Development of a Ground Test & Analysis Protocol for NASA's NextSTEP Phase 2 Habitation Concepts

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Abstract— The NASA Next Space Technologies for Exploration Partnerships (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. NASA first issued the Phase 1 NextSTEP Broad Agency Announcement to U.S. industries in 2014, which called for innovative cislunar habitation concepts that leveraged commercialization plans for low-Earth orbit. These habitats will be part of the Deep Space Gateway (DSG), the cislunar space station planned by NASA for construction in the 2020s. In 2016, Phase 2 of the NextSTEP program selected five commercial partners to develop ground prototypes. A team of NASA research engineers and subject matter experts (SMEs) have been tasked with developing the ground-test protocol that will serve as the primary means by which these Phase 2 prototypes will be evaluated. Since 2008, this core test team has successfully conducted multiple space-flight analog mission evaluations utilizing a consistent set of operational tools, methods, and metrics to enable the iterative development, testing, analysis, and validation of evolving exploration architectures, operations concepts, and vehicle designs. The purpose of implementing a similar evaluation process for the Phase 2 Habitation Concepts is to consistently evaluate different commercial partner ground prototypes to provide data-driven, actionable recommendations for Phase 3. This paper describes the process by which the ground test protocol was developed and the objectives, methods, and metrics by which the NextSTEP Phase 2 Habitation Concepts will be rigorously and systematically evaluated. The protocol has been developed using both a top-down and bottom-up approach. Top-down development began with the Human Exploration and Operations Mission Directorate (HEOMD) exploration objectives and ISS Exploration Capability Study Team (IECST) candidate flight objectives. Strategic questions and associated rationales, derived from these candidate architectural objectives, provide the framework by which the ground-test protocol will address the DSG stack elements and configurations, systems and subsystems, and habitation, science, and EVA functions. From these strategic questions, high-level functional requirements for the DSG were drafted and associated ground-test objectives and analysis protocols were established. Bottom-up development incorporated objectives from NASA SMEs in autonomy, avionics and software, communication, environmental control and life support systems, exercise, extravehicular activity, exploration medical operations, guidance navigation and control, human factors and behavioral performance, human factors and habitability, logistics, Mission Control Center operations, power, radiation, robotics, safety and mission assurance, science, simulation, structures, thermal, trash management, and vehicle health. Top-down and bottom-up objectives were integrated to form overall functional requirements – ground-test objectives and analysis mapping. From this mapping, ground-test objectives were organized into those that will be evaluated through inspection, demonstration, analysis, subsystem standalone testing, and human-in-the-loop (HITL) testing. For the HITL tests, mission-like timelines, procedures, and flight rules have been developed to directly meet ground test objectives and evaluate specific functional requirements. Data collected from these assessments will be analyzed to determine the acceptability of habitation element configurations and the combinations of capabilities that will result in the best habitation platform to be recommended by the test team for Phase 3.

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1. INTRODUCTION

The NASA Human Exploration and Operations Mission Directorate (HEOMD) has established human exploration and operations objectives to inform, identify, and prioritize agency technology and science developments to enable deep space habitation (Figure 1) [2]. They define four iterative exploration phases beginning with Earth-reliant operations and testing onboard the International Space Station (ISS) and within low Earth orbit (LEO) (Phase 0), followed by proving ground operations in cislunar space to verify deep space habitation capabilities and integrated human-robotic operations (Phases 1 & 2), and culminating in Earth-independent human missions to Mars (Phase 3). Each phase is characterized by increasing mission complexity and builds upon the scientific knowledge, technological advancements, and operational experiences of the previous phase to extend the capabilities needed for deep space exploration. Specific objectives to facilitate transportation, crew health, and working in space have been outlined for each phase [2].

A key part of the HEOMD deep-space habitation development strategy is the Deep Space Gateway (DSG), a crew-tended cislunar space station planned by NASA for construction in the 2020s [3]. The DSG will be initially placed in a Near-Rectilinear Halo Orbit (NRHO) around the Moon. It will be used as a staging point for the Deep Space Transport (DST), which will eventually take human crews to Mars in the 2030s, and is also being considered for use as a staging ground for robotic and crewed lunar surface missions by international partners. The various components of the DSG are planned for launch on the Space Launch System (SLS) as co-manifested payloads with Orion on Exploration Missions (EM) 2 through 8. The DSG is likely to incorporate components developed under the NextSTEP Phase 2 program.

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 [4]. The NextSTEP Phase 1 Broad Agency Announcement (BAA) called for innovative cislunar habitation concepts that leveraged commercialization plans for low Earth orbit (LEO). Phase 2 invited five commercial companies to refine their concepts and develop ground-based habitation prototypes. In addition, a NASA-developed Deep Space Gateway and Transport (DSG&T) reference will represent the current best representation of the DSG&T systems, operations, missions and manifests as guided by HEOMD requirements, partnership options and programmatic constraints. It will be used as a benchmark for comparing alternatives and will be adjusted on a periodic basis based on analysis, tests and programmatic priorities. Requirements for future development and acquisition will be eventually be derived from the DSG&T reference.

This paper describes the process by which the ground test objectives were derived. It then details the strategic questions, hypotheses, and describes the types of inspections, analyses, subsystem standalone tests, and HITL integrated tests that will be used to address the functional requirements

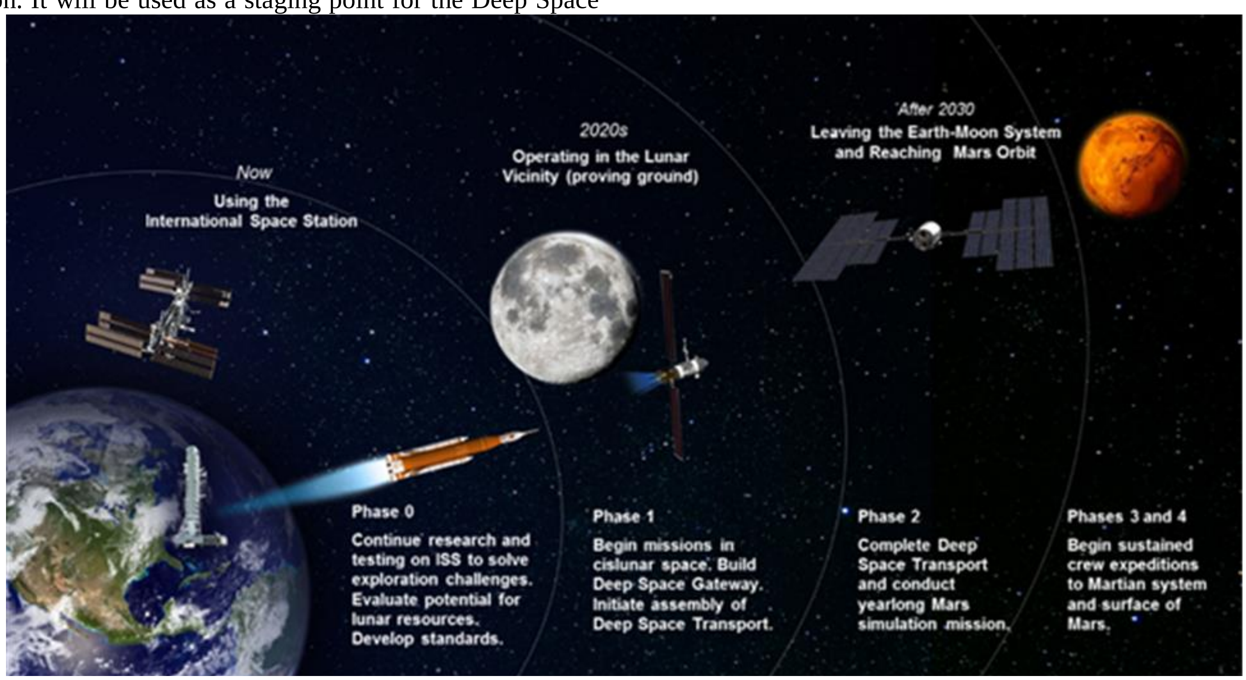


Figure 1. HEOMD deep-space habitation development strategy; from page 2 of [1].

and ground test objectives during evaluation of the NASA NextSTEP Phase 2 Habitation Concepts. The purpose of this assessment program is not to select a single specific configuration, but to provide data and recommendations regarding how the habitation, science, and EVA functions can be acceptably distributed across the elements of the Deep Space Gateway (DSG). The data will also be used to define minimum acceptable configurations and a variety of hybrid configuration options offering the highest levels of acceptability (though some of these may not be practically achievable).

2. Ground Test Objectives and Verification Methods

Ground test objectives were developed using a methodology that started with the mapping of HEOMD exploration objectives and the ISS Exploration Capability Study Team (IECST) phase objectives and capability test objectives to representative functional requirements for a DSG. Ground test objectives were then defined to evaluate how well different DSG configurations address each of the representative functional requirements. These objectives were further informed and refined by recommendations provided by NASA stakeholders. Four different verification methods, including inspection, subsystem standalone tests, analysis, and HITL integrated tests, will be used to assess the ground test objectives. The resulting data will be assimilated and analyzed to determine the combinations of capabilities, stack elements and function distributions that will result in acceptable DSG configurations. The results of this ground test and analysis evaluation protocol will inform recommendations for Phase 3. The flow chart below overviews this process (Figure 4). In the future, functional requirements will be expanded to address the DST. Additional ground test objectives and DST specific timelines will be developed and evaluated.

HEOMD Exploration Objectives

NASA's Human Exploration and Operations Mission Directorate (HEOMD) has established human exploration and operations objectives. The purpose of these objectives is to translate and bridge the gap between agency-level human exploration strategies to create clear and discrete objectives for implementation by HEOMD organizations and missions. There are three defined capability periods of exploration, starting with Earth Reliant exploration, through the Proving Ground of cislunar space, and culminating with Earth Independent exploration where human missions to the Mars system are possible. Each capability period is defined by increasing mission complexity, and builds upon the scientific knowledge, technical advances, and operational experience of the previous period to explore and extend capabilities for deep space exploration, leading to the eventual human exploration of the surface of Mars. The Earth Reliant, Proving Ground, and Earth Independent periods are divided into phases:

- Phase 0: exploration systems testing on ISS;
- Phase 1: cislunar demonstration of exploration systems;
- Phase 2: cislunar validation of exploration capability;
- Phase 3+: beyond Earth-Moon System.

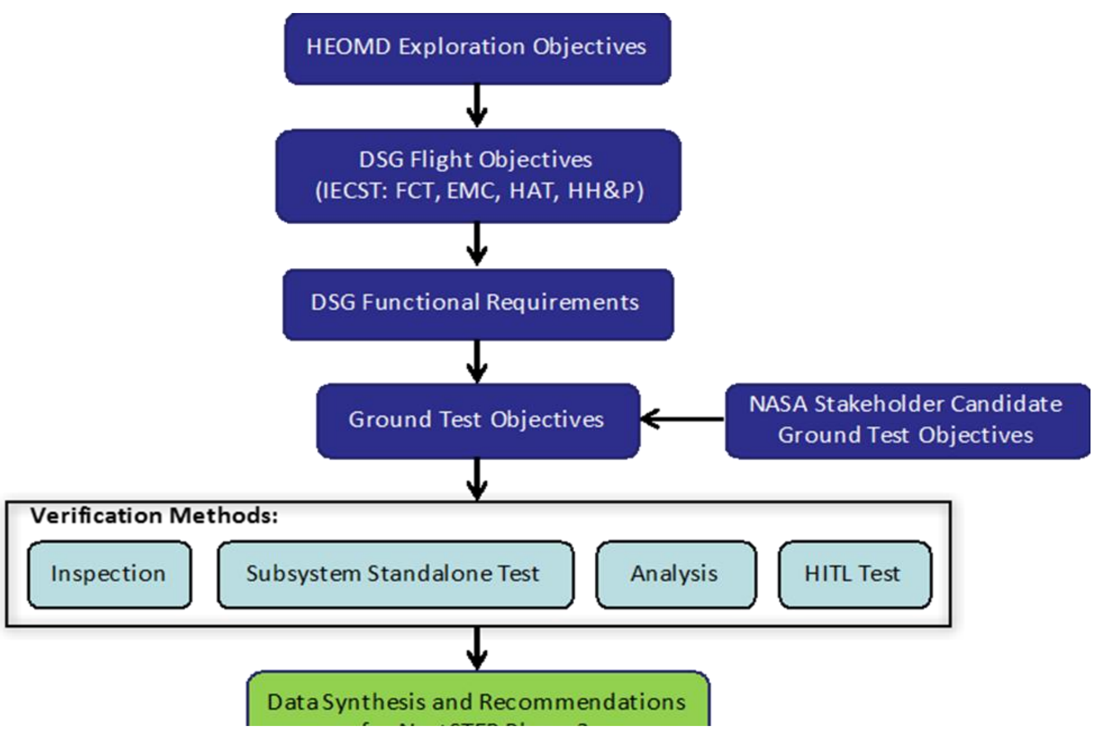


Figure 2. Flow chart depicting ground test objectives development methodology, verification methods, and data synthesis and recommendations for NextSTEP Phase 3

Table 1. Subset examples of HEOMD Phase 1 Objectives (left). (b) IECST Phase Objectives (right).

Objective Identifier	Objective	Objective Category
P1-01	Demonstrate SLS Block 1 elements in flight and integrated performance with Orion	Transportation
P1-02	Demonstrate Block 1B trans-lunar injection (TLI) performance	Transportation
P1-03	Demonstrate SLS Block 1B co-manifested capability	Transportation
P1-04	Demonstrate Orion's ability to support crew in deep space	Transportation
P1-05	Demonstrate Orion's ability in conjunction with additional habitation element(s) to support missions with at least 4- Crew for a minimum of 30 days	Transportation
P1-12	Demonstrate deep space crewed operations up to Mars communications latency	Working in Space
P1-13	Validate ability to conduct EVA in deep space	Working in Space
P1-14	Validate integrated radiation risk mitigation ability to provide As Low As Reasonably Acceptable (ALARA) exposure, including monitoring, mitigation, and operational strategies	Working in Space
P1-15	Demonstrate transition between crewed and uncrewed operations	Working in Space
P1-16	Demonstrate human/robotic interactions in deep space	Working in Space
P1-24	Demonstrate/evaluate exploration medical capabilities	Staying Healthy
P1-25	Demonstrate/evaluate human flight operations crew physiological well-being in deep space	Staying Healthy
P1-26	Demonstrate/evaluate human flight operations crew psychological well-being in deep space	Staying Healthy
P1-27	Demonstrate/evaluate human health countermeasures	Staying Healthy
P1-28	Evaluate the effects of deep space on complex organisms, plants, food, pharmaceuticals, and animal models	Staying Healthy

PO ID	Phase Objective
PO-01	Demonstrate delivery capability of SLS Block 1B and 2 with crew and co-manifested payload transportation system
PO-02	Demonstrate SLS Block 2 cargo only capability
PO-03	Determine Orion ability to support crew in deep space independently and while attached to habitation system
PO-04	Demonstrate autonomous deep space assembly, rendezvous and docking/berthing operations
PO-05	Demonstrate ability to dispose of assets from deep space
PO-06	Demonstrate operation of long duration high power solar electric propulsion capability
PO-07	Demonstrate exploration technologies which need the deep space environment
PO-08	Begin assembly of deep space exploration habitat and demonstrate performance of advanced habitation systems, including transitions to/from dormant operations
PO-09	Determine habitat capabilities, performance for uncrewed operations for periods of up to two years including transitions to and from crewed missions
PO-10	Leverage capabilities of human and robotic explorers to meet exploration objectives
PO-11	Demonstrate ability to conduct EVA in deep space
PO-12	Demonstrate ability to conduct autonomous EVR operations in deep space
PO-13	Demonstrate lunar vicinity and surface to Earth communication relay
PO-14	Enable scientific investigations by providing access to Phase 1 capabilities
PO-15	Perform sample collection, handling and return
PO-16	Extend international human presence to the Lunar Surface, demonstrate extended mobility systems, demonstrate surface power systems
PO-17	Initial study of combined effects of deep space environment, isolation, and confinement on human health and performance
PO-18	Demonstrate human spacecraft operations in and between various cislunar orbits

High-level exploration objectives have been identified for each phase; Phase 0 consists of 17 objectives, Phase 1 includes 28 objectives, and Phase 2 has 18 objectives. HEOMD broadly classifies these objectives into three cross-cutting categories: transportation, working in space, and staying healthy. Transportation objectives include those related to crew transport, heavy-lift, in-space propulsion, and deep space navigation and communication. Working in space objectives encompasses science, deep space operations, and in-situ resource utilization. Staying healthy objectives are focused on deep space habitation and crew health. These HEOMD phase objectives were used to guide the candidate DSG functional requirements and ground test objectives and analyses described in later sections of this paper. A subset of the HEOMD Phase 1 Objectives is shown in Table 1.

IECST Objectives

The IECST gathered input from the Future Capabilities Team, Evolvable Mars Campaign, Human Spaceflight Architecture Team, and Human Health and Performance team and proposed 18 high-level phase objectives (POs). These POs are intended to drive out the necessary capabilities to be demonstrated or tested in preparation for the development of a cislunar transit habitat [5].These POs are listed in Table 1. Each IECST PO is linked to a number of corresponding capability test objectives (CTOs). These CTOs describe the evaluations, demonstrations, validations, and tests that address the overarching PO. Furthermore, each CTO has been mapped to the HEOMD phase objectives. A sampling of several CTOs is displayed in Table 2. Like the HEOMD phase objectives, the IECST POs and CTOs were also used to guide the ground test objectives and analysis activities.

DSG Functional Requirements and Verification Methods

The HEOMD phase objectives and IECST POs and CTOs guided the development of a draft list of functional requirements for the DSG. From these high-level objectives, categories related to all aspects of the DSG were outlined. These categories were then organized into larger groups which encompass DSG architecture, transportation, operations, systems and subsystems, vehicle layout, EVA, human factors and performance, medical, sustainability and contingency, and science (Figure 3). The categories provided the framework under which the detailed DSG functional requirements were drafted. 88 representative DSG functional requirements were drafted and 88 corresponding ground test objectives were defined.

These objectives were further informed and refined by recommendations provided by the NASA stakeholder SMEs; this included detailed protocol descriptions and specific deliverables for each objective. The objectives were then organized into those that would be evaluated by inspection, demonstration, subsystem standalone testing, and/or HITL testing. A subset of these functional requirements and ground test objectives are displayed in Table 3.

These ground test objectives will be used to evaluate each contractor DSG configuration. One or more of the following verification methods [6] will be used to address each ground test objective:

- Inspection – visual examination of a design to verify physical design features; simple measurement
- Analysis – use of modeling, simulation, measurement, and/or analytical techniques to predict the suitability of a design
- Subsystem standalone test – use of an end product to obtain detailed data needed to verify performance or conduct further analysis
- HITL Test – integrated evaluation involving test subjects executing a representative mission timeline within an analog environment.

Table 2. Examples of IECST Candidate Test Objectives

IECST Objective	CTO ID	Phase 0	Phase 1	Phase 2	Phase 3	CTO Description	HEO Objective
(PO-07) Demonstrate exploration technologies which need the deep space environment	CTO-07.16	X				Demonstrate habitat operations with communication latency at cislunar distance	PO-03, Evaluate communications with increased delay
(PO-07) Demonstrate exploration technologies which need the deep space environment	CTO-07.08	X				Demonstrate exploration environmental control and life support system (ECLSS) and environmental monitoring technologies and validate real-time on-orbit environmental Monitoring	PO-05, Demonstrate exploration environmental control and life support system (ECLSS) and environmental monitoring technologies and validate real-time on-orbit environmental Monitoring
	CTO-07.01	X				Validate in-space fire detection, suppression, and cleanup technologies suitable for exploration missions	PO-06, Validate in-space fire detection, suppression, and cleanup technologies suitable for exploration missions
	CTO-07.02	X				Evaluate SPE & GCR space radiation monitoring and protection capabilities in a deep space environment	PO-07, Demonstrate radiation monitoring technologies in LEO and evaluate radiation mitigation capabilities
	CTO-07.09	X				Demonstrate technologies for in-space exploration EVA	PO-04, Demonstrate in-space exploration class extra-vehicular activity (EVA) technologies
	CTO-07.13	X				Evaluate vehicle autonomous operations of habitat systems during nominal operations	PO-08, Demonstrate autonomous operations in LEO
(PO-10) Leverage capabilities of human and robotic explorers to meet exploration objectives	CTO-10.01	X				Demonstrate human and robotic mission operations	PO-09, Demonstrate human and robotic mission operations
(PO-07) Demonstrate exploration technologies which need the deep space environment	CTO-07.03	X				Evaluate technologies that enable operations with reduced logistics capabilities	PO-10, Evaluate technologies that may enable operations with reduced logistics capabilities
(PO-04) Demonstrate autonomous deep space assembly, rendezvous and docking/berthing operations	CTO-04.01	X				Demonstrate docking and close-proximity technologies and operations	PO-11, Demonstrate docking and close-proximity technologies and operations
(PO-13) Enable scientific investigations by providing access to Phase 1 capabilities:	CTO-13.01	X				Perform science enabled by ISS in Low Earth Orbit	PO-12, Enable science community objectives in low earth orbit
(PO-07) Demonstrate exploration technologies which need the deep space environment	CTO-07.18				X	Evaluate habitat operations with communication latency at Mars distance	P1-12, Demonstrate deep space crewed operations up to Mars communications latency
(PO-11) Demonstr… ability to … in …	…O-11.01		X			Demonstrate E… …bility for deep space …	P1-13, Validate ab… …onduct EVA in deep space

Architecture
- mission architecture
- launch systems
- Orion
- cargo resupply
- transit habitat
- landers
- co-manifested payloads
- asteroid redirect vehicle
- stack integration
- commercial partners
- international partners
- asset disposal
- planetary protection

Transportation
- docking
- rendezvous & docking (R&D)

Operations
- remote operations
- autonomous operations
- robotic operations
- teleoperations
- crew operations
- human-robotic interactions
- crewed/uncrewed transition
- contingency
- emergency
- safety

Systems and Subsystems
- avionics
- propulsion
- guidance, navigation, & control (GN&C)
- attitude determination & control (AD&C)
- communication
- power
- thermal
- environmental control & life support systems (ECLSS)
- radiation
- micrometeoroid & orbital debris (MMOD)
- lighting
- sleep stations
- crew workstations
- displays and controls
- storage
- WCS operations
- trash management
- potable water
- food
- meal prep
- hygiene
- exercise
- in-situ resource utilization (ISRU)
- subsystems integration
- stabilization/translation aids

Vehicle Layout
- exterior layout
- interior layout

EVA
- EVA
- exploration atmosphere

Human Factors and Performance
- human factors engineering
- acoustic environment
- housekeeping
- inventory management
- crew autonomy
- crew performance
- crew habitation

Medical
- medical operations
- medical monitoring & countermeasures

Sustainability and Contingency
- monitoring
- maintainability
- reparability

Science
- life science
- planetary science
- sample return

Figure 3. DSG categories that provide the framework for the functional requirements and ground test objectives

Table 3. Examples of DSG-level requirements, test objectives, and verification methods

DSG ID	DSG-Level Functional Requirements	Test Objective Protocol Description/Deliverables	Verification Method: Analysis	Verification Method: Subsystem Standalone	Verification Method: Inspection	Verification Method: HITL
DSG-0020	The Deep Space Gateway shall accommodate one 30-day mission per year for up to 4 crew.	Analysis: Determine power, food, water, trash disposal plans as part of a multi-year logistics operations concept for one 30-day mission per year for 4 crew; assess contractor designs against multi-year logistics operations concept and determine if delivered designs are sufficient. HITL: Execute HITL test timeline; record objective metrics (e.g. task time, zone maps for location of crew) and subjective metrics via post-test crew consensus questionnaires (including extrapolations test time to make judgement about the acceptability of a 30-day duration).	X			X
DSG-0740	The Deep Space Gateway shall have a net habitable volume consistent with that required for one 30-day mission per year for up to 4 crew.	Analysis: determine net habitable volume of contactor designs HITL: Evaluate acceptability of the net habitable volumes through simulation of a mission timeline during HITL testing; execute 3-day mission timeline and collect subjective consensus ratings and comment via questionnaire	X			X
DSG-0090	The Deep Space Gateway shall provide docking ports for up to three visiting vehicles at the same time.	Analysis: Identify driving cases for simulation; simulate docking approach corridors and plume impingement	X			
DSG-0760	The Deep Space Gateway shall provide sleeping accommodations for 4 crewmembers.	Inspection: inspect contractor designs for sleeping accommodation sufficiency (i.e. number, placement, volume, etc.) HITL: Evaluate sleeping accommodations in mockups as part of HITL timeline; collect subjective consensus ratings and comment via questionnaire			X	X
DSG-0580	The Deep Space Gateway shall maintain control of the stack to within (+/-TBD) degrees of a commanded attitude in a defin[illegible] reference frame.	Subsystem Standalone: Develop stand-alone iPAS representation of the DSG; develop protocol and software to verify necessary sensor and data flows and calculations for attitude control of the DSG; execu[illegible] and verify required acc[illegible]nce frame		X		

Analysis tasks will be performed by either JSC or IAT SMEs and can consist of deliverables that include the use of modeling, simulation, measurement, and or analytical techniques. Subsystem standalone tests may involve SMEs and potentially require some crew involvement, but are performed as separate tests and will result in both quantitative and qualitative metrics. Inspections will be compiled into figures of merit for comparison of the various contractor DSG configuration options.

This ground test and analysis protocol will predominantly consist of analysis tasks due to the limitations associated with varying fidelity of contractor deliverables and the limitations of testing in a 1g environment. HITL testing will be performed where practical, and the results will be combined with the analyses to inform recommendations for future work. The analyses, were inferred from the functional requirements and test objectives. The analyses will include calculations, CAD assessments, modelling and simulation, and other analytical techniques as needed.

The HITL tests will be designed to provide a high-fidelity simulation of a cislunar mission, including the use of astronaut crew subjects and mission control, executing a representative mission timeline. The mission timeline was developed by integrating multiple ground test objectives into functional tasks and structuring them into a representative three-day mission. This study design is described in Section 6.0 Data Collection Methods. The detailed test timelines (Appendix A) were drafted and then reviewed and further refined at a two-day workshop with all stakeholders, SMEs and JSC flight controllers. The timelines include both habitation and operations-related tasks and are meant to provide a flight-like operations environment. Timeline tasks include habitation such as post-sleep, meals, WCS operations, exercise, and pre-sleep. Operation tasks include simulation of GNC and systems operations and monitoring, simulation of lunar robotic asset operation and DSG robotic arm used for sample return, EVA preparation and post EVA cleanup and servicing, routine maintenance and housekeeping, and selected in-flight maintenance activities.

3. STUDY DESIGN LIMITATIONS

The ground test and analysis protocol for the DSG has a number of limitations including but not limited to:

Number, Type, and Fidelity of DSG Contractor Mockups

Due to budget, schedule, and 1-g limitations the NextSTEP BAA testing will not include mockups of the Orion or logistics module. The contributions of Orion and the logistics module will be assessed through a combination of analyses, VR, and standalone testing rather than fully integrated HITL testing. The fidelity of DSG contractor habitation and EVA modules could vary widely, and for this reason, our simulation quality scale will be used to discriminate which data will be used for tests of the hypotheses and forward DSG recommendations.

1-g Test Environment

The DSG will be implemented in micro-gravity which is not possible to fully simulate in 1-g environment. However previous testing has shown that 1-g mockups which contain features required for microgravity operations (e.g. handholds, foot loops, Velcro, etc.) combined with the expertise of experienced astronauts can result in meaningful assessments. VR can also be used to address some aspects of microgravity such as full utilization of the habitation volume (e.g. exercise on ceiling versus floor) which would not be possible in a 1-g test.

HITL Study Design

The NextSTEP BAA will result in five different habitation configurations. At this time, the details of each individual DSG contractor configuration with respect to the number and type of modules and distribution of habitation, science, and EVA functions are not known. Also since each contractor will provide their own designs, we do not have the control to systematically vary the independent and dependent variables. For this reason, multiple specific hypotheses could not be prospectively developed. Instead, two high-level hypotheses are proposed that provide the framework to guide the HITL testing and evaluation. The results of the HITL testing across all five configurations will be assimilated, analyzed, and used to inform future requirements and design recommendations for the DSG.

In this type of HITL testing using the targeted population of astronauts as test subjects, it is not possible to execute the studies with large numbers of subjects (e.g. limited number of astronauts, scheduling constraints). Therefore, although individual will be collected, the crew consensus evaluation will be used for test of the hypotheses and to identify the actionable results.

4. HYPOTHESES AND STRATEGIC QUESTIONS

As mentioned previously the purpose of this testing is not to pick a specific "winning" configuration but through the study design and data collection metrics identify aspects of the contractor DSG configurations that are acceptable and unacceptable.

These hypotheses provide the broad framework from which to structure the study design, data collection, and analyses. For instance, we may hypothesize that the number and type of elements and distribution of functions across those elements will affect the overall acceptability and crew performance. If the hypotheses are rejected that would indicate that all contractor DSG configurations are acceptable, in which case future development decisions would be purely pragmatic. However, if the hypotheses are accepted that would indicate that differences in elements and distribution of functions are predictors of acceptability and performance. In this case, analysis of the data results would inform hybrid options that offer the best development solutions, taking into account acceptability, crew performance, and other pragmatic factors. The hypotheses and tests of hypotheses are listed below; objective and subjective metrics are described in Section 4.0: Data Metrics and Analysis Products, as well as a discussion and definition of "practical significance".

Hypothesis 1: The number and type of DSG stack elements (e.g., habitat + node + dedicated airlock) will be a significant predictor of crew performance and overall acceptability of the DSG configuration.

– Test of the hypothesis: Various contractor configuration options have been proposed that range from a minimum number of elements (i.e., a single combined habitat node, logistics module, and airlock) to stack configurations that involve six or more elements including two habitats. These habitation configurations will be evaluated through HITL tests using objective and subjective metrics along with analyses. A categorical difference in acceptability and a 10% difference in performance metrics will be considered practically significant. The resulting data will be evaluated to define the minimum acceptable configurations. If practically significant differences among the different stack options are observed, then the hypothesis will be accepted and recommendations for future work will be based on preferred stack element configurations. If there are not practically significant differences among the different configurations, then the

Table 4. Strategic questions addressing important aspects of the DSG habitation architecture

Strategic Questions	Analysis	Subsystem Standalone Test	HITL Test
1. What DSG habitation stack elements are needed to support a 30-day, 4-crew mission?	X	X	X
2. How should the habitation, science, and EVA functions be distributed across the DSG stack elements to enhance crew performance?	X		X
3. What systems and subsystems are needed to support a 30-day, 4-crew mission and how should they be distributed across the DSG stack?	X		X
4. What configuration of stack elements, and distribution of systems and subsystems protects for contingencies (e.g. loss of cabin pressure, subsystem failure, fire, toxic atmosphere, etc.)?	X		
5. How should the DSG systems and subsystems be packaged to support maintainability and serviceability?	X	X	
6. What minimum net habitable volume should the stack have?	X		
7. How many docking ports should the DSG have?	X		
8. Should there be a dedicated airlock or a multi-functional airlock?	X		X
9. What mass and volume of logistics are needed to support the DSG for 30 days (e.g. food, clothing, water, gases, spares, etc.)?	X		
10. What is the most effective way to manage logistics and trash removal for the DSG?	X		
11. What communications are needed for the DSG? (e.g. # of space-to-ground loops, DSG-to-visiting vehicle loops, DSG-to-lunar surface loops)?	X		X
12. What robotic assets are needed to support DSG task categories including, but not limited to, logistics handling, dormancy maintenance, sample return, experiment deploy/recover, EVA support, and aggregation of the DST?	X		
13. What exercise equipment and daily exercise durations are needed for the DSG?	X	X	X
14. What medical capabilities are needed on the DSG?	X	X	
15. What degree of crew and vehicle autonomy is needed for the DSG?	X		

hypothesis will be rejected and recommendations for future work will be solely based on other DSG pragmatic development considerations.

Hypothesis 2: The distribution of required functions (habitation, science, and EVA) within the DSG stack will be a significant predictor of crew performance and overall acceptability of the DSG configuration.

– Test of the hypothesis: Different distributions of functions have been proposed by the various NextSTEP contractors. The effects of these different distributions on crew performance and overall acceptability will be evaluated through HITL tests using objective and subjective metrics to define the most acceptable distributions. A categorical difference in acceptability and a 10% difference in performance metrics will be considered practically significant. If practically significant differences between different distributions of functions are found, then the hypothesis will be accepted and recommendations for future work will be based on preferred distributions of functions. If there are not practically significant differences between different distributions of functions, then the hypothesis would be rejected and recommendations for future work will be solely based on other DSG pragmatic development considerations.

Strategic Questions

To guide the evaluation of the various contractor DSG configuration concepts, a set of fifteen high-level strategic questions have been identified (Table 4) by NASA exploration program managers and SMEs including the methods by which they will be evaluated. These questions address the architectural elements and configurations, systems, subsystems, and distribution of habitation, science, and EVA functions associated with the DSG. The following provides rationale and describes a high-level summary of the analyses and tests that will be performed to address these questions.

Strategic Question 1: What DSG habitation stack elements are needed to support a 30-day, 4-crew mission?—The DSG functions that are needed to support a 30-day mission with 4 crew include: science, habitation (exercise, sleep, hygiene, meal prep, PAO, medical, safety, and recreation), docking, EVA, logistics utilization, and contingencies. Multiple different configuration options have been proposed that range from a minimum number of elements (i.e., a single combined habitat node, logistics module, and airlock) to stack configurations that involve six or more elements including two habitats. These configurations will be evaluated via analyses and HITL testing to assess their respective acceptability using quantitative and qualitative metrics. The results of these analyses and HITL tests will be analyzed to define acceptable configurations including number, type, and distribution of stack elements. These data will be combined with additional analyses related to the number and type of launches and the developmental and lifecycles costs to inform recommendations for NextSTEP Phase 3.

Strategic Question 2: How should the habitation, science, and EVA functions be distributed across the DSG stack elements to enhance crew performance?—The required habitation, science, and EVA functions of the DSG can be distributed across the elements of a particular architectural concept design in a variety of ways. The distribution of functions across the stack elements may affect crew performance with respect to task execution, efficiency, and acceptability. For example, the location and number of WCS and the location of the galley, sleep stations, exercise, robotic workstations, and EVA capabilities may affect the overall acceptability of the DSG stack configuration. To address this question, analyses and HITL tests will be performed on different DSG contractor stack configurations with the level of detail determined by the contractor deliverable fidelity. Objective and subjective metrics will be compiled for each configuration and the data analyzed to define the habitation configurations that provide minimally acceptable function distributions along with hybrid options that offer the highest levels of acceptability.

Strategic Question 3: What systems and subsystems are needed to support a 30-day, 4-crew mission and how should they be distributed across the DSG stack?—The functional requirements of the DSG will define the required systems and subsystems needed to support a 30-day, 4-crew mission including the functions of habitation, science, logistics utilization, EVA, etc. The distribution of those systems and subsystems will affect the mass, complexity, reliability, and redundancy of the stack and may impact crew performance. Analyses will be performed on all the contractor configurations and metrics produced to compare and inform recommendations for future development. Additionally, HITL testing may elucidate crew performance related differences, for example if routine maintenance is required in areas that conflict with other science or habitation functions.

Strategic Question 4: What configuration of stack elements, and distributions of functions, systems and subsystems protects for contingencies (e.g. loss of cabin pressure, subsystem failure, fire, toxic atmosphere, etc.)?—The DSG will need to support not only nominal operations but will also need to address contingencies such as loss of cabin pressure, subsystem failures, fire, toxic atmosphere, etc. A standardized list of contingencies will be developed and the DSG contractor stack configurations will be analyzed to define the contingency responses. Specific trades will be performed to compare risk against mission and programmatic consequences.

Strategic Question 5: How should the DSG subsystems be packaged to support maintainability and serviceability? —Exploration class missions will likely need to prioritize reliability, maintainability, and serviceability of systems and subsystems over conventional mass and performance metrics. Metrics such as mass of spares and tools, commonality, time to criticality (serious mission or crew impact), accessibility, and repair time will be evaluated by SMEs for the different subsystem packaging options developed by the DSG contractors. Quantitative and qualitative metrics will be collected and analyzed. Depending on the fidelity of contractor deliverables some standalone HITL testing may be performed to assess the maintainability and accessibility of subsystems.

Strategic Question 6: What minimum net habitable volume should the stack have? —The net habitable volume of the DSG that is required in order to support a 30-day mission for 4 crew will be determined by a combination of analyses to define the required volumes for vehicle systems, crew systems, and logistics along with HITL testing and subjective metrics relating to DSG element layouts. HITL testing will be performed during which subjective metrics will be collected in real-time and during end-of-day and post-test crew consensus questionnaires.

Strategic Question 7: How many docking ports should the DSG have? —The DSG will need to support at least two visiting vehicles and a logistics module and ensure pressurized access to the Orion at all times. The DSG contractor operational concepts will be evaluated by analysis against assembly sequences, logistics resupply plans, docking contingency plans, EVA capability, approach corridors and plume impingement, and other programmatic considerations.

Strategic Question 8: Should there be a dedicated airlock or a multifunctional airlock? —The DSG will need to support EVAs for nominal and contingency maintenance and repair, potentially for experiment deployment and retrieval, and for aggregation of the DST. There are at least two types of EVA modules that could be considered: a dedicated airlock/equipment lock or a multifunctional airlock/equipment lock. A dedicated airlock would be designed strictly for EVA, including pre-EVA preparation, post-EVA activities and servicing, and EVA stowage. A multifunctional airlock would also include habitation functions (e.g., sleep stations, exercise equipment, robotic work stations, potable water system, WCS). Advantages of a dedicated airlock include reduced mass and a simpler design that is specifically optimized for EVA. Advantages of a multifunctional airlock include additional habitable volume to further distribute work and habitation functions and provide redundancy in the case of contingencies. To compare these two different airlock options, analyses and HITL testing will be conducted. The analyses will include what volume is necessary to accommodate all EVA systems, logistics, consumables, prep/post and suit don/doff activities for each option. Also the mass, power, and development costs required for each option will be determined for an assumed number and frequency of EVAs across the lifetime of the DSG. Analysis will also include assessment of secondary EVA ingress capabilities and the associated operational and mission impacts. Each of the contractor's EVA concepts will be assessed by executing HITL tests of EVA prep/post activities including stowage and logistics utilization in a physical mockup or virtual environment depending on the fidelity of the deliverable. To determine the validity of a VR simulation of airlock operations, a crossover test will be performed with a physical habitable airlock and a matched VR model using the same crews. The data results and simulation quality will be used to assess the validity of evaluating the contractor options with VR and also elucidate the strengths and weaknesses of the VR tool for future work.

Strategic Question 9: What mass and volume of logistics are needed to support a DSG for 30 days (e.g. food, clothing, water, gases, spares, etc.)? —The DSG will need to support 30-day missions with 4 crew at least once per year. These missions will require logistics (e.g. food, clothing, water, gaseous oxygen, gaseous nitrogen, spares, etc.) for maintenance of the crew and the DSG itself. The amount of logistics (i.e. mass and volume) required to support the missions will be determined through analysis. Analysis will be performed to predict the logistics needed for the duration of the missions. CAD and VR models will be developed to evaluate logistics layouts and utilization.

Strategic Question 10: What is the most effective way to manage logistics and trash removal for the DSG? —The mass and volume of logistics will be determined from the products of Question 9. Logistics utilization, and trash management operational concepts will be developed by each contractor. These operational concepts will be evaluated through analysis, CAD models, VR models, and some limited HITL testing (e.g. transfer paths for CTBs/Spares through hatches). The analysis will include but is not limited to estimates of propellant usage for trash disposal, crew time, power, operational complexity, and risk considerations.

Strategic Question 11: What communications are needed for the DSG? (e.g. # of space-ground loops, DSG-visiting vehicle, DSG-lunar surface) —The DSG operations concept includes general support of the cislunar habitat stack in both a crewed and uncrewed state. While uncrewed, the ground-based mission control center will be fully responsible for monitoring and control of the DSG systems and subsystems. The ground will also be required to monitor and control rendezvous and docking of stack elements in preparation for crewed operations. During crewed operations, the crew will need to have two-way communication with the mission control center to support habitat operations and also to support other mission operations such as teleoperation of robotic and science assets on the lunar surface, robotic sample return, EVA and potentially visiting vehicles. To address this question, analysis will be performed to determine the data telemetry and commanding needs for crewed and uncrewed operations as well as the number of channels required for intra-habitat and space/ground voice communication during the crewed phase. Additional analyses will be performed to assess redundancy and robustness of communication systems including interoperability across the various elements of the DSG stack. HITL testing will also occur that will include simulation of a 3-day mission timeline from both a crew and mission control perspective. HITL subjective and objective metrics will be collected and assessed to define acceptable communication architectures for the DSG.

Strategic Question 12: What robotic assets are needed to support DSG task categories including, but not limited to, logistics handling, dormancy maintenance, sample return, experiment deploy/recover, EVA support, and aggregation of the DST? —Analyses will be performed to define the specific tasks associated with the above task categories during crewed and uncrewed mission phases. Once the candidate tasks have been defined, task decomposition and parameterization (e.g. forces, distances, accuracies, time durations, etc.) will be performed. The results will be used to evaluate proposed contractor concepts and also develop functional and performance requirements of the robotic work system(s) for the DSG. These requirements will include but are not limited to characteristics such as length, accuracy, forces and torques, kinematics, and mobility requirements for robotic arms (e.g. walking arm vs mobile base). These analyses will also be used to define design and interface requirements for the robotic tasks. To understand the requirements for robotic workstations (human factors design, number/location of stations, etc.), specific representative tasks including lunar rover teleoperations and sample return simulations will be performed with HITL testing. The NASA in-house and contractor tests will include different numbers, types, and locations of robotic workstations all used to execute a common representative mission timeline. Quantitative metrics, such as completion time and planned versus actual timeline differences, will be combined with subjective metrics to inform recommendations for the NextSTEP Phase 3.

Strategic Question 13: What exercise equipment and daily exercise durations are needed for a DSG? —The DSG will need to support the transport, stowage, and deployment, and utilization of these exercise devices. NASA Human Research Program (HRP) SMEs will be delivering candidate exercise devices for the DSG ground test program. The ground test and analysis program will evaluate these exercise devices to determine the mass, volume, power, and associated operational envelopes, and how those interact with the rest of the DSG crew and systems including impacts to crew performance and timeline execution. The tools used to perform this analysis and testing will include VR along with both standalone and integrated HITL tests with the different exercise devices in different locations within the habitation mockups. As a baseline assumption one hour of exercise will be performed per crewmember each day, with thirty minutes for prep/post activities. The impact of this one hour exercise period on crew performance, psychology, and overall mission execution will be assessed with quantitative (e.g., timeline inefficiencies due to exercise interference) qualitative (e.g., human factors) metrics. The results of these analyses, standalone, and integrated tests will be compiled to refine DSG exercise device requirements for NextSTEP

Phase 3.

Strategic Question 14: What medical capabilities are needed on a DSG? —The HRP and the NASA Exploration Medical Capabilities (ExMC) element will provide a list of medical contingencies and associated equipment and data telemetry required for a DSG mission. The ground test and analysis program will evaluate the mass, volume, stowage, telemetry/communications systems, and utilization of this equipment. These assessments will be conducted with standalone tests of the hardware and software related to the medical data system. Additionally, representative mockups and/or functional medical equipment will be provided for evaluation during integrated HITL testing. Specific medical contingencies will be simulated at different locations within the DSG stack to assess the location of the medical equipment and workstations, space utilization, the efficacy of medical response, and general mission impact. Quantitative (e.g., timeline impacts to mission, time to execute medical procedures, etc.) and qualitative (e.g., privacy) metrics will be collected and compiled with the analysis results to inform medical capabilities recommendations for NextSTEP Phase 3.

Strategic Question 15: What degree of crew and vehicle autonomy is needed for the DSG? —Analyses will be performed to define all of the required tasks during crewed and uncrewed operations, including all nominal and vehicle critical contingency tasks. Based on this analysis recommendations will be developed for appropriate levels of crew and vehicle autonomy. Additionally, HITL tests will evaluate techniques such as just-in-time training, augmented reality, decision support software, or procedure based displays.

5. DATA METRICS AND ANALYSIS PRODUCTS

Subjective and objective data related to test crew performance and overall acceptability will be collected for the HITL tests and standalone evaluations of the systems and subsystems. Integrated HITL evaluations will primarily be used to evaluate functional requirements related to habitability, human factors, and crew performance. Standalone tests and analyses will utilize the same set of subjective metrics where applicable. Where appropriate, objective metrics, including but not limited to task completion time, number of task interruptions, duration of crewmember task wait times, number of incidences of task location overlap, and overall crew location within and across the module(s) under test, will also be used.

HITL test crews will be asked to provide both individual and consensus ratings from the crew operator's point of view. The test crew consensus rating ensures consistent interpretation of the questions. If desired, an individual test subject can note a dissenting opinion in the test crew consensus. Whereas there is information content in the individual ratings and comments, the test crew consensus ratings are considered to be the actionable metrics. Their ratings will be based on observations during real-time testing, as well as their expert judgment to extrapolate beyond the tested conditions.

Practical Significance

Ratings of Acceptability, Capability Assessment, Workload,

Fatigue, Overall Configuration Acceptability, and Crew Performance will be collected. Descriptions of these subjective metrics, including examples of the types of data analysis products derived from each, are provided in the following sections. Each of these ratings are based on a 10-point scale divided into 5 distinct categories with 2 ratings within each category to discriminate preferences. In the HITL testing, sample sizes will not be large enough to use inferential statistics. For this reason, we prospectively define *practical significance* as a categorical difference on the 10-point rating scales. For example, as shown in Figure 4, the difference between a 3 and 4 is not considered practically significant whereas the difference between a 4 and 5 is considered significant. Any rating greater than a 2 requires a comment to explain the rationale for the rating.

For objective metrics, such as timeline task completion times, wait times, interrupt times, etc., we prospectively define practical significance to be a 10% difference. For standalone tests, objective metrics will include subsystem performance parameters. For analyses, objective metrics will include total mass, number and type of launches, cost, etc.

Acceptability Ratings

A 10-point scale of acceptability has been developed and used by the Exploration Analogs and Mission Development (EAMD) project during analog field testing since 2008 to

Figure 4. Acceptability rating scale describing practically significant (i.e., categorical) differences.

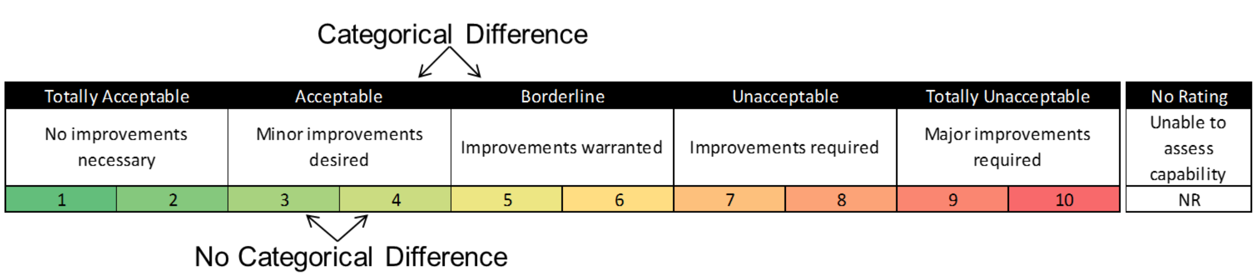
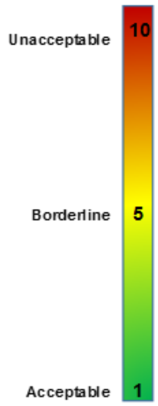


Figure 5. Notional example of acceptability ratings across five different DSG configurations

DSG Architectural Configuration Acceptability Ratings



	A	B	C	D	E	Acceptable Configurations	Most Acceptable Configuration
Robotic arm ops	2	8	9	3	9	A, D	A
EVA prep	6	10	2	6	1	C,E	E
EVA	7	3	6	1	8	B,D	D
Cooking	9	10	6	9	1	E	E
Hygiene	1	2	7	6	7	A,B	A
WCS ops	5	4	7	3	2	B,D,E	E
Suit Stowage	3	3	7	4	8	A,B,D	A or B
Sleeping	5	6	2	8	9	C	C
Docking and berthing	10	5	2	6	5	C	C
Logistics/Trash Stowage	7	3	7	5	10	B	B
Simulated contingencies	4	9	1	4	2	A,C,D,E	C
Experimental science	6	6	4	5	8	C	C
House keeping	2	5	2	3	5	A,C, D	A or C
Routine maintenance	2	7	1	4	9	A,C,D	C
IFM	2	4	2	10	6	A,B,C	A or C
Exercise	4	5	10	5	8	A	A
PAO	3	10	5	3	10	A,D	A or D
Medical	7	9	2	5	2	C,E	C or E

Acceptability Ratings > 4

Essential / Enabling		Significantly Enhancing		Moderately Enhancing		Marginally Enhancing		Little or No Enhancement		No Rating
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.		Unable to assess capability
1	2	3	4	5	6	7	8	9	10	NR

Figure 6. Capability assessment rating scale

measure the acceptability of different prototype systems and operations concepts and inform requirements for improvements when necessary. The scale, shown in Figure 4, 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.

These ratings will be provided by the test subjects performing the representative DSG mission timeline tasks with respect to the acceptability of a variety of habitation systems and functions. Test crews will be queried for their individual ratings following completion of various tasks and assessments. Additionally, there will be an end of mission day test crew consensus rating for each of these tasks.

From these ratings, the study team will also be able to evaluate the acceptability of each proposed DSG habitation configuration. The purpose of this evaluation is not to select a specific "winning" configuration. The results may range from all configurations being acceptable, in which case future development decisions will be based strictly on pragmatic decisions (e.g., number of launches, cost, schedule, etc.), to no specific configuration being totally acceptable, which might drive recommendations toward hybrid approaches for NextSTEP Phase 3. This information provides insight into how to improve the overall acceptability of a given configuration. Considering the configuration acceptability ratings outlined in Figure 5 as an example, an overall acceptable configuration might be Configuration A combined with the EVA function of Configuration B or D, the cooking arrangement from Configuration E, the docking and berthing elements from Configuration C, the logistics and trash stowage from Configuration B, and the medical elements from Configuration C or E.

Capability Assessment Ratings

A primary objective of this study is to identify which capabilities are required for exploration and which capabilities might enhance exploration but are not essential. It is also important to identify which capabilities provide marginal or no meaningful enhancement, and can therefore be excluded, resulting in cost savings without impact to mission success. Thus, a Capability Assessment (CA) scale (Figure 6) has been devised to rate the extent to which candidate capabilities are expected to enable and enhance future exploration missions. The CA scale consists of 5 categories: essential/enabling, significantly enhancing, moderately enhancing, marginally enhancing, and little of no enhancement. The CA scale will be used during HITL tests to provide information on the mission enhancing capabilities, different habitation designs and functional layouts designs of the DSG. In additional, SMEs performing standalone tests and analysis of systems and subsystems will also evaluate them against this scale in order to gather evidence for mission enabling designs/functions that should be included in Phase 3. Ratings will be gathered during end-of-mission test crew consensus discussions for the HITL tests and, where

Scale Rating	Criteria
1	Simulation quality (e.g. hardware, software, procedures, comm., environment) presented either zero problems or only minor ones that had no impact to the validity of test data.
2	Some simulation limitations or anomalies encountered, but minimal impact to the validity of test data.
3	Simulation limitations or anomalies made test data marginally adequate to provide meaningful evaluation of test objectives (please describe).
4	Significant simulation limitations or anomalies precluded meaningful evaluation of major test objectives (please describe).
5	Major simulation limitations or anomalies precluded meaningful evaluation of all test objectives (please describe).

Figure 7. Simulation quality rating scale

applicable, from SME discussions following subsystem standalone tests.

The consensus CA rating analysis, collected via end-of-test questionnaire, will be analyzed to show variation in the level of mission enhancement of each capability across the test conditions (e.g. architectural configurations). This analysis, along with objective data such as timeline execution duration, total crew idle time between tasks, etc., can also produce recommendations for distribution of capabilities across the DSG stack (example shown in Figure 8).

Capability Distribution

Data from all contractor tests will be assimilated and analyzed to develop a preferred capability distribution matrix, as notionally shown below in Figure 8. Additionally, test crew will complete a matrix for their preference of capabilities distributions across each specific contractor configuration.

Capabilities Distribution Preferences

	HAL	Node	Logistics	A/L	Small Habitat	Large Habitat
Robotic arm ops					x	x
EVA prep	x					
EVA	x					
Cooking					x	x
Hygiene					x	x
WCS ops	x					
Suit Stowage		x				
Sleeping	x				x	x
Docking and berthing					x	x
Logistics/Trash Stowage			x			
Simulated contingencies					x	x
Experimental science					x	x
House keeping	x	x	x	x	x	x
Routine maintenance	x	x	x	x	x	x
IFM	x	x	x	x	x	x
Exercise	x					
PAO	x	x			x	
Medical					x	

Figure 8. Notional example of rating- and data-derived preference for distribution of capabilities across DSG stack elements

Simulation Quality

Simulation quality ratings (Figure 7) will reflect the extent to which the simulation allows meaningful evaluation of the aspects of DSG habitation being assessed in this study. Unplanned communications drop-outs, unresolved hardware failures, or low-fidelity mockups are examples of factors that could affect simulation quality ratings. Aspects of DSG habitation that are not being assessed in this test will be intentionally excluded from consideration when providing ratings of simulation quality.

Each HITL test crew will provide consensus simulation quality ratings along with each acceptability or capability assessment rating because the same simulation may differ in quality depending on the types of operations or systems being assessed or the perspectives from which it is being assessed (e.g., by different groups). Where simulation quality ratings are rated as a four or five, the corresponding ratings by that group will not be used in hypothesis testing because, by definition, significant simulation limitations or anomalies preclude meaningful evaluation of major test objectives. It is understood, and expected, that not all habitation elements provided throughout the course of these proposed DSG habitation element evaluations will provide a flight-like simulation quality and obtaining this metric will enable the study team to place other ratings in context.

Crew Location Frequency Distribution

The amount of time the test crew spends in different locations within the DSG will be collected in order to evaluate habitation element task and function distribution. To develop the frequency distribution of area usage, the DSG configuration under test will be divided into different zones. Study team members then track the time each test subject spends in each zone with the objective of assessing the efficacy of crew time/motion as they execute the timeline. Any areas of the cabin that may be underutilized could potentially be eliminated or repurposed. An example crew location distribution map from previous evaluations of Mars Ascent Vehicle (MAV) cabin testing [7] is shown in Figure 9. This will provide valuable insight into cabin layout, volume utilization, and efficiency of task/function distributions throughout the stack to further inform functional requirement and habitation design refinements for NextSTEP Phase 3. Crew location data collected during the 3-day tests will be used to create location frequency distributions indicating the cumulative duration that crew were in specific locations within the habitable volumes. This analysis will further inform functional requirement and habitation design refinements in Phase 3.

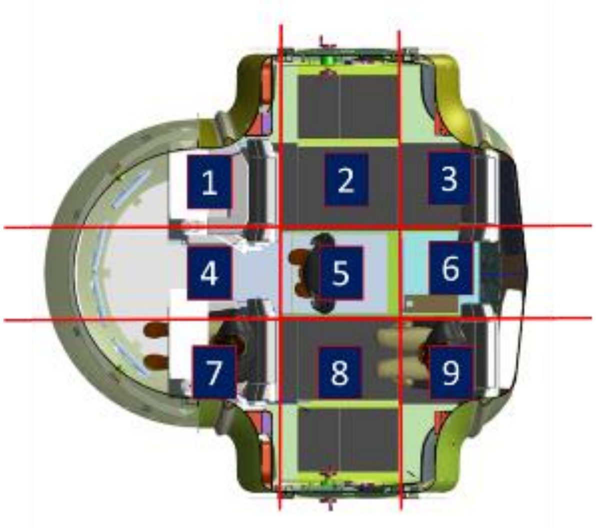


Figure 9. Crew location distribution characterization map example from MAV testing [7].

Crew Performance Metrics

Crew performance will be assessed through a combination of metrics collected during execution of the representative mission timeline. Data relating to task completion times, planned versus actual task execution durations, task wait times, task interrupt times, timeline re-planning, workload, fatigue, and ratings of perceived exertion will be collected.

Planned Versus Actual Timeline--Overall timeline and individual task durations will be collected and compared to the planned times to provide contextual understanding of other crew performance metrics. The study timeline has been developed in order to provide a common mission structure by which we are able to evaluate different DSG habitation concepts consistently across multiple tests. It is purposefully designed to limit the number of crewmembers performing a specific task at a given time in order to avoid crewmember overlap and wait times for use of cabin functions (e.g. WCS, galley, or exercise devices). The timeline was developed to be configuration independent and representative of a cislunar mission, however, the order of tasks may be changed to suit specific contractor DSG configurations.

The actual time to perform tasks on the mission timeline will be compared to the planned times and the results will be presented along with insight as to what may have caused the differences, such as conflicts for use of the same habitable volume, simulation quality effects, crew training for test, etc. Additionally, crewmember wait times and number of interrupts will be considered to evaluate DSG function layout.

Ratings of Perceived Exertion-- The rating of perceived exertion (RPE) scale is used to subjective quantify the acute physical effort required to complete a task (Figure 12). It gauges how much effort a person feels they must exert to perform a task on a scale of 6 to 20 which when multiplied by 10 roughly correlates with subject heart rate. This will be used during HITL and standalone evaluations of habitation elements, systems, and subsystems. For example, the physical effort related to reach and accessibility of subsystems during a repair task provides insight into vehicle layout and subsystem design.

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Figure 12. Borg's Rating of Perceived Exertion Scale

Fatigue Ratings-- The fatigue scale measures the level of underlying fatigue that a crewmember experiences during the course of the mission. This reflects multiple factors including sleep quality, task workload and complexity, stress, and physical exertion. The 10-point rating scale, shown in Figure 11will be collected at the beginning, middle, and end of each

Figure 10. Workload Rating Scale

Minimal Workload		Low Workload		Moderate Workload		Significant Workload		Extreme Workload		No Rating
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		Unable to assess workload
1	2	3	4	5	6	7	8	9	10	NR

Figure 11. Fatigue Rating Scale

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

mission test day, and will be plotted over the multiday period.

Workload Ratings-- Workload integrates mental, physical, and environmental factors into a 10-point scale (Figure 10), which will be analyzed for both peak and average per subject and across all subjects. This scale consists of 5 categories: Minimal workload; low workload; moderate workload; significant workload; and extreme workload. During the test, subjects will be prompted for workload ratings upon completion of specific tasks in the timeline and at the end of the test day. Workload refers to the crewmembers ability to maintain maximum possible task performance in a given environment, test condition, task overlap or interference from other crewmembers performing their own tasks. While this does not directly provide insight into the distribution of functions across the DSG configuration it does provide data into task and overall habitation system design. For example, workload may be rated high during setup of exercise equipment if the vehicle interfaces, accessibility, and procedures are complex. Crewmembers will be asked for workload ratings for tasks including but not limited to operation of the lunar rover simulation, display navigation, exercise equipment setup, WCS operations, and system checks. In the context of the analysis and standalone tests, SMEs may also be queried for workload ratings as it relates to system and subsystem routine maintenance and repair.

5. HUMAN-IN-THE-LOOP STUDY DESIGN

Since 2008, the core ground test team for the NextSTEP Phase 2 Habitation Concepts evaluations has successfully conducted multiple spaceflight analog mission evaluations utilizing 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 [5, 7-17]. This has been achieved by ensuring that the required level of rigor and consistency is applied before, during, and after the operational field 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 the rationales 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
- (for HITL tests) The selection of test subjects that are representative of the target population (e.g., flown astronauts) 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 (including hardware and software) to address the questions at hand
- (for HITL tests) The use of test subject consensus results to form a single set of data that reflects the agreed-upon results of any subjective input provided
- The mapping of the results to specific, actionable hardware, software, and/or procedural recommendations

Ground Test Protocol Study Design

Initial human-in-the-loop testing will occur at the NASA Johnson Space Center (JSC) and will integrate the Space vehicle mockup facility (SVMF), Analog Mission Control Center (AMCC), and Integrated Power, Avionics, and Software (iPAS), to result in a high-fidelity integrated simulation of a cislunar human mission. During FY 2018, this protocol will be evaluated in three multi-day, integrated HITL test series (one engineering dry run, and two tests with astronaut crew). Additionally, multiple standalone dry-run tests will be performed as the facilities are assembled and integrated. The purpose of these FY18 tests is to refine the protocol, and train the crew, mission control team, and SMEs, to prepare them for FY19 contractor configuration evaluations. As needed, the protocol will be updated based on the results of the FY 2018 testing. The specifics of the HITL study design, hardware mockups, and other evaluation facilities will be specifically tailored to the individual contractor deliverables, but will use the same cislunar timeline tasks and metrics to maintain consistency across all tests.

A four-person crew will live and work inside the simulated cislunar stack from where they will execute the standard reference mission timeline which has been systematically developed to incorporate the major ground test objectives. Flight-like communications will be simulated including round-trip communications latencies for cis-lunar space and robotic asset control. The following sections summarize the study conditions, test subjects, and the detailed test timelines.

HITL Test Conditions

In FY18 preliminary testing at JSC, two conditions will be executed to evaluate the allocation of DSG functions across those elements. The test conditions are shown in Figure 13. Each condition includes four crewmembers, with the differences among conditions reflecting different strategies for distributing the required DSG functions, systems, and subsystems across available elements. The conditions that will be tested are a "Habitat-Centric Function Allocation" and a "Distributed Function Allocation". The first test condition, Habitat-Centric Function Allocation, will assume all required DSG functions (e.g. robotic workstation, exercise, science, meals) are collocated in a single small habitat that includes a dedicated equipment lock/crew lock. The second test condition, Distributed Function Allocation, will spread the required DSG functions across available elements; functions such as exercise, meal preparation, robotic workstation, and science may be performed in a separate multifunction equipment lock/crew lock element with the remaining functions in a small habitat (Figure 13).

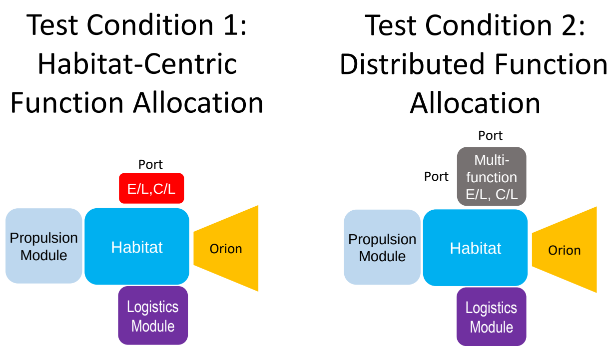


Figure 13. Graphical representation of test conditions 1 and 2 (E/L = equipment lock, C/L = crew lock).

During FY2018, each condition will be tested through the execution of a portion of the detailed 3-day mission timeline (full timeline shown in Appendix A). Day 1 of the 3-day mission timeline will test condition 1 (i.e. Habitat-Centric Function Allocation); day 2 of the timeline will test condition 2 (i.e. Distributed Function Allocation). Day 3 will be focused on EVA-related tasks and will use the appropriate portions of the habitat (represented by the Payload Development Lab in FY18) and the multifunction crew lock/equipment lock (represented by the Habitable Airlock in FY18) to accomplish these tasks.

HITL Test Subjects

The subjective nature of many of the HITL test objectives makes the selection of appropriate test subjects important. Test subjects will be recruited from the NASA astronaut office. Training will be performed to provide test subjects with the rationale and objectives of the test program, as well as familiarization with equipment, methods, and metrics.

To achieve this, engineering runs and training will be conducted prior to crew testing. A pool of astronaut crew subjects (1-8) and additional ground test support personnel (GTS) will be trained by executing 3 tests with integrated mission timelines (see details of timelines in the next section) at JSC in FY18. No more than four crew subjects will be required for any given test, the pool of eight will increase the likelihood that subjects will be available and provide ease of scheduling. These trained crews will then perform evaluation of contractor delivered DSG configurations in FY19 using the same integrated mission timeline and metrics to provide consistency of evaluation. It is recognized that the fidelity of the contractor deliverables may drive unique test configurations and plans.

HITL Timeline Tasks

The detailed test timelines were drafted and then reviewed and further refined at a two-day workshop with all stakeholders, SMEs and JSC flight controllers. The timelines include both habitation and operations-related tasks and are meant to provide a flight-like operations environment. Timeline tasks include habitation such as post-sleep, meals, WCS operations, exercise, and pre-sleep. Operation tasks include simulation of GNC and systems operations and monitoring, simulation of lunar robotic asset operation and DSG robotic arm used for sample return, EVA preparation and post EVA cleanup and servicing, routine maintenance and housekeeping, and selected in-flight maintenance activities. Table 5 shows a summary of the tasks that make up the detailed timeline with a high-level summary description of the tasks.

6. DATA COLLECTION METHODS

Integrated HITL Test

Acceptability, capability assessment, and simulation quality ratings will be requested from the crew both during the mission day and via end-of-day consensus questionnaire. The crew will provide real-time ratings at the completion of some tasks, which will serve as memory aids to guide the longer consensus discussions that occur at the end of each test day. All crewmembers will participate in these end-of-day consensus discussions. During these times, the crew will be tasked with providing a single agreed upon numerical rating and set of associated comments. In addition to rating and providing feedback on each of the test conditions, the crew will also complete consensus ratings and provide feedback on sub-modes and systems where applicable.

Table 5. Timeline tasks with high-level task summaries; tasks are organized/color coded by category.

Timeline Task	High-Level Task Summary
Reconfiguration	
Logistics Reconfiguration	Movement of logistics from one element to another
Pre-Exercise Prep & Set-Up	Set up exercise device and prepare it and area for use; change clothing
Post-Exercise Clean-Up & Reconfig.	Tear down exercise device and return it to stowage; hygiene; change clothing
Reconfigure HAL for EVA	Move items that cannot go to vacuum to other elements
Reconfigure HAL for Habitation	Return items that cannot go to vacuum to HAL
Checks	
Habitat Systems & Consumables Checks	Check that habitat systems/consumables are nominal
Orion Systems & Consumables Checks	Check that Orion systems/consumable are nominal
HAL Systems & Housekeeping	Check that HAL systems/consumables are nominal
Operations	
GNC Checks	Check nav. state & perform orbit/attitude adjusts
LLT Rover Sim	Perform low-latency teleops of small lunar rover
LLT Robotic Manipulation Sim	Perform low-latency teleops of robotic manipulator
Robotic Sample Return Capture	Capture of a sample return capsule w/ a robotic arm and docking of the capsule to a transfer port
Robotic Payload Repositioning	Perform repositioning of external payload
HFBP Assessments	Human factors & behavioral performance assessments
Exploration Medical Evaluation	Evaluate exploration medical methods/equipment
PAO Event	Perform education and public outreach event
Science	
Science	Tasks such as transfer port operations with samples
Biomedical Science	Tasks such as use of ultrasound for medical checks
EVA	
EVA Prep	Suit checks, donning, leak checks, communication checks, pre-breathe, tether configuration, egress
Post EVA	Ingress, suit doffing, suit checks, suit recharge
Ground Input	
Daily Planning Conferences (DPC)	Twice daily tags between space and ground
Personal	
Post-Sleep	Tasks including hygiene, WCS ops, meal prep, meal
Exercise	Utilize exercise device
Meal Prep	Unstow food/utensils, rehydrate food, prepare drink
Meal	Eat food, clean/stow utensils, dispose of trash
Private Medical Conference	Private calls between each crew and flight doctor
Pre-Sleep	Hygiene, WCS ops, personal time, sleep station prep
Sleep	Sleep, sleep station stow
Consensus Ratings	
Daily Habitation Questionnaires/Ratings	Discuss/fill in habitation questionnaires by consensus
EVA Questionnaires/Ratings	Discuss/fill in EVA questionnaires by consensus
End-of-Test Debrief	Verify and collect final comments/ratings from crew

Crew will be asked to provide ratings with respect to the crew's priorities and objectives, and to base their ratings on observations during testing as well as their consensus expert judgment. All crewmembers will review and discuss all end-of-day consensus ratings (Figure 14). At the end of the test and ratings may be may be updated as necessary to ensure day-to-day consistency. The crew will also perform a post-test review of ratings and comments following completion of the mission simulation before their data is considered finalized. Table 6 shows the frequency with which metrics will be collected.

Table 6 Metrics collection frequency.

Metric	Metric Collection Frequency		
	Real-Time	End of Day	End-of Test
Acceptability Rating	X	X	
Overall Acceptability Rating			X
Capability Assessment Rating		X	X
Simulation Quality Rating	X	X	X
Capability Distribution			X
Crew Location Frequency Distribution	X		X
Planned versus Actual Timeline	X		X
Ratings of Perceived Exertion	X		
Fatigue Ratings	X		
Workload Ratings	X		

System and Subsystem Standalone Test and Analysis

SMEs will also be asked via end-of-test questionnaire to rate each subsystem's conceptual design and operability, to the level possible based subsystem fidelity (which will be judged using simulation quality ratings).

	Rate the following **HABITATION** characteristics for this vehicle:	Rating			Comments
		Acceptability	Capability	Sim Quality	
	WCS/HYGIENE				
a.	Operability of the privacy curtains (e.g. deploying, stowing)				
b.	Volume of the WCS area				
c.	Access to hygiene items in the WCS area				
d.	Volume within the WCS do perform personal hygiene activities				
	GALLEY/MEAL PREP				
a.	Ability to access and locate the food stowage				
b.	Volume for food stowage				
c.	Volume for preparing a meal				
d.	Ability to access and locate the water dispenser for meal prep				
	DISPLAYS & CONTROLS WORKSTATION				
a.	Location of the station				
b.	Overall design/layout of the station				
c.	Functionality of the station				
d.	Accessibility to the station's displays and controls				
	ROBOTIC WORKSTATION				
a.	Location of the station				
b.	Overall design/layout of the station				
c.	Layout of the station for actual tele-robotics operation				
d.	Functionality of the station				
	RECONFIGURATION FOR EVA				
a.	Overall HAL volume for logistical EVA reconfiguration				
b.	Access to HAL stowage areas for storing common EVA equipment spares				
c.	Hatch size of HAL Logistics Transport Module Hatch for transfer of EVA equipment and supplies				
d.	Overall acceptability of EVA logistical staging within the HAL				
	EVA				
a.	Access to stow suits (consider size, location, arrangement, accessibility)				
b.	Volume for umbilical management				
c.	Volume for donning/doffing suits				
d.	Accessibility of translation paths for functional IVA				

Figure 14. Representative example of end-of-day acceptability rating questionnaire (all questions not shown)

7. TEST FACILITIES AND HABITATION MOCKUPS

Initial testing in FY18 will begin at NASA JSC and will utilize existing facilities and equipment. In FY19 contractor test articles will be made available for testing. Testing of contractor test articles will either occur at NASA JSC (i.e. the test articles will be brought to JSC), contractor facilities (i.e. key parts of the test infrastructure will be taken from NASA

JSC to the contractor facility), and other NASA centers. The following sections provide an overview of the facilities and equipment.

NASA JSC Facilities

Payload Development Laboratory—The Payload Development Laboratory (PDL) will be used to represent habitation articles that will eventually be provided by the NextSTEP contractors in later testing. The PDL is located in the JSC Space Vehicle Mockup Facility (SVMF), building 9N. It is used for development of procedures and training of astronauts on International Space Station (ISS) payloads. Its interior volume (Figure 15) can be made representative of the small habitat test articles being developed by the NextSTEP contractors. For FY18 testing, the PDL will be interfaced with the HAL cabin to provide a representative DSG stack for habitation testing.

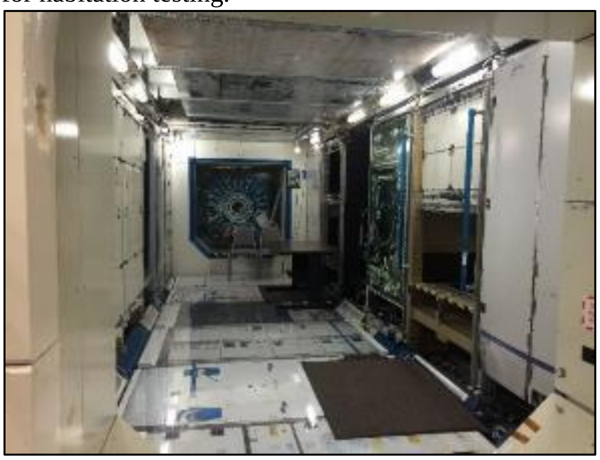


Figure 15 Interior of PDL Module

Future Capabilities Team Habitat and Logistics Mockups—The FCT has developed mockups of habitat and logistics modules that may be used as an alternative to the Payload Development Laboratory (Figure 16). Use of the FCT mockups will be integrated into the FY18 testing as availability and the level of fidelity allows.

Figure 16. FCT Habitat Mockup

Integrated Power, Avionics, and Software (iPAS)—Environment In order to demonstrate successful technology maturation, system integration, and mission operations, the Integrated Power, Avionics, and Software (iPAS) environment was developed for engineers to: 1) evaluate new technologies for human spaceflight, 2) efficiently integrate and mature technologies into capabilities within a hardware/software/operations environment, and 3) encourage engineers to apply advanced techniques for system design, integration, and test. This environment establishes the infrastructure to incorporate and test technologies as efficiently as possible, through careful design of interfaces within and external to the spacecraft. One goal of iPAS is to provide a template of test environment functions to the point that technologist can easily and cheaply integrate systems for evaluation.

Many capabilities and test environments are distributed in various labs and area, and do not lend themselves to colocation. In fact, federated labs often have unique, specialized environments that are vital for testing future vehicle systems. For instance, Environmental Crew and Life Support System (ECLSS) chambers at NASA/Johnson Space Center (JSC) create environments for testing of ECLSS capabilities. For cases where co-location is not feasible, a distributed data network has been developed to allow distributed but integrated testing to be performed. The existing iPAS networks include:

- Data connectivity across the various test beds within the iPAS environment
- Fiber network connections to a large number of specialized test environments across JSC
- A multi-center data network, called Distributed Simulation Network, or DSNet, which supports data exchange and mission execution involving several NASA centers.

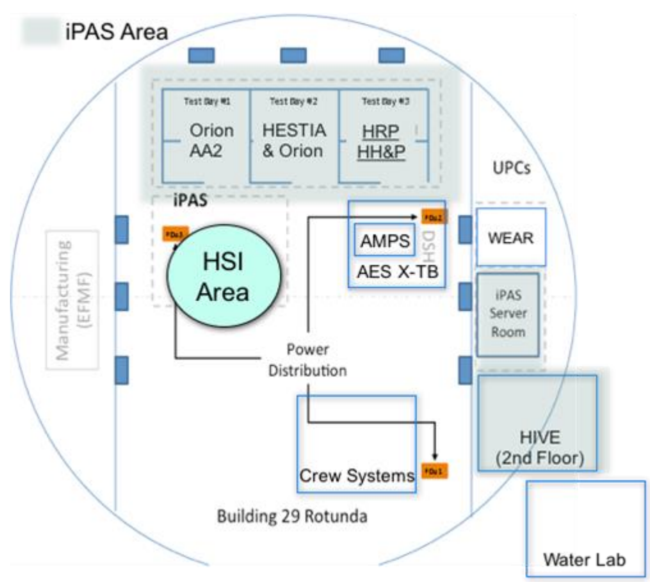


Figure 17. iPAS test area schematic in JSC Building 29.

Habitable Air Lock (HAL) — the habitable airlock (HAL) is one of several options being considered to provide airlock capability for the DSG. HAL is one of the elements that will be used to evaluate and refine the ground test protocol during FY18 testing at JSC in preparation for FY19 contractor tests and evaluations. The HAL consists of a core cabin with ECLSS, avionics and habitation systems (e.g. waste control system (WCS), potable water/food preparation system, sleep stations, exercise equipment accommodations), work stations for controlling various robotic operations, and all of the interfaces necessary to support EVA prep and post (e.g. umbilical interface panel that is compatible with the advanced EMU) (Figure 18).

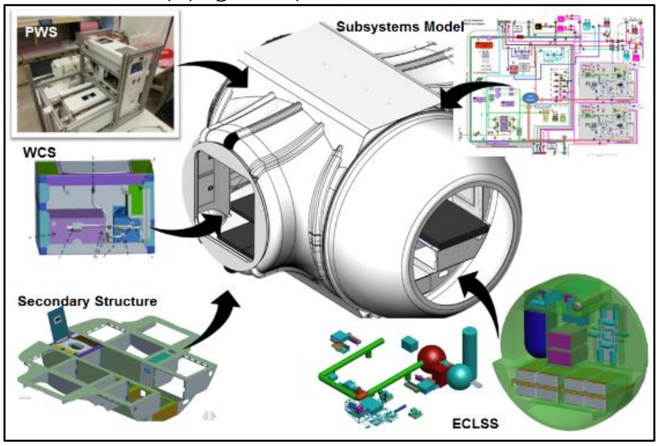


Figure 18. The Habitable Air Lock (HAL) 2B test article; Phase 2 Habitation Concept test articles will be integrated with the HAL 2B test article to enable HITL testing within an integrated DSG (PWS = potable water system; WCS = waste containment system)

The core cabin is outfitted with a hemispherical end cap on the nose that includes a docking port/ hatch. The aft bulkhead contains functional prototypes of the transfer ports, which will be fitted with a logistics stowage module and a science airlock. The science airlock serves as a low volume airlock capable of bringing in samples, ORUs and other hardware into and out of the vehicle with minimal gas losses. The HAL will be linked to the payload trainer in JSC Building 9, and interfaced to the iPAS "flat hab", where various high fidelity systems can be controlled from the HAL.

Analog Mission Control Center—The Analog Mission Control Center (AMCC) is a one room facility located at the Johnson Space Center established to allow the monitoring and coordination of test activities and crews within JSC as well as at remote locations. The AMCC will be staffed by support teams working at consoles located across the hall from the International Space Station Flight Control Room. It will provide the capability to manage two way communications with test subject crews and assets via audio, video, data and text exchanges for efficient operations.

NextSTEP BAA Phase 2 Habitation Concept Test Articles

The focus of each NextSTEP BAA Phase 2 contractor test (in FY19 and beyond) will be on the assessment of a Habitation Concept test article, with a different contractor test article being assessed in each test (representative test article shown in Figure 19). While details of the test articles are not known at this time, there are functions that all test articles are expected to provide, described below.

Figure 19. Representation of contractor habitation test integrated w/ HAL

Systems Integration: The prototypes will, at a minimum, serve as an integration platform at the form and fit level:

- Flight unit mockups of systems (not necessarily functional)
- Standard interfaces for mechanical, power, thermal and data tested
- Layout, installation, fit access tested

Human Factors & Operations: The prototypes will enable mission simulations with humans in the habitation environment:

- Habitability
- Mission Operations (Command and Control, Science, Teleoperations, Robotics, Crew Training, Maintenance and Repair)
- Health and Medical (including exercise)
- Logistics and Waste Management Operations
- EVA operations
- Contingency/Emergency Scenarios

8. GROUND TEST EXECUTION AND FORWARD WORK

As stated previously these ground tests and analyses will initially be conducted on a minimum of two in-house (primarily NASA-developed) configurations in early FY18, before testing begins on contractor habitation options later in the year and throughout FY19. The level of detail of these tests and analyses will be a function of the fidelity of the individual contractor deliverables. A team of subject matter experts (SMEs) and crew subjects will be trained via in-house testing and evaluations over a one-year period to ensure informed and consistent evaluation of the contractor options. The resulting datasets will be assimilated and analyzed to define a range of acceptable DSG habitation options, including elements and distributions of function across those elements.

Appendix A

Detailed Timelines for the 3-day HITL Test:

<table>
<tr><th>PET</th><th>Time of Day</th><th>CDR</th><th>Pilot</th><th>MS 1</th><th>MS 2</th></tr>
<tr><td>0:15</td><td>6:15</td><td colspan="4" rowspan="6">Post-Sleep
(Hygiene, WCS Ops, Meal Prep, Meal, Prep for DPC)</td></tr>
<tr><td>0:30</td><td>6:30</td></tr>
<tr><td>0:45</td><td>6:45</td></tr>
<tr><td>1:00</td><td>7:00</td></tr>
<tr><td>1:15</td><td>7:15</td></tr>
<tr><td>1:30</td><td>7:30</td></tr>
<tr><td>1:45</td><td>7:45</td><td colspan="2" rowspan="2">GNC Checks
(Nav State, Orbit & Attitude Adjusts)</td><td colspan="2" rowspan="2">Hab Systems & Consumables Checks
(ECLSS, Power, Thermal, Vehicle Health)</td></tr>
<tr><td>2:00</td><td>8:00</td></tr>
<tr><td>2:15</td><td>8:15</td><td colspan="4">DPC</td></tr>
<tr><td>2:30</td><td>8:30</td><td rowspan="4">LLT Rover Sim</td><td rowspan="4">LLT Robotic Manipulation Sim</td><td colspan="2">Orion Systems & Consumables Checks</td></tr>
<tr><td>2:45</td><td>8:45</td><td colspan="2">HAL Systems & Consumables Checks</td></tr>
<tr><td>3:00</td><td>9:00</td><td colspan="2" rowspan="2">Logistics Reconfig</td></tr>
<tr><td>3:15</td><td>9:15</td></tr>
<tr><td>3:30</td><td>9:30</td><td colspan="2">Pre-Exercise Prep and Set-up</td><td colspan="2">Trash Management</td></tr>
<tr><td>3:45</td><td>9:45</td><td rowspan="4">Exercise</td><td rowspan="4">Science</td><td rowspan="4">LLT Rover Sim</td><td rowspan="4">LLT Robotic Manipulation Sim</td></tr>
<tr><td>4:00</td><td>10:00</td></tr>
<tr><td>4:15</td><td>10:15</td></tr>
<tr><td>4:30</td><td>10:30</td></tr>
<tr><td>4:45</td><td>10:45</td><td rowspan="4">Science</td><td rowspan="4">Exercise</td><td colspan="2" rowspan="4">HRP Science
(Ultrasound)</td></tr>
<tr><td>5:00</td><td>11:00</td></tr>
<tr><td>5:15</td><td>11:15</td></tr>
<tr><td>5:30</td><td>11:30</td></tr>
<tr><td>5:45</td><td>11:45</td><td colspan="2">Post-Exercise Clean-up and Reconfig</td><td>Priv. Med. Conf.</td><td></td></tr>
<tr><td>6:00</td><td>12:00</td><td colspan="3">Meal Prep</td><td>Priv. Med. Conf.</td></tr>
<tr><td>6:15</td><td>12:15</td><td colspan="4" rowspan="2">Meal</td></tr>
<tr><td>6:30</td><td>12:30</td></tr>
<tr><td>6:45</td><td>12:45</td><td rowspan="4">LLT Robotic Manipulation Sim</td><td rowspan="4">LLT Rover Sim</td><td colspan="2" rowspan="4">Routine Maintenance & Housekeeping</td></tr>
<tr><td>7:00</td><td>13:00</td></tr>
<tr><td>7:15</td><td>13:15</td></tr>
<tr><td>7:30</td><td>13:30</td></tr>
<tr><td>7:45</td><td>13:45</td><td colspan="2" rowspan="4">Robotic Payload Repositioning</td><td colspan="2">Pre-Exercise Prep and Set-up</td></tr>
<tr><td>8:00</td><td>14:00</td><td rowspan="4">Exercise</td><td rowspan="4">HFBP Assessments
(Laptop)</td></tr>
<tr><td>8:15</td><td>14:15</td></tr>
<tr><td>8:30</td><td>14:30</td></tr>
<tr><td>8:45</td><td>14:45</td><td colspan="2" rowspan="4">Exploration Medical Eval</td></tr>
<tr><td>9:00</td><td>15:00</td><td rowspan="4">HFBP Assessments
(Laptop)</td><td rowspan="4">Exercise</td></tr>
<tr><td>9:15</td><td>15:15</td></tr>
<tr><td>9:30</td><td>15:30</td></tr>
<tr><td>9:45</td><td>15:45</td><td colspan="2" rowspan="4">HRP Science
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<tr><td>10:00</td><td>16:00</td><td colspan="2">Post-Exercise Clean-up and Reconfig</td></tr>
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<tr><td>10:30</td><td>16:30</td></tr>
<tr><td>10:45</td><td>16:45</td><td>Priv. Med. Conf.</td><td></td></tr>
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<tr><td>11:15</td><td>17:15</td><td rowspan="4">HFBP Assessments
(Laptop)</td><td rowspan="4">HFBP Assessments
(Laptop)</td><td colspan="2" rowspan="4">Exploration Medical Eval</td></tr>
<tr><td>11:30</td><td>17:30</td></tr>
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<tr><td>12:00</td><td>18:00</td></tr>
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<tr><td>12:30</td><td>18:30</td><td colspan="4" rowspan="2">Meal</td></tr>
<tr><td>12:45</td><td>18:45</td></tr>
<tr><td>13:00</td><td>19:00</td><td colspan="4" rowspan="2">PAO Event</td></tr>
<tr><td>13:15</td><td>19:15</td></tr>
<tr><td>13:30</td><td>19:30</td><td colspan="4">DPC</td></tr>
<tr><td>13:45</td><td>19:45</td><td colspan="4" rowspan="6">Daily Habitation Questionnaires and Metrics Ratings</td></tr>
<tr><td>14:00</td><td>20:00</td></tr>
<tr><td>14:15</td><td>20:15</td></tr>
<tr><td>14:30</td><td>20:30</td></tr>
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<tr><td>15:15</td><td>21:15</td><td colspan="4" rowspan="4">Pre-Sleep
(Hygiene, WCS Ops, Personal Time, Sleep Prep)</td></tr>
<tr><td>15:30</td><td>21:30</td></tr>
<tr><td>15:45</td><td>21:45</td></tr>
<tr><td>16:00</td><td>22:00</td></tr>
<tr><td>16:15</td><td>22:15</td><td colspan="4" rowspan="3">Sleep</td></tr>
<tr><td>16:30</td><td>22:30</td></tr>
<tr><td>0:00</td><td>6:00</td></tr>
</table>

<table>
<tr><th>PET</th><th>Time of Day</th><th>CDR</th><th>Pilot</th><th>MS 1</th><th>MS 2</th></tr>
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<tr><td>1:45</td><td>7:45</td><td colspan="2" rowspan="2">GNC Checks
(Nav State, Orbit & Attitude Adjusts)</td><td colspan="2" rowspan="2">Hab Systems & Consumables Checks
(ECLSS, Power, Thermal, Vehicle Health)</td></tr>
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<tr><td>2:15</td><td>8:15</td><td colspan="4">DPC</td></tr>
<tr><td>2:30</td><td>8:30</td><td colspan="2">Orion Systems & Consumables Checks</td><td rowspan="4">Robotic Sample Return Capture</td><td rowspan="4">HFBP Assessments
(Laptop)</td></tr>
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<tr><td>7:15</td><td>13:15</td></tr>
<tr><td>7:30</td><td>13:30</td><td colspan="2" rowspan="4">Routine Maintenance & Housekeeping</td><td colspan="2" rowspan="4">Robotic Payload Repositioning</td></tr>
<tr><td>7:45</td><td>13:45</td></tr>
<tr><td>8:00</td><td>14:00</td></tr>
<tr><td>8:15</td><td>14:15</td></tr>
<tr><td>8:30</td><td>14:30</td><td rowspan="4">LLT Rover Sim</td><td rowspan="4">LLT Robotic Manipulation Sim</td><td colspan="2" rowspan="4">HRP Science
(Ultrasound)</td></tr>
<tr><td>8:45</td><td>14:45</td></tr>
<tr><td>9:00</td><td>15:00</td></tr>
<tr><td>9:15</td><td>15:15</td></tr>
<tr><td>9:30</td><td>15:30</td><td colspan="2">Pre-Exercise Prep and Set-up</td><td>Priv. Med. Conf.</td><td></td></tr>
<tr><td>9:45</td><td>15:45</td><td rowspan="4">Exercise</td><td rowspan="4">Science</td><td></td><td>Priv. Med. Conf.</td></tr>
<tr><td>10:00</td><td>16:00</td><td rowspan="4">LLT Rover Sim</td><td rowspan="4">LLT Robotic Manipulation Sim</td></tr>
<tr><td>10:15</td><td>16:15</td></tr>
<tr><td>10:30</td><td>16:30</td></tr>
<tr><td>10:45</td><td>16:45</td><td rowspan="4">Science</td><td rowspan="4">Exercise</td></tr>
<tr><td>11:00</td><td>17:00</td><td rowspan="4">LLT Robotic Manipulation Sim</td><td rowspan="4">LLT Rover Sim</td></tr>
<tr><td>11:15</td><td>17:15</td></tr>
<tr><td>11:30</td><td>17:30</td></tr>
<tr><td>11:45</td><td>17:45</td><td colspan="2">Post-Exercise Clean-up and Reconfig</td></tr>
<tr><td>12:00</td><td>18:00</td><td rowspan="4">HFBP Assessments
(Laptop)</td><td rowspan="4">Robotic Sample Return Capture</td><td rowspan="4">HFBP Assessments
(Laptop)</td><td rowspan="4">Robotic Sample Return Capture</td></tr>
<tr><td>12:15</td><td>18:15</td></tr>
<tr><td>12:30</td><td>18:30</td></tr>
<tr><td>12:45</td><td>18:45</td></tr>
<tr><td>13:00</td><td>19:00</td><td colspan="4">Meal Prep</td></tr>
<tr><td>13:15</td><td>19:15</td><td colspan="4" rowspan="2">Meal</td></tr>
<tr><td>13:30</td><td>19:30</td></tr>
<tr><td>13:45</td><td>19:45</td><td colspan="4">EVA Reconfig and Planning Review</td></tr>
<tr><td>14:00</td><td>20:00</td><td colspan="4">DPC</td></tr>
<tr><td>14:15</td><td>20:15</td><td colspan="4" rowspan="4">Daily Habitation Questionnaires and Metrics Ratings</td></tr>
<tr><td>14:30</td><td>20:30</td></tr>
<tr><td>14:45</td><td>20:45</td></tr>
<tr><td>15:00</td><td>21:00</td></tr>
<tr><td>15:15</td><td>21:15</td><td colspan="4" rowspan="4">Pre-Sleep
(Hygiene, WCS Ops, Personal Time, Sleep Prep)</td></tr>
<tr><td>15:30</td><td>21:30</td></tr>
<tr><td>15:45</td><td>21:45</td></tr>
<tr><td>16:00</td><td>22:00</td></tr>
<tr><td>16:15</td><td>22:15</td><td colspan="4" rowspan="3">Sleep</td></tr>
<tr><td>16:30</td><td>22:30</td></tr>
<tr><td>0:00</td><td>6:00</td></tr>
</table>

PET	Time of Day	CDR	Pilot	MS 1	MS 2
0:15	6:15	**Post-Sleep** (Hygiene, WCS Ops, Meal Prep, Meal, Prep for DPC)			
0:30	6:30				
0:45	6:45				
1:00	7:00				
1:15	7:15				
1:30	7:30				
1:45	7:45	**GNC Checks** (Nav State, Orbit & Attitude Adjusts)		**Hab Systems & Consumables Checks** (ECLSS, Power, Thermal, Vehicle Health)	
2:00	8:00				
2:15	8:15	**DPC**			
2:30	8:30	**Orion Systems & Consumables Checks**		**Reconfigure HAL for EVA** (Configure HAL from Habitation to EVA Mode)	
2:45	8:45	**Exploration Medical Eval**			
3:00	9:00				
3:15	9:15				
3:30	9:30				
3:45	9:45	**Pre-Exercise Prep and Set-up**			
4:00	10:00	**Exercise**	**Science**		
4:15	10:15				
4:30	10:30			**EVA Prep** (Suit Checks, Suit Donning, Leak Checks, Comm Checks, Prebreathe, Tether Config, Egress)	
4:45	10:45				
5:00	11:00	**Science**	**Exercise**	**Post EVA** (Ingress, Suit Doffing, Suit Checks, Suit Recharge)	
5:15	11:15				
5:30	11:30			**Reconfigure HAL for Habitation** (Configure HAL from EVA Mode to Habitation)	
5:45	11:45				
6:00	12:00	**Post-Exercise Clean-up and Reconfig**			
6:15	12:15	**HRP Science** (Ultrasound)			
6:30	12:30				
6:45	12:45				
7:00	13:00				
7:15	13:15	**Priv. Med. Conf.**			
7:30	13:30	**Meal Prep**	**Priv. Med. Conf.**	**Meal Prep**	
7:45	13:45	**Meal**			
8:00	14:00				
8:15	14:15	**Reconfigure HAL for EVA** (Configure HAL from Habitation to EVA Mode)		**Exploration Medical Eval**	
8:30	14:30				
8:45	14:45				
9:00	15:00				
9:15	15:15			**Pre-Exercise Prep and Set-up**	
9:30	15:30			**Exercise**	**Science**
9:45	15:45				
10:00	16:00				
10:15	16:15	**EVA Prep** (Suit Check Out, Suit Donning, Leak Checks, Comm Checks, Prebreathe, Tether Config)			
10:30	16:30			**Science**	**Exercise**
10:45	16:45	**Post EVA** (Ingress, Suit Doffing, Suit Checks, Suit Recharge)			
11:00	17:00				
11:15	17:15	**Reconfigure HAL for Habitation** (Configure HAL from EVA Mode to Habitation)			
11:30	17:30			**Post-Exercise Clean-up and Reconfig**	
11:45	17:45			**HRP Science** (Ultrasound)	
12:00	18:00				
12:15	18:15				
12:30	18:30				
12:45	18:45			**Priv. Med. Conf.**	
13:00	19:00				**Priv. Med. Conf.**
13:15	19:15	**Meal Prep**			
13:30	19:30	**Meal**			
13:45	19:45				
14:00	20:00	**DPC**			
14:15	20:15	**Daily Habitation Questionnaires and Metrics Ratings** **EVA Questionnaires and Metrics Ratings**			
14:30	20:30				
14:45	20:45				
15:00	21:00				
15:15	21:15	**End-of-Test Debrief**			
15:30	21:30				
15:45	21:45				
16:00	22:00				
16:15	22:15	**END OF SIM**			

ACKNOWLEDGEMENTS

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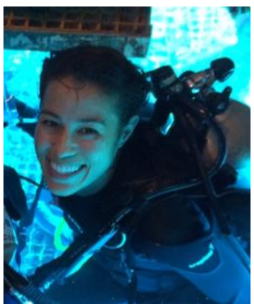
BIOGRAPHY

Andrew Abercromby received an M.Eng. in mechanical engineering from the University of Edinburgh in 2002 during which he worked on X-38 in the Flight Mechanics Laboratory at Johnson Space Center (JSC). He earned a Ph.D. in motor control from the University of Houston while working in the JSC Neurosciences Laboratory and is now the lead of NASA’s EVA Physiology Laboratory and also serves as EVA Scientist for the Biomedical Research and Environmental Sciences Division. His current research focuses on measurement and optimization of human performance and operations in extreme exploration environments and includes research studies in desert, ocean, lake, virtual reality, Arctic, and Antarctic environments including experience in saturation and under-ice scientific research diving.



Kara Beaton received her bachelor's and master’s degrees in aerospace engineering from the University of Illinois and Massachusetts Institute of Technology, respectively. She completed her doctoral studies in biomedical engineering at the Johns Hopkins University School of Medicine. She has extensive experience with operationally driven aerospace and biomedical research with the US Navy, NASA, and various clinical laboratories. She is currently a research engineer in the EVA Physiology Laboratory at JSC, where she is involved in the Exploration Analogs and Mission Development team.

Omar Bekdash received his bachelor's and master’s degrees in bioengineering from the University of Maryland in 2010 and 2012, respectively. He is currently a research engineer in the EVA Physiology Laboratory at the NASA Johnson Space Center. In addition to working with the Mars Moons Human Spaceflight Architecture Team, his work focuses on characterizing human performance during EVA and the impact that operations, tasks, and environments have on EVA capability.

Steve Chappell attended the University of Michigan and earned a bachelor’s degree in aerospace engineering. He also earned master’s and doctoral degrees from the University of Colorado in aerospace engineering sciences, researching human performance and spacesuit systems in simulated reduced gravity. His career has spanned many areas of engineering and science, including work on embedded software for fighter aircraft, satellite ground systems development, and Earth-observing satellites systems engineering. Currently, in addition to helping lead the Mars Moons Human Spaceflight Architecture Team, his work has been focused on optimizing human and system performance for the next generation of space exploration. He has extensive experience leading and taking part in research in multiple exploration analog environments including arctic, desert, underwater, alpine, and partial gravity simulators.

Michael Gernhardt is a NASA astronaut who has been a mission specialist on four Space Shuttle missions. He has a bachelor’s degree in physics from Vanderbilt University as well as master’s and doctorate degrees in bioengineering from the University of Pennsylvania.