Defining the Required Net Habitable Volume for Long-Duration Exploration Missions

Chel Stromgren, Callie Burke, Jason Cho, and Robert Calderon
Binera, Inc.
77 S. Washington St.
Rockville, MD 20850
chel.stromgren@nasa.gov
c.burke@binera.com
j.cho@binera.com
r.calderon@binera.com

Michelle Rucker
NASA Johnson Space Center
2101 Nasa Parkway
Houston, TX 77058
michelle.a.rucker@nasa.gov

***Abstract*—As the National Aeronautics and Space Administration continues planning for long-duration space missions, specifically to Mars, it will be necessary to understand the requirements for a "transit habitat", the element that the crew will live in as they travel to and from Mars. In particular, understanding of volume requirements for the transit habitat is of significant importance because the volume is a first order driver of the habitat size and mass, and therefore the propulsion and propellant requirements for future Mars missions. Despite this importance, there is significant uncertainty regarding how much habitable volume is required to support the crew on these missions. Prior studies provide valuable background, but their focus has largely been on investigating historical analogs in order to develop parametric sizing formulas. Other research has focused on specific drivers of habitat volume and stressors to the crew. However, there has been limited focus on establishing a comprehensive minimum required habitable volume based on crew activity needs and crew health requirements. This paper will describe a detailed effort to establish the minimum required net habitable volume for a Mars Transit Habitat employing a bottom-up methodology. The process used to establish volumetric requirements involves the definition of a set of specific "crew functions" and the assignment of required volumes to each function. This type of bottom-up approach is the most accurate method to establish required habitat volume and is specifically recommended by the NASA Chief Medical Officer for future space missions. The authors established a taxonomy of crew functions that could be required during a Mars transit. These functions include direct operational activities, such as command and control or system maintenance, habitation activities, such as eating and sleeping, or health maintenance activities, such as exercise and leisure. Health maintenance activities also include "pseudo-activities", such as psychological wellbeing, that are directly related to habitat volume. The authors then defined required volumes for each defined activity, based on habitat analogs, prior research, and SME input. The potential for various activities to share volumetric space was then evaluated, based on temporal usage, compatibility of tasks, and crew health. Finally, the required minimum net habitable volumes for a four crew and six crew Mars Transit Habitats were assessed, including consideration of specific geometrical constraints. Results of this study will be used to evaluate deep space habitat options, and also help formulate future Mars mission requirements. Ultimately, results of this study will support the refinement of NASA's Mars Design Reference Architectures, and help realize future long duration exploration missions.**

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1. INTRODUCTION

Importance of Determining Habitable Volume

As the National Aeronautics of Space Administration (NASA) continues planning for long-duration space missions, specifically to Mars, it will be necessary to understand the requirements for the required habitable volume within crew habitats. Understanding volume requirements for the transit habitat is significant because volume is a first order driver of the habitat size and mass, and therefore the propulsion and propellant requirements for future Mars missions. Despite this importance, there is significant uncertainty regarding how much habitable volume is required to support the crew on these missions. Past attempts to evaluate required volume have focused on the evaluation of historical analogs in order to develop parametric sizing formulas. While this type of top down approach can be informative, there is large uncertainty in the derived results.

A preferred method for establishing net habitable volume is to apply a bottom-up approach, in which individual requirements are established for defined functions and then integrated across the habitat to develop a total required habitable volume. While there has been research focused on evaluating individual elements of habitable volume and stressors to the crew, there have been limited efforts to establish an integrated minimum required habitable volume based on a comprehensive assessment of crew activities and crew health requirements.

The effort described in the paper, conducted in support of NASA's Mars Integration Group (MIG), is the first comprehensive study within NASA to evaluate the required net habitable volume for a Mars Transit Habitat applying a rigorous bottom-up approach. The MIG is conducting a series of activities to define capability requirements and options for crewed Mars missions. As part of this effort, the team is developing a reference design for a Mars Transit Habitat. While this reference is not intended to necessarily represent the final habitat design, it is being used as a common element to evaluate potential Mars mission architectures. Accurately defining the required Net Habitable Volume (NHV) is an important part of the effort.

The results of the effort described in the paper are intended to serve as a reference to guide future NASA habitat designs. The defined crew functions and established minimum required volumes for these functions will serve as common design guidelines for future efforts within NASA.

Net Habitable Volume

NASA has established a standard process for measuring the Net Habitable Volume of a spacecraft, outlined in Net Habitable Volume Verification Method (JSC-63557) [1]. This document codifies a standard for how NHV is defined and measured.

The NHV represents only a portion of the total habitat pressurized volume. The pressurized volume consists of the sum of four components:

- NHV – The volume that the crew lives and works in.
- Systems Volume – Interior volume occupied by the habitat systems.
- Storage Volume – Volume used to store consumables and other logistics.
- Voids – Empty spaces that are not accessible to the crew.

Systems volume is a function of the habitat systems design and packaging. The storage volume is a function of crew size, mission duration, and architecture. Voids are a function of the packaging of volumes into a functional habitat.

The purpose of this effort was not to architect a specific habitat or to calculate the volumes for that habitat. Rather, the goal of this effort was to define the minimum NHV for Mars missions with various crew sizes. The defined NHV represents a floor level of habitable volume that must be accommodated by an actual habitat design. Actual NHV in a functional habitat will likely be somewhat greater than the defined NHV. It is difficult to exactly fit the defined volumes for different functions into a habitat, given the various design constraints. In addition, designers may wish to allocate additional NHV in the habitat for various reasons, including support of mission specific goals, such as utilization. An example of fitting the defined required minimum volume into an actual habitat design is presented in Section 4 of this paper.

It has generally been assumed that required NHV does not vary for mission durations of greater than 180 days. Rather, the volume that is required for the crew to work and live is constant for durations longer than that threshold. Other volumes (systems and storage) will still vary with duration. Since this effort was intended to define minimum NHV for long duration exploration missions, those longer than 180 days, duration was not a factor in this analysis.

Historical Precedents for Net Habitable Volume

Prior efforts to establish guidance for net habitable volume of spacecraft have centered around two approaches: parametric design standards and analysis of historical spacecraft analogs.

<u>Celentano/NASA-STD-3000</u> - In the early 1960s Celentano, Amorelli, and Freeman of North American Aviation, as part of an effort to establish a 'Habitability Index' for spacecraft conducted a series of ground-based experiments, evaluating how well 'crews' functioned and could complete tasks while living in cabins of different sizes Celentano et al. [2]. The authors used this data to establish what generally became known as the "Celentano Curves". These curves established the required minimal habitable volume (and required minimal floor area) per crew member as a function of mission duration. Parametric curves were established for three different levels of functionality: "Tolerable", "Performance", and "Optimal".

The Celentano curves were adopted as an accepted reference for NHV and were eventually adopted as a standard in NASA's Man-Systems Integration Standards (MSIS), also known as NASA-STD-3000 [3].

However, the use of the Celentano curves is problematic. The test conducted by Celentano et al, which are the basis of the curves, had a maximum duration of seven days. All data beyond that time frame was extrapolated from the testing results. In addition, the Celentano curves did not consider the types of functions that might need to be accommodated by the habitable volume. Often the Celentano curves are referenced without full understanding of the conditions of the original study and the limits of their application.

As the understanding of crew volume requirements with respect to mission duration progressed, the use of the Celentano curves has generally been discontinued. NASA's STD-3000 [3] has now been superseded by NASA-STD-3001 [4] and the Human Integrated Design Handbook (HIDH) [5], which no longer reference the Celentano Curves.

<u>Empirical Methods</u> - To establish volume requirements that were more well founded than the Celentano curves, researchers have undertaken a series of activities to improve the assessment of NHV. These efforts generally have focused on an examination of the habitable volume of historic spacecraft and other analogs, evaluating the available habitable volume per crew member versus mission duration.

There are several issues with using empirically based methods to specify NHV. At longer durations, those which are significant to future Mars missions, there are only a limited number of historical data points (Skylab, Salyut, Mir, and ISS). The volumes of these analogs, which establish the shape and position of the NHV curve, do not necessarily represent the minimal required volume for the mission. The design of each of these habitats was dependent on numerous factors but, to a varying degree, were not focused on minimizing habitable volume. Additionally, there is a large variation in the habitable volume per crew for these historical cases, resulting in significant uncertainty in any parametric curve fit through the data.

Finally, as with the Celentano curves, the empirical methods do not take account of the types of functions that the crew will need to perform.

Bottom-Up Methodology - Recent focus for establishing NHV has concentrated on bottom-up approaches. As part of these methods, the effort is focused on defining volume requirements for individual crew functions and then integrating those into an overall volume requirement, rather than trying to define required NHV at the top level. A group of habitation experts from NASA, industry, and academia participated in the 2012 Net Habitable Volume Workshop [6] in Houston, TX. One of the major products of this workshop was the definition of a process for conducting a comprehensive bottom-up habitable volume assessment referenced here. This process flow, originally presented in the workshop report, outlines the high-level steps for assessing required habitat functionality and defining required volume for any spacecraft. This basic process was adapted and applied for this effort.

The process utilized in this paper and outlined in Section 2 evaluates required volume following this type of bottom-up approach. Individual required crew functions are identified and required volumes for each individual function are defined based on anthropomorphic data, simulation, historical analogs, and/or design standards. The overall required volume is then built up from the individual functional volumes, accounting for potential overlaps in functionality. The result is a minimum net habitable volume for a specific mission.

NASA Guidance

In addition to existing NASA guidance on crew habitability, such as NASA-STD-3001 [4] and HIDH [5], there also exist additional documentation that directly relate to net habitable volume.

Chief Medical Officer Memo - A significant piece of internal NASA guidance was issued on December 19, 2016. The agency Chief Medical Officer, in a Technical Memorandum [7], recommended that the process outlined during the 2012 Net Habitable Volume Workshop [6] be adopted for all future crewed space missions and that the defined process be the desired method to verify the adequacy of spacecraft volume.

NHV Design Standard - One other notable NASA document related to NHV is the Net Habitable Volume Verification Method from the Human Health and Performance Directorate [1]. This document describes the method to use to calculate NHV and is applicable to all crewed program vehicles and habitats with an imposed NHV requirement. The document establishes a standard for defining, calculating, monitoring, evaluating, and verifying NHV.

2. ANALYSIS

The process employed in this effort is derived from the basic process described in the 2012 Net Habitable Volume Workshop [6] and endorsed by the NASA Chief Medical Officer. The process involves a series of steps to identify required crew functions and to then define the volumes required to safely and efficiently conduct those functions.

First the team defined specific functional activities or tasks that must be completed by the crew during a long-duration exploration mission. Next the team defined minimum required operational volume for each specific identified function. Once individual functions and volume requirements were defined, the team then identified functional overlaps within categories, where individual functions could overlap with overlapping functions each accommodated in a given space. Based on identified overlaps, a final set of 'Functional Spaces' were defined. The Functional Spaces are the unique set of volumes that are required to accommodate all defined functions in the category. Each Functional Space may accommodate one or more required functions. The sum of these spaces was calculated to define the minimal NHV for a given crew size.

Classification of Crew Functional Tasks

The first step in the overall process was to identify the set of all crew functional activities that must be accommodated by the habitat and which allow the crew to conduct mission operations and to live comfortably and safely in the habitat. These functions form the basis for estimating required volume in a bottom-up process. Functions are defined as activities that the crew must or could be expected to perform, either in nominal or contingency conditions, during the mission. Functions include crew work functions, such as command and control of the spacecraft and repair activities, crew living functions, such as eating and sleeping, and crew recreation functions.

The definition of functions for this activity was derived from previous work completed by Howard [8]. As part of that effort, the author developed an initial set of crew functions for application in NHV definition. The team combined the functions defined in Howard with additional functions identified in Rucker and Thompson [9] and the Net Habitable Volume Workshops [6] to develop an all-inclusive set of candidate functions derived from all relevant sources. The team then refined the final list of functions, accounting for overlaps in definitions and criticality of the described functions. As part of this refinement the team established a taxonomy to capture how individual functions could be grouped into operational categories. These categories represent sets of functions that all have similar operational parameters. For example, the category of 'Meal Prep and Dining' represents a set of functions that includes Meal Prep, Eating, and Clean Up.

For this study three categories of identified functions were not included in the analysis to establish a minimum NHV. First, the set of EVA related functions that would likely be accomplished in an airlock space were not included. In most cases, a segregated airlock space, which would generally house a significant amount of EVA equipment, is not considered to be habitable volume. Required EVA volumes should be determined based on EVA requirements and Concept of Operations and combined with Habitable Volume to determine the overall required pressurized volume for a candidate mission.

Similarly, the volume required for 'Crew Safe Haven' was also not included in the analysis of minimum NHV. While it is possible that space(s) to provide safe haven may be incorporated into the habitat, and could contribute to NHV, it is also possible that those space(s) might exist in the airlock or in some other element.

The required habitable volume for both Airlock and Safe Haven related functions are provided for reference in this paper, to assist in future habitat design. However, the volumes for those functions are not included in the determination of minimum NHV.

Additionally, habitable volume for utilization functions were also not included in this analysis. The types and scope of utilization can vary heavily for different missions and are dependent on the mission parameters and goals of the utilization. Because those volumes are mission dependent, they are not included in the minimum NHV.

Functional Categories

As part of the effort to define functional activities, individual functions were grouped into 'Functional Categories'. The categories define sets of functions that all have related types of operations and which are likely to be conducted in similar and/or contiguous spaces.

Exercise – Deals with crew's need to counteract the adverse physiological effects of long duration space travel. The definition of functions for Exercise was based on the use of a suite of devices that is like the one employed on ISS. It is anticipated that the types of devices used for exercise could evolve for future exploration missions. However, it is also anticipated that the number of devices and the required volume will be similar to the requirements for the current equipment. Specific functions include:

- Aerobic exercise (cycle ergometer)
- Aerobic exercise (treadmill)
- Resistive exercise
- Bone loading
- Sensorimotor
- Conditioning

Group Socialization and Recreation – Encompasses functions for social and recreational crew interactions. Specific functions include:

- Athletic games
- Personal recreation space
- Tabletop games & artistic/creative recreation
- Video/movie watching
- Window viewing

Human Waste Collection – Covers the collection and disposal of human waste products. Specific functions include:

- Hand cleaning
- Liquid waste collection
- Solid waste collection

Hygiene – Deals with functions that relate to maintaining health, cleanliness, and personal appearance. Specific functions include:

- Full body changing
- Facial cleaning
- Finger/toe nail clipping
- Full body cleaning
- Hair styling/grooming
- Hand cleaning
- Oral hygiene
- Hygiene supply surface access
- Viewing appearance
- Shaving
- Skin care

Logistics – Covers functions that relate to logistics storage, transfer, management, and access. Specific functions include:

- Logistics surface access
- Small item containment
- Temporary stowage

Maintenance and Repair – Encompasses functions for routine maintenance for spacecraft and its systems. Specific functions include:

- Computer display and control interface
- Equipment diagnostics
- Telemaintenance
- Repair and maintenance work surface access
- Soft goods fabrication

EVA Support - Encompasses functions that deal with the volume for storage, maintenance, and pre/post EVA support activities that are required outside of the airlock. The volume described by this category does not include the airlock that is required for crewmember entry/exit, as the airlock is not considered habitable volume. Specific functions include:

- Suit component testing
- Computer display and control interface
- Audio Communication
- Video Communication

Meal Preparation – Deals with functions for preparation of food for crew consumption. Specific functions include:

- Food item sorting
- Food preparation
- Utensil and food equipment hygiene

Meal Consumption – Functions for daily meal consumption. Specific functions include:

- Full crew dining

Medical Operations – Encompasses the necessity to provide health care for the crew. Specific functions include:

- Advanced medical care (basic surgical care, trauma care, advanced life support)
- Ambulatory care
- Basic medical care (space motion sickness, first aid, anaphylaxis response, clinical diagnostics, medical imaging)
- Computer data entry/manipulation
- Dental care
- Private telemedicine
- Medical meetings

Mission Planning – Covers group and individual planning and interfaces for the execution of mission tasks. Specific functions include:

- Command and control interface
- Physical mission planning surface access
- Team meetings
- Mission training

Private Habitation – Covers functions done in private away from other crewmembers excluding hygiene and waste management functions. Specific functions include:

- Clothes changing
- Meditation
- Non-sleep rest/relaxation in private quarters
- Personal work surface access
- Single person private work, entertainment, and communication
- Sleep accommodation
- Stretching
- Two person meetings
- Viewing appearance in private quarters

Spacecraft Monitoring and Commanding – Covers functions that refer to the capability of the crew to operate the spacecraft and monitor spacecraft subsystems. Specific functions include:
- Command and control
- Teleoperation and crew communication

Waste Management – Encompasses functions dealing with trash packaging, containment, and disposal. Specific functions include:
- Trash containment
- Trash packing for disposal

In addition to the categories and functions listed above, which contribute to the minimum NHV, the following functions may also be required and may exist within the habitat, but are not included in the minimum NHV.

Airlock - Airlock operations encompass functions that deal with the EVA operational activities. The volume described by this includes only activities that would occur within the airlock. Specific functions include:
- Depressurization
- Repressurization
- Hyperbaric isolation
- Hypobaric isolation
- Airlock command and control
- EVA suit donning and doffing
- Crew egress/ingress
- Payload egress/ingress
- Suit servicing
- Suit repair

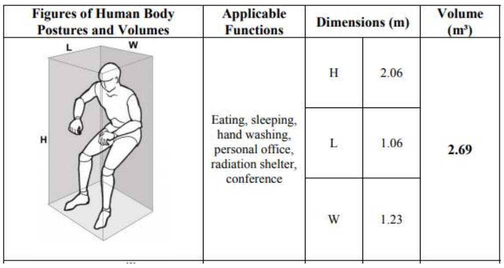
Safe Haven – Covers crew necessity for safe haven in emergency situation. Specific functions include:
- Safe haven

Volumetric Requirements

Once a final set of functions and categories was identified, the team next defined the minimum required operational volume for each specific identified function. Minimum volumes included the volume for the crew to perform the function, spaces for necessary access, and any required clearances.

The minimum volume for each function was defined based on three key assumptions:
1. Functions will occur in zero to minimal gravity.
2. Volumes are defined based on anthropometric data from the 99th percentile male/female body depending on the maximum sizes for each body part.
3. Mission length is at least 180 days. If the duration is longer than 180 days it is assumed that the minimum habitable volume is a fixed number.

The most significant resource that the team relied on was NASA's HIDH [5]. This document defines required volume envelopes for a number of habitat functions in micro-gravity. Figure 1 shows an example of Volume Envelope found in the HIDH [5].



Figures of Human Body Postures and Volumes	Applicable Functions	Dimensions (m)		Volume (m³)
	Eating, sleeping, hand washing, personal office, radiation shelter, conference	H	2.06	**2.69**
		L	1.06	
		W	1.23	

Figure 1: Example Volume Envelope

Anthropometric data for a variety of crew tasks is also defined in NASA-STD-3001 [4]. Additional results from Rucker and Thompson [9], Fitts [10] and the 2012 Habitable Volume Workshop [7] include volume requirements for other functions.

Other sources for volumetric data included results from laboratory studies and human-in-the-loop simulation testing. One such example of this is the University of Maryland's (UMD) Space Systems Laboratory analytic study in Akin et al. [11] pertaining to habitat design as part of a NASA Exploration Systems Mission Directorate grant. UMD has developed full-scale mockups that have been tested on land and in a Neutral Buoyancy Research Facility (NBRF) to simulate a partial gravity environment. Results from these studies [11] indicate required volumes for many tasks.

In certain cases, three dimensional Computer Aided Design (CAD) models based on empirical information, including photographic and video evidence, regarding volumetric usage on ISS were utilized to assess the required volume. In these cases, a CAD model was developed that captured the performance of the required function based on anthropometric information.

It is important to note that for many functions the required volume includes not only a net minimal cubic volume but also a set of minimum required dimensions. Minimum dimensions represent an additional constraint on how the required habitable volume must be arranged in the habitat. One to three minimum dimensions may be specified. In all cases both the minimum volume and any minimum dimension constraints must be satisfied.

Unlike previous parametric methods, this study did not attempt to reduce NHV requirements down to a standard 'per crew member' value. The required NHV will not necessarily vary linearly with crew size. Certain functions, such as maintenance and repair, required a relatively fixed volume, independent of crew size. Others, such as exercise may be defined based on a step function – each four crew members, or fraction thereof, would require an additional set of exercise equipment. Certain functional volumes were identified as being dependent on crew size.

The defined volumes are shown in Table 1. A more in-depth explanation of how each volume was derived can be found in Appendix A.

Table 1: Individual Functional Spaces and Volumes

	FUNCTION	VOLUME - 4 CREW (m^3)	VOLUME - 6 CREW (m^3)
Exercise	Aerobic Exercise	3.38	6.76
	Aerobic Exercise	4.91	9.82
	Resistive Exercise	3.92	7.84
	Bone Loading	4.91	9.82
	Sensorimotor Conditioning	4.91	9.82
Group Socialization & Recreation	Athletic Games	18.2	27.3
	Personal Recreation	1.2	1.2
	Tabletop games & artistic/creative recreation	10.09	15.14
	Video/movie viewing	4.8	7.2
	Window viewing	4.62	4.62
Human Waste Collection	Hand cleaning	2.69	5.38
	Liquid waste collection	2.36	4.72
	Solid waste collection	2.36	4.72
Hygiene	Changing Volume	2.18	4.36
	Facial cleaning	2.69	5.38
	Finger/toenail clipping	2.34	4.68
	Full body cleaning	4.34	8.68
	Hair styling/grooming	2.34	4.68
	Hand cleaning	2.69	5.38
	Oral hygiene	2.34	4.68
	Physical work surface access	4.35	8.7
	Viewing appearance	1.8	3.6
	Shaving	2.34	4.68
	Skin care	2.34	4.68
Logistics	Physical work surface access	4.35	4.35
	Small item containment	1.2	1.2
	Temporary stowage	6	6
Maintenance & Repair	Computer display and control interface	1.7	3.4
	Equipment Diagnostics	4.35	4.35
	Physical work surface access	4.35	4.35
	Soft goods fabrication	2.69	2.69
EVA Support	Suit Component Testing	4.82	4.82
	Computer Display and Control Interface	1.7	1.7
	Video Communication	1.7	1.7
	Audio Communication	1.7	1.7
Meal Consumption	Full Crew Dining	10.09	15.14
Meal Preparation	Food Item Sorting	3.3	3.3
	Food Preparation	4.35	4.35
	Utensil and food equipment hygiene	3.3	3.3
Medical Operations	Advanced Medical Care	5.8	5.8
	Ambulatory care	1.7	1.7
	Basic Medical Care	5.8	5.8
	Computer data entry / manipulation	1.2	1.2
	Dental care	5.8	5.8
	Private telemedicine	1.2	1.2
	Two person meetings	3.4	3.4
Mission Planning	Command and control interface	3.42	3.42
	Physical work surface access	10.09	15.14
	Team Meetings	4.8	7.2
	Mission Training	18.2	27.3
Private Habitation	Changing clothes	8.72	13.08
	Meditation	4.8	7.2
	Non-sleep rest/relaxation in private quarters	4.8	7.2
	Physical work surface access	17.4	26.1
	Single person private work, entertainment, and comm.	4.8	7.2
	Sleep accommodation	10.76	16.14
	Stretching	13.96	20.94
	Two person meetings	13.6	20.4
	Viewing appearance in private quarters	7.2	10.8
Spacecraft Monitoring and Commanding	Command and Control	3.42	3.42
	Teleoperation and Crew Communication	1.7	1.7
Waste Management	Trash Containment	2.55	2.55
	Trash Packing for Disposal	3.76	3.76

Functional Overlaps

Once volumes were defined for each individual function, the team next assessed potential overlaps in volumetric usage between functions within a given category. Identifying potential overlaps between functional activities is key to understanding the overall habitat minimum volume requirements. Most functions do not require dedicated volumes and several functions may share a common volume. Individual spaces can accommodate multiple functions, as long as they are separated in time and are operationally compatible.

Potential overlaps were identified based on similarities volume and design considerations and temporal independence (e.g., ensuring that functions would not occur at the same time). Overlaps can be flexible. For example, some hygiene functions, such as grooming, could take place in personal quarters, or in a designated hygiene space.

The team used analysis matrices to assess the compatibility of each possible pair of functions within a functional category. The team individually evaluated each pair of functions, assessing the schedule and duration of tasks, the requirements for resources such as power and water, and impacts of overlaps on crew health, safety, and comfort. If a pair of functions could reasonably be accommodated in a common volume, the pair was noted as a potential overlap.

Based on the mapping of potential overlaps, the team identified a set of Functional Spaces within each category. Functional Spaces are the unique set of volumes that are required to accommodate all defined functions in the category. Each Functional space may accommodate one or more required functions. Volumes for functional spaces were determined by taking the largest required volume of the grouped functions.

An example of the overlap process is demonstrated in the Hygiene category. One set of potential functional overlaps that were identified included fingernail clipping, full-body cleaning, oral hygiene, and shaving. These functions would typically take place in the same general area with access to cleansing wipes and a small vacuum or vent for hair, nail clippings, etc. The function that takes the most volume to complete is full-body cleaning, so this is the volume that represents the minimum volume for the entire overlapping section.

The team applied past research to ensure overlap decisions were based on minimizing psychological stressors due to volume. Overlaps and improvements in volumetric efficiency should not contribute to a feeling of crowdedness. From the 2011 NASA workshop on habitable volume, discussed in Simon et al. [12], habitat design guidance factors that can help mitigate crowdedness include separation of high traffic functions, task scheduling, and rotating shifts, dedicated translation paths in an integrated environment, and increased volume or dimensions that increase the perception of space. Particularly for the psychological well-being of the crew, overlaps should refrain from impeding on social common area volume. It was found in the workshop that layout contributes more to most psychological-behavioral health stressors than does internal volume. Additionally, the workshop emphasized the importance of identifying overlaps in task volumes as a desired body of work for volume requirements determination. Tables 2-15 show the mapped functional overlaps and resultant functional spaces for each operational category.

Table 2: Exercise Overlaps and Functional Spaces

	Aerobic Exercise (Cycle Ergometer)	Aerobic Exercise (Treadmill)	Resistive Exercise	Bone Loading	Sensorimotor Conditioning
Aerobic Exercise (Cycle Ergometer)					
Aerobic Exercise (Treadmill)	0				
Resistive Exercise	0	0			
Bone Loading	0	**1**	0		
Sensorimotor Conditioning	0	**1**	0	**1**	

Functional Space	**Minimum Volume - 4 crew (m³)**	**Minimum Volume - 6 crew (m³)**	**Functions**		
Exercise-1 (Cycle Ergometer)	3.38	6.76	Aerobic Exercise (Cycle Ergometer)		
Exercise-2 (Treadmill)	6.12	12.24	Aerobic Exercise (Treadmill)	Bone Loading	Sensorimotor Conditioning
Exercise-3 (Resistive Device)	3.92	7.84	Resistive Exercise		

Table 3: Group Socialization and Recreation Overlaps and Functional Spaces

	Athletic Games	Personal Recreation	Tabletop Games & Recreation	Video/Movie Viewing	Window Viewing
Athletic Games					
Personal Recreation	**1**				
Tabletop Games & Recreation	0	0			
Video/Movie Viewing	**1**	**1**	0		
Window Viewing	**1**	**1**	0	**1**	

Functional Space	**Minimum Volume - 4 Crew (m^3)**	**Minimum Volume - 6 Crew (m^3)**	**Functions**			
Group Social-1 (Open Area)	18.20	27.30	Athletic Games	Personal Recreation	Video/Movie Viewing	Window Viewing
Group Social-2 (Table)	10.09	15.14	Tabletop Games & Recreation			

Table 4: Hygiene Overlaps and Functional Spaces

	Changing Volume	Facial Cleaning	Finger/toe Nail Clipping	Full Body Cleaning	Hair Styling/ Grooming	Hand Cleaning	Oral Hygiene	Physical Work Surface Access	Viewing Appearance	Shaving	Skin Care
Changing Volume											
Facial Cleaning	**1**										
Finger/toe Nail Clipping	**1**	**1**									
Full Body Cleaning	**1**	**1**	**1**								
Hair Styling/Grooming	**1**	**1**	0	0							
Hand Cleaning	**1**	**1**	**1**	**1**	0						
Oral Hygiene	**1**	**1**	**1**	**1**	0	**1**					
Physical Work Surface Access	**1**	**1**	**1**	**1**	**1**	**1**	**1**				
Shaving	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**			
Skin Care	**1**	**1**	**1**	0	**1**	**1**	**1**	**1**	**1**		
Viewing Appearance	**1**	**1**	**1**	0	**1**	**1**	**1**	**1**	**1**	**1**	

Functional Space	**Minimum Volume - 4 Crew, (m^3)**	**Minimum Volume - 6 Crew, (m^3)**	**Functions**							
Hygiene-1 (Cleansing)	4.35	8.7	Changing Volume	Facial Cleaning	Finger/Toe Nail Clipping	Full Body Cleaning	Hand Cleaning	Oral Hygiene	Physical Work Surface Access	Shaving
Hygiene-2 (Non-Cleansing)	2.34	4.68	Hair Styling/ Grooming	Skin Care	Viewing appearance					

Table 5: Logistics Overlaps and Functional Spaces

	Physical Work Surface Access	Small Item Containment	Temporary Stowage
Physical Work Surface Access			
Small Item Containment	0		
Temporary Stowage	0	**1**	

Functional Space	**Minimum Volume - 4 Crew, (m^3)**	**Minimum Volume - 6 Crew, (m^3)**	**Functions**	
Logistics-1 (Work Surface)	4.35	4.35	Physical Work Surface Access	
Logistics-2 (Temporary Stowage)	6.00	6.00	Temporary Stowage	Small Item Containment

Table 6: Maintenance and Repair Overlaps and Functional Spaces

	Computer Display and Control Interface	Equipment Diagnostics	Physical Work Surface Access	Soft Goods Fabrication
Computer Display and Control Interface				
Equipment Diagnostics	0			
Physical Work Surface Access	0	**1**		
Soft Goods Fabrication	0	**1**	**1**	

Functional Space	**Minimum Volume - 4 Crew, (m^3)**	**Minimum Volume - 6 Crew, (m^3)**	**Functions**		
Maintenance-1 (Computer)	1.70	3.40	Computer Display and Control Interface		
Maintenance-2 (Work Surface)	4.35	4.35	Physical Work Surface Access	Soft Goods Fabrication	Equipment Diagnostics

Table 7: EVA Support Overlaps and Functional Spaces

	Computer Display and Control Interface	Suit Component Testing	Video Communication	Audio Communication
Computer Display and Control Interface				
Suit Component Testing	0			
Video Communication	1	0		
Audio Communication	1	0	1	

Functional Space	**Minimum Volume - 4 Crew, (m^3)**	**Minimum Volume - 6 Crew, (m^3)**			
EVA-1 (Suit Testing)	4.82	4.82	Suit Component Testing		
EVA-2 (EVA Computer/Data)	1.70	1.70	Computer Display and Control Interface	Video Communication	Audio Communication

Table 8: Meal Consumption Overlaps and Functional Spaces

Functional Space	Minimum Volume - 4 Crew, (m^3)	Minimum Volume - 6 Crew, (m^3)	Functions
Meal Consumption (Table)	10.09	15.14	Meal Consumption

Table 9: Meal Preparation Overlaps and Functional Spaces

	Food Item Sorting	Food Preparation	Utensil and Food Equipment Hygiene
Food Item Sorting			
Food Preparation	0		
Utensil and Food Equipment Hygiene	**1**	0	

Functional Space	Minimum Volume - 4 Crew, (m^3)	Minimum Volume - 6 Crew, (m^3)	Functions	
Meal Preparation-1 (Food Prep)	4.35	4.35	Food Preparation	
Meal Preparation-2 (Table/Work Surface)	3.30	3.30	Food Item Sorting	Utensil and Food Equipment Hygiene

Table 10: Medical Operations Overlaps and Functional Spaces

	Advanced Medical Care	Ambulatory Care	Basic Medical Care	Computer Data Entry / Manipulation	Dental Care	Private Telemedicine	Two Person Meetings
Advanced Medical Care							
Ambulatory Care	0						
Basic Medical Care	**1**	0					
Computer Data Entry / Manipulation	0	0	0				
Dental Care	**1**	0	**1**	0			
Private Telemedicine	0	0	0	**1**	0		
Two Person Meetings	0	**1**	0	0	0	0	

Functional Space	Minimum Volume - 4 Crew, (m^3)	Minimum Volume - 6 Crew, (m^3)	Functions		
Medical-1 (Computer)	1.20	1.20	Computer Data Entry / Manipulation	Private Telemedicine	
Medical-2 (Ambulatory Care)	3.40	3.40	Ambulatory Care	Two Person Meetings	
Medical-3 (Medical Care/Work Surface)	5.80	5.80	Advanced Medical Care	Basic Medical Care	Dental Care

Table 11: Mission Planning Overlaps and Functional Spaces

	Command and Control Interface	Physical Work Surface Access	Team Meetings	Mission Training
Command and Control Interface				
Physical Work Surface Access	0			
Team Meetings	0	**1**		
Mission Training	0	0	0	

Functional Space	**Minimum Volume - 4 Crew, (m^3)**	**Minimum Volume - 6 Crew, (m^3)**	**Functions**	
Mission Planning-1 (Table/Work Surface)	10.09	15.14	Physical Work Surface Access	Team Meetings
Mission Planning-2 (Computer/Command)	3.42	3.42	Command and Control Interface	
Mission Planning-3 (Training)	18.20	27.30	Mission Training	

Table 12: Private Habitation Overlaps and Functional Spaces

	Changing Clothes	Meditation	Non-Sleep Rest/ Relaxation	Physical Work Surface Access	Single Person Private Work, Ent., and Comm.	Sleep Accomm.	Stretching	Two Person Meetings	Viewing Appearance
Changing Clothes									
Meditation	**1**								
Non-Sleep Rest/Relaxation	**1**	**1**							
Physical Work Surface Access	0	0	0						
Single Person Private Work, Ent., and Comm.	0	0	0	**1**					
Sleep Accommodation	**1**	**1**	**1**	**1**	0				
Stretching	**1**	**1**	**1**	**1**	0	**1**			
Two Person meetings	0	0	0	**1**	**1**	0	0		
Viewing Appearance	**1**	**1**	**1**	**1**	0	**1**	**1**	0	

Functional Space	**Minimum Volume - 4 Crew, (m^3)**	**Minimum Volume - 6 Crew, (m^3)**	**Functions**					
Private Habitation-1 (Desk/Work Surface)	4.35	4.35	Single Person Private Work, Entertainment, and Communication	Physical Work Surface Access	Two Person Meetings			
Private Habitation-2 (Sleep & Relaxation)	3.49	3.49	Sleep Accommodation	Non-Sleep Rest/Relaxation	Meditation	Stretching	Changing Clothes	Viewing Appearance

Table 13: Spacecraft Monitoring and Command Overlaps and Functional Spaces

	Command and Control	Teleoperation and Crew Communication
Command and Control		
Teleoperation and Crew Communication	**1**	

Functional Space	**Minimum Volume - 4 Crew, (m^3)**	**Minimum Volume - 6 Crew, (m^3)**	**Functions**	
Spacecraft Monitoring (Computer/Command)	3.42	3.42	Command and Control	Teleoperation and Crew Communication

Table 14: Waste Management Overlaps and Functional Spaces

	Trash Containment	Trash Packing for Disposal
Trash Containment		
Trash Packing for Disposal	1	

Functional Space	Minimum Volume - 4 Crew, (m^3)	Minimum Volume - 6 Crew, (m^3)	Functions	
Waste Management	3.76	3.76	Trash Containment	Trash Packing for Disposal

Table 15: Airlock Overlaps and Functional Spaces

	Computer Display and Control Interface	Depressur-ization	Repressur-ization	Hyper-baric Isolation	Hypo-baric Isolation	EVA Suit Don/ Doffing	Crew Ingress/ Egress	Subsystem or Payload Ingress/ Egress	Suit Servicing	Suit Repair	Suit Component Testing
Airlock Display and Control Interface											
Depressur-ization	0										
Repressur-ization	0	1									
Hyperbaric Isolation	0	1	1								
Hypobaric Isolation	0	1	1	1							
EVA Suit Don/Doffing	0	1	1	1	1						
Crew Ingress/Egress	0	1	1	1	1	1					
Subsystem or Payload Ingress/Egress	0	1	1	1	1	1	1				
Suit Servicing	0	1	1	1	1	1	1	1			
Suit Repair	0	1	1	1	1	1	1	1	1		

Functional Space	Minimum Volume - 4 Crew, (m^3)	Minimum Volume - 6 Crew, (m^3)	Functions						
A/L-1 (External Airlock)	6.35	6.35	Depressur-ization	Repressur-ization	Hyperbatic Isolation	Hypobatic Isolation	EVA Suit Don/Doffing	Crew Ingress/ Egress	Subsytem or Payload Ingress/Egress
A/L-2 (Suit Maintenance)	4.82	4.82	Suit Servicing	Suit Repair					
A/L-3 (EVA Computer/Data)	1.70	1.70	Airlock Display and Control Interface						

Cross Category Overlaps

A second step in classifying overlaps involved identifying overlaps among Functional Spaces across functional categories. Because functions in different categories naturally tend to have different functional requirements and constraints, there is generally less potential for overlaps in these areas. However, there are certain cases where it is possible to combine Functional Spaces across categories in order to reduce overall volume.

The team utilized the same basic process for identifying these overlaps as was done at the category level. A single matrix was used to compare Functional Space pairs across categories and to identify cases where there was potential for overlaps. This matrix is shown in Appendix B.

3. RESULTS

Spaces with identified overlaps were then combined and a final comprehensive list of cross category Combined Functional Spaces was developed. As with the previous step, the minimum volume between functional spaces was used for the Combined Functional Space. Table 16 lists the Combined Functional Spaces and resultant minimum habitable volumes for the four and six crew cases.

Table 16: Functional Spaces and Volumes

Combined Functional Space	Minimum Volume - 4 crew (m^3)	Minimum Volume - 6 crew (m3)
Exercise-1 (Cycle Ergometer)	6.12	12.24
Exercise-2 (Treadmill)	3.38	6.76
Exercise-3 (Resistive Device)	3.92	7.84
Group Social-1 (Open Area) / Mission Planning-3 (Training)	18.20	27.30
Group Social-2 (Table) / Meal Consumption / Mission Planning-1 (Table)	10.09	15.14
Human Waste-1 (Waste Collection)	2.36	4.72
Human Waste-2 (Cleansing) / Hygiene-1 (Cleansing)	4.35	8.70
Logistics-2 (Temporary Stowage)	6.00	6.00
Maintenance-1 (Computer) / EVA-2 (EVA Computer/Data)	3.40	3.40
Maintenance-2 (Work Surface) / Logistics-1 (Work Surface) / EVA-1 (Suit Testing)	4.82	4.82
Meal Preparation-1 (Food Prep)	4.35	8.70
Meal Preparation-2 (Work Surface)	3.30	3.30
Medical-1 (Computer)	1.20	1.20
Medical-3 (Medical Care)	5.80	5.80
Mission Planning-2 (Computer/Command) / Spacecraft Monitoring	3.42	3.42
Private Habitation-1 (Work Surface) / Medical-2 (Ambulatory Care)	17.40	26.10
Private Habitation-2 (Sleep & Relaxation) / Hygiene-2 (Non-Cleansing)	13.96	20.94
Waste Management	3.76	3.76
TOTAL MINIMUM NHV	**115.83**	**170.14**
MINIMUM NHV PER CREW	**28.96**	**28.36**

This exercise resulted in 18 unique volumes, or Combined Functional Spaces, that represent different physical areas. Many of these areas can be used for multiple functions, while some are reserved for only one specific function (e.g. exercise). These Combined Functional Spaces were summed to derive total net habitable volumes for both a 4-person crew and a 6-person crew.

The resulting Functional Spaces are in line with what has been recommended in previous research. Two large common areas exist, one open area for group recreational activities, group training, watching movies, etc. and one area with a large enough surface for eating, working, and playing tabletop games. As mentioned in Simon et al. [14], having designated recreation areas away from work areas is critical to crew psychological well being in long-duration missions.

As stated previously, these values represent a floor for NHV. Constraints in an actual habitat design will likely result in an actual NHV that is greater than these values. In addition, the total habitat volume represented here is simply a combination of individual required spaces. The habitat must provide adequate volume for each identified combined functional space based on minimum volumes and dimensions.

4. HABITAT CASE STUDY

Mars Transit Habitat

The habitable volume results outlined in this paper only represent a minimum NHV. Any design for the Mars Transit Habitat will ultimately be subject to numerous constraints, including shape and size. To demonstrate how the defined NHV can be applied to a specific habitat design, the team developed a habitat based on the basic design and constraints of the Mars Transit Habitat (MTH) Conceptual Layout proposed in the Human Exploration of Mars: A Basis of Comparison Architecture [13]. This habitat design is not intended to serve as a final concept for a Mars habitat but rather to demonstrate how the NHV requirements would be applied to develop an actual habitat design.

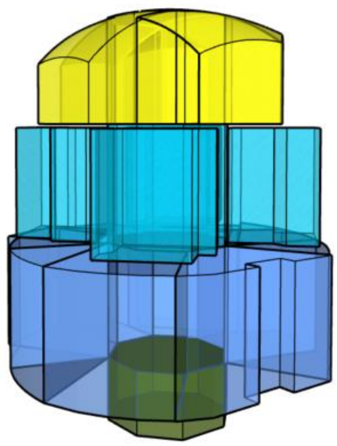


Figure 2: Case Study NHV Envelope

The team adjusted the proposed layout and dimensions to accommodate the minimum volumetric requirements derived in this paper. The team applied a three-dimensional CAD model to alter the design and to create and measure representations of Functional Spaces.

The case study assumed a crew size of four and mission duration of 1,200 days. The MTH is sized to fit the SLS 8.4 m fairing diameter, with a diameter of 7.2 m. The length was set to accommodate the required volume and layout. For the defined mission, volume had to be provided to house 987 CTBEs of logistics and a utilization volume of 5.22 m^3.

The resultant habitat had a length of 8.91 m and a total pressurized volume of 306 m^3 (not including the volume of the external airlock used in the MTH). To account for additional functionalities required, the team allocated additional habitable volume for utilization, logistics access, and passageways. These volumes are driven entirely by design and mission requirements and so do not have minimum volume specifications. Figure 2 shows the resultant habitable volume envelope of the MTH.

The team adjusted the original design to accommodate the functional spaces defined in this effort. Deck heights were shifted to more efficiently accommodate the defined spaces and storage spaces were consolidated. The adjustments resulted in the habitat design shown in Figure 3. After these adjustments were made, each Functional Space was defined within the spacecraft. Arrangements were based on requirements and limitations for functional space design. Then volumes representing each Functional Space were evaluated to ensure that the space met the required minimum volumes.

In most aspects, after adjusting the floors and storage, the original design exceeded or equaled minimum volume requirements. But in some areas, Functional Spaces did not meet the minimum and the design had to be adjusted accordingly. Private quarters, for example, had approximately half of the volume required according to the NHV results. To accommodate the greater volume, private habitation areas were expanded and additional storage was moved from the second deck to the lower dome area. The orientation of the sleeping area was also changed, from horizontal to vertical, to better maximize the space. These adjustments demonstrate how a design might be catered to meet the needs of a minimum habitable volume. This design serves to demonstrate how minimum habitable volume design considerations can be used to drive a conceptual layout.

The minimal NHV and final NHV for each Combined Functional Space in the MTH are shown in Table 17. A summary of all the contributors to the pressurized volume are shown in Table 18.

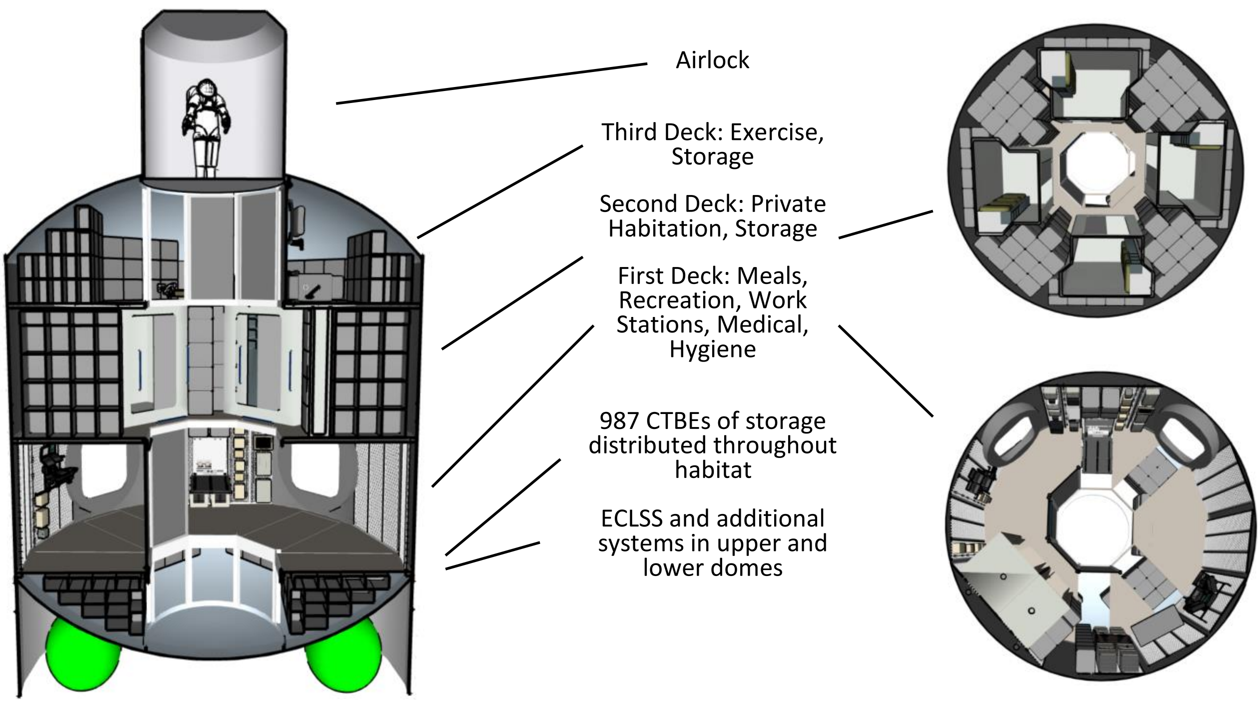


Figure 3: Case Study Habitat

Table 17: Comparison of Minimum Habitable Volumes and Case Study Habitable Volumes

Functional Space	Minimum Volume (m^3)	MTH Volume (m^3)
Exercise-1 (Cycle Ergometer)	3.38	3.50
Exercise-2 (Treadmill)	6.12	6.20
Exercise-3 (Resistive Device)	3.92	4.29
Group Social-1 (Open Area) / Mission Planning-3 (Training)	18.20	21.21
Group Social-2 (Table) / Meal Consumption (Table) / Mission Planning-2 (Table)	10.09	10.48
Human Waste-1 (Waste Collection)	2.36	2.36
Human Waste-2 (Cleansing) / Hygiene-1 (Cleansing)	4.35	4.35
Logistics-2 (Temporary Stowage)	6.00	6.18
Maintenance-1 (Computer) / EVA-2 (EVA Computer/Data)	3.40	3.55
Maintenance-2 (Work Surface) / Logistics-1 (Work Surface) / EVA-1 (Suit Testing)	4.82	5.11
Meal Preparation-1 (Food Prep)	4.35	4.35
Meal Preparation-2 (Work Surface)	3.30	3.30
Medical-1 (Computer)	1.20	1.65
Medical-3 (Medical Care)	5.80	6.40
Mission Planning-2 (Computer/Command) / Spacecraft Monitoring	3.42	3.55
Private Habitation-1 (Work Surface) / Medical-2 (Ambulatory Care)	17.40	17.40
Private Habitation-2 (Sleep & Relaxation) / Hygiene-2 (Non-Cleansing)	13.96	14.00
Waste Management	3.76	4.43
Logistics-3 (Storage Access)	-	2.14
Utilization-1 (Scientific Research)	-	5.22
Passageway to Hygiene	-	3.84
Passageway to Second Deck	-	10.25
Passageway to Third Deck / Egress/Ingress for Airlock	-	3.43
Total NHV	115.83	147.19
NHV per Crewmember	28.96	36.80

The final Net Habitable Volume of the derived MTH is approximately 147.19 m^3, not including the external airlock. Storage volume, based on the requirement for 987 CTBEs is 52 m^3. Volume allocated for vehicle systems equipment equals 104 m^3. The Airlock, not included in final volume estimates, has a pressurized volume of 13.2 m^3 and a habitable volume of 11.05 m^3.

Table 18: Case Study Volume Breakdown

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

The NHV of the MTH is approximately 27% larger than the minimum possible NHV defined for the four-crew case in this paper. This additional volume is partially from added spaces for access and utilization but is also due to the inefficiencies of packaging functional spaces into the cylindrical form.

5. CONCLUSION

Previous parametric studies have suggested that a value of approximately 25 m^3 per crew is a reasonable estimate for habitable volume. The results of this study indicate that required minimum NHV should be close to that value. For both the four and six crew cases, the minimum estimated NHV per crew was between 28 m^3 and 29 m^3. However, it is important to note that once applied to an actual habitat design, the resultant habitable volume was significantly larger than the established minimum, after accounting for additional access spaces and the efficiencies of providing spaces in a cylindrical habitat. Based on the case study developed in this paper, it is likely that the total net habitable volume required to provide the minimum functional volumes described in this paper will be closer to 37 m^3 per crew.

This study developed two important products for establishing future designs for exploration habitats. The first product is a set of minimum habitable volume standards for all required crew functional spaces based on functional needs. These requirements establish a floor for habitable volume necessary for operations and safety of the crew.

The second product is a method for applying the established habitable volume requirements to the development of an actual habitat design. By applying the minimum volumes as part of a bottom-up methodology, habitat architects can ensure that design efforts are acceptable, safe, and human-centric for long-duration missions.

The volume standards and application method formulated in this study can be used to help plan future Mars mission requirements and evaluate future habitat designs.

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BIOGRAPHY

Chel Stromgren *currently serves as the Chief Scientist of Binera, Inc. Risk Analytics Division. In this role, Mr. Stromgren leads the development of probability and risk-based strategic models and strategic analysis of complex system development. Mr. Stromgren has supported NASA in the analysis of Space Shuttle and International Space Station operations in the post-Columbia environment and has led the development of strategic campaign models for the lunar exploration initiatives. He holds a Bachelor of Science degree in Marine Engineering and Naval Architecture from the Webb Institute and a Master of Science degree in Systems Management from the Massachusetts Institute of Technology.*

Michelle Rucker *received a B.S. (1984) and M.A. (1986) in Mechanical Engineering from Rice University and has been with NASA for 29 years. She currently serves in the Exploration Integration and Science Directorate at the Johnson Space Center. She began her NASA career as a test engineer at the White Sands Test Facility before moving onto roles as a deputy subsystem manager for the International Space Station, EVA and Spacesuit Systems Deputy Branch Chief, and Altair Lunar Test and Verification Lead. She currently leads the Mars Integration Group.*

***Callie Burke** is a Senior Analyst at Binera, Inc. where she has worked since 2018 in the area of Risk Analytics. She has supported multiple projects for NASA's Human Spaceflight and Exploration Team including volumetric analyses for lunar landing designs and research related to long-duration exploration missions. She holds a Bachelor of Arts in Diplomacy and World Affairs from Occidental College and a Master of Arts in Law and Diplomacy from The Fletcher School at Tufts University.*

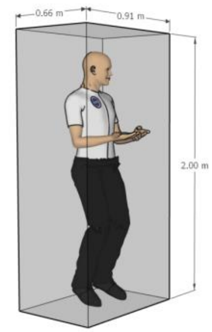
***Jason Cho** received a B.S (2019) in Aerospace Engineering from The University of Maryland and currently serves as an Aerospace Engineer at Binera, Inc. Mr. Cho supports NASA in the analysis of campaign and probabilistic modeling for lunar and deep space exploration efforts.*

***Robert Calderon** received his B.S. in Mechanical Engineering (2010) and his Master of Engineering Management (2013) from the Johns Hopkins University and Dartmouth College, respectively. He provides analytical support as a Junior Operations Research Analyst to Binera, Inc. in their multiple risk-informed, statistically-driven assessments. He interned at the Jet Propulsion Laboratory in 2012, assisting in the research efforts to view exoplanets.*

APPENDIX A: FUNCTIONS, VOLUMES, & JUSTIFICATIONS

EXERCISE					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Aerobic Exercise - Cycle Ergometer	Use of a cycle ergometer with access and appropriate separation. One device per four crew.	3.38	6.76	HIDH [5] – 3.38 m^3 per device 2012 HVW [6] – 3.31 m^3 per device (Exercise in ISS Zvezda Service Module); **Final Value:** 3.38 m^3 per device;	Width: 0.65 m Depth: 0.69 m
Aerobic Exercise - Treadmill	Use of a treadmill with access and appropriate separation. One device per four crew.	6.12	12.24	HIDH [5] – 6.12 m^3 per device (Table 8.2-1);	Height: 1.91 m
Resistive Exercise	Use of the ARED Device. One device per four crew.	3.92	7.84	ISS-IVC [10] – 3.92 m^3 per crew;	Height: 1.91 m
Bone Loading	Use of a treadmill with access and appropriate separation. One device per four crew.	4.91	9.92	HIDH [5] – 6.12 m^3 per device (Table 8.2-1) Same envelope as: “Aerobic Exercise – Treadmill”;	Width: 0.65 m Depth: 0.69 m
Sensorimotor Conditioning	Use of a treadmill with access and appropriate separation. One device per four crew.	4.91	9.92	HIDH [5] – 6.12 m^3 per device (Table 8.2-1) Same envelope as: “Aerobic Exercise – Treadmill”;	Width: 0.65 m Depth: 0.69 m

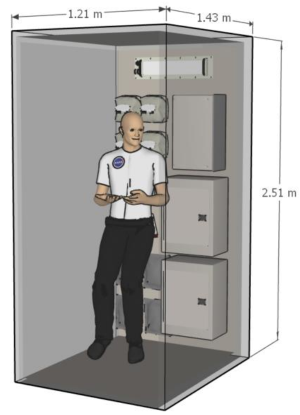
GROUP SOCIALIZATION AND RECREATION					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Athletic Games	All crewmembers standing with maximum volume used by means of different arm positions. Past examples of activities include handball and soccer.	18.20	27.30	HIDH [5] - 4.35 m^3 per crewmember crew = 17.4 m^3 for four crewmembers (Table 8.2-1: General workstations, food preparation, partial body cleaning, housekeeping); CAD Modeling: 18.2 m^3 for four crewmembers (Volume of crewmembers with different arm members and space between); 27.3 m^3 for 6 crewmembers; **Final Value**: 18.2 m^3 per four crew;	Depth: 1.95 m
Personal Recreation	Sufficient volume for one crewmember to be in relaxed position - away from work station.	1.20	1.20	HIDH [5] - 1.2 m^3 (Table 4.3-5: Neutral body in 0g);	Width: 0.91 m Depth: 0.66 Height: 2.00

					
Tabletop Games & Artistic/ Creative Recreation	All crew members seated at table. Historical examples include boardgames like chess.	10.09	15.14	2012 HVW [6] – 10.09 m^3 for four crewmembers (Based on measurement of Deep Space Habitat Demonstration Unit Wardroom); HIDH [5] – 2.69 m^3 per crewmember = 10.76 m^3 for four crewmembers; **Final Value:** 10.09 m^3 per four crew;	Width: 1.91 m Depth: 1.91 m Height: 1.49 m
Video/Movie Viewing	Up to four crewmembers are seated with ideal viewing distance of a 1.5m 4k screen.	4.80	7.20	HIDH [5] – 1.7 m^3 (Table 8.2-1: Body waste management facilities, ascent and descent, spacecraft duty station); CAD Modeling: 4.8 m^3; **Final Volume**: 4.8 m^3 per four crew;	Width: 2.61 m Height: 1.49 m
Window Viewing	One crewmember looking out window	4.62	4.62	HIDH [5] – 4.62 m^3 (Image 8.6-6: Window implementation in 0g);	Width: 0.65 m

HUMAN WASTE COLLECTION					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Hand Cleaning	Sufficient volume for one crewmember to clean hands, separate from waste collection; Gravity-appropriate system for deep cleaning and drying of hands and forearms, inclusive of contamination from medical, bodily waste, or maintenance activities. One station per four crew, two stations per six crew.	2.69	5.38	HIDH [5] – 2.69 m^3 (Table 8.2-1: Eating, sleeping, hand washing, personal office, radiation shelter, conference);	Width: 0.65 m Depth: 0.54 m
Liquid Waste Collection	Volume needed to accommodate the UWMS. One station per four crew, two	2.36	4.72	HIDH [5] – 1.7 m^3 (Table 8.2-1: Body waste management facilities, ascent and descent, spacecraft duty station);	Width: 0.65 m Height: 1.49 m

	stations per six crew.			CAD Modeling: 2.36 m^3; **Final Value:** 2.36 m^3 per system;	
Solid Waste Collection	Volume needed to accommodate the UWMS. One station per four crew, two stations per six crew.	2.36	4.72	HIDH [5] – 1.7 m^3 (Table 8.2-1: Body waste management facilities, ascent and descent, spacecraft duty station); CAD Modeling: 2.36 m^3; **Final Value:** 2.36 m^3 per system; Same envelope as "Liquid Waste";	Width: 0.65 m Height: 1.49 m

HYGIENE					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Changing Volume	One crewmember with sufficient room to change clothes in dry environment with visual separation. One station per four crew, two stations per six crew.	2.18	4.36	HIDH [5] – 1.2 m^3 (Table 4.3-5: Neutral body in 0g); CAD Modeling: 2.18 m^3 (Neutral body with .15 m of extra space on all sides);	Width: 0.93 m Height: 2.00 m
Facial Cleaning	Volume for one crewmember to clean and dry face, separate from full body cleaning area; Gravity-appropriate system for deep cleaning and drying of face and hair, inclusive of contamination from medical, bodily waste, or maintenance activities, and for application of cosmetics or other facial products. One station per four crew, two stations per six crew.	2.69	5.38	HIDH [5] – 2.69 m^3 (Table 8.2-1: Eating, sleeping, hand washing, personal office, radiation shelter, conference); Same envelope as "Hand Cleaning" in Human Waste Collection;	Width: 0.65 m Depth: 0.54 m
Finger/Toenail Clipping	Sufficient volume, gravity accommodation, tool fixtures, and debris capture for self-performed finger and toenail clipping. One station per four crew, two stations per six crew.	2.34	4.68	HIDH [5] – 2.34 m^3 (Table 8.2-1: Shaving, grooming, oral hygiene); CAD Modeling: 2.34 m^3;	Width: 0.65 m
Full Body Cleaning	Deep washing and drying of entire body exterior, inclusive of contamination from medical, bodily waste, or maintenance activities. One station per four crew, two stations per six crew.	4.34	8.68	HIDH [5] – 4.35 m^3 (Table 8.2-1: General workstations, food preparation, partial body cleaning, housekeeping); CAD Modeling: 4.34 m^3 (Based on hygiene practices aboard the ISS in regards to showering, shampooing, and nail clipping);	Width: 1.21 m Depth: 1.43 m Height: 2.51 m

					
Hair Styling/ Grooming	Sufficient volume, gravity accommodation, tool fixtures, and debris capture for self-performed male and female hair styling, grooming, and cutting inclusive of a wide range of hair styles. One station per four crew, two stations per six crew.	2.34	4.68	HIDH [5] – 2.34 m^3 (Table 8.2-1: Shaving, grooming, oral hygiene); CAD Modeling: 2.34 m^3;	Width: 0.65 m Depth: 0.54 m
Hand Cleaning	Volume for one crewmember to clean and dry hands, separate from full body cleaning; Gravity-appropriate system for deep cleaning and drying of hands and forearms, inclusive of contamination from medical, bodily waste, or maintenance activities. One station per four crew, two stations per six crew.	2.69	4.68	HIDH [5] – 2.69 m^3 (Table 8.2-1: Eating, sleeping, hand washing, personal office, radiation shelter, conference); Same envelope as “Facial Cleaning”;	Width: 0.65 m Depth: 0.54 m
Oral Hygiene	Sufficient volume for one crewmember to perform oral hygiene tasks; Gravity appropriate system for tooth brushing, flossing, mouth rinsing, and visual inspection of teeth, tongue, and mouth interior. One station per four crew, two stations per six crew.	2.34	4.68	HIDH [5] – 2.34 m^3 (Table 8.2-1: Shaving, grooming, oral hygiene); CAD Modeling: 2.34 m^3;	Depth: 0.98 m
Physical Work Surface Access	One crewmember standing in front of deployable or fixed work surface for accommodating items	4.35	4.35	HIDH [5] – 4.35 m^3 (Table 8.2-1: General workstations, food preparation, partial body cleaning, housekeeping); 2012 HVW [6] – 4.78 m^3 (Based on	Height: 1.91 m

	associated with hygiene activity.			measurement of Deep Space Habitat Demonstration Unit Workstation); CAD Modeling: 3.97 m^3; **Final Value:** 4.35 m^3 per station;	
Viewing appearance	Volume for one crewmember to stand in front of full-length mirror or other display system sufficient to provide both facial close-up and full body inspection within private volume. One station per four crew, two stations per six crew.	1.80	3.60	HIDH [5] – 1.2 m^3 (Table 4.3-5: Neutral body in 0g); CAD Modeling: 1.8 m^3 (Neutral body with 0.5m of space in front of body for viewing ability);	Width: 0.91 m Depth: 0.99 m Height: 2.00 m
Shaving	Sufficient volume, gravity accommodation, tool fixtures, and debris capture for self-performed shaving, inclusive of facial and bodily extremities. One station per four crew, two stations per six crew.	2.34	4.68	HIDH [5] – 2.34 m^3 (Table 8.2-1: Shaving, grooming, oral hygiene); CAD Modeling: 2.3 m^3 (1.18 m x 0.9 m x 2.16 m)	Depth: 0.98 m
Skin care	Gravity appropriate solution for application of creams, ointments, or other skin care solutions to the entire body or localized portions. One station per four crew, two stations per six crew.	2.34	4.68	HIDH [5] – 2.34 m^3 (Table 8.2-1: Shaving, grooming, oral hygiene); CAD Modeling: 2.3 m^3 (1.18 m x 0.9 m x 2.16 m)	Depth: 0.98 m

LOGISTICS					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Physical Work Surface Access	Volume for one crew member in front of surface area fixed or deployable, dedicated or shared, surface near a logistics module docking port for inspection, repacking, or transfer of logistics items.	4.35	4.35	HIDH [5] – 4.35 m^3 (Table 8.2-1: General workstations, food preparation, partial body cleaning, housekeeping); 2012 HVW [6] – 4.78 m^3 (Based on measurement of Deep Space Habitat Demonstration Unit Workstation); CAD Modeling: 3.97 m^3; **Final Value:** 4.35 m^3 per station;	Width: 2.02 m Depth: 0.98 m Height: 1.91 m
Small Item Containment	Volume for one crew member in front of workstation or crew station specific small trash or small stowage units.	1.20	1.20	HIDH [5] – 1.2 m^3 (Table 4.3-5: Neutral body in 0g);	Width: 0.65 m Depth: 0.54 m Height: 1.91 m
Temporary Stowage	Volume for one crewmember to pack and unpack temporary stowage.	6.00	6.00	HIDH [5] – 6 m^3 (Table 8.2-1: Food stowage, personal locker, accessing stowage);	Width: 0.98 m Depth: 2.02 m Height: 2.31 m

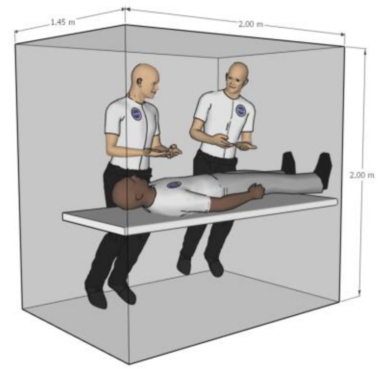
MAINTENANCE AND REPAIR					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Computer Display and Control Interface	One crew member standing in front of computers and controls with sufficient volume for arm span and movement. One station for four crew, two stations for six crew.	1.70	3.40	2012 HVW [6] – 1.71 m^3 per crewmember (Volume estimate based on measurements of the Mid-Fi Orion mockup). HIDH [5] – 1.7 m^3 per crewmember (Table 8.2-1)	Width: 0.65 m Height: 1.91 m
Equipment Diagnostics	One crew member standing in front of surface for component sterilization, isolation, etc. One station for four and six crew.	4.35	4.35	HIDH [5] – 4.35 m^3 (Table 8.2-1: General workstations, food preparation, partial body cleaning, housekeeping); 2012 HVW [6] – 4.78 m^3 (Based on measurement of Deep Space Habitat Demonstration Unit Workstation); CAD Modeling: 3.97 m^3; **Final Value:** 4.35 m^3 per station;	Height: 1.91 m
Physical Work Surface Access	One crew member standing in front of surface for analysis of materials, electronics, etc. One station for four and six crew.	4.35	4.35	HIDH [5] – 4.35 m^3 (Table 8.2-1: General workstations, food preparation, partial body cleaning, housekeeping); 2012 HVW [6] – 4.78 m^3 (Based on measurement of Deep Space Habitat Demonstration Unit Workstation); CAD Modeling: 3.97 m^3; **Final Value:** 4.35 m^3 per station;	Height: 1.91 m
Soft Goods Fabrication	One crewmember with sufficient volume to have soft goods in front of body and movement associated with sewing, cutting, patching, etc. One station for four and six crew.	2.69	2.69	HIDH [5] – 2.69 m^3 (Table 8.2-1: Eating, sleeping, hand washing, personal office, radiation shelter, conference);	Width: 0.65 m

EVA SUPPORT					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Suit Component Testing	Positions will vary (see source). Use maximum dimensions for bodily volume. -- probably need space for one suited crew member and one unsuited crewmember	4.82	4.82	CAD Modeling: 4.82 m^3;	Height: 2.31 m
Computer	Crewmember in the seated	1.70	1.70	2012 HVW [6] – 1.71 m^3 per crewmember	Width: 0.65 m

Display and Control Interface	position at computing station for EVA operations.			(Volume estimate based on measurements of the Mid-Fi Orion mockup); HIDH [5] – 1.7 m^3 per crewmember (Table 8.2-1)	Height: 1.49 m

MEAL PREPARATION					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Food Item Sorting	One crewmember in front of a surface area with attachment points to contain crew meal packets for pre-meal sorting.	3.30	3.30	CAD Modeling: 3.3 m^3 (Assume neutral position in 0g, assume 2 m^2 perpendicular surface);	Width: 1.41 m Depth: 1.41 m
Food Preparation	Crewmember standing in front of prep unit (includes rehydration, food warming, food chilling, food cooking, etc.).	4.35	4.35	HIDH [5] – 4.35 m^3 Body volume associated with food preparation in 0-g (HIDH Table 8.2-1); CAD Modeling: 4.35 m^3 (Assume neutral position in 0g);	Height: 1.91 m
Utensil and Food Equipment Hygiene	Crewmember standing in front of cleaning/utensil sanitation unit for operation (either surface or machine) - assume this is in a slightly separate area than the food prep area and food sorting area so needs extra habitable volume. For the ISS, utensils and trays are cleaned using moist sanitizing towelettes, eliminating the need for a dishwasher or kitchen sink.	3.30	3.30	CAD Modeling: 3.3 m^3 (Assume sitting/neutral in 0g);	Width: 1.41 m Depth: 1.41 m

MEAL CONSUMPTION					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Full Crew Dining	Volume for four or six crewmembers seated with restraints at perpendicular surface. Gravity appropriate restraints or accommodations at each intended crew dining position; Capability to attach meal items and utensils to dining surface.	10.09	15.14	2012 HVW [6] – 10.09 m^3 for four crewmembers (Based on measurement of Deep Space Habitat Demonstration Unit Wardroom, assuming a 2 ft zone around the wardroom table); HIDH [5] - 2.69 m^3 per crewmember = 10.76 m^3 for four crewmembers; **Final Value:** 10.09 m^3 per four crew;	Width: 1.19 m Depth: 1.19 m Height: 1.91 m

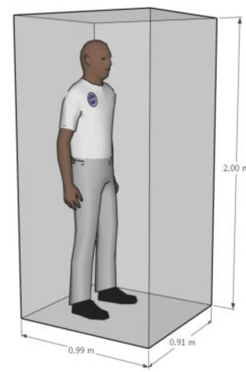
MEDICAL OPERATIONS					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Advanced Medical Care (basic surgical care, trauma care, advanced life support)	One crewmember lying down on surface with restraints, room for at least two crewmembers preform operations, crewmember should be laying perpendicular to those administering care with space below and above. Use of a ventilator, defibrillator, cardioversion, etc. and drug infusions.	5.80	5.80	CAD Modeling: 5.8 m^3; 	Width: 2.00 m Depth: 1.45 m Height: 2.00 m
Ambulatory Care	One crewmember sitting up independently self-administering care and using oral or topical medications.	1.70	1.70	HIDH [5] – 1.7 m^3 (Table 8.2-1: Body waste management facilities, ascent and descent, spacecraft duty station);	Height: 1.49 m
Basic Medical Care (space motion sickness, first aid, anaphylaxis response, clinical diagnostics, medical imaging)	One crewmember laying down on surface with restraints or sitting up; one crewmember administering IV or doing diagnostics treatment for space motion sickness, injecting, reaching for fluids, kits, etc., possibly carrying/lifting patient into room. May require CPR, airway management, supplemental oxygen, large volumes of IV fluids, and close monitoring. A diagnosis made on the basis of medical signs and patient-reported symptoms, rather than diagnostic tests.	5.80	5.80	CAD Modeling: 5.8 m^3 (1.45 m x 2 m x 2 m); https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20070032039.pdf; Same envelope as Advanced Medical Care;	Width: 2.00 m Depth: 1.45 m Height: 2.00 m
Computer Data Entry / Manipulation	One crew member in front of computer terminal.	1.20	1.20	HIDH [5] – 1.2 m^3 (Table 8.2-1: Neutral body in 0g);	Width: 0.65 m Height: 1.49 m
Dental Care	One man lying down or upside down; one man performing	5.80	5.80	CAD Modeling: 5.8 m^3;	Width: 2.00 m Depth: 1.45 m

	dental examination or dental surgery in extreme cases.			Same as Advanced Medical Care	Height: 2.00 m
Private Telemedicine	One crew member in front of computer terminal - with ability for private conversations.	1.20	1.20	HIDH [5] – 1.2 m^3 (Table 4.3-5: Neutral body in 0g);	Width: 0.65 m Height: 1.49 m
Two Person Meetings	Sufficient volume for two crew to sit, facing each other, with unobstructed line of sight, with physical work surface between them, with at least six inches separation between the nearest body parts of the two.	3.40	3.40	HIDH [5] – 1.7 m^3 per crewmember; CAD Modeling: 3.4 m^3 for two crewmembers;	Height: 1.49 m

MISSION PLANNING					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Command and Control Interface	Two crewmembers standing up using two monitors. Assumed 24" monitors. One station needed for four crew and six crew.	3.42	3.42	2012 HVW [6] – 1.71 m^3 per crewmember (Volume estimate based on measurements of the Mid-Fi Orion mockup); HIDH [5] – 1.71 m^3 per crewmember (Table 8.2-1: Body waste management facilities, ascent and descent, spacecraft duty station); CAD Modeling: 3.37 m^3 for two crewmembers; **Final Value:** 3.42 m^3 for two crewmembers.	Height: 1.91 m H
Physical Work Surface Access	Four or six crewmembers sitting around a table (with restraints) taking notes, space for laptop use.	10.09	15.14	2012 HVW [6]: 10.09 m^3 for four crewmembers (Based on measurement of Deep Space Habitat Demonstration Unit Wardroom, assuming a 2 ft zone around the wardroom table); HIDH [5]: 2.69 m^3 per crewmember = 10.76 m^3 for four crewmembers (Extra overlap due to shared volume at table justifies using the smaller volume of 10.09 m^3);	Width: 1.19 m Depth: 1.19 m Height: 1.91 m
Team Meetings	Four or six crewmembers in front of video and monitors.	4.80	7.20	HIDH [5]: 1.70 m^3 (Table 8.2-1: Body waste management facilities, ascent and descent, spacecraft duty station); CAD Modeling: 4.8 m^3; **Final Value**: 4.8 m^3;	Width: 2.61 m Height: 1.49 m
Mission Training	Four crewmembers in front of video and monitors with sufficient space to move around, possible use of VR.	18.20	27.30	HIDH [5]: 4.35 m^3 per crewmember = 17.4 m^3 for four crewmembers (Table 8.2-1: General workstations, food preparation, partial body cleaning, housekeeping); CAD Modeling: 18.2 m^3 for four crewmembers (Volume of crewmembers with different arm members and space between);	Depth: 1.95 m

				Final Value: 18.2 m^3 for four crew;	

PRIVATE HABITATION					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Changing Clothes	Sufficient open volume in quarters to change clothing.	8.72	13.08	HIDH [5]: 1.2 m^3 (Table 4.3-5: Neutral body in 0g); CAD Modeling: 2.18 m^3 (Neutral body with 0.15 m of extra space on all sides);	Width: 0.93 m Height: 2.00 m
Meditation	Sufficient crew quarters volume to support meditation postures consistent with most philosophies and religious faiths.	4.8	7.2	HIDH [5]: 1.2 m^3 (Table 4.3-5: Neutral body in 0g);	Width: 0.65 m
Non-Sleep Rest/Relaxation in Private Quarters	One crewmember in seated or reclined position.	4.8	7.2	HIDH [5]: 1.2 m^3 (Table 4.3-5: Neutral body in 0g);	Width: 0.65 m
Physical Work Surface Access	Surface area that can accommodate laptop and space for writing, one person sitting in repositionable chair.	17.4	26.1	HIDH [5]: 4.35 m^3 (Table 8.2-1: General workstations, food preparation, partial body cleaning, housekeeping); 2012 HVW [6]: 4.78 m^3 (Based on measurement of Deep Space Habitat Demonstration Unit Workstation); CAD Modeling: 3.97 m^3; **Final Value:** 4.35 m^3 per station;	Height: 1.91 m
Single Person Private Work, Entertainment, and Communication	One person sitting or lying down looking at monitor or laptop.	4.8	7.2	HIDH [5]: 1.2 m^3 (Table 4.3-5: Neutral body in 0g);	Width: 0.65 m
Sleep Accommodation	One crewmember in sleeping bag with enough headspace to be in a sitting position.	10.76	16.14	HIDH [5]: 2.69 m^3 (Table 8.2-1: Eating, sleeping, hand washing, personal office, radiation shelter, conference);	Width: 0.65 m
Stretching	Sufficient crew quarters volume to stretch standing, sitting, or prone.	13.96	20.94	CAD Modeling: 3.49 m^3 (0.9 m x 1.55 m x 2.5 m)	Width: 0.65 m
Two Person Meetings	Sufficient volume for two crew to sit, facing each other, with unobstructed line of sight, with physical work surface between them, with at least six inches separation between the nearest body parts of the two.	13.6	20.4	HIDH [5]: 1.7 m^3 per crewmember CAD Modeling: 3.4 m^3 for two crewmembers **Final Value:** 3.4 m^3 per two crew station;	Height: 1.49 m
Viewing	Full length mirror and	7.2	10.8	HIDH [5]: 1.2 m^3 (Table 4.3-5: Neutral body in	Width: 0.91 m

Appearance in Private Quarters	sufficient volume in quarters to back far enough away to see full body.			0g); CAD Modeling: 1.8 m^3 (Neutral body with 0.5 m of space in front of body for viewing ability): 	Depth: 0.99 m Height: 2.00 m

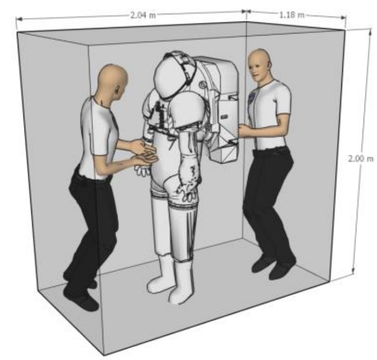
SPACECRAFT MONITORING AND COMMANDING					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Command and Control	Two crewmembers in front of separate monitors. Access to controls (assumed size of keyboard + basic control inputs).	3.42	3.42	2012 HVW [6]: 1.71 m^3 per crewmember (Volume estimate based on measurements of the Mid-Fi Orion mockup); 2012 HVW [5]: 1.71 m^3 per crewmember (Table 8.2-1: Body waste management facilities, ascent and descent, spacecraft duty station); CAD Modeling: 3.37 m^3 for two crewmembers; **Final Value:** 3.42 m^3 per two crew station;	Height: 1.91 m H
Teleoperation and Crew Communication	One crewmember in front of one monitor. Access to keyboard.	1.70	1.70	2012 HVW [6]: 1.71 m^3 per crewmember (Volume estimate based on measurements of the Mid-Fi Orion mockup). HIDH [5]: 1.7 m^3 per crewmember (Table 8.2-1)	Width: 0.65 m Height: 1.49 m

WASTE MANAGEMENT					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Trash	Volume for one crewmember to	2.55	2.55	HIDH [5]: 2.55 m^3 (Table 8.2-1: Egress,	Width: 0.65 m

Containment	carry and stow trash - use egress volume from HIDH.			translation, passageways);	
Trash Packing for Disposal	Crewmember will either be stuffing small trash bag or maneuvering with larger trash container through spacecraft (see note). Allow for sufficient space to all sides of crewmember; overhead reach is likely not necessary.	3.76	3.76	CAD Modeling: 3.76 m^3 (based on Trash packing & maintenance on ISS)	Width: 0.65 m

Airlock Functions

AIRLOCK OPERATIONS					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Depressurization	Two fully suited crewmembers standing with sufficient room. Not included inside Common Habitat; in external Airlock.	4.51	4.51	CAD Modeling: 4.51 m^3;	Width: 1.30 m Height: 1.91 m
Repressurization	Two fully suited crewmember standing with sufficient room. Not included inside Common Habitat; in external Airlock.	4.51	4.51	CAD Modeling: 4.51 m^3; Same envelope as "Depressurization";	Width: 1.30 m Height: 1.91 m
Hyperbaric Isolation	Two unsuited crewmembers standing. Not included inside Common Habitat; in external Airlock.	4.51	4.51	CAD Modeling: 4.51 m^3; Same envelope as "Depressurization";	Width: 1.30 m Height: 1.91 m
Hypobaric Isolation	2 unsuited crewmembers standing. Not included inside Common Habitat; in external Airlock	4.51	4.51	CAD Modeling: 4.51 m^3; Same envelope as "Depressurization;	Width: 1.30 m Height: 1.91 m
EVA Suit Don/Doffing	Unsuited crewmember with sufficient volume to don/doff suit with assistance of fellow crewmember (either in EVA suit or in plain clothes). Not included inside Common Habitat; in external Airlock.	6.35	6.35	HIDH [5]: 6.35 m^3 per one crewmember (Table 8.2-1: Dressing (don and doff), EVA suiting area);	Height: 2.31 m
Crew Ingress/Egress	Sufficient room for crewmember to enter and exit airlock - volume around hatch. Not included inside Common Habitat; in external Airlock.	4.64	4.64	HIDH [5]: 4.64 m^3 per crewmember (Table 8.2-1: EVA Suit Ingress/Egress);	Width: 1.30 m Height: 1.91 m

Subsystem or Payload Ingress/Egress	Sufficient room for payload to enter and exit airlock - volume around hatch; Not included inside Common Habitat; in external Airlock.	4.64	4.64	HIDH [5]: 4.64 m^3 per crewmember (Table 8.2-1: EVA Suit Ingress/Egress);	Width: 1.30 m Height: 1.91 m
Suit Servicing	Sufficient room for two crewmembers and one suit; in external Airlock.	4.82	4.82	CAD Modeling: 4.82 m^3; 	Width: 1.18 m Depth: 2.05 m Height: 2.00 m
Suit Repair	Sufficient room for two crewmembers and one suit; Suit washing, full Maintenance & Fabrication workstation capabilities; in external Airlock.	4.82	4.82	CAD Modeling: 4.82 m^3;	Width: 1.30 m Height: 1.91 m

SAFE HAVEN					
FUNCTION	**FUNCTION DESCRIPTION & VOLUME ASSUMPTIONS**	**MIN. VOLUM - 4 CREW (m^3)**	**MIN. VOLUM - 6 CREW (m^3)**	**SOURCES**	**MINIMUM HABITABLE DIMENSIONS (AS REQUIRED)**
Safe Haven	Area that holds space for all four or six crewmembers to take safe haven in an emergency; in external Airlock.	10.76	16.14	HIDH [5] 2.69m^3 per one crew (Table 8.2- 1);	Width: 1.3 m Depth: 1.98 m Height: 1.91 m

APPENDIX B: FULL OVERLAPS ACROSS CATEGORIES

	MIN. VOLUME - 4 CREW (m^3)	MIN. VOLUME - 6 CREW (m^3)	EVA-1 (Suit Testing)	EVA-2 (EVA Computer/Data)	Exercise-1	Exercise-2	Exercise-3	Group Social-1 (Open Area)	Group Social-2 (Table)	Human Waste-1 (Waste Collection)	Human Waste-2 (Cleansing)	Hygiene-1 (Cleansing)	Hygiene-2 (Non-Cleansing)	Logistics-1 (Work Surface)	Logistics-2 (Temporary Stowage)	Maintenance-1 (Computer)	Maintenance-2 (Work Surface)	Meal Consumption (Table)	Meal Preparation-1 (Food Prep)	Meal Preparation-2 (Table/Work Surface)	Medical-1 (Computer)	Medical-2 (Ambulatory Care)	Medical-3 (Medical Care/Work Surface)	Mission Planning-1 (Table/Work Surface)	Mission Planning-2 (Computer/Command)	Mission Planning-3 (Training)	Private Habitation-1 (Desk/Work Surface)	Private Habitation-2 (Sleep & Relaxation)	Spacecraft Monitoring (Computer/Command)	Waste Management
EVA-1 (Suit Testing)	4.82	4.82																												
EVA-2 (EVA Computer/Data)	1.70	1.70	0																											
Exercise-1 (Cycle Ergometer)	3.38	6.76	0	0																										
Exercise-2 (Treadmill)	6.12	12.24	0	0	0																									
Exercise-3 (Resistive Device)	3.92	7.84	0	0	0	0																								
Group Social-1 (Open Area)	18.20	27.30	1	0	0	0	0																							
Group Social-2 (Table)	10.09	15.14	0	0	0	0	0	0																						
Human Waste-1 (Waste Collection)	2.36	4.72	0	0	0	0	0	0	0																					
Human Waste-2 (Cleansing)	2.69	5.38	0	0	0	0	0	0	0	0																				
Hygiene-1 (Cleansing)	4.35	8.70	0	0	0	0	0	0	0	0	1																			
Hygiene-2 (Non-Cleansing)	4.68	4.68	0	0	0	0	0	0	0	0	0	0																		
Logistics-1 (Work Surface)	4.35	4.35	1	0	0	0	0	0	1	0	0	0	0																	
Logistics-2 (Temporary Stowage)	6.00	6.00	0	0	0	0	0	0	0	0	0	0	0	0																
Maintenance-1 (Computer)	3.40	3.40	0	1	0	0	0	0	0	0	0	0	0	0	0															
Maintenance-2 (Work Surface)	4.35	4.35	1	0	0	0	0	0	0	0	0	0	0	1	0	0														
Meal Consumption (Table)	10.09	15.14	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0													
Meal Prep.-1 (Food Prep)	4.35	8.70	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0												
Meal Prep.-2 (Table/Work Surface)	3.30	3.30	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0											
Medical-1 (Computer)	1.20	1.20	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0										
Medical-2 (Ambulatory Care)	3.40	3.40	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0									
Medical-3 (Medical Care/Work Surface)	5.80	5.80	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0								
Mission Planning-1 (Table/Work Surface)	10.09	15.14	1	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	1	0	0	0							
Mission Planning-2 (Computer/Command)	3.42	3.42	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0						
Mission Planning-3 (Training)	3.42	3.42	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					
Private Habitation-1 (Desk/Work Surface)	17.40	26.10	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0				
Private Habitation-2 (Sleep & Relaxation)	13.96	20.94	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	1			
Spacecraft Monitoring	3.42	3.42	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	1	0	0	0		
Waste Management	3.76	3.76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

APPENDIX C: FULL OVERLAPS

COMBINED FUNCTIONAL AREAS	MIN. VOLUME - 4 CREW (m^3)	MIN. VOLUME - 6 CREW, (m^3)	FUNCTION AREAS ACCOMODATED		
Exercise-1 (Cycle Ergometer)	3.38	6.76	Exercise-1 (Cycle Ergometer)		
Exercise-2 (Treadmill)	6.12	12.24	Exercise-2 (Treadmill)		
Exercise-3 (Resistive Device)	3.92	7.84	Exercise-3 (Resistive Device)		
Group Social-1 (Open Area) / Mission Planning-3 (Training)	18.20	27.30	Group Social-1 (Open Area)	Mission Planning-3 (Training)	
Group Table - (Recreation, Meal Prep, Dining)	10.09	15.14	Group Social-2 (table)	Meal Consumption (Table)	Mission Planning-1 (Table/Work Surface)
Human Waste-1 (Waste Collection)	2.36	4.72	Human Waste-1 (Waste Collection)		
Human Waste-2 (Cleansing) / Hygiene-1 (Cleansing)	4.35	8.70	Human Waste-2 (Cleansing)	Hygiene-1 (Cleansing)	
Logistics-2 (Temporary Stowage)	6.00	6.00	Logistics-2 (Temporary Stowage)		
Maintenance-1 (Computer) / EVA-2 (EVA Computer/Data)	3.40	3.40	Maintenance-1 (Computer)	EVA-2 (EVA Computer/Data)	
Maintenance-2 (Work Surface) / Logistics-1 (Work Surface) / EVA-1 (Suit Testing)	4.82	4.82	Maintenance-2 (Work Surface)	EVA-1 (Suit Testing)	Logistics-1 (Work Surface)
Meal Preparation-1 (Food Prep)	4.35	8.70	Meal Preparation-1 (Food Prep)		
Meal Preparation-2 (Work Surface)	3.30	3.30	Meal Preparation-2 (Table/Work Surface)		
Medical-1 (Computer)	1.20	1.20	Medical-1 (Computer)		
Medical-3 (Medical Care)	5.80	5.80	Medical-3 (Medical Care/Work Surface)		
Mission Planning-2 (Computer/Command) / Spacecraft Monitoring	3.42	3.42	Mission Planning-2 (Computer/Command)	Spacecraft Monitoring (Computer/Command)	
Private Habitation-1 (Work Surface) / Medical-2 (Ambulatory Care)	13.96	20.94	Private Habitation-1 (Desk/Work Surface)	Medical-2 (Ambulatory Care)	
Private Habitation-2 (Sleep & Relaxation) / Hygiene-2 (Non-Cleansing)	17.40	26.10	Private Habitation-2 (Sleep & Relaxation)	Hygiene-2 (Non-Cleansing)	
Waste Management	3.76	3.76	Waste Management		
Total	**115.83**	**170.14**			
Total per Crewmember	**28.96**	**28.36**			