DEVELOPING A HABITAT FOR LONG DURATION, DEEP SPACE MISSIONS

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One possible next leap in human space exploration for the National Aeronautics and Space Administration (NASA) is a mission to a near Earth asteroid (NEA). In order to achieve such an ambitious goal, a space habitat will need to accommodate a crew of four for the 380-day round trip. The Human Spaceflight Architecture Team (HAT) developed a conceptual design for such a habitat. The team identified activities that would be performed inside a long-duration, deep space habitat, and the capabilities needed to support such a mission. A list of seven functional activities/capabilities was developed: individual and group crew care, spacecraft and mission operations, subsystem equipment, logistics and resupply, and contingency operations. The volume for each activity was determined using NASA STD-3001 and the companion Human Integration Design Handbook (HIDH). Although, the sum of these volumes produced an over-sized spacecraft, the team evaluated activity frequency and duration to identify functions that could share a common volume without conflict, reducing the total volume by 24%. After adding 10% for growth, the resulting functional pressurized volume was calculated to be a minimum of 268 m^3 (9,464 ft^3) distributed over the functions. The work was validated through comparison to Mir, Skylab, the International Space Station (ISS), Bigelow Aerospace's proposed habitat module, and NASA's Trans-Hab concept. Using HIDH guidelines, the team developed an internal layout that (a) minimized the transit time between related crew stations, (b) accommodated expected levels of activity at each station, (c) isolated stations when necessary for health, safety, performance, and privacy, and (d) provided a safe, efficient, and comfortable work and living environment.

I. BACKGROUND

Spacecraft design is an iterative process, requiring a conceptual design of some sort as a starting point. This initial starting point is often an educated guess, but it provides a framework for designers to make informed choices.

The Exploration Mission Systems Office (EMSO) at the NASA Johnson Space Center was asked to develop a conceptual layout design for a Deep Space Habitat (DSH) module. Working from this conceptual design, specialty teams would then develop detailed subsystem designs. After integrating the subsystems together, the design concept would be modified if necessary, and the process would continue through several rounds of design refinements. The purpose of this paper is to outline the methodology and logic used to develop the initial design concept.

I.I Design Reference Mission

The team was directed to work to Design Reference Mission Hybrid 2 with High Apogee Highly Elliptical Orbit (HEO) Aggregation and Low Apogee HEO Crew Rendezvous. For the purpose of this exercise, it was assumed that the mission destination was a Near Earth Object requiring 157 days transit from Earth, followed by 30 days at the Near Earth Object, and a 193 day return to Earth, for a crewed mission duration of 380 days. The DSH module would be launched as much as 825 days before the crew arrived. Both 3- and 4-crew missions were proposed, but the team assumed a 4-crew mission, as this was the worst case in terms of sizing scenario.

I.II Constraints

DSH diameter was originally targeted at 4 to 7.5 m (13.12 to 24.6 ft), though it was thought that the dynamic envelope could accommodate some incursion up to 7.6 m (24.93 ft) diameter. Although the launch shroud diameter was not explicitly defined, it was thought that the transport vehicle could accommodate a payload up to 12 m (39.37 ft) in length.

I.III Habitat Interfaces

The DSH was intended to be part of an integrated vehicle, shown in Figure 1, which also includes a Solar Electric Propulsion (SEP) module; a Cryogenic Propulsion Stage (CPS); a Multi-Mission Space Exploration Vehicle (MMSEV); and a Multi Purpose Crew Vehicle (MPCV), also known as Orion.

Note that MMSEV and Orion would be accessible during the out-bound journey, but the MMSEV would remain at the destination, therefore, it would not be available during the return voyage.

II. GENERAL ASSUMPTIONS

For this exercise, a number of general assumptions were made in collaboration with subsystem subject matter experts.

Fig. 1: Integrated Vehicle Stack.

II.I Docking Ports

Given the integrated vehicle architecture shown in Figure 1, DSH must be able to dock with the SEP, Orion, and an MMSEV. Additionally, it was assumed that DSH must have one contingency docking port for a total of 4 Docking Systems.

II.II Hatches

The DSH must have crew transfer hatches to both Orion and the MMSEV. Additionally, it was assumed that DSH must have one contingency EVA hatch, for a total of 3 hatches. Further, it was assumed that the DSH contingency EVA hatch must be sized to accommodate EVA pressure-suited crew, and a large piece of external equipment to pass through for shirt-sleeve repair and maintenance inside the DSH.

II.III MMSEV/Orion

It was assumed that minimal power would be provided for Orion and MMSEV keep-alive functions during the out-bound journey. Except for emergency safe haven use, it was assumed that the Orion and MMSEV would only be used for temporary equipment stowage and not habitation, while the integrated vehicle was in transit.

II.IV Equipment Racks

For the purpose of estimating equipment volumes, each DSH equipment rack was assumed to be the same volume as a standard International Space Station (ISS) rack, 1.571 m^3 (55.48 ft^3). This is not to say that ISS racks would necessarily be used, only that DSH racks would be roughly the same volume as their ISS counterparts to provide a starting point for design.

II.V Module Diameter

Because radiation exposure is thought to be one of the highest crew risks for a lengthy mission, crew protection must be factored into habitat design. A large diameter module allows designers to place more equipment between the crew and the habitat outer shell, helping to shield the crew. On the other hand, prior experience cautions against too large a diameter, as this will drive ground-handling, transportation, and test costs. A 7.3 m (23.95 ft) maximum launched outer diameter module could be accommodated by existing transportation aircraft and test facilities. The team also assumed at least 30 cm (11.8 in) was needed between the module outer shell diameter and the inner shroud dynamic envelope to accommodate micrometeoroid-orbital debris shield stand-offs[1]. This gap could also be used for other externally mounted equipment such as antennas, power cables, or fluid lines. Therefore the team decided on a 7.0 m (22.97 ft) maximum launched outer diameter module.

III. INTERIOR DESIGN APPROACH

The Team began by identifying the activities or capabilities needed for a long-duration, deep space mission. Next, the volume required for each activity/capability was calculated based on NASA standards and requirements using NASA Standard 3001, Vol. 2: Human Factors, Habitability, and Environmental Health[2]. Details on how much volume to provide for various activities are given in the companion Human Integration Design Handbook (HIDH)[3].

In an attempt to optimize volume, the frequency and duration of each activity was examined to identify functions that could share the same volume without conflict. Based on this assessment, the team brainstormed internal layouts that would: (a) minimize the transit time between related crew stations; (b) accommodate expected levels of activity at each station; (c) isolate areas when necessary for health, safety, performance, and privacy; and (d) provide a safe, efficient, and comfortable work and living environment.

IV. FUNCTIONAL ACTIVITIES/CABABILITIES

As a descriptor, the term “functional” means *the ability to perform an activity at an optimal level of performance*. Therefore, functional activities are those tasks that are not hindered by the design or architecture of the habitat. The team developed seven functional activity or capability categories that the DSH was expected to accommodate: individual crew care; group crew care; spacecraft operations; mission operations; subsystem equipment; logistics and resupply; and contingencies. Generally speaking, these seven categories could be applied to almost any spacecraft, but within each category the team developed a detailed list of activities/capabilities specific to this DSH mission.

The functional volume required for individual line items was then calculated using two pieces of information: (1) the volume of the hardware required to support that particular activity/capability, as estimated by the subsystems; and (2) the body volume(s) of the crew(s) performing the activity (if applicable), per the HIDH. For example, an exercise treadmill requires approximately one rack of equipment, 1.571 m^3 (55.48 ft^3), but the HIDH recommends an additional 6.12 m^3 (216.1 ft^3) of free volume above the treadmill deck to accommodate the exercising crew member (Figure 2).

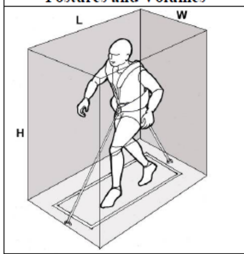
Figures of Human Body Postures and Volumes	Applicable Functions	Dimensions (m)		Volume (m^3)
	Exercise-1 (Treadmill with Vibration Isolation System (TVIS))	H	2.10	6.12
		L	2.37	
		W	1.23	

Fig. 2: Treadmill Crew Exercise Envelope.

IV.I Individual Crew Care

Individual crew care activities were those that required some level of privacy and were therefore evaluated separately from group activities. Individual crew care activities included: full body cleansing; routine hand/face cleansing; exercise; personal hygiene; urination/defecation; sleep; personal recreation/leisure; clothing maintenance; dressing and undressing; and private medical care.

The team estimated a total volume of 59.2 m^3 (2090.6 ft^3) for all individual crew care activities and capabilities. This included medical and exercise equipment, and a waste/hygiene compartment, based on ISS historical volumes, plus full body cleansing, individual crew quarters, personal item storage, and a small desk area estimated using HIDH guidelines.

IV.II Group Crew Care

Group activities and capabilities were expected to occupy contiguous volumes that could support more than one activity. Group crew functions included meal preparation, group meals, meal cleanup, and group recreation/leisure.

The team estimated a total volume of 38.4 m^3 (1,356 ft^3) for Group activities/capabilities. This included a meal preparation and clean-up area; a group dining table; and an area for recreational activities, all based on HIDH guidelines.

IV.III Spacecraft Operations

Spacecraft Operations were defined as tasks that need to be done regardless of specific mission objectives or destinations. These included general housekeeping; maintenance and repair; subsystem monitoring and control; integrated stack command and control; and mated element docking/command and data interface.

The team estimated a total volume of 64 m^3 (2,260 ft^3) for Spacecraft Operations. At 10.91 m^3 (385.3 ft^3) Maintenance and Repair was the largest single Spacecraft Operations activity volume; the team assumed the maintenance area must accommodate two crew body volumes, plus a work bench, a rack-sized item to be repaired, and a large commercial tool box. Each remaining spacecraft operations function was assumed to require a dedicated equipment rack or console plus at least one (and in some cases two) crew body volumes in front of the console. Note that general housekeeping consumables were book-kept under Logistics and Resupply, but cleaning equipment (such as a portable vacuum cleaner) was accounted for in this category.

IV.IV Mission Operations

Mission Operations are those tasks specific to a particular mission, destination, or science objective, such as meetings, planning/scheduling, Orion or MMSEV crew transfer, extravehicular activity (EVA); pre/post EVA Operations, intra-vehicular activity support of EVA, proximity operations, training, payload support, life sciences experiments, and materials processing experiments.

The team estimated a total volume of 63.9 m^3 (2,257 ft^3) for Mission Operations. Although relatively large volumes were estimated for activities such as group meetings or life sciences experiments, the team found that these volumes did not require dedicated areas, and could share volume with other activities. For example, group meetings could occur in the group meal area, and life science experiments could share volume with medical operations.

IV.V Subsystem Equipment

A distinction was made between the actual subsystem equipment (which would likely be distributed around the habitat) and subsystem control consoles (which may be consolidated in a central command area). Spacecraft subsystems typically include environmental control and life support (ECLS), thermal control, power, EVA, command and data handling (C&DH), guidance, navigation and control (GN&C), structures, mechanisms, propulsion, human factors, and communications and telemetry (C&T). For the purpose of this exercise it was assumed that all propulsion function would reside in the attached modules, therefore no volume was allocated in the DSH for propulsion subsystem equipment. Even if this assumption were to be revisited in a final design implementation, very little propulsion subsystem equipment would likely be housed inside the DSH cabin and would thus have very little impact on internal layout.

In lieu of detailed subsystem designs, the team estimated a preliminary Subsystem Equipment volume of 71.7 m^3 (2,532 ft^3) by looking to the ISS's Laboratory and Quest Airlock Modules for functional volume equivalents. It was assumed that DSH EVA equipment needs would be roughly equivalent to Quest's 34 m^3 (1,201 ft^3) equipment volume, which includes volume to stow space suits, support equipment, and EVA tools. This may be an overly conservative estimate, since DSH must only support contingency EVA activities. However, until detailed subsystem designs are available to inform the scope and probability of various contingencies, this volume assumption provided a logical starting point.

Non-EVA subsystem volume was assumed to be roughly equivalent to the 37.7 m^3 (1,331 ft^3) dedicated to the 24 equipment racks in ISS's Destiny Laboratory Module. The team intended to revise these numbers after subsystem designs were refined.

IV.VI Logistics and Resupply

The long duration of a DSH mission will drive stowage volume for consumable, non-regenerative items. The team estimated a total volume of 20.02 m^3 (707 ft^3) for food and water, clothing, medicine, subsystem spares, and other consumables, such as filters or wipes. More than a quarter of the stowage volume is comprised of food. Stowage volume was estimated in terms of Cargo Transfer Bags (CTB), which are about 0.0681 m^3 (2.4 ft^3) volume, and ISS-equivalent rack volumes, as noted previously.

Food, water, clothing, and medical supply volume estimates were based on historical ISS values. Spares/resupply volume estimates were provided by the Human Factors, Power, and GN&C subsystems; in lieu of detailed estimates from the remaining subsystems, the team allocated one equipment rack's worth of volume to each of the remaining subsystems for spares and consumables. Although this is likely an *over*estimate for some subsystems (C&T, for example) it is likely an *under*estimate for other subsystems (such as ECLS). Note that water used for crew radiation protection was book-kept under the Contingencies category, rather than as a consumable.

To gain a sense of the consumables volume—as well as the resulting waste volume generated by consumption of these items—on a long-duration mission, select examples calculated by the Human Factors team are presented.

Food and Drinks

Unlike current ISS missions, fresh food will not be resupplied during a DSH mission. The long unmanned loiter period before the crew arrives will also drive shelf life requirements of the foods provided to the crew.

According to the NASA Johnson Space Center's Food Lab, ISS food requirements are based on a minimum caloric intake per day (approximately 3000 calories) [3]. Four crew members each eating 3 meals per day for 380 days will require approximately 4,560 meals. Meals are made up of an assortment of thermostabilized, rehydratable, and bite-size foods. Figure 3 shows food stowage in a CTB which typically holds about 27 meals. Assuming each crew member will also consume up to five flavored drinks per day (coffee, tea, etc.), a total of 7,600 dehydrated drink powder bags will also be required.

Fig. 3: A crew transport bag with food packed inside.

Clothing Packaging and Volume

On ISS, crewmembers are issued one pair of shorts and a t-shirt for every three exercise days. Crew work shirts and pants/shorts are changed, on average, once every 10 days. Crewmembers generally use a new T-shirt to wear under their work shirts every 10 days. Underwear and socks are changed every other day, but thicker socks, which are worn if a crewmember's feet get cold, must last a month. Crew members are also issued two sweaters. In addition, each crew member receives one pair of running shoes to use on the treadmill and another pair of shoes to wear when using the exercise bicycle.

On average, a single CTB holds about 2 weeks of ISS clothing, not including socks and underwear (see Figure 4). Unlike ISS, which has the luxury of regular resupply flights, a long duration DSH mission would require higher efficiency clothing packaging than currently used for ISS. For example the use of vacuum-sealed bags which can reduce volume by up to 80% would allow approximately 5 weeks of clothing to be stowed in a single CTB. Another suggested strategy for long duration missions is for work clothing to be worn until it is soiled, and then used for exercise until it is disposed of. Recent strides in the development of lower-volume materials used for disposable clothing also promise future mass and volume reductions, though it should be noted that these fabrics are not yet certified to meet the flammability and off-gassing standards for spacecraft use.

Fig. 4: A CTB with 2 weeks of clothing.

Waste Management Supplies

Waste generated on a long duration mission poses a number of questions. For example, should waste be discarded or recycled for other purposes? One interesting idea is to melt food package waste and compress into plastic bricks to serve as crew radiation protection. On the other hand, this would require DSH to carry additional equipment and increase power loads. Although the baseline assumption for this exercise was to discard waste generated during the outbound trip with the jettisoned MMSEV, future trade analyses should evaluate the costs and benefits of recycled waste.

It was assumed that trash volume created during the mission would be roughly equivalent to consumable volume (food, wet wipes, etc.) depleted. Therefore, for the purpose of this exercise, trash volume does not contribute to the overall cabin volume calculation. That said, it should be noted that trash can not necessarily be returned to the same stowage location that its constituent consumables once occupied so, in practice, a dedicated staging area may be required.

There are two types of human waste containers, one for urine and wastewater collection and another for solid waste. With a liquid reclamation system, current urine/wastewater containers have a life of about 90-days. With proper compression of waste, current solid waste containers can be used 21 times. Using current equipment, a 380-day mission with 4 crew would need about 5 urine/wastewater containers and approximately 108 solid waste containers. This does not include estimates for urine hoses and filter inserts, which were included as part of the ECLS subsystem spares volume.

Hygiene Supplies

Hygiene supplies include personal items such as toothpaste and hand/face wipes, but also group items such as antibacterial wipes and biocidal cleanser. Currently on ISS, there are several different wipes that support housekeeping: dry, durable, detergent, disinfectant, and utensil wipes. There is no limit on the usage rate for dry and durable wipes, however, for detergent and disinfectant the usage rate is about 6 of each per crewmember per day and 3 utensil wipes are used per person per day. There are 50 dry wipes per package and 30 per package for all others. To place in perspective, for a 380-day mission, the minimum number of dry wipes used would be around 15,200 or 304 packages.

On ISS each person is allotted 1 wet towel and 2 dry towels per day which would require a total of 4,560 towels during the DSH mission. DSH is assumed to have a full body wash compartment, but it is unknown how this would affect the number of towels needed. Additional volume is required for other hygiene supplies such as toothpaste, deodorant, lotion, and shampoo. Electric razors would probably be used rather than straight razors and shaving cream, but an electric razor would require a vacuum cleaner.

IV.VII Contingencies

The team evaluated the functional volume required to address a number of possible contingency scenarios. These included fire, toxic atmosphere, cabin depressurization, radiation events, and crew fatality.

The team estimated a total volume of 5.4 m^3 (190.7 ft^3) for contingencies, with the bulk of the volume being shared with other areas.

V. TOTAL FUNCTIONAL VOLUME

Using the numbers outlined above, and before taking into account shared volumes, the total functional volume was found to be 322.65 m^3 (11,394 ft^3), distributed across the seven functional categories as shown in Figure 5.

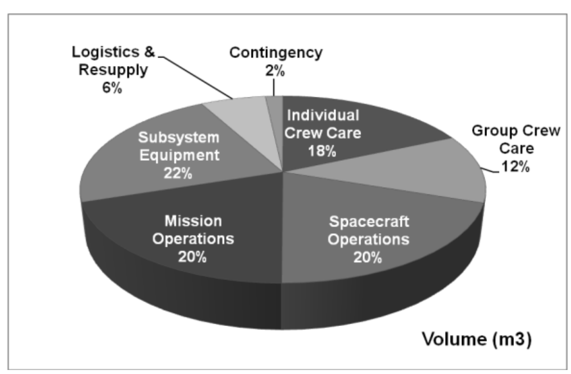


Fig. 5: Total Functional Activity Volume Distribution.

As expected, Logistics/Resupply and Contingency functions require considerably less volume than Subsystem Equipment, Crew Care, or Mission and Spacecraft Operations.

VI. ACTIVITY FREQUENCY AND DURATION

Once the functional activity list was established, the team made engineering judgements about the expected frequency and duration of each activity. This information would then be used to determine which activities could share the same volume without conflict. Some activities, such as EVA, require a stationary, dedicated functional volume for technical reasons. Other activities, such as stowage, also require a dedicated volume, but can move around the habitat as needed (e.g., food resupply in the galley). Many activities do not require either a dedicated or a stationary volume and can share space with other activities, particularly if the two functions occur at different times of the day. For example, a group dining area would lend itself well to also hosting planning meetings or group recreational activities. Frequent or long-duration activities often require larger volumes to accommodate crew comfort and safety, although this is not always the case. For example, maintenance of large items may be a rare contingency, but would require a relatively large area.

VII. SHARED VOLUME ASSESSMENT

In addition to the frequency and duration information, the team categorized location (stationary or moveable) and whether a function required a dedicated volume. Obvious candidates for shared volumes were noted. After taking into account shared volumes, the total required volume dropped 24% to 244.2 m^3 (8,623.8 ft^3), distributed as shown in Figure 6 (cf., Figure 5).

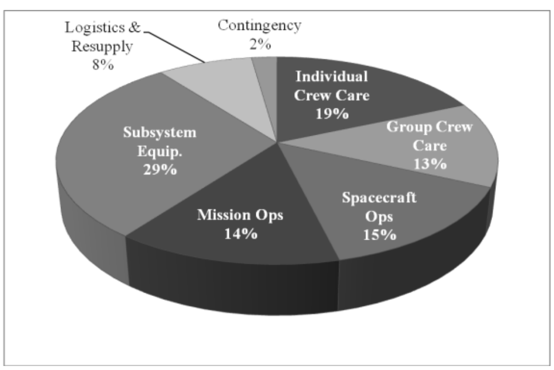


Fig. 6: Shared Functional Activity Volume Distribution.

VIII. MODULE LENGTH

To arrive at a module length, the team added 10% to the 244.2 m^3 (8,623.8 ft^3) shared volume to account for internal structural elements (such as floor thickness) and "unknown unknowns" due to the low fidelity of the design. This resulted in a minimum pressurized volume of 268.6 m^3 (9,486 ft^3) to accommodate all anticipated DSH activities. Assuming elliptical end caps, a 7 m (22.97 ft) diameter cylinder would be just under 8 m (26.5 ft) long, so the team "rounded up" to an 8 m length, resulting in a module with a total pressurized volume of approximately 274.9 m^3 (9,708.5 ft^3).

IX. MODULE ORIENTATION

As shown in Figure 7, the problem with a horizontal cylinder is the loss of ceiling height toward the sides of the module. To avoid this inefficient design, different internal orientations for equipment near the edges could be implemented, but that violates best practices guidelines for consistent equipment orientation. "Floors" could be positioned to provide sufficient head-height at the edges, but that would result in a very high ceiling height at the center of the module, potentially impeding crew mobility in microgravity. On the other hand, a vertical orientation could provide consistent ceiling heights across each level. Although wall curvature would drive conformal design for equipment placed near the walls, the curvature is relatively small, compared to a 4.5 m (14.76 ft) diameter ISS module. For these reasons, the team selected a vertical cylinder.

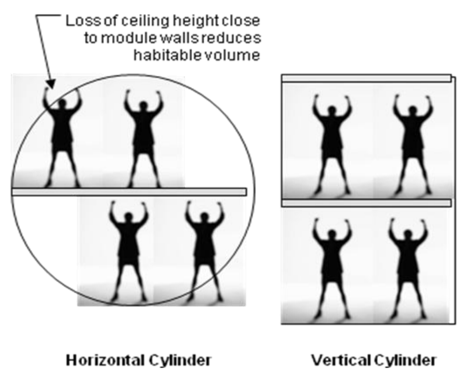


Fig. 7: Horizontal versus Vertical Orientation.

Based on the proposed vessel length of 8 m (26.2 ft) and a 99th percentile crew stature of 1.92 m (6 ft 4 in), the DSH was organized into four decks, each with a volume as shown in Figure 8.

X. DSH CONCEPTUAL LAYOUT

Once functional area volumes were defined, and activity frequency and duration were established, the team developed candidate layouts that could accommodate all activities in the most efficient manner, while providing safe, comfortable living and working spaces.

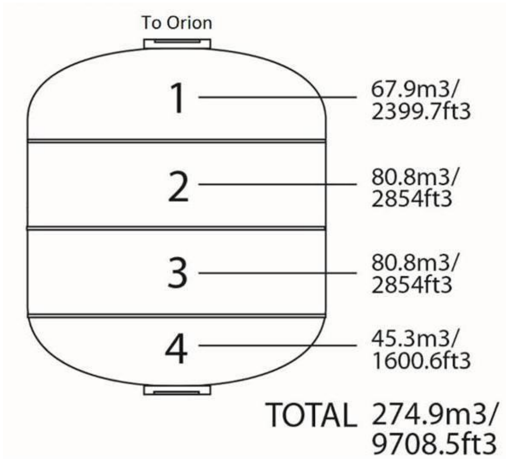


Fig. 8: Four-level DSH Concept.

Based on anecdotal evidence from crew collected during evaluations[5] and ISS post-mission debriefs, the crew typically wants a clear separation of "work" and "leisure" areas. Therefore, the team tried to group maintenance, geological science, and EVA operations (suits and airlock) into a single area. Crews have also expressed a desire to separate "noisy and dirty" from "quiet and clean" areas. Exercise and waste containment system (WCS) activities fell into the former category, while galley and sleeping areas were placed in the latter. The multi-level DSH concept allowed these groupings to be separated by distance for safety and hygiene. This resulted in the four decks being categorized as: 1) group living and operations; 2) personal living; 3) work and hygiene; and 4) stowage and subsystems (Figure 9). A central translation tunnel provides access between decks.

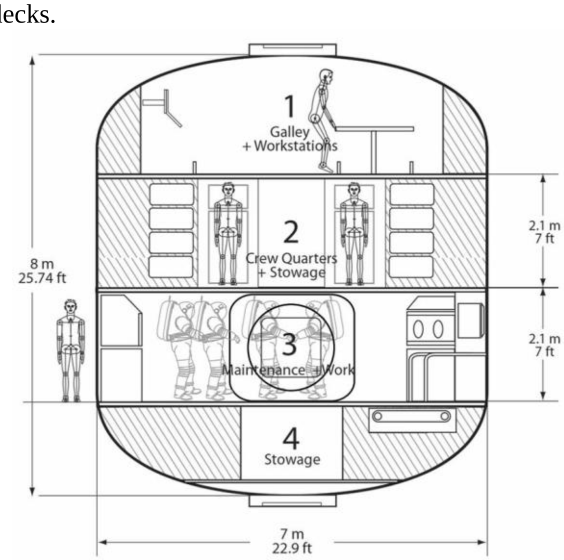


Fig. 9: Conceptual DSH Layout.

Three areas required careful consideration during placement: the waste containment system (WCS), exercise, and medical areas. Due to the private nature of WCS activities, it was advantageous to have this area separate from group leisure and crew quarters. Exercise tends to be dirty and loud, so it was desirable to locate exercise equipment away from food and crew quarters. The medical area, which normally would be considered clean, should be located near exercise for metabolic monitoring. Therefore, these three areas were co-located with one another and grouped with the "dirty" and "work" activities, isolated from the galley, but close enough to crew quarters as to make the WCS readily accessible. It was assumed that the maintenance and medical areas would have a lower frequency of use than WCS or exercise equipment, but privacy curtains could be used between areas to prevent contamination.

Some sub-system equipment would necessarily be distributed throughout the vessel, for example carbon dioxide removal units could be located on each level to reduce the number of fans, which tend to be noisier pieces of equipment. As noted in earlier work done to estimate the ECLS functions for a Lunar Outpost[5], each deck would need to accommodate volume for air revitalization, fire detection and suppression, and emergency response functions.

X.I Deck 1: Control Room and Group Living

The upper-most deck, or Deck 1 (Figure 10), is where the Orion would dock. This deck contains the subsystem and spacecraft control consoles, the galley, and a dining area that doubles as a conference room or group recreation area.

This deck would share sub-systems operations with group living. It is assumed during the journey that most day-to-day activities will be taking place in this area. This deck would provide the space for crew recreational activities (e.g., games, watching movies), eating/group meals, and personal or group work space (e.g., group meetings). All sub-systems will be monitored and controlled from this area.

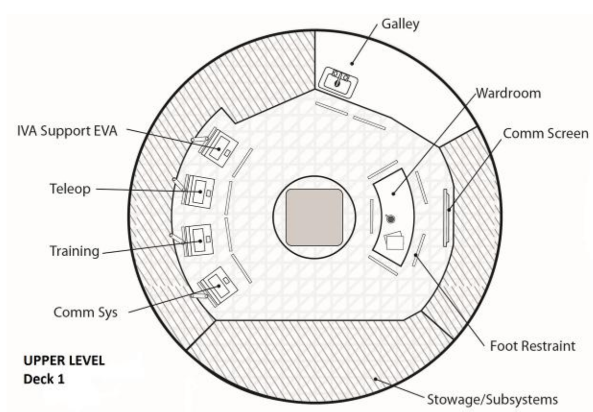


Fig. 10: Deck 1- Group Living and Operations.

As previously mentioned, the team proposed distributed stowage. Stowing some food, water, and hygiene supplies on Deck 1 not only provides modest crew radiation shielding, but also streamlines operations by limiting the need to continually retrieve items from a central storage area. Because Orion is the designated safe haven, having a supply of food and water near Orion could also aid in emergency response.

X.II Deck 2: Crew Quarters and Stowage

Deck 2 (Figure 11) was primarily dedicated to four individual crew quarters, arranged around a central translation pathway. The crew quarters were positioned as far towards the center of the module as possible, in order to maximize radiation protection by way of stowage (e.g., clothing or water) and other non-hazardous items between the crew and the pressure shell. The team avoided mounting moving equipment on the floor above, or the ceiling below, to minimize noise in the crew cabins. Using the same distributed stowage logic as outlined above, the team assumed that crew clothing and some hygiene supplies would be located in the crew quarters on Deck 2 to streamline operations and provide modest radiation protection benefit.

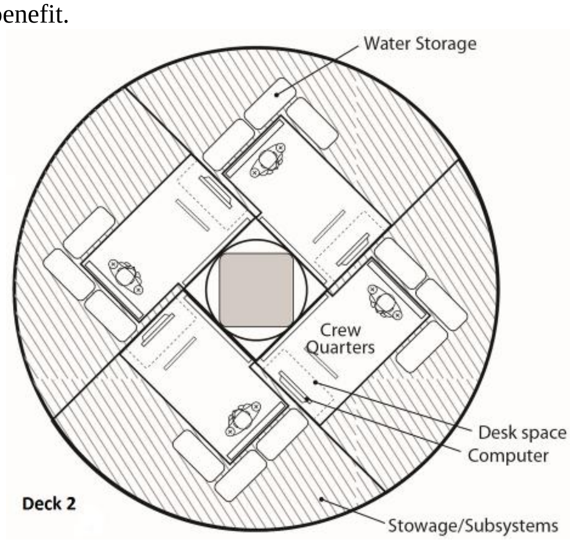


Fig. 11: Deck 2 – Crew Quarters.

The living quarters are approximately two times larger than those currently on ISS, but it is expected that the larger space would be desirable for long-duration missions and distributed stowage. For example, the crew quarters will support personal activities (e.g., report writing) and communication, some hygiene activities (e.g., wet towel bath, brushing teeth), changing clothes, long-term medical care, and possibly a safe-haven during a radiation event.

In a 2006 report[4], the activities that were performed in the ISS crew quarters (besides that of sleep) included: using personal computer (i.e., emails), changing clothes, reading (i.e., review of procedures or books), listening to music/watching a movie, hygiene, family and ground conferences, and non-sleep resting periods.

X.III. Deck 3: Maintenance, Hygiene, Medical, and Exercise Area

Deck 3 (Figure 12) is where most hands-on activities would occur. This area houses space for science, maintenance, hygiene, exercise, and medical operations. To minimize translation (and potential contamination) external maintenance items come into the DSH through the Airlock, and go straight to the maintenance area. The waste/hygiene areas are readily accessible from the crew quarters, but relatively isolated from the galley. The exercise equipment is also on Deck 3.

The bulk of medical and biological operations would center on crew health and routine medical care. Therefore, it was desirable to have the medical station located close the exercise area to collect metabolic data. The medical station will also be used to collect crew health data (e.g., blood draws, BP and heart rate, intracranial pressure data, etc.). Thus, having the biological station close to the medical station was desirable. Most medical care will consist of minor emergencies (e.g., cuts/scraps) with more critical medical needs having a low probability of occurrence. Although the medical station should be able to accommodate minor surgeries, it was assumed that long-term care and recovery would occur in the crewmembers' personal quarters.

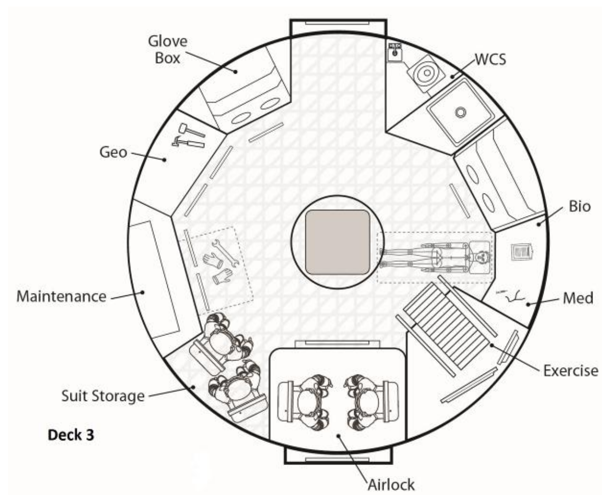


Fig. 12: Deck 3- Maintenance, Hygiene, Medical, and Exercise Area

X.IV Deck 4: Subsystem Equipment and Stowage

Due to the low ceiling height, Deck 4 is limited to stowage and some subsystem equipment. Noisy or dangerous equipment is mounted on Deck 4 as this is as far away as possible from the crew quarters and Orion. For example, the treadmill's vibration isolation and stabilization system is a relatively noisy piece of equipment, so it was designed to mount through the Deck 4 ceiling, as far as possible from the crew's personal quarters and work areas. Other sub-system equipment located on Deck 4 would include the water reclamation system and some high pressure oxygen ECLS equipment.

XI. VOLUME COMPARISON

XI.I Pressurized Volume

As a sanity check on the DSH estimated volume, the team compared the DSH to Mir, Skylab, ISS, TransHab, and Bigelow Aerospace's BA330. As shown in Table 1 (refer to the last page of this paper), the DSH has the lowest pressurized volume of the six spacecraft. When divided by the crew complement, the DSH pressurized volume per crew member falls within the range of other historical spacecraft.

XI.II Habitable Volume

Habitable volume, defined as free volume, unencumbered by equipment or stowage, is difficult to assess at this level of design detail. From the initial estimates outlined above, DSH is predicted to contain approximately 118 m^3 (4,167 ft^3) of equipment. Subtracting this and 24.42 m^3 (862 ft^3) (the 10% margin for internal structural features and packing inefficiency noted in section VIII) from the total pressurized volume of 274.9 m^3 (9,708.5 ft^3), yields 132.48 m^3 (4,678.5 ft^3) habitable volume. Divided by four crew members, this leaves about 33.12 m^3 (1169.6 ft^3) habitable volume per crewmember, not including Orion or MMSEV volume. Although NASA-STD-3000[6] has recently been retired, historical recommendations from that document (Figure 13) serve to illustrate how the DSH compares in terms of habitable volume. Using the long-duration habitable volume guideline of approximately 19 m^3 (671 ft^3), and assuming actual DSH equipment volume does not exceed preliminary estimates, the DSH architecture exceeds the optimal habitable volume for a crew of 4, particularly when enhanced with MMSEV and Orion habitable volumes.

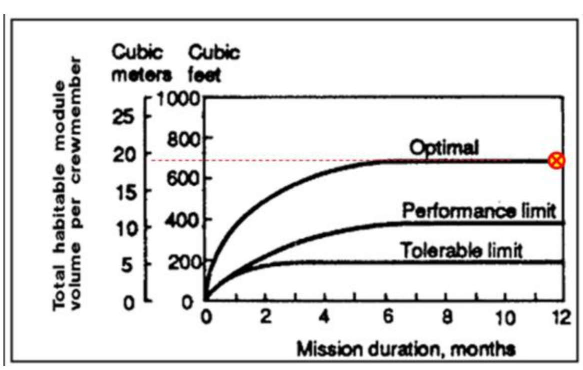


Fig. 13. NASA-STD-3000 habitable volume guideline

XII. CONCLUSIONS

XII.I Methodology

For the purposes of establishing a preliminary volume and vehicle layout from which subsystem teams could begin working detailed designs, the methodology outlined in this paper was successful. Although the exercise was suspended prior to completing detailed designs, the preliminary concept discussed here allowed each of the subsystem teams to formulate a design strategy, and begin developing integrated assessments.

XII.II DSH Volume

Based on an assessment of *total pressurized volume*, an argument could be made that the proposed DSH concept may be *under-sized* in comparison with some historical spacecraft, particularly since DSH must be self-sufficient for more than a year, with no emergency resupply or rescue options. Of course, technology advancements and equipment miniaturization could make some of these historical comparisons inaccurate.

On the other hand, preliminary assessment of *habitable volume* suggests that the proposed DSH concept could be *over-sized* with respect to historical guidelines, though this may also be misleading because equipment volume is not well defined at this level of design fidelity. It should also be noted that the historical guidelines did not envision missions exceeding 12 months.

What can be said is that the conceptual DSH volume calculated using this method appears to be reasonable with respect to historical spacecraft experience, though obviously much more detailed design would be required for proper validation.

XII.III Applicability to Other Spacecraft

Although the design presented in this paper is specific to a particular mission, destination, and crew size, the logic used to size this spacecraft may be useful in establishing conceptual designs to initiate other long-duration, microgravity spacecraft design exercises.

REFERENCES

[1]Christensen, Eric L, (2003). *Meteoroid/Debris Shielding*. TP−2003-210788.

[2]NASA-STD-3001, Volume 2: Human Factors, Habitability, and Environmental Health. National Aeronautics and Space Administration.

[3]NASA/SP-2010-3407, *Human Integration Design Handbook (HIDH)*. National Aeronautics and Space Administration.

[4]Rando, C., and Duvall, L. (2006). *Summary of Evaluation Results for the 2006 International Space Station (ISS) PDR Low-Fidelity Crew Quarters Mock-up*, CQ-06-064.

[5]Carrasquillo, R., Bagdigian, R., Anderson, M., and Lewis, J. (2008). *Support Requirements and Technology Challenges for NASA's Constellation Program.* ICES Paper 2008-01-2018.

[6]NASA-STD-3000, Revision B, Space Flight Human-System Standard, Volume 1, Section 8, NASA, July 1995.

Parameter	**DSH**	[*] **Mir**	[t] **Skylab**	[:t] **TransHab**	[§] **BA 330**	[<J[] **6-Crew ISS**
Crew	**4**	2 – 6 (3 typ.)	3	6	6	6
Mission Duration	**380 Days**	Up to 437 Days	Up to 84 Days	180 Days	180 Days Per Expedition	180 Days Per Expedition
Length	**8 m (26.25 ft)**	14.4 m (Spektr Module) (47.2 ft)	14.66 m (Workshop Module) (48.1 ft)	11 m (36 ft)	14 m (45 ft)	8.5 m (Destiny Module) (27.9 ft)
Diameter	**7.0 m (22.97 ft)**	4.15 m max. (13.6 ft)	6.7 m (Workshop Module) (22 ft)	8.2 m (27 ft)	6.7 m (22 ft)	Typ. 4.2 m (13.8 ft)
Total Pressurized Volume	**274.9 m^3 (9,708 ft^3)**	380.1 m^3 (13 419 ft^3)	>345 m^3 (12,184ft^3)	339.8 m^3 (12,000 ft^3)	330 m^3 (11,653.8 ft^3)	Total 916 m^3 (32,348 ft^3)
Pressurized Volume per Crewmember	**68.73 m^3 (2,427 ft^3)**	126.7 m^3 w/3 crew (4,474 ft^3)	>115 m^3 (4,061 ft^3)	56.63 m^3 (2,000 ft^3)	55 m^3 (1,942 ft^3)	152.7 m^3 (6crew) (5,393ft^3)
Habitable Volume per Crewmember	**33.12 m^3 (1,170 ft^3)**	--	115 m^3 (4,061 ft^3)	--	--	64.67 m^3 (2,284 ft^3)

Table 1: Comparison of DSH pressurized volume against historical spacecraft

[*] http://spaceflight.nasa.gov/history/shuttle-mir/spacecraft/s-mir.htm
[t]http://history.nasa.gov/SP-400/ch2.htm. Note: volume includes Workshop, Airlock, and Docking Adapter, but not Crew and Service Module.
[:t]http://spaceflight.nasa.gov/history/station/transhab/
[§]Bigelow Aerospace, as of August 30, 2011. http://www.bigelowaerospace.com/ba330.php
[<J[]International Space Station "Facts & Figures," http://www.nasa.gov/mission_pages/station/main/onthestation/facts_and_figures.html