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# 2012 Habitable Volume Workshop Results: Technical Products

## Prepared for Human Research Program (HRP) Space Human Factors Engineering (SHFE) Portfolio

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## Executive Summary

With NASA's vision for humans to explore space beyond low-Earth orbit, habitability and human factors issues will be more critical. Inadequate design and insufficient habitable volume may lead to reduced crew safety, decreased efficiency, and lower satisfaction. The Space Human Factors and Habitability (SHFH) and Behavioral Health and Performance (BHP) Elements of NASA's Human Research Program (HRP) hosted the 2012 Habitable Volume Workshop, which focused on spacecraft/habitat volume design and assessment for long-duration missions. The workshop produced concrete products to aid in the design and assessment of habitable volume in space vehicles and habitats based on both NASA and industry approaches, and sought to identify research and technology development gaps and provide recommendations for forward work.

Workshop products included the Process Flow, Task List, and Metrics and Tools Lists. These form a suite of tools for engineers, designers, and integrators in driving the design of habitable volumes, assessing the goodness of design, and assisting in communication among stakeholders. The Process Flow identifies three major elements in human systems engineering and habitability design - Plan, Design, and Assess - and establishes how they feed one another in an iterative work flow for assessing habitable volume. The Task List provides a minimal set of long-duration mission tasks that are volume-driving, and provides design constraints as well as volume and layout characteristics to inform the design process. The Metrics and Tools Lists capture design and behavioral metrics as well as example methods and tools that are used to measure them.

As part of gap mitigation efforts, volume-impacting countermeasures for optimizing behavioral health and performance were identified. Critical steps in determining whether countermeasures should be implemented, such as characterizing their effectiveness, may be addressed by further research. A list of outcomes, standardized measures, and analog characteristics was defined and is being used towards the development of a joint research plan.

This technical memo summarizes the workshop and its products, which expanded the existing NASA knowledge base by collaborating with industries such as oil and gas, and by placing special emphasis design for long-duration missions. The workshop and its products serve as a critical step on the path to address HRP risks related to reduced safety and efficiency due to an inadequately designed vehicle or habitat.

## Introduction

In July 2012, the Human Research Program (HRP) hosted a Habitable Volume Workshop focused on assessing habitable volume of space vehicles and habitats for long-duration missions. The 2012 workshop served as follow-on to a prior HRP-sponsored workshop held in April 2011 (Simon, Whitmire, Otto, & Neubek, 2011) that focused on identifying behavioral health stressors and associated mitigations. This memo serves to summarize the 2012 workshop and present technical products that were developed as a result of the workshop.

Held in Houston, Texas, the 2012 workshop was well-attended by participants from both NASA and outside industry experts. NASA participants included Space Human Factors Engineering (SHFE) representatives, Behavioral Performance and Health (BHP) representatives, human factors handbook and standards experts, International Space Station Internal Vehicle Configuration Working Group (ISS IVC WG) team members, Flight Crew Integration (FCI) team members, Habitability Design Center (HDC) team members, Advanced Exploration Systems (AES) team members, and the Astronaut Office. Participants from outside industries and academia included representatives from oil and gas, submersibles, maritime shipping, mining, United States Navy, Lamar University, Thomas Jefferson University, and University of Pennsylvania. Together they brought a wealth of experience and differing perspectives on aspects relevant to the design of confined habitats. A complete list of workshop participants is provided in Appendix B.

## Workshop Strategy and Findings

The overarching goal of the 2012 Habitable Volume Workshop was to produce concrete products that could aid in the design and assessment of habitable volume in space vehicles and habitats. In addition, the workshop sought to identify research and technology development gaps in the area of habitability design and assessment, and provide recommendations on forward work. The workshop products were drafted before the workshop, refined during the workshop via a series of splinter working sessions, and finalized by a smaller team post-workshop.

The workshop discussions revealed that similar design and assessment processes were used in adjacent industries, including task analysis, use of standards and regulations, reliance on modeling and/or mockup evaluations. The consensus expert opinion was that providing designers with a volume number is an inadequate approach; rather, an organized process including critical steps, such as task analysis, is needed on a case-by-case- basis to determine appropriate volume. Discussions also yielded specific recommendations from participants on improvements to the workshop technical products, and helped to define future research strategies. Some of these strategies include exploration of new technologies through a technology watch to determine the current state-of-the-art, development of inputs for the Integrated Research Plan, and the development of targeted NASA Research Announcements and Small Business Innovative Research opportunities, and Directed Research Projects. As part of gap mitigation efforts, volume-impacting countermeasures for optimizing behavioral health and performance were identified. Critical steps in determining whether countermeasures should be implemented, such as characterizing their effectiveness, may be addressed by further research. A list of outcomes, standardized measures, and analog characteristics was defined and is being used towards the development of a joint research plan.

NASA's experience in human-system design and integration is rooted in lessons learned from legacy space programs, and the processes and best practices have been documented in agency standards, handbooks, and technical memorandums. The workshop and the resulting products sought to augment the existing knowledge base by soliciting expertise from adjacent terrestrial industries and by placing special emphasis on habitable volume design and assessment for long-duration missions. The workshop and its products serve as a critical step in the overall roadmap to address an HRP risk as identified in the Human Research Roadmap (Risk of an Incompatible Vehicle/Habitat Design), which relates to the risk of reduced safety and efficiency due to an inadequately designed vehicle or habitat.

## Products

The following products were developed as a result of the Habitable Volume Workshop: Process Flow, Task List, and Metrics and Tools Lists. Together they serve as a suite of tools available to human factors engineers, habitat designers, and integrators in driving the design of habitable volumes, assessing the goodness of design, and assisting in communication among stakeholders regarding details such as data needs, assumptions, and constraints. The Process Flow identifies three major elements in human systems engineering and habitability design – Plan, Design, and Assess – and establishes how they feed one another in an iterative work flow. The Task List aims to standardize a minimal set of long-duration mission tasks that are volume-driving, and provides design constraints as well as volume and layout characteristics to inform the design process. The Metrics and Tools Lists aid the assessment of habitable volume by capturing both design and behavioral metrics, and the example methods and tools that are used to measure them. All of these products are tied together within the Process Flow, which captures how each product can be applied at specific stages of a design and development cycle, often as a starting point for a planning, design, or assessment activity.

These products reflect existing habitability assessment practices used by NASA as well as by other organizations such the Navy and the offshore industries. However, the intent is not to comprehensively capture data and provide wide-ranging applicability. Rather, these products focus on developing a minimally necessary set of reference tools to set boundaries for the expectations of the practitioners involved in the complex process of designing and assessing habitability.

It should also be noted that the definition of a "long-duration mission" is still an ongoing topic of discussion. For the purposes of this workshop, the assumption is that a long-duration mission exceeds 6 months in duration. While emphasis is placed on considerations for long-duration missions, it is necessary to acknowledge the limits in the collective knowledge on the impacts and thresholds associated with mission duration longer than 6 months. How longer-duration missions impact the physical volume requirements or affect the crew's behavioral and psychological health is still not completely understood.

Additional caveats as well as gaps specific to each product are further discussed in the Process Flow, Task List, Metric and Tool Lists, and Forward Work sections of this document.

### Process Flow

The Process Flow (see Appendix C) for assessing habitable volume was developed based on existing NASA processes and inputs from workshop attendees. Net Habitable Volume (NHV) Verification Method (JSC-63557) (NASA, 2009) documents processes developed specifically to assess NHV for the Orion vehicle. The basic process outlined in JSC-63557 was generalized and combined with additional information from Commercial Human Systems Integration Process (JSC-65995) (NASA, 2011), which provides guidance for assessing habitable volume in commercial spacecraft. This compilation of historical information was represented in a process flow format, and annotations were added to provide examples and guidance for the user. The goal was to document processes already in use while making adjustments to reflect considerations specific to long-duration missions (exceeding 6 months in duration).

During the 2012 workshop, external industry participants were asked to discuss their standard processes for assessing a habitable volume. It was agreed that a similar process-based approach to assessing habitable volume is taken across all of the represented industries. All external participants agreed especially on the importance of reviewing existing standards and regulations, as well as performing task analysis with participation from the stakeholders.

The Process Flow is intended to provide a high-level guidance with some details about the execution provided in the annotations. Users may step through the process to plan out and execute an assessment of habitable volume, making fine adjustments as required. The process outlined in this product is not intended to replace a system-level Human-Systems Integration (HSI) plan; rather, it is considered to be a part of the HSI approach to design. Emphasis should also be placed on the iterative nature of habitable volume estimation and assessment. In particular, the portion of the Process Flow labeled as “Assess Habitable Volume” is intended to indicate a need to select and execute appropriate tests, iterate among appropriate levels of fidelity, adjust designs as more knowledge is gained, and eventually leave the iterative loop when further adjustments to layouts and configurations are not needed.

When using the Process Flow, there are certain caveats to bear in mind. First, the Process Flow is intended to provide a high-level guidance during the early phase of the design lifecycle, and is not intended to be comprehensive. Also, it is anticipated that even the high-level process steps will need adjustments and updates based on individual circumstances, such as new design reference missions. Processes can be tailored due to contracts and other forces outside of the control of habitability and human factors practitioners. Finally, it should be noted that the Process Flow does not result in a “pass or fail” judgment. Rather, it ensures that appropriate considerations are made, which coupled with appropriate experts executing the process should provide confidence in the results.

## Task List

The Task List (Appendix D) is intended for use by vehicle and habitat designers, and it focuses on capturing key information that can inform design. The Task List identifies 14 long-duration mission tasks that are volume-driving:

- Exercise
- Whole Body Hygiene
- Waste Collection and Management
- Private Personal Activities
- Sleep
- Food Preparation
- Group Meet and Eat
- Recreation
- Suit Don/Doff/Stowage and Maintenance
- Radiation Shelter
- D&C Console Operations

- Mission-Specific On-Board Research
- Crew Health/Medical
- Stowage

Each main task outlines the subtasks, and contains information such as:

- Whether a task is nominal or contingency
- Task duration and frequency
- Degree of privacy
- Whether minimal or no reconfiguration is required
- Potential concurrence or adjacency of tasks

While these details would be refined as part of the task analysis, initial data can help the designers as they begin to impose organizational order or hierarchy to a given space. Finally, example volumes are provided for each task to give the designers a starting point when sizing habitable spaces and establishing layout. These examples were drawn from legacy hardware, the Human Integration Design Handbook (NASA, 2010), the American Bureau of Shipping (ABS) Guide for Habitability (American Bureau of Shipping, 2001), and applicable vehicle mockups. The ABS guide, which provides guidance for maritime shipping as well as many offshore oil and gas applications, was selected as the primary industry reference based on its detailed approach to habitability assessments. This source was selected also due to the parallels between the maritime industry it serves and NASA, both of which place volume at a premium in habitat design.

Nominal tasks are planned tasks for the mission, while contingency tasks are unplanned, off-nominal, and may be due to emergencies. Task duration types are categorized into “minutes” to indicate short-duration (less than 1 hour), and “hours” to indicate medium- to long-duration. Task frequency types include “per hours” to indicate hourly or once every few hours, “per day” to indicate daily, “per week” to indicate weekly, and “per mission” to indicate low-frequency events. Degree of privacy is conceived of as a privacy scale bookended by “completely private” and “completely public”, in which privacy is all or none with respect to relevant human senses such as acoustic, visual, and olfactory. “Semi-public” is used to denote partial degree of privacy tending towards the “public” end of the scale, while “semi-private” is toward the “private” end of the scale. Such differentiation can be useful when considering design implementations that manipulate elements such as enclosures, traffic patterns, and means of attenuation and isolation to varying degrees.

A task designated as “dedicated” means that the accommodations for the task require minimal to no reconfiguration of hardware or space. It does not necessarily mean the task is performed in isolation, as supportive or operationally relatable tasks could conceivably occur in the same space. Among the identified 14 tasks, ones that are operationally relatable and could occur in the same space are identified as “potential concurrences”. Tasks that could precede or follow others are listed in “potential adjacencies”, and this signifies that some translation logic should be considered. Sometimes tasks are identified as both concurrent and adjacent. This means that depending on the design implementation, tasks could be organized spatially in the same or separate areas. Reconfigurability, concurrences, and adjacencies provide spatial characterizations and layout considerations that are critical to vehicle layout and habitat design.

A major caveat with the Task List lies with the example footprints and volumes provided for each task. First, within the available data, there exists a wide variety and range of numbers that require further scrutiny. Although an attempt was made to control the pedigree of the numbers by focusing on heritage space programs, published design standards and handbooks, and mockup or analog environments of development programs, it was not possible to reduce the data variation or validate the adequacy of volume. At this time, the provided example volumes are only meant to help the designers “intuit” the size of a space. Second, the volume survey is not comprehensive and contains many gaps. In the literature surveyed, often volume needs are prescribed via a set of considerations and constraints rather than a definitive volume or footprint number. It is worthwhile to note that one consistent message that came out of the workshop is that the optimal design of habitable volume is dependent on the layout and other design interventions, and can only be achieved by following an iterative process. The example volumes are intended to be used during the early design phase, as part of a defined process that ensures the volume design meets the needs of the mission and its concept of operations.

## Metrics and Tools Lists

The Metrics and Tools Lists (Appendices E and F) provide a survey of habitability metrics, methods, and tools that have been used to measure and assess habitable spaces or vehicles. The Metrics List identifies 19 habitability metrics, such as habitable volume, volume-to-shell ratio, equipment colocations, translation efficiency, error rates, workload, and behavioral health-related metrics such as isolation and sleep quality.

The Tools List captures 18 methods or tools in use today to perform measures related to habitability, and ranges from human-in-the-loop assessment, to video, to computer-aided design (CAD), and human and environmental modeling software. Documented in the Metrics List are cross-references to the Tools List, to show interdependencies between metrics and the tools or methods that can be used to measure them. For example, CAD (labeled in the Tools List as T-11) is a tool that can be applied to measure metrics such as habitable volume/floor area (labeled in the Metrics List as M-1), volume to structural shell ratio (M2), spatial vista (M-4), equipment colocation (M-5), anthropometry interferences (M-6), placement for function and ergonomics (M-7), and hardware protrusions (M-10).

A metric can be measured objectively or subjectively, and its usage comes with advantages and limits that must be taken into consideration. For instance, while workload metric (M-12) captures information on how the task or a design can impact crew performance, its measurements are indirect and can be biased by other factors such as fatigue, and the results may not be consistent across the population to provide a good comparison between configurations.

The Metrics List identifies required inputs and desired outcome for a metric. It also identifies which phases of the development lifecycle as well as which evaluation environment and fidelity the metric can be of use. Using error-rate metric (M-11) as an example, a required input may be task procedures or steps, and the desired outcome would be that design-induced error rate is minimized. Error rate as a metric can be applied in mature design and verification phases, and it can be evaluated in simulation environment or in mid- to high-fidelity mockup environment, including operational analogs, where hardware elements are accurately represented with appropriate level of details.

In this broad survey of habitability metrics, certain knowledge gaps that affect the application of the metrics become apparent. Captured in the Metrics List, these gaps often relate to metrics that are subjective and with desired outputs that are often not easily quantified. For instance, adequacy of dedicated private space (M-3) is not quantifiable, and a potential research need may lie in how to parametrically determine the adequacy of privacy. The Metrics List also captures how potential research needs for a metric can be mapped to existing HRP Gaps. The dedicated private space metric, for example, is mapped to the HRP gap on methods of modifying the environment for the prevention of behavioral health issues (HRP Gap BMed7).

The Metrics and Tools Lists serve as a snapshot-in-time of the changing research and technology landscape in the domain of habitability design and assessment. Neither survey on metrics and tools should be considered exhaustive, but should be considered as minimally necessary set within a designer or an evaluator's arsenal when planning an analysis or an assessment activity.

## Forward Work

The 2012 workshop and its products serve as a beginning step toward addressing the HRP-identified risk to ensure optimized vehicle and habitat designs for future space missions. The products also identify several gaps and areas of forward work that may help to shape future research, by augmenting existing HRP Gaps and potentially guiding future research plans.

### Definition of Task Volumes

A prerequisite in estimating the total habitable volume for a vehicle or habitat is estimating the required volume for each necessary task. This process was started as part of the Task List product, and several gaps were identified. For some tasks, there are no identified industry standards or documented NASA heritage values for footprints or volumes. For other tasks, there is a need for further validation of existing numbers. Estimating unknown task volumes may require a combination of task analysis with the input of operations experts, CAD modeling, and human-in-the-loop data collection. It is desirable to document required volumes based on a set of assumptions, allowing for wider application and tailoring of the results. In addition to the physical volume required for a person to perform a task, it is important to document total work envelopes including equipment and point-of-use stowage. Psychological clearances must also be considered based on Behavioral Health and Performance research and expert inputs.

### Refinement of Modeling and Simulation Approaches

There is a need for higher-fidelity modeling and simulation related to habitable volume assessments. One area of forward work is the physical representation of humans. Although a variety of software packages exist, there are gaps in capabilities needed for microgravity application as well as missing validation for some considerations such as conformable tissue and suited models.

There is also potential for the development of an analytical tool for the purpose of estimating required total vehicle volume. For example, an optimization or Monte Carlo model might be developed to project estimates of required vehicle or habitat volume for a given mission, based on initial input of mission parameters. Another approach might include a tool to assess the "appropriateness" of a given volume based on an assessment of the design against desired metrics.

Additional modeling needs identified include models for specific habitability and human factors problems. For example, there is a need to simulate communications scenarios and allow designers to see how layouts affect information flow. There is also a need to model or simulate measures such as design-induced error rate and physical and mental workload. Improved modeling and simulation of environmental conditions in the vehicle are needed as well. While some existing models may be used, they must be validated via in-flight performance data and, where feasible, validated for use in long-duration spaceflight scenarios.

### Definition of Behavioral Health and Performance Impacts

Another major area of forward work is in defining the design impacts of behavioral health and performance concerns. Some of these concerns directly impact the required volume, while others are related to the mitigation of stressors that might otherwise require additional volume. One of the major areas of research identified is the determination of adequacy of privacy, which may drive design implementations such as private crew quarters. Additional areas of forward work include quantitative measures of spatial quality and acceptability, thresholds at which isolation impacts behavioral health and performance, the degree to which individuals must be able to personalize their surroundings, and the desired values of environmental parameters such as lighting and noise. It is important to integrate these types of concerns with any ongoing work to design and assess habitable volume.

### Collection of In-Flight Data

Multiple areas examined as part of the workshop stand to benefit from the collection of in-flight data, either as validation or as input to further the development of guidelines for the design and assessment of habitable volume. Specific in-flight data needs include insights into how crewmembers use space inside the ISS, and the definition of postures assumed for various tasks in a microgravity environment. Such information may feed directly into estimates of habitable volume in future spacecraft design. In addition, there is a need for a database of modifications made to hardware on existing spacecraft to better inform how a habitable volume is being used. Crewmember-initiated modifications are routinely documented in industry practices, and while anecdotal evidence exists regarding such modifications in spaceflight, it would be beneficial to systematically document these occurrences. Similarly, a systematic documentation of behavioral adaptations throughout missions would be useful. For example, if evidence points to changes in translation strategies after long exposures to microgravity, designers might modify the shapes and sizes of translation paths. Finally, as specific areas of subjective data needs are identified, it may be desirable to work with the ISS Operational Habitability (OpsHab) team to ensure that ISS post-mission crew debriefs address these items. For example, if Behavioral Health and Performance experts cannot find enough information regarding crew perception of privacy on ISS, it may be appropriate to work with the OpsHab team to add more targeted questions during crew debriefs.

## Conclusion

The 2012 Habitable Volume Workshop brought together academics, researchers, and practitioners from both aerospace and terrestrial industries to share respective experience in the field of human-systems integration and habitability design, and offer wide-ranging perspectives on considerations for space habitability in long-duration missions. The resulting workshop products are distillations of this shared expert knowledge, streamlined and retooled for use by designers, evaluators, and integrators who are shaping space habitats for current and future missions. As appropriate, contents of these products will be incorporated into standards and handbooks as updates, and identified areas of forward work will be considered for additions to the HRP research plans.

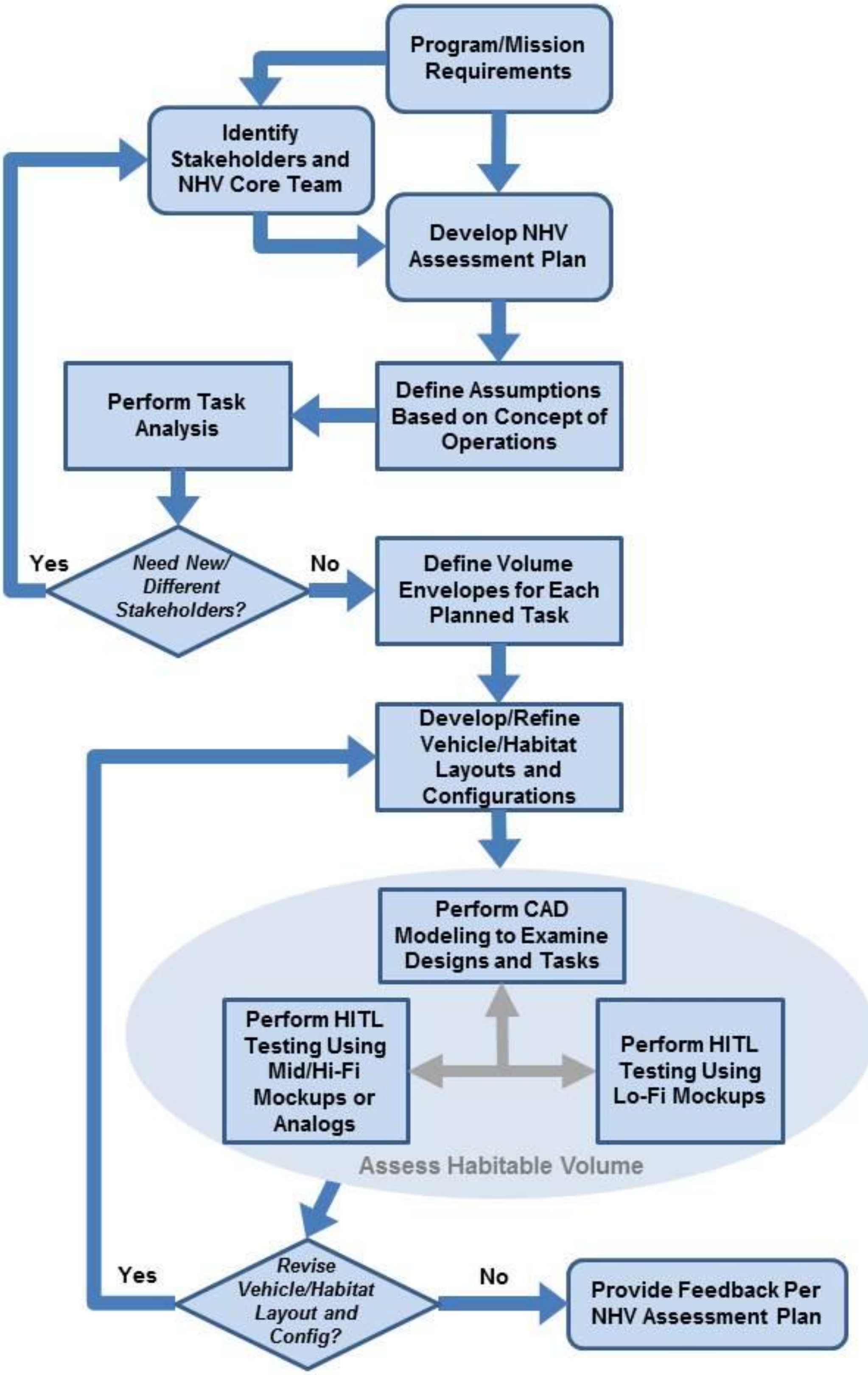
# Appendix A – 2012 Habitable Volume Workshop Agenda

| Date | Start | End | Duration | Topic | Comments |
|---|---|---|---|---|---|
| 7/30/2012 | 1:00 PM | 1:15 PM | 0:15 | Opening Remarks | |
| | 1:15 PM | 2:15 PM | 1:00 | Workshop welcome and overview | Workshop objectives<br>Review of pre-work<br>Guidance to splinter sessions |
| | 2:15 PM | 3:45 PM | 1:30 | Splinter session A | Splinter Session A.1 SHFE<br>Review SHFE products:<br>• Standard task list<br>• Habitable volume/layout design and evaluation process<br>For each product, determine pros & cons, gaps, current tools/metrics that are/could be used<br><br>Splinter Session A.2 BHP<br>• Review BHP-related task list<br>• Review evaluation process<br>• Define metrics and tools |
| | 3:45 PM | 4:00 PM | 0:15 | Break | |
| | 4:00 PM | 5:00 PM | 1:00 | Joint session | • Report out the findings from each session<br>• Integrate overlapping areas<br>• Realign agenda if necessary |
| 7/31/2012 | 8:00 AM | 8:15 AM | 0:15 | Welcome and agenda review | |
| | 8:15 AM | 9:15 AM | 1:00 | Joint Session | Review known facilities/capabilities for research (includes open brainstorming session) |
| | 9:15 AM | 10:45 AM | 1:30 | Splinter session B | Splinter Session B.1 SHFE Research and technology gaps<br>• Identify and prioritize the gaps<br>• Identify relevant existing research/ technology outside NASA, level of maturity and/or technology readiness<br><br>Splinter Session B.2 BHP Research or technology gap discussion<br>• Identify and prioritize the gaps<br>• Identify relevant existing research/ technology outside NASA, level of maturity and/or technology readiness<br>• Discuss duration needed for conducting research<br>• Discuss number of individuals, teams |
| | 10:45 AM | 11:00 AM | 0:15 | Break | |
| | 11:00 AM | 12:30 PM | 1:30 | Joint session | • Report out the findings from each session (research/technology gaps, facility/capability needs/requirements, etc.)<br>• Integrate overlapping areas<br>• Information should allow us to then develop an integrated research plan which defines the types of studies we need, (analog, chamber, flight) the numbers of individuals, etc. – what needs microgravity, what doesn't<br>• Realign agenda if necessary |
| | 12:30 PM | 1:30 PM | 1:00 | Lunch | |
| | 1:30 PM | 3:30 PM | 2:00 | Splinter session C | Complete products |
| | 3:30 PM | 4:00 PM | 0:30 | Break | |
| | 4:00 PM | 5:30 PM | 1:30 | Joint session/wrapup | • Review products<br>• Finalize integration across overlapping areas<br>• Identify actions and forward work |

# Appendix B – 2012 Habitable Volume Workshop Participants

| Name | | Affiliation | Sub-Affiliation/Expertise |
|---|---|---|---|
| Neda | Abdul-Razzak | NASA | Behavioral Health and Performance (BHP) |
| Diana | Arias | NASA | BHP |
| Lora | Bailey | NASA | Advanced Exploration Systems |
| Jennifer | Boyer | NASA | Human Factors Handbooks and Standards |
| George | Brainard | Thomas Jefferson Medical College | BHP (Faculty) |
| Maijinn | Chen | NASA | Habitability Design Center |
| Barbara | Corbin | NASA | HRP Management |
| Brian | Craig | Lamar University | Human Factors (Faculty) |
| Theo | Dekoker | Chevron | Human Factors (Oil and Gas) |
| Patrick | Dempsey | NIOSH | Human Factors (Mining) |
| David | Dinges | University of Pennsylvania | BHP (Faculty) |
| Alvin | Drew | NASA | Astronaut Office |
| William | Hahn | NASA | ISS Internal Volume Configuration (IVC) |
| James-Paul | Hierhozer | Germanischer Lloyd USA Inc | Submersibles |
| Eileen | Hoff | AMEC Paragon | Oil and Gas |
| Stephen | Hoffman | NASA | Mission Planning |
| Robert | Howard | NASA | Habitability Design Center |
| Scott | Howe | NASA | Jet Propulsion Laboratory |
| Anne | Kearney | Kearney Environmental LLC | BHP |
| Kriss | Kennedy | NASA | Advanced Exploration Systems |
| Lauren | Leveton | NASA | BHP |
| Yvonne | Masakowski | US Navy | Human Factors Psychology |
| Kerry | McGuire | NASA | Space Human Factors Engineering (SHFE) |
| Kevin | McSweeney | American Bureau of Shipping | Human Factors (Maritime) |
| Deb | Neubek | NASA | SHFE |
| Martin | Orr | University of Auckland | BHP (Faculty) |
| Christian | Otto | NASA | BHP |
| Regina | Peldszus | Kingston University London | Space Habitability Researcher |
| Esau | Perez | Chevron | Human Factors (Oil and Gas) |
| Rebekah | Prine | NASA | ISS IVC |
| Alex | Salam | Oxford University | BHP |
| Michael | Sapp | NASA | ISS IVC |
| Lacey | Schmidt | NASA | BHP |
| Matthew | Simon | NASA | Langley Research Center |
| Walter | Sipes | NASA | BHP |
| Peter | Suedfeld | University of British Columbia | BHP (Faculty) |
| Rich | Szabo | NASA | Operational Habitability |
| Sherry | Thaxton | NASA | SHFE |
| Shelby | Thompson | NASA | SHFE |
| Larry | Toups | NASA | Exploration Missions and Systems Office |
| Kevin | Toy | NASA | SHFE |
| Howard | Wagner | NASA | Advanced Exploration Systems |
| Alexandra | Whitmire | NASA | BHP |
| Mihriban | Whitmore | NASA | SHFE |
| Barbara | Woolford | NASA | SHFE |

# Appendix C – Process Flow



## Program/Mission Requirements

- **Program/Mission requirements and constraints provide descriptors for system drivers and solutions, and they reflect users'/customers' mission objectives.**
- **Top-level mission requirement areas can include:**
  - Performance
  - Duration
  - Survivability
  - Logistics
  - Resources
- **Top-level mission constraints can include:**
  - Cost
  - Schedule
  - Environments
  - Interfaces
  - Human capabilities/tolerances

**Mission objectives, requirements and constraints form the basis for program planning, including how to conduct human-systems integration (of which NHV assessment is a part) to ensure mission success.**

## Identify Stakeholders and NHV Core Team

- **Example stakeholders might include representatives from:**
  - Human factors
  - Subsystem designers
  - Project managers
  - Operations
  - Astronaut Office
  - Safety
  - Contractor team
  - Health and Medical team
  - System Maintenance/Ground Operators
  - Mission Planners
  - Systems Engineering and Integration
  - Behavioral Health and Performance
  - Science Teams
- **Stakeholder role:**
  - Participate in task analysis
  - Provide input regarding assumptions and design details
  - Act as design decision makers
  - Participate in determining frequency and fidelity of assessments

The exact membership of the stakeholders/core team may vary based on the specific project and phase in the project. It may be necessary to reassess the list throughout the design process.

## Develop NHV Assessment Plan

- **A plan of action should be developed and tailored to meet the needs of a specific assessment. JSC 63557, a document developed specifically for assessing NHV of the Orion vehicle, provides an example process. The plan will vary based on design cycle and specific needs. The plan should take into account:**
  - Current design maturity and corresponding fidelity of assessment
  - Potential iterations among CAD and mockup assessments
  - Stakeholder data needs
  - Plans for how recommendations or findings can impact the design.
  - Plans for requirement verification

## Define Assumptions Based On Concept of Operations

- **Concept of Operations describes how the vehicle/systems works and why. It informs on what tasks are needed to meet mission objectives.**
- **If not already defined in the ConOps, the team must define assumptions for at least the following:**
  - Program, mission and design priorities
  - High level tasks (e.g. science, EVAs)
  - Number of crewmembers
  - Duration of mission
  - Destination of mission
  - Mission objectives
  - Vehicle-specific operations (e.g. pre-defined emergency procedures and contingency scenarios)
  - Known timeline constraints and time-critical tasks
  - Psychological countermeasures
  - Gravity conditions
  - Acceptable crew risk
  - Crew composition (culture, gender, knowledge, skills, abilities)
  - Level of autonomy
  - Communications delay
  - Timeline
  - Workload
- **High-level assumptions should have additional details fleshed out in the task analysis.**

## Perform Task Analysis

- **Refer to companion workshop product, the Task List, for identified long-duration volume-driving mission and their key parameters.**
  - Determine which apply to current mission and whether there are others unique to mission
- **Additional considerations:**
  - Does the long-duration mission affect the steps/products of the task itself?
  - Should the number of people involved change based on social needs for long-duration?
  - Will the task take longer during a long-duration mission?
  - Does duration increase stowage needs for this task?
  - Will a different type of hardware be required for long-duration missions? (e.g. food warmer rather than using MREs)
  - Co-location vs. separation considerations for tasks (e.g. separate "messy" ops from "clean" ops)
  - Shared space vs. private space
  - Quality of life (Multiple demands/shifts, fatigue)
  - Level of autonomy & ground support
  - Cultural considerations
  - Cognitive load
  - Reconfigurability
  - Maintenance

## *Need New/Different Stakeholders?*

- **The need to reassess the list of stakeholders/core NHV group may arise periodically. Task analysis has the potential to reveal this need.**

## Define Volume Envelopes for Each Planned Task

- **For each task, define one or more three-dimensional work envelopes based on best assumptions. Integrated human modeling in CAD environment is often used to define volume envelopes.**
- **Take into account at least the following:**
  - Anthropometric sizes and postures of people performing tasks
  - Range of motion
  - Possibility of multiple hardware configurations (may result in multiple options for a given task)
  - Psychological clearances
  - Reach volume
  - Simultaneous task scheduling
  - Additional task requirements discovered during task analysis (such as point-of-use stowage and volume required for ancillary/preparatory tasks)
- **Existing resources may be used to assist with estimating work envelopes. These include:**
  - NASA-STD-3001
  - HIDH
  - HSIR
  - Task analysis
  - Design reference missions
  - Architecture design data
  - Operational concepts
  - Any previous NHV studies on the specific/analogous spacecraft
  - Previous space experience

## Develop/Refine Vehicle/Habitat Layouts and Configurations

- **The creative process of developing vehicle/habitat layout and configuration can start with functional allocations as defined by the task analysis.**
- **Vehicle/habitat layouts are informed by task volumes and their relationships, as well as equipment sizing and design.**
- **Concepts are iterated as requirements and constraints are traded and balanced. Often multiple configurations need to be assessed.**

**Optimization of NHV will depend greatly upon layout and configuration.**

## Assess Habitable Volume

- **Perform CAD Modeling to Examine Designs and Tasks**
  - CAD analysis can provide an initial rough estimate of the appropriate volume and layout based on tasks to be performed, and should be repeated iteratively based on new findings from subsequent human-in-the-loop testing. Using CAD modeling, assess the amount of available volume and visualize concepts based on best assumptions. Take into account at least the following:
    - Previously defined work envelope volumes for each task
    - Scheduling requirements
    - Co-location considerations
    - Volume dedicated to subsystems and stowage
    - Volumetric and environmental impacts of the subsystems

**Refer to companion workshop product, the Metrics/Tools List, for relevant habitability metrics.**

## Assess Habitable Volume (Cont'd)

- **Perform HITL Testing Using Lo-Fi Mockups**
  - As part of the iterative assessment process, it is customary to proceed from CAD assessment to increasingly higher-fidelity mockup assessments.
  - Mockup assessments "walk" participants through the tasks, examine human performance metrics and interactions with the hardware or software systems, and can serve as a demonstration of design to the stakeholders.
  - Mockup assessments take into account:
    - Adaptability and flexibility of the human body
    - Comfort levels, pain, and fatigue
    - Task completion effectiveness and efficiency
    - Subjective feedback

**Refer to companion workshop product, the Metrics/Tools List, for relevant habitability metrics.**

## Assess Habitable Volume (Cont'd)

- **Perform HITL Testing Using Mid/Hi-Fi Mockups or Analogs**
  - Findings from mockup assessments should be fed back into any future CAD assessments as well as future higher-fidelity mockup assessments. Factors that feed into mockup fidelity include, but are not limited to:
    - Hardware: Inclusion of high-fidelity hardware increases the realism and allows for the identification of representative issues
    - Environmental Conditions: Simulating the task under the anticipated environmental conditions (e.g., noise levels) will provide realism and increase the potential for identifying NHV related issues
    - Timeline: Performing a simulated mission where subjects spend their days and nights working a simulated mission timeline allows for the assessment of additional concepts such as behavioral variables

**Refer to companion workshop product, the Metrics/Tools List, for relevant habitability metrics.**

## *Revise Vehicle/Habitat Layout and Configuration?*

- **CAD and HITL assessments may reveal issues relating to human-system interactions or verification of volumes that could impact vehicle/habitat layout and configuration development. Program/mission needs and constraints, as reflected in the NHV assessment plan, determine the appropriate level of iterations.**

# Provide Feedback Per NHV Assessment Plan

- **Following CAD and HITL assessments, recommendations developed by the NHV core team should be delivered as per the NHV assessment plan. Examples of types of recommendations include:**
  - Specific layout or configuration recommendations based on assessment results provided to design teams and project management
  - Documentation to be used during verification processes
  - Specific data requested by stakeholder groups
  - More detailed information to feed back into future design assessments
  - Comments regarding acceptability of layout design and NHV

# Appendix D – Task List

| CREW TASK | | | NOMINAL/ CONTINGENCY | TASK DURATION | TASK FREQUENCY | PRIVACY | REQUIRES MIN / NO RECONFIG OF SPACE? (Dedicated) | POTENTIAL CONCURRENCES | POTENTIAL ADJACENCIES | EXAMPLE VOLUMES | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | TASK/FUNCTIONAL AREA VOLUME | | | | | | ADDT'L ANCILLARY VOL | | | ADDITIONAL NOTES |
| ID | Main Task | Description | | | | | | | | Source | No. Of Crew | Foot print (ft or ft2) | | Height (ft) | Volume (ft3) | HW/Sys | Point-of-Use Stow | Trans-lation | |
| 1 | Exercise | -Whole Body Aerobic<br>-Whole Body Resistive | Nominal | Hours | Per Day | Semi-Private | Yes | -Recreation<br>-Crew Heath/Medical (e.g. Monitoring) | -Crew Heath/Medical (e.g. Monitoring)<br>-Whole Body Hygiene<br>-Waste Collection and Management<br>-Stowage | Heritage | 1 | 5.31 | 2.89 | 7.61 | 116.78 | Included | Excluded | Excluded | Exercise in ISS Zvezda Service Module |
| | | | | | | | | | | Human Integration Design Handbook | 1 | 7.78 | 4.04 | 6.89 | 216.56 | Excluded | Excluded | Excluded | Body volume for operating Treadmill with Vibration Isolation System (TVIS) (HIDH Table 8.2-1). |
| | | | | | | | | | | | 1 | 4.69 | 4.04 | 3.18 | 60.25 | Included | Excluded | Excluded | Body volume for operating Cycle Ergometer with Vibration Isolation System (CEVIS) (HIDH Table 8.2-1) |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | 1 | 20.00 | | 6.50 | 130.00 | Included | Excluded | Excluded | Volume estimates reference ABS Guide for Crew Habitability on Ships (p.108). Size given is for one physical fitness station. ABS requires stations to permit aerobic, flexibility and strength training capabilities. |
| | | | | | | | | | | Other | 1 | 4.30 | 3.30 | 7.30 | 103.59 | 6.7 | Excluded | Excluded | Volume estimates reference CEV-T-70024 HSIR Rev D, based on anthro dimensions for max standing stature and max sitting height while using rower/cycle ergometer (no arms overhead). HW Vol estimates reference Table 18-5 "Mass and Volume Factors for Crew Accommodations" in "Human Spaceflight Mission Analysis and Design" |
| 2 | Whole Body Hygiene | -Don/Doff Clothes<br>-Access Hygiene Consumables<br>-Whole Body Cleaning<br>-Encompass Partial Hygiene Activities and Other Self-Groom Activities | Nominal | Minutes | Per Day | Completely Private | Yes | -Waste Collection and Management | -Waste Collection and Management<br>-Suit Don/Doff<br>-Exercise<br>-Crew Health/Medical<br>-Sleep<br>-Food Preparation | Heritage | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | Human Integration Design Handbook | 1 | 3.48 | 6.53 | 6.76 | 153.62 | Excluded | Excluded | Excluded | Body Volume for Partial Body Cleaning in 0-g (HIDH Table 8.2-1) |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | 1 | 2.50 | 2.50 | 6.50 | 40.63 | Excluded | Excluded | Excluded | Volume estimates reference ABS Guide for Crew Habitability on Ships (p.94). Dimensions are minimum provided for a shower stall. |
| | | | | | | | | | | Other | 1 | 3.00 | 3.00 | 6.40 | 57.60 | Excluded | Excluded | 3 x 4 x 6.4 | Volume estimates reference Architectural Graphic Standards of a typical manuf. one-piece shower stall. By comparison, estimates from Table 18-5 in "Human Spaceflight Mission Analysis and Design" for a shower/handwash/mouthwash is 50.15 ft3 |
| 3 | Waste Collection and Management | -Don/Doff Clothes<br>-Urinate and Defecate, Separately or Simultaneously<br>-Access Hygiene Consumables<br>-Clean and Self-Inspect<br>-Changeout WMS Consumables<br>-Depending on Implementation May Accommodate Maintenance and Repair | Nominal | Minutes | Per Hours | Completely Private | Yes | -Whole Body Hygiene | -Whole Body Hygiene<br>-Sleep<br>-Suit Don/Doff<br>-Crew Heath/Medical<br>-Exercise | Heritage | 1 | 4.50 | 2.40 | 6.00 | 64.80 | Included | Included | Excluded | Shuttle WMS volume. Estimates reference measurements made in the CCTII Shuttle mockup. Includes floor to ceiling height of WMS volume. |
| | | | | | | | | | | Human Integration Design Handbook | 1 | 2.99 | 4.04 | 4.99 | 60.28 | Excluded | Excluded | Excluded | Body Volume for body waste management in 0-g (HIDH Table 8.2-1) |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | 1 | 8.00 | | 6.70 | 53.60 | Included | Included | Excluded | Volume estimates reference ABS Guide for Crew Habitability on Workboats (p.70). Given for minimal habitation rating. Note that difference between ABS standards for Ships and Workboats is minimal, based on a 6.5 vs. 6.7 ft ceiling height in shipping vs. workboat guides. |
| | | | | | | | | | | Other | 1 | 2.00 | 3.75 | 6.25 | 46.88 | Included | Included | Excluded | Volume estimate based on measurement of the Multi-Mission Space Exploration Vehicle (MMSEV) Gen 2A WMS for one crewmember. The volume assumes 24" deep volume in front of the WCS for cleaning, clothing don/doff, etc. |
| 4 | Private Personal Activities | -Conduct Personal Training<br>-Private Emails/Videos<br>-Personal Recreation<br>-Clothing don/doff | Nominal | Hours | Per Day | Completely Private | Yes | -Sleep | -Sleep | Heritage | 1 | 3.44 | 2.80 | 6.60 | 63.57 | Included | Included | Excluded | Volume estimates reference ISS CQ (ISS ISPR equivalent). This volume encompasses sleep volume. |
| | | | | | | | | | | Human Integration Design Handbook | 1 | 3.48 | 4.04 | 6.76 | 95.04 | Excluded | Excluded | Excluded | Body Volume for Sleeping/personal office in 0-g (HIDH Table 8.2-1) |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | 1 | 8.60 | | 6.50 | 55.90 | Included | Included | Excluded | Vol estimates reference ABS Guide for Crew Habitability on Ships (p.86, 90). Berthing room includes berths, lockers, chest of drawers, and seats. Smallest footprint for a one-person room (passenger ship b/w 1000 and 3000 tons) is 25.5 sq ft including berth footprint. The est. provided in this table exclude the berth footprint, accounting for sleep vol separately. |
| | | | | | | | | | | Other | 1 | 4.00 | 7.83 | 4.33 | 135.62 | Included | Included | Excluded | Volume estimate based on measurement of Deep Space Habitat Demonstration Unit Crew Quarter for one crewmember. This volume encompasses sleep volume. |
| 5 | Sleep | -Perform Pre-/Post-Sleep Activities Including Deploy Sleep Hardware<br>-Sleep | Nominal | Hours | Per Day | Completely Private | Yes | -Private Personal Activities<br>-Radiation Shelter | -Private Personal Activities<br>-Whole Body Hygiene (i.e. partial hygiene tasks)<br>-Waste Collection and Management | Heritage | 1 | 2.50 | 2.50 | 6.27 | 39.19 | Included | Excluded | Excluded | Space Shuttle sleep provision is based on sleep bag restraints. |
| | | | | | | | | | | Human Integration Design Handbook | 1 | 3.48 | 4.04 | 6.76 | 95.04 | Excluded | Excluded | Excluded | Body Volume for Sleeping in 0-g (HIDH Table 8.2-1) |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | 1 | 2.00 | 2.60 | 6.50 | 33.80 | Included | Excluded | Excluded | Volume estimates reference ABS Guide for Crew Habitability on Workboats (p.69). |
| | | | | | | | | | | Other | * | * | * | * | * | * | * | * | |

| CREW TASK | | | NOMINAL/ CONTINGENCY | TASK DURATION | TASK FREQUENCY | PRIVACY | REQUIRES MIN / NO RECONFIG OF SPACE? (Dedicated) | POTENTIAL CONCURRENCES | POTENTIAL ADJACENCIES | EXAMPLE VOLUMES | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | TASK/FUNCTIONAL AREA VOLUME | | | | | | ADDT'L ANCILLARY VOL | | | |
| ID | Main Task | Description | | | | | | | | Source | No. Of Crew | Foot print (ft or ft2) | | Height (ft) | Volume (ft3) | HW/Sys | Point-of-Use Stow | Trans-lation | ADDITIONAL NOTES |
| 6 | Food Preparation | -Access Food Stowage<br>-Collect/Remove Trash<br>-Use Food Hardware Including Oven and Dispenser<br>-May Require Assistance | Nominal | Minutes | Per Day | Completely Public | Yes | -Group Meet and Eat<br>-Stowage | -Stowage<br>-Whole Body Hygiene (i.e. partial hygiene tasks such as handwash) | Heritage | * | * | * | * | * | 5.8 | * | * | Hardware volume estimate based on measurement of galley hardware in CCTII Shuttle mockup |
| | | | | | | | | | | Human Integration Design Handbook | 1 | 6.53 | 3.48 | 6.76 | 153.62 | Excluded | Excluded | Excluded | Body volume associated with food preparation in 0-g (HIDH Table 8.2-1) |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | Other | 2 | 3.58 | 4.00 | 6.50 | 93.08 | 37.6 | Excluded | Excluded | Volume estimate based on measurement of Deep Space Habitat Demonstration Unit Galley. By comparison, volume estimates referencing Architectural Graphic Standards for a minimum kitchen dimension for two people side by side in front of a refrigerator is 125 ft3. HW estimates from Table 18-5 in "Human Spaceflight Mission Analysis and Design" is 57.21 |
| 7 | Group Meet and Eat | -Group Eat<br>-Group Meet<br>-Common Recreation Activities Such As Watching Movies<br>-PAO Events<br>-Team Training<br>-All crewmembers should be accommodated at the same time | Nominal | Hours | Per Day | Completely Public | Yes | -Food Preparation<br>-Recreation | -Recreation | Heritage | 3 | 87.00 | | 6.54 | 568.98 | 209 | | Included | Skylab Wardroom (NASA TM X-58163 Skylab Experiment M487 Habitability/Crew Quarters, Table C-I (a)) |
| | | | | | | | | | | Human Integration Design Handbook | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | 1 | 10.80 | | 6.70 | 72.36 | Included | Included | Included | Volume estimates reference ABS Guide for Crew Habitability on Workboats (p.75). Given as minimal habitation certification value for deck area per person of planned seating capacity. Note that difference between ABS standards is minimal, based on a 6.5 vs. 6.7 ft ceiling height in shipping vs. workboat guides. |
| | | | | | | | | | | Other | 4 | 12.17 | 4.50 | 6.50 | 355.97 | Included | Excluded | Included | Volume estimate based on measurement of Deep Space Habitat Demonstration Unit Wardroom, assuming a 2 ft zone around the wardroom table. |
| 8 | Recreation | -Dedicated Recreation Activities | Nominal | Minutes | Per Day | Completely Public | No | -Group Meet and Eat<br>-Exercise | -Group Meet and Eat | Heritage | 7 | 6.23 | 6.23 | 6.23 | 241.80 | Included | Included | Included | Space Shuttle Leisure (HIDH Table 8.2-3). By comparison, Skylab is 9535 ft3. |
| | | | | | | | | | | Human Integration Design Handbook | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | Other | * | * | * | * | * | * | 13.4 | * | Point-of-Use stowage volume estimate reference Table 18-5 in "Human Spaceflight Mission Analysis and Design" |
| 9 | Suit Don/Doff, Stowage and Maintenance | -Access Suit stowage<br>-Don/Doff Suit<br>-Suit cleanup | Nominal and Contingency | Hours | Per Day | Semi-Private | Yes | -Stowage | -Whole Body Hygiene<br>-Waste Collection and Management<br>-D&C Console Operations | Heritage | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | Human Integration Design Handbook | 1 | 4.76 | 6.53 | 7.22 | 224.42 | Excluded | Excluded | Excluded | Body Volume for EVA suiting area (don/doff EVA suit) (HIDH Table 8.2-1) |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | * | * | * | * | * | * | * | * | NA |
| | | | | | | | | | | Other | 1 | 2.63 | 3.32 | 6.40 | 55.88 | Excluded | 10 | Excluded | Donning volume estimates reference CxP EVA Systems LEA Flight Suit Element Requirements Document Figure 3.2-1 Minimum Donning Volume Figure. POU stowage volume reference Table 3.5-9 Suit Element Stowage for ISS Missions of the same document and refers to the stowed volume of the LEA suit. |
| 10 | Radiation Shelter | -Prep/Configure Shelter if required<br>-Sheltering | Contingency | Hours | Per Mission | Semi-Public | No | -Sleep | -Waste Collection and Management<br>-Stowage<br>-D&C Console Operations | Heritage | 1 | 3.44 | 2.80 | 6.60 | 63.57 | Included | Included | Included | ISS CQ as radiation shelter |
| | | | | | | | | | | Human Integration Design Handbook | 1 | 3.48 | 4.04 | 6.76 | 95.04 | Excluded | Excluded | Excluded | Body Volume for radiation shelter (same as body volume for sleeping) in 0-g (HIDH Table 8.2-1) |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | * | * | * | * | * | * | * | * | NA |
| | | | | | | | | | | Other | 2 | 3.50 | 2.20 | 2.20 | 16.94 | Included | Included | Included | Volume estimate based on measurement of Orion Mid-Fi mockup. Radiation shelter implementation based on one stowage bay for two crewmembers. |

| CREW TASK | | | NOMINAL/ CONTINGENCY | TASK DURATION | TASK FREQUENCY | PRIVACY | REQUIRES MIN / NO RECONFIG OF SPACE? (Dedicated) | POTENTIAL CONCURRENCES | POTENTIAL ADJACENCIES | EXAMPLE VOLUMES | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | TASK/FUNCTIONAL AREA VOLUME | | | | | | ADDT'L ANCILLARY VOL | | | |
| ID | Main Task | Description | | | | | | | | Source | No. Of Crew | Foot print (ft or ft2) | | Height (ft) | Volume (ft3) | HW/Sys | Point-of-Use Stow | Trans-lation | ADDITIONAL NOTES |
| 11 | D&C Console Operations | -On-board Piloting & Navigation<br>-On-board Subsystem Monitoring and Control<br>-Rendezvous, Proximity Operations and Docking<br>-Control of External Devices<br>-May be Suited | Nominal Contingency | Hours | Day | Completely Public | Yes | | -Radiation Shelter<br>-Suit Don/Doff | Heritage | 2 | 5.30 | 6.30 | 4.50 | 150.26 | Included | Included | Included | Volume estimate based on measurements of cockpit area of CCTII Shuttle mockup. Includes seating area for two crewmembers from back to seat to console, from floor to ceiling. |
| | | | | | | | | | | Human Integration Design Handbook | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | * | * | * | * | * | * | * | * | NA |
| | | | | | | | | | | Other | 2 | 1.80 | 5.80 | 5.80 | 60.55 | Included | Included | Included | Volume estimate based on measurements of the Mid-Fi Orion mockup. Includes seating area for two crewmembers from external should to external shoulder, bottom of foot pan to top of head rest, and back of head rest to front of control panel. |
| 12 | Mission-Specific On-Board Research | -Conduct Geological Experiments<br>-Conduct Materials/Chemical Experiments<br>-Conduct Biological Experiments<br>-Conduct Tabletop General Maintenance Tasks<br>-May Require Unique workstations/Racks | Nominal | Hours | Per Day | Semi-Public | Yes | | -Stowage<br>-Crew Health/Medical | Heritage | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | Human Integration Design Handbook | 1 | 6.53 | 3.48 | 6.76 | 153.62 | Excluded | Excluded | Excluded | Body volume associated with General Workstation in 0-g (HIDH Table 8.2-1) |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | Other | 2 | 6.00 | 4.33 | 6.50 | 168.87 | Included | Included | Excluded | Volume estimate based on measurement of Deep Space Habitat Demonstration Unit Workstation, assuming a 2 ft work volume in front of the workstation table. Volume estimate is approximate as the actual workstation config is pie-shaped. |
| 13 | Crew Health/Medical | -Routine Examinations and Consultations<br>-Medical Procedures<br>-Emergency and Ambulatory Medical Support<br>-Biological Sample analysis | Nominal Contingency | Minutes<br>Hours | Per Week<br>Per Mission | Completely Private | Yes | -Mission-Specific Onboard Research | -Exercise<br>-Waste Collection and Management<br>-Mission-Specific Onboard Research | Heritage | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | Human Integration Design Handbook | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | Other | 2 | 12.83 | 6.00 | 6.50 | 500.37 | Included | Included | Included | Volume estimate based on measurement of Deep Space Habitat Demonstration Unit Med Ops Workstation, with the privacy curtains drawn. Volume estimate is approximate as the actual workstation config is pie-shaped. |
| 14 | Stowage | -Non-dedicated stowage excluding point-of-use and personal stowage<br>-Should Accommodate Stowage Access, Transfer and Resupply Tasks | Nominal Contingency | Hours | Per Day | Completely Public | Yes | -Food Preparation<br>-Suit Don/Doff, Stowage and Maintenance | -Exercise<br>-Food Preparation<br>-Radiation Shelter<br>-Mission-Specific On-Board Research | Heritage | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | Human Integration Design Handbook | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | American Bureau of Shipping (ABS) Guide for Crew Habitability | * | * | * | * | * | * | * | * | |
| | | | | | | | | | | Other | 2 | * | * | * | 36.80 | Excluded | Excluded | Excluded | Volume estimate based on MMSEV Gen 2A crew stowage for 2 crew and 14 mission days. By comparison, Orion Crew Stowage Layout in the Aft bay (OASIS) for 607A configuration (2 crew, 14 mission days) is 41 ft3 (does not include majority of EVA stowage that is stowed outside OASIS). |

# Appendix E – Metrics List

| METRIC ID | HABITABILITY METRIC | | | SUB/ OBJ | PROS | CONS | APPLICABLE TOOLS (see Tools List) | REQUIRED INPUTS | DESIRED OUTCOME | APPLICABLE LIFECYCLE PHASES | APPLICABLE EVAL ENVIRONMENT | | POTENTIAL RESEARCH GAPS | REFERENCE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Title | Description | Units | | | | | | | | Model/Sim | Physical/ Operational | | |
| M-1 | **Net Habitable Volume/Floor area** | Net habitable volume is the total remaining volume provided for crew living and work functions, after accounting for system/equipment layout and installations, stowage, secondary structures and any unusable volume. The Habitable Floor Area indicates available floor area for crew living and work functions. | m3<br>m2 | Objective | - Good proxy measure of usability of space<br>- Floor area may be a better measure of usable, accessible space for non-zero gravity environments than habitable volume | - Requirements not universally agreed upon. | T-11 | Pressure vessel geometry, size and arrangement of interior subsystems | Maximized up to a point; adequate volume to perform tasks effectively | Early Design Phases | Low-Fi CAD | | Maps to Human Research Program (HRP) Gap SHFE-HAB-02: What tools can be used to evaluate habitability concepts for on-orbit and planetary missions | Human Integration Design Handbook (HIDH) (NASA/SP-2010-3407)<br><br>Net Habitable Volume Verification Method (JSC-63557 )<br><br>Report 1: Figure of Merit Criteria for Evaluating and Selecting Lunar Habitat Module Concepts (SICSA, 2008) |
| M-2 | **Habitable Volume to Structural Shell Ratio** | Total volume, habitable volume, or habitable floor area per unit of structural mass or surface area is an indicator of the structural/geometric efficiency of a pressure vessel to enclose the volume and accommodate habitable functions. | m3/kg<br>m2/kg<br>m3/m2 | Objective | - An indicator of structural efficiency and "goodness" of geometry | -Not a measure of the usefulness or habitability of the enclosed volume | T-11 | Pressure vessel geometry, size and arrangement of interior subsystems, total structural mass and surface area | Maximize | Early Design Phases | Low-Fi CAD | | HRP Gap SHFE-HAB-02: What tools can be used to evaluate habitability concepts for on-orbit and planetary missions | Report 1: Figure of Merit Criteria for Evaluating and Selecting Lunar Habitat Module Concepts (SICSA, 2008) |
| M-3 | **Dedicated Private Space** | Adequacy of allocated spaces for private occupation by the crew can impact the psychological acceptability of an interior for long duration missions, and this is partially informed by the physical measurement of the volume occupied by private functions/facilities/subsystems. | m3 | Subjective/ Objective | - Adequate private space maps well to overall psychological acceptability of a habitat interior | - Minimum value for adequate private space is not known, and values likely vary across the population | T-3<br>T-4<br>T-11 | Interior layout, identification of private functions and facilities [NASA 10] | Size meeting needs | Early Design Phases | Low-Fi CAD | Low-Fi Mockup<br>Mid-Fi Mockup | Parametric determination of adequacy of privacy<br><br>HRP Gap BMed7: What are the most effective methods for modifying the environment to prevent and remedy behavioral health problems during spaceflight missions | Evaluation and Automation of Habitat Interior Layouts, Ph.D Proposal (Simon, 2012) (Unpublished) |
| M-4 | **Spatial Vista** | Spatial vista is a measure of the maximum contiguous line of sight/ contiguous field of view swept by the eye of a crew member. This is a measure of spaciousness and psychological/ physiological acceptability of the environment. This is also a measure of the quality of the interior volume and layout as affected by interior shapes and functional utilities. [SICSA 09] | m3<br>m2<br>m | Subjective/ Objective | - Good measure of quality of open space and spaciousness | -Acceptability of a space or layout is subjective | T-11<br>T-17 | Pressure vessel geometry, interior subsystems geometries and locations, astronaut anthropometric dimensions | Maximized up to a point; adequate volume to perform tasks effectively | Early Design Phases | Low-Fi CAD | | Quantitative measures of spatial quality and acceptability<br><br>HRP Gap BMed7: What are the most effective methods for modifying the environment to prevent and remedy behavioral health problems during spaceflight missions<br><br>HRP Gap SHFE-HAB-04: How can existing models be modified to adequately represent the specified user population (e.g. field of view, visibility) in reduced gravity and be portable to other simulations environments? | Report 1: Figure of Merit Criteria for Evaluating and Selecting Lunar Habitat Module Concepts (SICSA, 2008)<br><br>Evaluation and Automation of Habitat Interior Layouts, Ph.D Proposal (Simon, 2012) (Unpublished) |

| METRIC ID | HABITABILITY METRIC | | | SUB/ OBJ | PROS | CONS | APPLICABLE TOOLS (see Tools List) | REQUIRED INPUTS | DESIRED OUTCOME | APPLICABLE LIFECYCLE PHASES | APPLICABLE EVAL ENVIRONMENT | | POTENTIAL RESEARCH GAPS | REFERENCE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Title | Description | Units | | | | | | | | Model/Sim | Physical/ Operational | | |
| M-5 | **Colocation of Equipment by Function and Sequential Tasks** | A measure of the grouping and colocation of equipment and components based upon the function, task, and their dependencies such that, on average, crew translation path lengths are minimized. This can be informed by functional relationship analysis, cluster analysis capturing sequential relationships between functions, or by calculating the distances between groups of common functions. [Tullis 88] | | Subjective/ Objective | -Can simplify and anticipate complex issues such as traffic patterns early on in the design process via desired groupings of hardware | - Non-intuitive values difficult to interpret<br>- May be an over-simplification of task performance | T-5<br>T-11<br>T-15<br>T-16 | Interior subsystem locations, associated subsystem functions, list of equipment/storage associated with each function, crew schedules [Tullis 88] | Closer grouping of sequential functions | Early Design Phases | Low-Fi CAD | | Spaceflight data providing researchers with insight into current space utilization<br><br>'HRP Gap SHFE-HAB-02: What tools can be used to evaluate habitability concepts for on-orbit and planetary missions | Space Station Functional Relationships Analysis Final Technical Report (Tullis, Thomas, Bied, Barbra, 1988) (NASA-CR-177497)<br><br>Evaluation and Automation of Habitat Interior Layouts, Ph.D Proposal (Simon, 2012) (Unpublished) |
| M-6 | **Anthropometry Interferences** | A measure of the number of tasks whose anthropometric volumes interfere with either the anthropometric volumes of other tasks, translation paths, or hatch clearance areas.[Fitts 02, Simon 10] | | Objective | - Captures reserved/dedicated volumes, preventing task overlap<br>- Provides a simpler, lower-fidelity method to analyze scheduling of tasks without creating a detailed simulation | - Can be computationally intensive | T-11<br>T-13<br>T-15 | Pressure vessel geometry, interior subsystems geometries and locations, astronaut anthropometric geometries associated with each piece of hardware, durations of tasks, scheduling of tasks | Minimized. No official requirement | Early Design Phases | High-Fi CAD | | Volume required by crewmembers to perform each task based on a variety of potential hardware designs<br><br>'HRP Gap SHFE-HAB-02: What tools can be used to evaluate habitability concepts for on-orbit and planetary missions | International Space Station (ISS) Internal Volume Configuration (IVC) (Fitts, 2002) (AIAA 2002-6114 )<br><br>Evaluation and Automation of Habitat Interior Layouts, Ph.D Proposal (Simon, 2012) (Unpublished) |
| M-7 | **Placement for Function / Ergonomics** | Placement of interior equipment items with ergonomic considerations including force, repetition, and posture, and based on the need for comfortable, long-duration or frequent access to a piece of equipment. | | Objective | - Captures ergonomics in the placement of subsystems, particularly in gravity orientations | | T-2<br>T-5<br>T-10<br>T-11<br>T-13<br>T-15<br>T-16 | Ranges of acceptable positions for use of objects, nominal position for frequent use of object, locations of objects subject to ergonomic/functional constraints, frequency of use and duration of use for each object [Tullis 88, Salvendy 97, NASA 10] | Minimize ergonomic stressors such as excessive force, highly repetitive motions, and awkward postures | Early Design Phases | High-Fi CAD | Low-Fi Mockup<br>Mid-Fi Mockup | Definition of postures assumed for various tasks in a microgravity environment<br><br>'HRP Gap SHFE-HAB-02: What tools can be used to evaluate habitability concepts for on-orbit and planetary missions | Space Station Functional Relationships Analysis Final Technical Report (Tullis, Thomas, Bied, Barbra, 1988) (NASA-CR-177497) |
| M-8 | **Functional Separations** | A measure of the separation of public from private functions, clean (e.g. crew quarters) from dirty functions/zones (e.g. EVA workstations), or noisy from quiet functions/zones, ranked by degree of desired separation. [Tullis 88] | | Subjective | - Captures effectiveness of a layout design to accommodate functional relationships between hardware | | T-15<br>T-16 | Interior subsystem locations, associated subsystem functions, separation relationships [Tullis 88] | Maximize separation- no standardized requirement | Early Design Phases | Low-Fi CAD | | HRP Gap SHFE-HAB-02: What tools can be used to evaluate habitability concepts for on-orbit and planetary missions<br><br>HRP Gap BMed7: What are the most effective methods for modifying the environment to prevent and remedy behavioral health problems during spaceflight missions | Space Station Functional Relationships Analysis Final Technical Report (Tullis, Thomas, Bied, Barbra, 1988) (NASA-CR-177497) |
| M-9 | **Translation Efficiency** | This is a measure of how efficiently the crew can translate between functional areas or modules. Proper design of translation paths will increase crew performance, optimize logistics and movement, avoid traffic congestion and optimize emergency procedures. Considerations include flow movements, traffic envelopes, traffic time, collisions, and adequate path width to allow access to hatches or systems. | | Subjective/ Objective | - Good measure for crowding and tracking translation path requirements | - Requires detailed knowledge of ConOps and actual crew behaviors for accurate analysis | T-2<br>T-5<br>T-10<br>T-13<br>T-15<br>T-16 | 2D data for deployed layout geometry, and any systems/equipment which must be on the translation path; location of crewmembers within habitat | Maximize efficiency | All Design Phases | High-Fi CAD | Low-Fi Mockup<br>Mid-Fi Mockup<br>High-Fi Mockup<br>Operational Analog | Spaceflight data providing researchers with insight into current space utilization<br><br>'HRP Gap SHFE-HAB-02: What tools can be used to evaluate habitability concepts for on-orbit and planetary missions | Human Integration Design Handbook (HIDH) (NASA/SP-2010-3407) |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Title | Description | Units | | | | | | | | Model/Sim | Physical/ Operational | | |
| M-10 | **Hardware Protrusions and Interferences** | Identifies and measures the impact of the protrusions (particularly unplanned protrusions) on the habitable volume and crew operational volume envelopes necessary for supporting crew tasks. One potential impact could be on the keep-out zones or clearances for emergency egress paths and fire extinguishers, etc. required for emergency operations. | | Objective | - Protects habitable volume and usability of layout interior<br>- Repeatable measurement | - Detailed CAD analysis needed | T-2<br>T-11<br>T-13 | Detailed 3D CAD interior model | Minimized interferences and clearances resulting in performance decrements | Design and Verification | High-Fi CAD | Low-Fi Mockup<br>Mid-Fi Mockup<br>High-Fi Mockup<br>Operational Analog | Volume required by crewmembers to perform each task based on a variety of potential hardware designs<br><br>'HRP Gap SHFE-HAB-02: What tools can be used to evaluate habitability concepts for on-orbit and planetary missions | International Space Station (ISS) Internal Volume Configuration (IVC) (Fitts, 2002) (AIAA 2002-6114 ) |
| M-11 | **Design-Induced Error Rate** | For optimal safety and productivity, software and hardware crew interfaces must support crew performance with minimal errors. Errors may lead to significant timeline impacts or task failure; therefore errors can cause loss of efficiency, effectiveness, and satisfaction. A design-induced error is an intentional action that does not reach its intended goal due to design issues. Error analysis requires human-in-the-loop assessment using simulation, mockup, or hardware. | | Objective | - Provides quantitative error rate useful for comparison between designs | - Easiest to test for clearly described tasks with defined steps<br>- May be difficult to differentiate between design-induced errors and random errors | T-2<br>T-14<br>T-15 | Task design, definitions of procedure steps, definition of "error", outcome of HITL test | Minimize error rate | Design and Verification | High-Fi Sim | Mid-Fi Mockup<br>High-Fi Mockup<br>Operational Analog | Modeling and simulation of expected design-induced errors<br><br>HRP Gap Sleep1: What are the most effective tools to detect and assess performance decrements due to fatigue resulting from sleep loss, circadian desynchronization, extended wakefulness, and work overload? | Baseline Multi-Purpose Crew Vehicle Program Human-Systems Integration Requirements (HSIR) (2012) (MPCV 70024) |
| M-12 | **Workload** | This includes measures of physical and mental workload. Physical workload can be quantified by physiological measures including VO2 consumption, heart rate, force exerted, etc., as well as subjective assessments of perceived exertion. Mental workload can be captured using validated scales such as Bedford or NASA TLX. Workload levels may be raised or lowered through the combination of user-interface design and task design. Evaluation of workload requires human-in-the-loop assessment using simulation, mockup, or hardware | | Subjective/ Objective | - Provides designers/researchers with information about how the task or design is impacting crewmember performance | - All measures are indirect, and perception of workload can be confounded by factors such as fatigue<br>- Comparison across people may not be accurate for all workload measures | T-2<br>T-7<br>T-8<br>T-9<br>T-15<br>T-18 | Task design, vehicle layout as applicable, outcome of HITL test | As a rule, minimize workload; however, workload remaining too low for long periods of time is related to boredom and decreased vigilance | Design and Verification | High-Fi Sim | Low-Fi Mockup<br>Mid-Fi Mockup<br>High-Fi Mockup<br>Operational Analog | Modeling and simulation of expected workload. Although there are some existing models, their applicability for NASA purposes must be validated.<br><br>HRP Gap Sleep7: Does sleep loss, circadian desynchronization, work overload and extended wakefulness as it is experienced on long duration missions, affect well-being, crew interaction and performance? If so, how? | Human Integration Design Handbook (HIDH) (NASA/SP-2010-3407) |
| M-13 | **Degree of Isolation** | The level of access the individual has to others outside of their team. Could be informed by the amount of time people are spending alone. Subjectively, this is about perception of access to others outside of the environment. | | Subjective/ Objective | | | T-1<br>T-5<br>T-17 | Psychological profiles, team dynamics, external communication (frequency, content, effectivity) | Degree of isolation optimizes human behavioral health and performance | All Design Phases | | Operational Analog | Threshold at which isolation impacts behavioral health and performance<br><br>HRP Gap BMed5: What individual characteristics predict successful adaptation and performance in an isolated, confined and extreme environment, especially for long duration missions?<br><br>HRP Gap BMed8: How do family, friends, and colleagues affect astronauts' behavioral health and performance before, during, and after spaceflight? | |

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| | Title | Description | Units | | | | | | | | Model/Sim | Physical/ Operational | | |
| M-14 | **Personalization of Space** | Degree of control one has over being able to adjust features of their environment (e.g. temperature, lighting, space configuration) | | Subjective | - Captures subjective feedback on degree of control over an environment | - Inconsistent measure across population due to individual preferences/ tolerances | T-1<br>T-5<br>T-17 | Videos or snapshots of the spaces throughout the mission; feedback from environmental systems recording the changes that are made - temperature, lights, etc. | Degree of personalization meets user needs | All Design Phases | | Operational Analog | Degree of personalization needed is undefined | Office Clutter or Meaningful Personal Displays: The Role of Office Personalization in Employee and Organization Well-Being (Wells, 2000) |
| M-15 | **Sleep Quality** | Includes quantitative aspects of sleep (such as sleep duration) and more subjective aspects, such as 'restfulness'. Could also be enhanced to include measure of sleep stages (e.g. Slow Wave Sleep) | | Subjective/ Objective | - Good indicator of performance state and well-being.<br>- Can serve as a risk factor for a multitude of health and performance outcomes. | - Measure can be obtrusive and require crew time (e.g. requires crewmembers to wear an Actiwatch or Zeo (EEG)) | T-1<br>T-17<br>T-18 | Sleep-wake data (from Actiwatch) gives a schedule of their sleep-wake time and a measure of sleep duration, as well as level of activity. EEG provides comprehensive assessment of sleep quality. OSTPV would provide planned sleep schedule. Sleep logs would allow for context. | Provide adequate sleep quality for optimal crew performance | All Design Phases | | Operational Analog | Commercial off the shelf, validated tools are available, but their feasibility and acceptability in spaceflight is not yet established. Tools must minimally impact human resource requirements (e.g. crew time, volume) | Sleep-Wake Actigraphy and Light Exposure During Spaceflight (Czeisler, 2012) |
| M-16 | **Environments** | This metric measures effects of temperature, humidity, pressure, noise, vibration, and other environmental characteristics that affect human comfort and performance within a habitable environment. | | Subjective/ Objective | - The measures themselves are objective and easy to measure | - Effects of environment on human performance and comfort are not always completely known, with large variance between people | T-12<br>T-18 | Vehicle layout as applicable, environmental control system parameters, noise and vibration data, human performance and comfort data related to environmental parameters | Optimize environmental parameters to ensure comfort and performance of crewmembers | Design and Verification | High-Fi Sim | High-Fi Mockup<br>Operational Analog | Desired values for environmental parameters, particularly when related to psychological impacts (e.g., lighting, noise); Improved modeling and simulation capabilities<br><br>HRP Gap SHFE-HAB-01: What validated acoustic model can predict the effects of structures, materials, crew and equipment on the acoustic environment of a spacecraft or habitat?<br><br>HRP Gap SHFE-HAB-03: How can we determine the effects of combined vibration and acceleration on task performance?<br><br>HRP Gap SHFE-HAB-05: What is the effect of microgravity on spinal elongation? | |
| M-17 | **Positives** | In addition to documenting issues with designs, it is necessary to document positive aspects. This documentation provides evidence for the inclusion of design features in future designs. Positives may be documented through means such as questionnaires and crew debriefs. | | Subjective | - Provides valuable information to designers and researchers with direct applicability to future designs | - Consists of subjective data and may be limited in scope based on crew perception<br>- Most valuable for high fidelity analogs or operational habitats | T-1<br>T-17 | Subjective feedback from crewmembers | No set outcome. The goal is to document observations for use in the future | All Design Phases | | Operational Analog | Adequate database of positive observations related to design elements of interest in existing spacecraft<br><br>SHFE-HAB-06 (SBIR): How can crews easily document human factors related issues that occur on orbit? | |

| METRIC ID | HABITABILITY METRIC | | | SUB/ OBJ | PROS | CONS | APPLICABLE TOOLS (see Tools List) | REQUIRED INPUTS | DESIRED OUTCOME | APPLICABLE LIFECYCLE PHASES | APPLICABLE EVAL ENVIRONMENT | | POTENTIAL RESEARCH GAPS | REFERENCE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Title | Description | Units | | | | | | | | Model/Sim | Physical/ Operational | | |
| M-18 | **Crew modifications** | For operational vehicles or habitats, documenting crew-initiated modifications to hardware is useful. These modifications are often indicators of areas for improvement in design and should be recorded as lessons learned. For example, crewmembers might rearrange hardware in a layout that they discover to be more efficient for their workflow. | | Subjective | - Provides valuable information to designers and researchers with direct applicability to future designs | - Information regarding modifications may not be straightforward to obtain<br>- Modifications may not always result in improvements<br>- Modifications could potentially result in violations of other requirements<br>- Only applicable for operational hardware; cannot be established during design phase | T-1<br>T-5<br>T-14<br>T-17 | Original hardware design and layout; hardware design and layout following operational use | No set outcome. The goal is to document observations for use in the future | All Design Phases | | Operational Analog | Adequate database of modifications made to hardware on existing spacecraft<br><br>'HRP Gap SHFE-HAB-02: What tools can be used to evaluate habitability concepts for on-orbit and planetary missions<br><br>HRP Gap SHFE-HAB-06 (SBIR): How can crews easily document human factors related issues that occur on orbit? | |
| M-19 | **Physical/Behavioral Adaptation** | Understanding of physical and behavioral adaptability can drive the design of crew hardware and interfaces in addition to impacting crew training strategies. Examples of expected behavior adaptations include body orientation during translation, strategies for carrying and moving hardware, use of crew restraints such as handrails and foot restraints, adaptation to communication protocols and social dynamics etc. Points of psycho-physical adaptation specifically tied to human performance include: Spatial orientation/awareness, locomotion and navigation, body restraint, mass handling, mass discrimination, artificial gravity, and zero gravity item management. | | Subjective/ Objective | - Provides valuable information to designers and researchers with direct applicability to future designs | - Requires human performance data collection on-orbit throughout a mission, which presents challenges<br>- Some behavior adaptations may be developed specific to layout and processes for a given vehicle | T-1<br>T-5<br>T-17 | Performance parameters for tasks throughout the duration of a mission (e.g. number of times a crewmember uses a given handrail at the beginning of a mission compared to at the end of a mission) | No set outcome. The goal is to document patterns of behavioral adaption for use in the future | All Design Phases | | Operational Analog | Adequate database of behavioral adaptations documented during spaceflight<br><br>HRP Gap BMed5: What individual characteristics predict successful adaptation and performance in an isolated, confined and extreme environment, especially for long duration missions? | Behavioral Adaptation to Space Flight (Barratt, 2011) |

# Appendix F – Tools List

| TOOL ID | HABITABILITY TOOLS | | | SUB/ OBJ | PROS | CONS | REFERENCE |
|---|---|---|---|---|---|---|---|
| | Title | Description | Measures | | | | |
| T-1 | **iSHORT** | Space Habitability Observation Reporting Tool is an iPad-based tool that allows users to report HF/habitability issues near real-time, using media files to enhance reports. | | Subjective | - Allows crewmembers to report data near real-time<br>- Incorporates media files into reports<br>- User-friendly interface<br>- Options to customize app for future use such as ISS deployment | - Requires subjects to take the initiative to use it<br>- Capture only a sampling of HF/hab issues, based on crewmember discretion<br>- Requires use of hardware | Developmental Testing of Habitability and Human Factors Tools and Methods During NEEMO 15 (Thaxton, Litaker, Holden, Adolf, and Morency, 2012). |
| T-2 | **Human-In-The-Loop (HITL) Assessment** | Test conductors design protocols in which participants perform tasks in a mockup or analog environment. HITL assessments typically include the use of additional tools targeted for specific objectives (e.g., participants may be asked to rate perceived physical exertion as they perform a task), and HITL assessments often employ customized questionnaires and/or checklists. It is typical to examine human performance metrics and/or interactions with hardware and software. | | Subjective/ Objective | - Provides information about what happens when humans actually perform planned tasks<br>- May also serve as a demonstration of designs to stakeholders such as crewmembers<br>- Depending on necessary fidelity, may provide a low-cost method to test a design | - For more complex tasks or designs, may require high fidelity mockups<br>- In order to achieve statistical results, it may be necessary to test more participants than is typically feasible<br>- Robustness of HITL results is dependent on good assessment design | Habitability and Environmental Factors: The Future of Closed-Environment Tests (Lane and Feeback, 2002) |
| T-3 | **Index of Habitability** | A scale intended to screen out major factors affecting safety, health and performance of people living and working in space such as physical layouts, tasks, and their durations. These factors interact in complex ways and will in turn affect likelihood of success or failure of the mission. Factors are rated on a 7-point scale, resulting in "red", "yellow", and "green" levels of accommodation. | 1-7 Scale | Subjective | -Screening of major factors affecting human performance will free up the scarce human factors resources to deal with more complex problems and tradeoffs. | -This tool is rarely used.<br>-The index is not intended to be used blindly and user training must be completed. | An Index of Habitability (Peacock, Blume, and Vallance, 2002) |
| T-4 | **Operational habitability workbook** | Operational Habitability Workbook (OHW) - a tool designed to capture data and information regarding spaceflight-analogue living, working and mission environment. The workbooks were designed to collect data in several areas: Team Member Demographics Survey, Habitability Characterization Scale, the Habitability Descriptive Questionnaire, and the Well-being/Productivity Measurement Scale. | Scales | Subjective | - Provides comprehensive set of questionnaires designed to collect data across multiple habitability factors<br>- Data collected near real-time | - Developed for demonstration on a specific Antarctic mission, so may need to be modified for use in other environments | NASA/JSC Operational Habitability Team: Antarctic 2000 Human Factors and Habitability Case Study (Vallance, 2001- unpublished) |
| T-5 | **Video/ Photogrammetry** | Video captured within a habitat or vehicle may be analyzed for a variety of purposes. Examples include determining utilization of workstations, capturing postures of crewmembers, analyzing facial expressions, etc. In addition to video captured continuously throughout a mission, a targeted approach may be used. In this approach, investigators ask crewmembers to use video cameras to provide tours of habitat or to wear a head-worn camera while performing a task. Crewmember description of tasks and/or surroundings aimed to capture good and bad observations should be documented. | | Subjective | - Provides direct link for crewmember to visually and verbally demonstrate to HF experts<br>- Allows opportunity to share insight that experts did not specifically think to ask<br>- May use existing equipment in many cases<br>- Low cost and time commitment | - Captures only a sampling<br>- Needs to organize distribution of data<br>- Must document data in an accessible way<br>- Video may not be available for all desired data (i.e., video may not continuously be captured in all areas of a habitat) | Participant observation of a Mars surface habitat mission simulation (Clancey, 2006) |

| TOOL ID | HABITABILITY TOOLS | | | SUB/ OBJ | PROS | CONS | REFERENCE |
|---|---|---|---|---|---|---|---|
| | Title | Description | Measures | | | | |
| T-6 | **Cooper-Harper Scale** | A set of criteria used by test pilots and flight test engineers to evaluate the handling qualities of aircraft during flight test. Consists of a hierarchical decision tree that guides the operator through a ten-point rating scale, each point being accompanied by a description of the associated handling qualities. | Scale 1 (Excellent/ Highly desirable) to 10 (Major deficiencies) | Subjective | - Widely accepted in the aerospace industry<br>- Provides consistent results suitable for use during both design and verification | - Requires high fidelity mockups and multiple HITL assessments using experienced pilot subjects<br>- Requires well-designed tasks with defined mission objectives and performance criteria<br>- Test operator must help guide the subject through the scale, because ratings are restricted in some cases based on performance | The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities (Cooper and Harper, 1969) |
| T-7 | **Bedford Workload Scale** | Uni-dimensional rating scale designed to identify operator's spare mental capacity while completing a task. The single dimension is assessed using a hierarchical decision tree that guides the operator through a ten-point rating scale, each point of which is accompanied by a descriptor of the associated level of workload. | Scale from 0 (Workload insignificant) to 10 (task abandoned) | Subjective | - Simple to administer<br>- Allows across-subject comparisons | - Does not provide diagnostics of what is causing high workload | A subjective rating scale for assessing pilot workload in flight: A decade of practical use (Roscoe and Ellis, 1990) |
| T-8 | **Borg Rating of Perceived Exertion (RPE)** | A way of measuring physical activity intensity level. Perceived exertion is how a person feels as if their body is working. It is based on the physical sensations a person experiences during physical activity, including increased heart rate, increased respiration rate, increased sweating, and muscle fatigue. The Borg RPE is based on a scale of 6 - 20 and correlates well with heart rate. This scale is appropriate for extended aerobic activity. A variation of this scale is the Borg CR10, which uses a scale of 0 - 10 and is more appropriate for assessments such as localized muscle fatigue, lifting tasks, and discomfort. | Scale runs from 6 to 20 | Subjective | - Although subjective, the scale provides fairly consistent results even across subjects<br>- Provides an estimate of heart rate without requiring hardware | - Heart rate monitors are now more accessible and may capture the same underlying issues more accurately<br>- Must be administered real-time | Psychophysical bases of perceived exertion (Borg, 1982) |
| T-9 | **NASA TLX** | The NASA TLX is a multi-dimensional rating tool that asks subjects to rate six factors associated with performance: mental and perceptual load, physical load, temporal load, performance success, effort required, degree of frustration experienced. Also allows for weighting each category, but weighting is not required. | Scale 0 - 100 with 0 indicating low load and 100 indicating high load | Subjective | - Multi-dimensional aspects allow for diagnostics of causes of high workload<br>- Developed at NASA Ames specifically to assess workload for scenarios relevant to NASA | - Scale lacks anchors, so results cannot be compared across subjects<br>- Data collection is relatively time-consuming, especially when weightings are used | Development of NASA-TLX: Results of empirical and theoretical research (Hart and Staveland, 1988) |

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|---|---|---|---|---|---|---|---|
| | Title | Description | Measures | | | | |
| T-10 | **Maneuverability Assessment Scale** | Scale designed to rate one's ability to move in any direction at the desired pace and accuracy. | Scale runs from 1 to 5, 1 being Excellent (not affected), 5 being Very Poor (Severely Affected) | Subjective | -Easily administered during real-time evaluations.<br>-Useful in evaluating space suit maneuverability when used in various space suit and volumetric evaluations. | -Formal validation not yet completed. | JSC-66182 ESPO Test 8: JENOM Neutral Buoyancy Laboratory Test Report (Manning, Patrick, 2011)<br><br>Factors Affecting Maneuverability. Internal JSC report (Archer, Sandor, and Holden, 2010)<br><br>Lunar Surface Systems Wet-Batch Design Evaluation. Internal JSC report. (Thompson, Szabo, and Howard, 2009) |
| T-11 | **Computer-Aided Design** | Software/tools including ProE, SolidWorks, and AutoCAD can assist in the creation, modification, analysis or optimization of a design. They can be used to assess volume and layout related metrics. | | Objective | -Increased precision<br>-Increased efficiency<br>-Improved communication throughout design process due to better documentation | -Insufficient tool to measure human performance metrics | The Human as a System- Monitoring Spacecraft Net Habitable Volume Throughout the Design Lifecycle (Szabo, Kallay, Twyford and Maida, 2007). |
| T-12 | **Environmental Modeling** | Modeling tools such as Computational Fluid Dynamics (CFD) or FLUINT can be used to simulate flow and heat transfer processes, and analyze complex thermal or air/fluid environments. Other tools model environmental variables such as acoustic noise (e.g, Statistical Energy Analysis) and lighting (e.g., Radiance). Environmental modeling software can be used in both design and verification phases. | | Objective | -Ability to simulate complex processes that cannot be easily tested | -can only be as accurate as the initial/boundary conditions and assumptions provided to the model | Human Factors Research for Space Exploration: Measurement, Modeling, and Mitigation (Kaiser, Allen, Barshi, Billman, and Holden, 2010) |
| T-13 | **Anthropometric/ Biomechanics Modeling** | Human modeling tools such as DELMIA or NX plug-ins can be used to provide integrated human models in a CAD environment to enable design and analysis of human-system interactions. Biomechanics tools like 3DSSPP, WATBACK, HumoSim, etc.) can be used to model and analyze human mechanics such as joint stress, static strengths, and human motion dynamics. In addition to these off-the-shelf options, customized models may be developed to suit the needs of a specific analysis. | | Objective | - Allows for analysis of multiple scenarios at a relatively low expense<br>- Does not require high fidelity hardware<br>- Enables testing of theoretical human subjects (e.g. worst-case anthropometry) who may not be available for an actual HITL test<br>- Enables estimates of measurements that are difficult to get in vivo (e.g. muscle stress, spinal pressure) | - Even widely accepted off-the-shelf models are not validated for all scenarios<br>- Models are not completely customizable (e.g. specific anthropometric dimensions, suited subjects, alternate gravity)<br>- Custom models can be time consuming to develop and validate<br>- Models may sometimes serve as a "black box", resulting in faulty conclusions that do not take into account all human factors considerations | Development of computerized human static strength simulation model for job design (Chaffin, 1997) |
| T-14 | **Root Cause Analysis** | An analytical method that tries to identify the root causes of failures. RCA is typically done after an event as occurred, but an understanding of the root causes could produce lessons-learned that can help forecast or predict probable events before they occur. | | Subjective/ Objective | -Solves problems by correcting the root causes, rather than simply addressing the symptoms | -Typically a reactive rather than pro-active method | Integration of Human Factors into Classification/Certification (Card, 2002) |

| TOOL ID | HABITABILITY TOOLS | | | SUB/ OBJ | PROS | CONS | REFERENCE |
|---|---|---|---|---|---|---|---|
| | Title | Description | Measures | | | | |
| T-15 | **Task Analysis** | The purpose of a task analysis is to identify user and system level tasks in order to determine operator needs for established mission objectives and concepts of operation. The methodology breaks an event down into individual tasks and break tasks down into components. Task analysis data should include mission phases and scenarios, tasks required for each mission phase, task sequences, human-systems interactions, task criticality, time-related data, and any vehicle, environmental, safety or operational constraints related to a task. | | Objective | -Enables rigorous and structured characterizations of user activity<br>-Can be used to help drive the design of optimal human-system interfaces | -Requires participation of SMEs for each topic area with specialized knowledge for a system or an operation. This takes considerable time and resources to coordinate.<br>-May not fully capture system dynamics and contextual factors. | Commercial Human Systems Integration Processes (CHSIP- JSC 65995) |
| T-16 | **Link Analysis** | Link analysis examines relationships between components, which may consist of either people or things. These links, which may consist of communication, control, or movement, may be studied for frequency, sequence, and importance. Results are often used to assist in designing control or facilities layouts, with physical arrangements made according to the functional links. Link analysis may provide a tool for objectively evaluating vehicle and habitation layout based on usage patterns observed through video data or other means. | Relationships between people and things | Subjective/ Objective | - Reveals relationships among people and their environment (e.g. movement paths, communication lines, task frequency)<br>- Provides objective data to feed into heuristic design decisions (e.g. determining where a piece of commonly used equipment should be placed) | - Needs operational data that must be collected through video and/or other means<br>- Requires expert analyst to interpret and apply data | Human Factors in Engineering and Design (Sanders and McCormick, 1993)<br><br>Ergonomics Methods in the Design of Consumer Products (Stanton and Young, 1999) |
| T-17 | **Crew Debriefs** | The Operational Habitability group at Johnson Space Center collects and analyzes data from all ISS post-flight crew debriefs. This information is compiled in a database of crew comments. | | Subjective | - Provides direct feedback from crewmembers<br>- Allows systems groups to ask specific questions of interest<br>- Incorporated as part of the standard ISS operations | - Crewmembers do not provide debriefs until many weeks after the completion of their missions<br>-Data is inconsistent, based on what and how debrief questions are asked | Human engineering and habitability: the critical challenges for the International Space Station (Novak, 2000) |
| T-18 | **Physiological Measurement** | Sensors, instrumentations and systems such as temperature and pressure sensors, accelerometers, biochemical sensors, and heart rate monitor are used to measure and monitor the user's physiological conditions when in the environment or when confronted with environmental, physical or psychological stressors. Measurements can be used in the design, modeling and analysis of the environmental control and life support system, or assist in the characterization of a behavioral health and performance related issue. | | Objective | -Provides quantitative assessment and visualization of a physiological function | - Extensive instrumentation may be required | A comparison of heart rate, eye activity, EEG and subjective measures of pilot mental workload during flight (Hankins and Wilson, 1998) |

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13. ABSTRACT *(Maximum 200 words)*

The Space Human Factors and Habitability and Behavioral Health and Performance Elements of NASA's Human Research Program hosted the 2012 Habitable Volume Workshop, which focused on spacecraft/habitat volume design and assessment for long-duration missions. The workshop produced concrete products to aid in design and assessment of habitable volume in space vehicles and habitats, and sought to identify research and technology development gaps and provide recommendations for forward work. Workshop products included Process Flow, Task List, and Metrics and Tools Lists. Process Flow identifies three major elements in human systems engineering and habitability design and establishes how they feed one another in an iterative work flow for assessing habitable volume. Task List provides a minimal set of long-duration mission tasks that are volume-driving, and provides design constraints as well as volume and layout characteristics to inform the design process. Metrics and Tools Lists capture design and behavioral metrics as well as example methods and tools used to measure them. Volume-impacting countermeasures for optimizing behavioral health and performance were identified. The workshop and its products serve as a critical step on the path to address HRP risks related to reduced safety and efficiency due to an inadequately designed vehicle or habitat.

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