners, pip-pins) reduces the number of different tools needed on board and overall crew overhead.	• Overall Acceptability → E • IFM Acceptability → C, E • Capability Assessment (≤ 30 days) → E • Capability Assessment (> 30 days) → E

Design Guideline #	Design Guideline	Supporting Data References
13	If deployable multipurpose work surfaces are used, they should be adjustable in size/orientation and include attachment points that provide power and data ports.	• MPWS Acceptability → B, C, E • Science Acceptability → B, C, E • Medical Acceptability → B, C, E • IFM Acceptability → A, B, C, E
14	A simple, clearly defined coding reference scheme should be implemented to locate items, allowing crewmembers to quickly and reliably locate logistics.	• Overall Acceptability → A, D • Stowage Acceptability → A, D
15	At least one viewing window (not a virtual window) should be included to increase safety during robotics operations through direct visual situational and spatial awareness, to allow photography opportunities for science and public outreach, and to enhance crew morale.	• Overall Acceptability → A, B, C, D, E • Exercise Acceptability → A, B, C • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, B, C, D, E
16	An omni-directional viewing window that can be relocated to different ports (e.g., as stack architecture evolves) is preferred over a permanent smaller window.	• Overall Acceptability → A, B
Crew Quarters		
17	Private quarters should be provided for each crewmember; for missions ≤ 30 days, the crew quarters can be deployable; for missions > 30 days, crew quarters should be permanent.	• General Layout Acceptability → D, E • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, D • Pairwise Comparison (> 30 day)→ A, B, D • Element Distribution → A, B, C, D, E • AllTraq → A, B, D, E
18	The crew quarters should be co-located with other "clean" areas of the habitat (e.g., galley, science workspaces, and medical workspaces).	• Crew Quarters Acceptability → A, B, D, E • Element Distribution → A, B, C, D, E • AllTraq → A, B, D, E
19	Each crew quarter should incorporate a rigid enclosure and a door.	• Overall Acceptability → A, D, E • General Layout Acceptability → E • Crew Quarters Acceptability → A
20	Each crew quarter should incorporate light and sound proofing.	• Overall Acceptability → A, B, D • Crew Quarters Acceptability → A, B, D
21	Each crew quarter should incorporate adjustable ventilation (adjustable airflow speed and direction for personal preference and to mitigate CO_2 buildup).	• Crew Quarters Acceptability → A, D, E
22	Each crew quarter should incorporate caution and warning indicators (audible and visual).	• Crew Quarters Acceptability → A
23	Each crew quarter should incorporate power and data connections (for laptops, tablets, task lighting, general charging).	• Crew Quarters Acceptability → A, D

Design Guideline #	Design Guideline	Supporting Data References
24	Each crew quarter should incorporate peripheral mounts (for laptops and tablets).	• Crew Quarters Acceptability → A
25	Each crew quarter should incorporate customizable mood and spot lighting (relocatable, adjustable color/brightness).	• Crew Quarters Acceptability → A, B, D, E • Capability Assessment→ ≤ 30 day → A, B, C, D, E • Capability Assessment→ ≥ 30 day → A, B, C, D, E • Pairwise comparison → A, B, D, E
26	Each crew quarter should incorporate flexible temporary stowage (e.g., Velcro, bungees, nets, caddies).	• Crew Quarters Acceptability → A, B, D, E • Capability Assessment (≤ 30 day) → A, B, D, E • Capability Assessment (> 30 day) → A, B, D, E • Pairwise comparison (≤ 30 day) → A, B, D, E • Pairwise comparison (> 30 day) → A, B, D, E
27	Each crew quarter should incorporate adjustable sleeping bag positioning (both orientation and location within the crew quarter).	• Crew Quarters Acceptability → A, B, D, E
28	Each crew quarter should incorporate direct access to any additional personal crew stowage lockers from within the crew quarters.	• Crew Quarters Acceptability → A, D
29	Adjustable stability and translation aids should be provided to accommodate crew activities, such as working on a laptop/tablet, changing clothes, reading, and watching entertainment.	• Overall Acceptability → B, C, E • General Layout Acceptability → B, E
30	Crew quarters dimensions should be at least 30” wide x 30” deep x 78” long.	• Overall Acceptability → D • Crew Quarters Acceptability → B, D, E • Capability Assessment (≤ 30 day) → A • Capability Assessment (> 30 day) → A
Hygiene Stations		
31	At least one dedicated, enclosed hygiene station, separate from other functional areas including the WCS and crew quarters, should be provided.	• Overall acceptability → A • General Layout Acceptability → B, C • Hygiene Acceptability → A, B, C, D, E • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise comparison (≤ 30 day) → A, B, C, D, E • Pairwise comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E

Design Guideline #	Design Guideline	Supporting Data References
32	The hygiene station(s) should be co-located near other "dirty" areas in the habitat (e.g., WCS and exercise); locating hygiene stations near exercise minimizes translation through clean areas of the habitat and thus decreases the risk of cross-contamination.	• Overall Acceptability → A • General Layout Acceptability → B, D, E • Hygiene Acceptability → A, C, D, E • Capability Assessment (≤ 30 day) → A, B, D, E • Capability Assessment (≥ 30 day) → A, B, D • Overall Capability Assessment → A, D • Pairwise comparison (≤ 30 day) → A, D, E • Pairwise comparison (> 30 day) → A, D, E • Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E
33	Each hygiene station should be permanent, private, easy to clean, and sufficiently ventilated	• Overall Acceptability → A, D • General Layout Acceptability → C, D • Hygiene Acceptability → A, C, D • Crew Quarters Acceptability → B • Capability Assessment (≤ 30 day) → A, B, C, D • Capability Assessment (> 30 day) → A, B, C, D • Pairwise comparison (≤ 30 day) → A, B, C, D • Pairwise comparison (> 30 day) → A, B, C, D • Element Distribution → A, B, C, D • AllTraq → A, B, C, D, E
34	The hygiene enclosure should have rigid walls and door, and surfaces should be slick, smooth, and non-porous surfaces to repel water, facilitate easy cleaning, and prevent bacterial growth.	• General Layout Acceptability → C • Hygiene Acceptability → A, C • Element Distribution → A, B, C, D, E
35	To ensure privacy, the hygiene enclosure door should be securable to prevent it from inadvertent opening if bumped.	• Overall Acceptability → A, C, D • Hygiene Acceptability → A, C, D • Capability Assessment (≤ 30 day) → E • Element Distribution → A, B, D
36	The hygiene station should have adjustable stability aids for body, hands, and feet.	• Overall Acceptability → A • General Layout Acceptability → A, C, E • Hygiene Acceptability→ A, E • WCS Acceptability→ C, E • IFM Acceptability→ C
37	The hygiene station should have temporary stowage accommodations (e.g., to include cleanable and removable caddies for stowage of shampoo, soap, etc.).	• Overall Acceptability → A, D • General Layout Acceptability → A, C, D • Hygiene Acceptability → A, C, D, E • WCS Acceptability→ C, E • Capability Assessment (≤ 30 day) → A, C, D, E • Capability Assessment (> 30 day) → A, C, D, E

Design Guideline #	Design Guideline	Supporting Data References
38	Long-term stowage of hygiene-related items should be available outside of the hygiene station to prevent cross-contamination and facilitate cleaning of the interior of the hygiene station.	• Overall Acceptability → A, D • General Layout Acceptability → A, D • Hygiene Acceptability → A, D • Stowage Acceptability→ A, D • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, C, D • Pairwise Comparison (> 30 day) → A, C, D • Element Distribution → A, C, D
39	The volume should provide adequate space for body movements and positions required during showering, changing clothes, and be tall enough to accommodate crewmembers with long hair (note that long hair floats in 0g and should not contact the enclosure during washing).	• Overall Acceptability → A, D • General Layout Acceptability → E • Hygiene Acceptability → A, B, D, E • Capability Assessment (≤ 30 day) → A, C, D • Overall Capability Assessment → A, D • Element Distribution → A, B, C, D, E • AllTraq → E
40	Hygiene station dimensions should be at least 45” wide x 30” deep by 78” tall; a portion of the station can be deployable to achieve this size.	• Overall Acceptability → A • Hygiene Acceptability → A, C, E • WCS Acceptability→ C, E • Capability Assessment (≤ 30 day) → A • Element Distribution → A, C
WCS Stations		
41	At least one private, dedicated WCS separate from Orion should be provided.	• Overall acceptability → A, C, D • General Layout Acceptability → B, C • WCS Acceptability → A, B, C, D, E • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E

Design Guideline #	Design Guideline	Supporting Data References
42	The WCS(s) should be co-located with other “dirty” functions in the habitat.	• Overall Acceptability → A, C, D • General Layout Acceptability → A, B, C, D, E • WCS Acceptability → A, C, D, E • Hygiene Acceptability → A, B, C, D, E • Galley Acceptability → C • Crew Quarters Acceptability → B • IFM Acceptability → C • Science Workspaces Acceptability → C • Overall Capability Assessment → A, D • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, D, E • Pairwise Comparison (> 30 day) → A, D, E • Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E
43	Each WCS should be permanent, private, easy-to-clean, well ventilated, and separate from the hygiene station.	• Overall acceptability → A, C, D • General Layout Acceptability → B, C • WCS Acceptability → A, B, C, D, E • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E
44	The WCS enclosure should have rigid walls and a door, and surfaces should be slick, smooth, and non-porous to repel water, facilitate easy cleaning, and prevent mold growth.	• General Layout Acceptability → C • Hygiene Acceptability → A, C • Element Distribution → A, B, C, D, E
45	To ensure privacy, the WCS station door should be securable to prevent it from inadvertent opening if bumped.	• Overall Acceptability → A, C, D • Hygiene Acceptability → A, C, D • Capability Assessment (≤ 30 day) → E • Element Distribution → A, B, D
46	The WCS enclosure should provide sound abatement.	• Overall acceptability → A, D • WCS Acceptability → D
47	The WCS should be appropriately located within the WCS enclosure to enable adequate space to position the body during WCS operations, as well as sufficient space to access all sides when conducting maintenance.	• WCS Acceptability → A, C

Design Guideline #	Design Guideline	Supporting Data References
48	Adjustable stability aids for hands and feet should be provided in front and to the sides of the WCS itself.	• General Layout Acceptability → C, D, E • WCS Acceptability → C • IFM Acceptability → C
49	Temporary stowage accommodations should be provided for items such as toilet supplies and urine funnels and should be easily reachable while performing WCS operations.	• Overall Acceptability → A, B, D • General Layout Acceptability → A, B, C, D, E • WCS Acceptability→ A, C, D, E • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E
50	Separate, long-term storage of WCS wet trash and waste should be provided within the WCS enclosure or in a temporary canister that is then combined with all wet trash and stowed elsewhere; this stowage should be vented directly into the trace contaminant control system (TCCS) to catalyze and absorb odors, rather than allowing odors to leak into the cabin atmosphere.	• General Layout Acceptability → A • WCS Acceptability → A • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E
51	The enclosure should have adjustable task lighting to assist crewmembers during cleaning, maintenance, and servicing.	• WCS Acceptability → A, D, E • Capability Assessment (≤ 30 day) → A, D • Capability Assessment (> 30 day) → A, D
52	WCS compartment dimensions should be at least 40” wide x 30” deep and 78” tall.	• WCS Acceptability → A, B, C, D, E
Exercise		
53	For missions ≤ 30 days, a deployable exercise device is acceptable, provided adequate volume is available to perform all required exercises and operation does not interfere with other crewmember activities.	• Capability Assessment (≤ 30 day) → A, B, C, D, E
54	For missions > 30 days, the exercise equipment should be permanently installed in a dedicated area to avoid setup and stow before and after each use.	• Capability Assessment (> 30 day) → A, B, C, D, E

Design Guideline #	Design Guideline	Supporting Data References
55	The exercise station should be located in close proximity to other "dirty" areas of the habitat; e.g., positioning the exercise station near a hygiene station reduces the distance crewmembers need to translate to clean up after exercising, thereby reducing the risk of cross-contamination within the habitat.	• Overall acceptability → A, C • General Layout Acceptability → A, B, C, D, E • Exercise Acceptability → A, B, C, D, E • Hygiene Acceptability → A, E • Galley Acceptability → C • Crew Quarters Acceptability → B • Radiation Shelter Acceptability → B • IFM Acceptability → C • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E
56	Adequate ventilation should be provided in the exercise area to prevent CO_2 buildup.	• Exercise Acceptability → D
57	Temporary stowage accommodations, adjustable mounts, and power connections for exercise gear, a water bag, towel, laptop or tablet, and personal electronics should be provided within in reach and view of the exercise equipment.	• Exercise Acceptability → A, D, E
58	A window near the exercise area could provide for external viewing during exercise.	• Exercise Acceptability → B
59	The dimensions of the exercise area are dependent on the flight exercise equipment and exercise protocol, but should accommodate full range of motion for the tallest crewmembers for all exercises.	• Exercise Acceptability → A, B, C, D, E
Galley & Galley Table		
60	An additional galley separate from Orion should be provided for missions of any duration.	• Galley Acceptability → A, B, C, D, E • Overall Capability Assessment → D • Capability Assessment (≤ 30 day) → A, B, C, D • Capability Assessment (> 30 day) → A, B, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, C, D, E • AllTraq → A, B, C, D, E

Design Guideline #	Design Guideline	Supporting Data References
61	The galley should be located near other "clean" areas of the habitat and be separated from "dirty" areas to prevent cross-contamination.	• Galley Acceptability → A, B, C, D, E • General Layout Acceptability → A, B, D, E • Capability Assessment (≤ 30 day) → A, B, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E
62	For mission durations ≤ 30 days, a minimal galley that includes a potable water dispenser (PWD) and possibly a food warmer is sufficient.	• Capability Assessment (≤ 30 day) → A, B, C, D, E
63	For mission durations > 30 days, additional galley features are appreciated, such as hot and cold PWDs, food warmers, cold storage, local stowage for one week's worth of food, and a galley table large enough for all crew to gather together to eat a meal.	• Capability Assessment (≤ 30 day) → A, B, C, D, E
64	Simple PWD interfaces should be used (e.g., the needle-captured septum used in previous spacecraft including the Space Shuttle and ISS).	• Galley Acceptability → A, C
65	Food warming systems should incorporate swing-open doors rather than long pull-out drawers, which require additional space and stability aids to access.	• Galley Acceptability → A
66	Local food stowage should be near the galley and readily accessible while the PWDs and food warmers are being used and while other crewmembers are gathered at the table.	• Galley Acceptability → A, B, C, D, E
67	A galley table should be no smaller than that provided on the ISS (e.g., at least 22" wide x 50" long when fully extended) allowing all crewmembers to gather and eat together.	• Galley Acceptability → A, B, C, D • AllTraq → A, B, C, D, E
68	The galley table should be located in an area that does not interfere with other critical workspaces (e.g., it should not inhibit access to a multipurpose workstation used for critical commanding).	• Galley Acceptability → A, B, C, D, E • General Layout Acceptability → B, D • Overall Capability Assessment→ A, D • Capability Assessment (≤ 30 day) → A • Capability Assessment (> 30 day) → A • Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E
69	The galley table may be deployable and adjustable in size (e.g., foldout leafs).	• Galley Acceptability → B, E
70	Stability aids should be provided that enable use of all galley functions and to enable all crew to "sit" at the table.	• Galley Acceptability → A, B, C, D, E • General Layout Acceptability → A, C, D, E • Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E
71	Sufficient local temporary stowage should be provided to accommodate meal preparation and consumption and should include the ability to stow multiple small items, such as condiments, food packets, and utensils.	• Galley Acceptability → A, B, C, D, E • Capability Assessment (≤ 30 day) → A • Capability Assessment (> 30 day) → A • Element Distribution → A, B, C, D, E

Design Guideline #	Design Guideline	Supporting Data References
72	Separate wet and dry trash stowage should be provided in or near the galley; this could be implemented by attaching trash bags directly to the galley table (e.g., as is done to the handrails along the ISS galley table).	• Galley Acceptability → A, B, C, D, E • General Layout Acceptability → C • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E
73	If the galley table is also used as a common gathering area for crewmembers to perform work or for entertainment, it should provide easily accessibly power/data connections and mounts (e.g., for lap-tops, tablets, task lighting, etc.).	• Galley Acceptability → D • AllTraq → A, B, C, D, E
74	All galley surfaces should be easily cleanable.	• Element Distribution → A, B, C, D, E • AllTraq → A, B, C, D, E
Trash Management		
75	Wet and dry trash should be collected and stowed separately.	• General Layout Acceptability → A, B, C, D, E • Hygiene Acceptability → A, D • WCS Acceptability → A, D • Galley Acceptability → A, B, C, D • Stowage Acceptability → C • Medical Workspaces Acceptability → A • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E
76	Wet and dry trash containers should be provided near areas where trash is generated so that it does not have to be translated large distances.	• General Layout Acceptability → A, B, C, D, E • Hygiene Acceptability → A, D • WCS Acceptability → A, D • Galley Acceptability → A, B, C, D • Medical Workspaces Acceptability → A, D

Design Guideline #	Design Guideline	Supporting Data References
77	Routine trash management should be a timelined activity and should include trash consolidation and movement to long-term stowage locations.	• General Layout Acceptability → A, B, C, D, E • Hygiene Acceptability → A, B, D, E • WCS Acceptability → A, B, D, E • Science Workspaces Acceptability → A, D, E • Galley Acceptability → A, B, C, D, E • Medical Workspaces Acceptability → A, D • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (>30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E
78	Dedicated accommodations should be made for the storage of biological waste (non-WCS) and sharps (e.g., needles, catheters) to prevent exposure to biohazards.	• Medical Acceptability → A
79	If trash needs to be stowed long-term, it should be located outside of the main habitation areas (e.g., inside a rarely-used logistics module); long-term stowage of WCS waste and wet trash should be vented directly into the TCCS to absorb and catalyze odors rather than allowing odors to leak into the cabin atmosphere.	• General Layout Acceptability → A, C, D, E • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (>30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E
80	A method of removing trash from Gateway at least every 30-days (e.g., via a trash ejection capability) should be provided.	• Trash Management Acceptability → B • Capability Assessment (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E
81	A volume of approximately 36 ft^3 is needed to store a typical 30 day mission's worth of trash.	• General Layout Acceptability → A, B, C, D, E • Trash Management Acceptability → B • Capability Assessment (≤ 30 day) → A, B, C, D, E • Capability Assessment (> 30 day) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E
Multipurpose Workstations		
82	At least one hardwired multipurpose workstation must be provided to ensure reliable critical commanding.	• Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E
83	A second hardwired multipurpose workstation can be provided for redundancy and to accommodate parallel operations.	• Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E
84	Wireless workstations or tablets are acceptable for monitoring and status checks only.	• MPWS Acceptability → E

Design Guideline #	Design Guideline	Supporting Data References
85	Critical commanding workstations should not be blocked at any time.	• MPWS Acceptability → C, E
86	Workstations should be positioned away from heavy traffic/high-use areas to avoid inadvertent interference by other crewmembers translating nearby or conducting other tasks.	• MPWS Acceptability → C, E
87	Workstation monitors and hand controllers should be adjustable, in both the vertical and depth directions and in tilt, to accommodate variability in crew height and ergonomic preferences as well as right and left-handedness; adjustments should be easy, quick, and require no tools.	• MPWS Acceptability → A, B, C, D, E
88	Adjustable foot restraints should be provided to allow the crewmember to effectively and comfortably position themselves in relation to displays, keyboards, and hand controllers; handholds, adjustable arm rests, and body restraints may be needed for additional stability during delicate hand controller inputs.	• MPWS Acceptability → A, B, C, D
89	Separate translational and rotational hand controllers should be used; each controller should have stick forces that enable precise inputs and an easily identifiable central detent that provides no input.	• MPWS Acceptability → A, B, C, D
90	If touchscreen workstation displays are used, the touchscreen should include a locking feature; when this feature is unlocked, a firm touch input should be required to prevent inadvertent commands if a crewmember accidently brushes against the screen.	• MPWS Acceptability → A, C
91	Critical functions accessed through a touchscreen should have a manual back-up method (e.g., bezel buttons, keyboard inputs, mouse inputs) ensuring these functions are always available in the event that the touchscreen capability malfunctions.	• MPWS Acceptability → C
92	For all inputs, regardless of whether they are provided via touchscreen, bezel button, keyboard or mouse, immediate feedback (e.g., visual, audible, and/or tactile indicators) should be given that the input has been accepted to avoid crewmembers from inadvertently inputting multiple commands. Any lag between input and execution of a command should be minimized.	• MPWS Acceptability → C
93	Small work surfaces, mounts, and temporary stowage accommodations (e.g. Velcro, bungees, nets, pockets, etc.) for checklists, notebooks, laptops, and tablets should be provided near multipurpose workstations.	• MPWS Acceptability → A, B
94	Power and data connections for laptops, tablets, and task lighting should be provided in all multipurpose workstations.	• MPWS Acceptability → A
Dedicated Science Workspaces and Surfaces		

Design Guideline #	Design Guideline	Supporting Data References
95	Dedicated science workspaces and surfaces are not required if sufficient multipurpose workspaces and surfaces are provided.	• Science Acceptability → B, C, E • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E
96	If dedicated science workspaces and surfaces are not included, at least one multipurpose work area should be available for science for missions of any duration.	• Science Acceptability → B, C, E
97	Multiple multipurpose work areas should be provided for longer duration missions to allow for parallel science and/or medical tasks.	• Science Acceptability → B, C, E • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, D, E
98	Workspaces and surfaces used for science should be grouped with other "clean" areas to mitigate risks of cross-contamination from "dirty" areas. Note that some science tasks could be considered "dirty" (e.g., animal-based research experiments), and these tasks should be able to be isolated within the science work area (e.g., inside a glovebox that can be thoroughly cleaned).	• Overall Acceptability → A, B, C, D, E • General Layout Acceptability → A, B, C, D, E • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, B, C, D, E
99	Science work surfaces could be deployable as long as proper interfaces to secure them are provided, including e.g., standoffs that can accommodate vertical loads on the surface.	• Science Acceptability → B, E
100	Science work surfaces can be adjustable in size (e.g.; quarter, half, and full size to accommodate different needs).	• Science Acceptability → B, C, E
101	Workspaces that accommodate science should have smooth, non-porous surfaces that repel liquids for ease of cleaning.	• Science Acceptability → A
102	Adjustable stability aids (i.e., foot restraints and handrails) should be provided to allow different sized crewmembers to appropriately position themselves in relation to the work area.	• Science Acceptability → A, C, D
103	Temporary stowage (e.g., Velcro, bungees, pockets, caddies) should be available at the workspaces to accommodate the anticipated science tools and instruments, including various small items.	• Science Acceptability → A, C
104	Power and data connections and adjustable mounts and for laptops, tablets, task lights, and science equipment should also be provided.	• Science Acceptability → A, B, C, D, E
Glovebox		

Design Guideline #	Design Guideline	Supporting Data References
105	If a glovebox is used for science and operations (e.g., maintenance) tasks, it should be able to be thoroughly cleaned.	
106	A glovebox does not need to be permanently deployed unless it will be used regularly (e.g., at least once per week); it could be deployed in a multipurpose work area when needed and stored in a logistics module when not in use to allow the volume otherwise dedicated for a glovebox to be allocated to other, higher priority functions.	• Science Acceptability → A, B, C, E
107	The area around an installed glovebox should allow access to all glove ports.	• Science Acceptability → C
108	A glovebox should have nearby work surfaces, mounts, and data connections for tablets, laptops, and notebooks.	• Science Acceptability → A, B, C, D. E
109	Adjustable stability aids (e.g., foot and body restraints) should be provided near the glovebox allowing the installed height of the glovebox to accommodate a range of crew heights and arm lengths.	• Science Acceptability → A, B, C, D, E
110	Reach access within the glovebox should account for a range of crew anthropometrics; all locations inside the glovebox should be reachable, including the back and side walls, airlock access port, instruments (e.g., microscope), and tools.	• Science Acceptability → A
111	Power/data connections, adjustable lighting and temporary stowage accommodations for tools, samples, equipment, etc., should be provided both inside and outside the glovebox.	• Science Acceptability → A
112	A glovebox may need to accommodate an ultraviolet bulb to assist in sterilizing, viewing reagents, etc., and an ultra-pure water source for molecular and/or biomedical work.	• Science Acceptability → D
Dedicated Medical Workspaces and Surfaces		
113	Dedicated medical workspaces and surfaces for crew medical diagnostics and treatment (not medical science research) are not required if sufficient multipurpose work areas are provided.	• Medical Acceptability → B, C, E • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E
114	If dedicated medical workspaces and surfaces are not included, at least one multipurpose work surface should be available for medical use for missions of any duration.	• Medical Acceptability → B, C, E
115	Multiple multipurpose work areas should be provided for longer duration missions to enable parallel science and/or medical tasks.	• Medical Acceptability → B, C, E • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, D, E

Design Guideline #	Design Guideline	Supporting Data References
116	Workspaces used for medical tasks should be grouped with other "clean" areas of the habitat to mitigate risks of cross-contamination from "dirty" areas (e.g., exercise, WCS, hygiene).	• Overall Acceptability → A, B, C, D, E • General Layout Acceptability → A, B, C, D, E • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • Element Distribution → A, B, C, D, E
117	At least one multipurpose workspace should allow a patient to be restrained to a surface with enough space for one other crewmember to access the patient from all sides.	• Medical Acceptability → A, B, C, D, E
118	Adjustable stability aids (e.g., foot restraints and handrails) should be provided around the patient to enable non-patient crewmembers to conduct medical care, including CPR.	• Medical Acceptability → A, D
119	Workspaces that accommodate medical tasks should have smooth, non-porous surfaces that repel liquids for ease of cleaning.	• Medical Acceptability → A
120	Temporary stowage (e.g., Velcro, bungees, pockets, caddies) should be available and accommodate all expected medical tools and instruments.	• Medical Acceptability → A, B, C, D, E
121	Separate wet and dry trash receptacles, sharps containers, and biohazard bags should be located in the medical workspace and near the patient.	• Medical Acceptability → A
122	Power and data connections and adjustable mounts for laptops, tablets, task lights, and medical equipment should be provided.	• Medical Acceptability → A, B, D
Crew Common Area		
123	A crew common area that is large enough for all crewmembers to gather together provides positive benefits for individual and team morale.	• Galley Acceptability → A, B, D, E • Common Area Acceptability → A • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E • AllTraq → A, B, C, D, E
124	A crew common area could be integrated into other areas (e.g., the galley table) or could have its own dedicated volume if space is available.	• Galley Acceptability → A, B, D, E • Common Area Acceptability → A
125	Large, high-resolution viewing screens in a crew common area could be used for planning meetings, videoconferencing, public outreach, press conferences, displaying external Gateway cameras views (which could provide a psychological benefit, but are not a substitute for windows), and entertainment (e.g., watching movies).	• Galley Acceptability → D • Common Area Acceptability → A
126	Crew common areas should have power/data connections and adjustable mounts (for viewing screens, additional lighting, laptops, tablets, etc.).	• Galley Acceptability → D • Common Area Acceptability → A

Design Guideline #	Design Guideline	Supporting Data References
127	Adjustable stability aids should be available in crew common areas to allow crew-members to view the screens and interact with each other.	• Galley Acceptability → A, D • Common Area Acceptability → A
128	All lights in areas adjacent to the common area should be adjustable (including an option to turn them off) to avoid glare and unwanted reflections on viewing screens.	• Common Area Acceptability → A
Logistics Stowage and Location Referencing		
129	The habitat should have dedicated stowage for approximately one week's worth of consumables (approximately 85-95 ft^3 for food and clothes), frequently used items, and critical spares; the remaining logistics should be stowed in the logistics module thereby freeing up space in the main habitat for other habitation and work systems.	• Stowage Acceptability → B, C, D, E • Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E
130	One week's worth of consumables, frequently used items, and spares stowed in the habitat should be located close to the areas in which they will be used (e.g., food should be stored near the galley).	• Stowage Acceptability → B, C, D, E • Hygiene Acceptability → C, D • WCS Acceptability → A, B, C, D, E • Exercise Acceptability → A, B, C, D, E • Galley Acceptability → B, C, D, E • Science Acceptability → A, B, C, D, E
131	Cargo transfer bags (CTBs) should be stored no more than one layer deep for easy identification and retrieval; if accessible from both sides, CTBs can be stored 2 layers deep.	• Stowage Acceptability → A, C, D
132	CTBs with transparent sides would ensure that the contents are easily verified while stowed and when retrieved.	• Stowage Acceptability → A, C, D
133	CTBs can be held in their respective volumes with cross-over elastic straps or bungee cords that keep bags in place but can also be individually removed to access specific items; elastic straps or bungees are preferred over large cargo nets, which make it difficult to access individual bags without unstowing others.	• Stowage Acceptability → A, C, D
134	A stowage tracking system (e.g., radio-frequency identification [RFID], scanner, camera, etc.) as well as a clear and concise location coding scheme should be implanted to assist crewmembers in locating logistics.	• Stowage Acceptability → A, D
135	The location coding scheme should include a definitive grid (i.e., radial, horizontal/vertical) that uses simple letters and/or numbers; colors or icons can also be included for simplicity.	• Stowage Acceptability → A, D
136	The same location coding scheme should apply to all equipment and all possible work and habitation areas.	• Stowage Acceptability → D
137	The coding scheme should be labeled throughout the habitat modules in multiple areas, so it is easy to see from any location within each module.	• Stowage Acceptability → E
138	Stowage bags/containers should have a clear, concise numbering scheme with labels that are visible on all sides while the bags are in their stowage location.	• Stowage Acceptability → A, C, D

Design Guideline #	Design Guideline	Supporting Data References
139	There should be a sufficient number of temporary stowage accommodations in all areas and surfaces of habitat (e.g., Velcro, bungees, tethers, caddies, etc.).	• Stowage Acceptability → A, C
140	Temporary stowage staging areas should be located near the hatches for cargo bags being transferred from and to visiting vehicles as they arrive and depart the Gateway.	• Stowage Acceptability → A
Lighting		
141	Habitat lighting should incorporate both general and task (i.e., spot) lighting in all habitable volumes	Crew Quarters Acceptability → A, B, C, D, E Hygiene Acceptability → A, WCS Acceptability → A, D Science Acceptability → A, B, C, D, E Medical Acceptability → A Common Area Acceptability → A, D IFM Acceptability → A, B, C, D, E
142	Bright general overhead lighting in each module and functional area should help crewmembers orient themselves to the associated work area (i.e., in the heads-up/nadir-zenith direction).	• Overall Acceptability → A
143	Private crew quarters should have an option to completely darken the inside.	• Crew Quarters Acceptability → A, B, D, E
144	Automatic or manual circadian lighting to facilitate day/night cycles may benefit the health and performance of some crewmembers.	• Capability Assessment (≤ 30 days) → A, B, C, D, E • Capability Assessment (> 30 days) → A, B, C, D, E • Pairwise Comparison (≤ 30 day) → A, B, C, D, E • Pairwise Comparison (> 30 day) → A, B, C, D, E
145	Caution and warning lighting, paired with audible indicators, should be provided throughout the habitat.	• Crew Quarters Acceptability → A • IFM Acceptability → B • Fire Emergency Acceptability → B
146	A "smart" subsystem caution and warning indicator lighting system could be employed so that crewmembers can readily distinguish subsystem failures.	• IFM Acceptability → A, B • Fire Emergency Acceptability → B
147	In cases where an emergency evacuation is necessary, translation path lighting should lead the way to Orion.	• IFM Acceptability → A, B
In-Flight Maintenance		
148	Habitat designs should enable simple and efficient in-flight maintenance (IFM).	• IFM Acceptability → A, B, C, D, E • Overall Capability Assessment → A, D
149	All subsystems that may need IFM should have adequate access to replace components, including for mating/demating power, and to access data, and fluids interfaces.	• General Layout Acceptability → B, C, D • IFM Acceptability → A, B, C, D, E • Overall Capability Assessment → A, D
150	Where needed, methods that enable access to all sides of subsystems should be implemented (e.g., "drawers" that allow pallets to first be pulled out and then rotated for better access).	• IFM Acceptability → D • Overall Capability Assessment → A, D

Design Guideline #	Design Guideline	Supporting Data References
151	Common tool kits and/or tool-less interfaces minimize the tools required on board and can make IFM more time efficient.	• IFM Acceptability → A, B, C, D, E
152	Dedicated subsystem IFM kits will reduce the time needed to gather supplies; this is particularly important for time-sensitive maintenance tasks, such as pressure vessel leaks.	• IFM Acceptability → A • AllTraq → A
153	The operator performing a maintenance task should be able to view all fasteners, holes and interfaces (i.e., eliminate blind mating); there should be no spurious holes nearby intended fastener holes.	• IFM Acceptability → C
154	Common relocatable multipurpose work surfaces with movable temporary stowage that can be affixed where needed during maintenance tasks should be provided.	• IFM Acceptability → A, B, C, D, E
155	A deployable multipurpose temporary stowage caddy with elastic pouches, Velcro, etc. that is independent of the work surface itself could provide movable temporary stowage and better accommodate tools, parts, and equipment.	• IFM Acceptability → A, B, C, D, E
156	Mobile and adjustable stability aids (i.e., hand and foot restraints) and task lighting are also required; these should be able to be secured wherever maintenance is needed.	• IFM Acceptability → A, B, C, D, E
Radiation Protection		
157	A radiation shelter does not need to be permanently deployed within the habitat.	• Radiation Shelter Acceptability → A, B
158	If a radiation shelter is constructed when needed, all necessary components (e.g., water tiles, compacted trash tiles) should be easy to identify and have simple construction plans that clearly denote where each component is to be placed.	• Radiation Shelter Acceptability → A
159	Since radiation events may last for several days, essential habitation and operations functions (e.g., the ability to eat, sleep, perform basic hygiene and WCS ops, and conduct critical commanding) must be provided and accessed within the shelter; if any of these are not possible, the radiation shelter should be constructed in close proximity to these functions to limit the amount of time that crewmembers must be outside of the shelter (e.g., a single exit/entry point with direct access to the WCS).	• Radiation Shelter Acceptability → A
160	The shelter should contain ventilation, power and data connectivity (e.g., for lighting and laptops/tablets, including a hardwired monitoring/commanding interface), methods for securing sleeping bags, and temporary stowage accommodations.	• Radiation Shelter Acceptability → A
161	Privacy barriers (e.g., curtain, door) within the shelter should be provided where crewmembers can perform tasks such as changing clothes.	• Radiation Shelter Acceptability → A
Multipurpose Airlocks		
162	Modules may be designed to provide both habitation functions (e.g., exercise and science) and to serve as an airlock for EVA.	• Overall Acceptability → C • General Layout Acceptability → C • Multipurpose Airlock Acceptability → C

Design Guideline #	Design Guideline	Supporting Data References
163	Airlocks for EVA should be designed to have both an equipment lock (where EVA preparation and post activities occur) and a crew lock (where suited crew-members egress and ingress the spacecraft).	• Multipurpose Airlock Acceptability → C
164	Nominally the equipment lock does not go to vacuum, but it could be necessary if the interior crew lock hatch fails to seal. Thus, habitation-related equipment in the equipment lock that cannot tolerate a vacuum must be moved to other modules during EVA preparation activities.	• General Layout Acceptability → C • Multipurpose Airlock Acceptability → C
165	Sufficient volume and stability aids must be provided in the equipment lock to mount 2 EVA suits and to allow up to 4 crewmembers to work on and around them simultaneously.	• Multipurpose Airlock Acceptability → C
166	The suits should be accessible in the equipment lock for donning (upward through a hard upper torso or through a rear-entry hatch) and mounting of all necessary EVA tools and equipment on the suits.	• Multipurpose Airlock Acceptability → C
167	Stowage volume and accommodations (permanent and temporary) in the equip-ment lock should accommodate all necessary EVA tools, equipment, suits, and umbilicals.	• Multipurpose Airlock Acceptability → C
168	Umbilicals must be long enough to reach from the interior of the crew lock to any location in the equipment lock.	• Multipurpose Airlock Acceptability → C
169	Any permanent (e.g., lockers) or temporary stowage (e.g., Velcro, bungees) ac-commodations in the equipment lock must accommodate suit servicing kits, crew preference items, tools, etc., during EVA prep and post operations.	• Multipurpose Airlock Acceptability → C
170	Crew lock umbilical interfaces and restraint designs currently in use on ISS should be provided.	• Multipurpose Airlock Acceptability → C