Habitable Working and Living Spaces in the Deep Space Science Vessel

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The Deep Space Science Vessel (DSSV) is a conceptual design of a very large spacecraft intended as a mobile microgravity science platform. It represents an effort to conceptualize the systems and internal architectures needed to support a forty-eight-person crew for multi-year missions throughout the inner solar system and potentially beyond. The general arrangement of the DSSV is a modular spacecraft. Considering only the pressurized, habitable elements, the DSSV includes two large pressurized modules (Hab and Lab) docked together along with eight smaller node modules completing the habitable configuration. The Hab and Lab modules are docked side by side, with the longitudinal axes parallel to each other and a single docking port connecting them. A node module is docked to each dome on the Hab and Lab modules, such that the two small node modules on each end of the large Hab and Lab domes are docked both to each other and to the Hab and Lab. This creates a "racetrack" translation path on the interior. The other four node modules are docked at the center of the Hab and Lab modules, two on each side, creating another "racetrack" translation path perpendicular to the first one. The DSSV has a generally vertical orientation. Within the Hab and Lab modules the decks are perpendicular to the longitudinal axis. The node modules are oriented with their longitudinal axes perpendicular to those of the Hab and Lab modules, so the nodes have a horizontal internal orientation. Decks are numbered one through nine, with decks two and eight representing the "top" and "bottom" domes of the Hab and Lab modules. The Hab Module decks encompass the ship's galley, crew quarters, waste, hygiene, portions of crew exercise, and group recreation. The Lab Module contains food production facilities, the life science lab, the ship's infirmary, the physical science lab, and the maintenance and fabrication workshop. The Node Modules serve a number of different functions. The two Exercise Nodes are docked to deck five of both the Hab and Lab modules and contain most of the aerobic and resistive exercise devices. Also docked to deck five but on the opposite side of the Hab and Lab modules are the Observation Deck and Space Café. These two node modules provide social gathering space for small numbers of crew. The Mission Operations Node is on deck nine directly above the Galley and contains spacecraft monitoring and commanding capabilities. Docked to it is the EVA Operations Node, which contains suit maintenance and storage. (The airlock is a separate, external element docked to the EVA Operations Node.) The Subsystems Node is on deck one beneath the maintenance and fabrication workshop. Docked to it is the Stowage Node. This node does not house DSSV primary stowage, but is a staging point where stowage brought in from logistics modules can be sorted, unpacked, or repacked as needed prior to distribution to the appropriate sections of the spacecraft.

I. Nomenclature

ARED = Advanced Resistive Exercise Device

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CEVIS = Cycle Ergometer with Vibration Isolation System
CIR = Combustion Integrated Rack
CMG = Control Moment Gyroscope
CTB = Cargo Transfer Bag
DSEV = Deep Space Exploration Vehicle
DSSV = Deep Space Science Vessel
ECLSS = Environmental Control and Life Support Subsystem
EKG = Electrocardiogram
EVA = Extravehicular Activity
FBHU = Full Body Hygiene Unit
FIR = Fluids Integrated Rack
I_{sp} = Specific Impulse
MCC = Mission Control Center
MISSE = Materials International Space Station Experiment
NEA = Near Earth Asteroid
PMAD = Power Management and Distribution
RCS = Reaction Control System
SOS = Science on a Sphere®
T2 = Treadmill 2 (Second Generation Treadmill with Vibration Isolation System)
UWMS = Universal Waste Management System
VAA = Vehicle Architecture Analysis

II.Introduction

The Deep Space Science Vessel (DSSV) is an exploratory study to understand the habitability considerations needed to sustain and ensure the productivity of a relatively large crew for long-duration microgravity missions away from Earth. It is not part of any current NASA exploration program but is envisioned as a possible follow-on that might be implemented after the initial human Mars exploration missions. The DSSV is a multi-purpose, multi-disciplinary, microgravity science vessel intended for human space flight operations throughout the inner solar system. Potential missions encompass orbits of Mercury, Venus, Earth, Moon, Mars, Phobos, Deimos, and Ceres as well as other Near-Earth Asteroids (NEAs), main belt asteroids, and interplanetary space. The DSSV is based on a crew size of forty-eight and anticipates missions in of five or more years in duration. While some technologies do not yet permit missions of this duration, this study begins to conceptualize the habitation systems that might be required to support a forty-eight-person crew for multi-year missions throughout the inner solar system and potentially beyond. Aside from the inherent discovery directly relevant to this study, this data may help prioritize areas of research and technology development for more near-term missions and encourage the development of systems that can feed forward to future exploration systems of this type.

III.History and Background

The concept of the DSSV originated based on an initially rhetorical question of what the next human spaceflight goal should be after long-duration surface missions on Mars have been completed. It also reflects an effort to understand the implications for spacecraft habitation systems extending beyond the traditional small crew sizes that have characterized flown spacecraft throughout the history of human spaceflight.

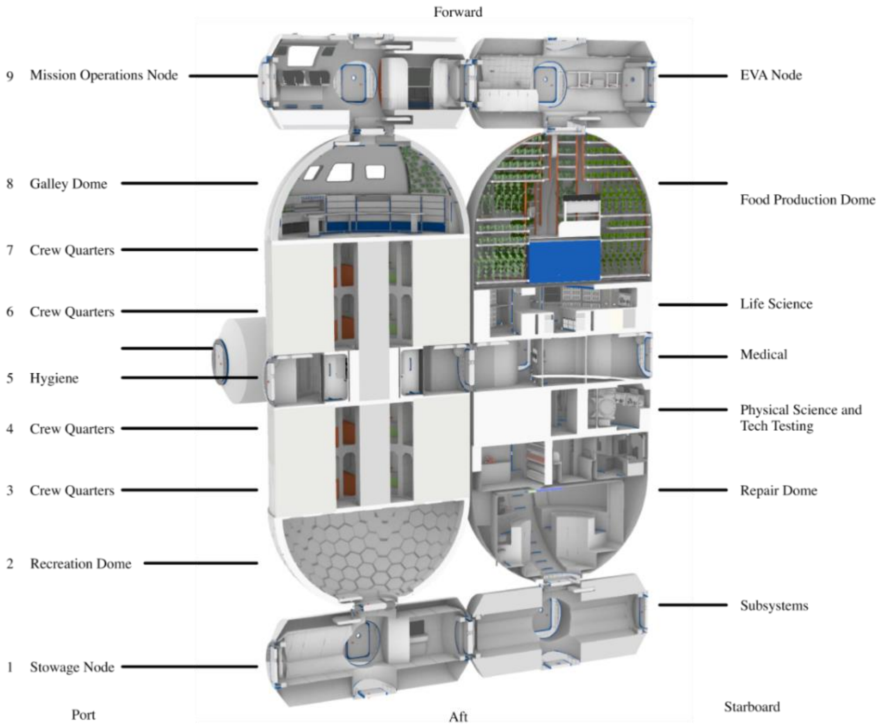
This is, of course, not the first study where habitats with large crew sizes have been conceived. Space colony studies have explored populations in excess of 20,000 people. [1] Most recently, SpaceX has suggested an intention to transport 100 people at a time to Mars in a single Starship. [2] However, the specific habitation details for these and other large crew size studies do not appear to be publicly available.

Work on the DSSV has been primarily conducted as a student exercise involving Industrial Design students from the Rhode Island School of Design. A rough, initial concept was developed by NASA personnel. A RISD design studio undergraduate course next focused on prototyping of select living areas within the Hab Module. Finally, two RISD undergraduate interns worked with a NASA mentor to develop a human-centered CAD layout of the pressurized volumes of the DSSV. The focus thus far has been on defining the crew-centered functions and layout associated with a forty-eight-person science spacecraft intended for long-duration microgravity operations throughout the inner solar system.

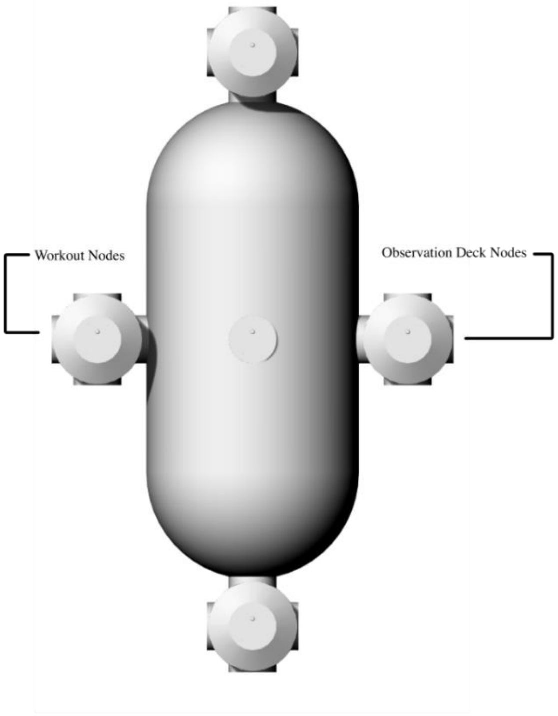
IV.General Arrangement of the DSSV

A. Module Arrangement

The general arrangement of the DSSV is a modular spacecraft. Considering only the pressurized, habitable elements, the DSSV includes two large pressurized modules (Hab and Lab) docked together along with eight smaller node modules completing the habitable configuration, shown in Fig. 1. The Hab and Lab modules are each 10 meters in diameter and 22.5 meters in length. Each node module is 4.5 meters in diameter and 10 meters in length. The Hab and Lab modules are docked side by side, with the longitudinal axes parallel to each other and a single docking port connecting them. A node module is docked to each dome on the Hab and Lab modules, such that the two small node modules on each end of the large Hab and Lab domes are docked both to each other and to the Hab and Lab. This creates a “racetrack” translation path on the interior. The other four node modules are docked at the center of the Hab and Lab modules, two on each side, creating another “racetrack” translation path perpendicular to the first one. The DSSV has a generally vertical orientation. Within the Hab and Lab modules the decks are perpendicular to the longitudinal axis. The node modules are oriented with their longitudinal axes perpendicular to those of the Hab and Lab modules, so the nodes have a horizontal internal orientation. Decks are numbered one through nine, with decks two and eight representing the “top” and “bottom” domes of the Hab and Lab modules. The Hab Module decks encompass the ship’s galley, crew quarters, waste, hygiene, portions of crew exercise, and group recreation. The Lab Module contains food production facilities, the life science lab, the ship’s infirmary, the physical science lab, and the maintenance and fabrication workshop. The Node Modules serve a number of different functions. The two Exercise Nodes are docked to deck five of both the Hab and Lab modules and contain most of the aerobic and resistive exercise devices. Also docked to deck five but on the opposite side of the Hab and Lab modules are the Observation Deck and Space Café. These two node modules provide social gathering space for small numbers of crew. The Mission Operations Node is on deck nine directly above the Galley and contains spacecraft monitoring and commanding capabilities. Docked to it is the EVA Node, which contains suit maintenance and storage. The Subsystems Node is on deck one beneath the maintenance and fabrication workshop. Docked to it is the Stowage Node.



3/4 Split View



Port Side View

Fig. 1 DSSV Deck Overview

B. Circulation and Utilities

1. Circulation

The DSSV employs modified racetrack circulation patterns in both the vertical and horizontal dimensions as shown in Fig. 2. Within the Hab Module, there are two vertical translation paths running through the center of the module's barrel sections. Within each dome there are two translation paths along the dome surface, offset 180 degrees from each other. The dome exits to the barrel section through the two center vertical translations and to the node though a single hatch opening. The nodes connect to each other through a single hatch. In the Lab Module, vertical translation is through parallel paths that run along the pressure vessel, offset 180 degrees from each other. Horizontally, there is a complete racetrack configuration on deck 5, encompassing the Hab and Lab modules as well as the exercise and lounge nodes. All hatch openings, whether vertical or horizontal, measure 40 inches in width and 60 inches in height. There are twenty-four docking ports for connections to airlocks, attached spacecraft, or visiting vehicles.

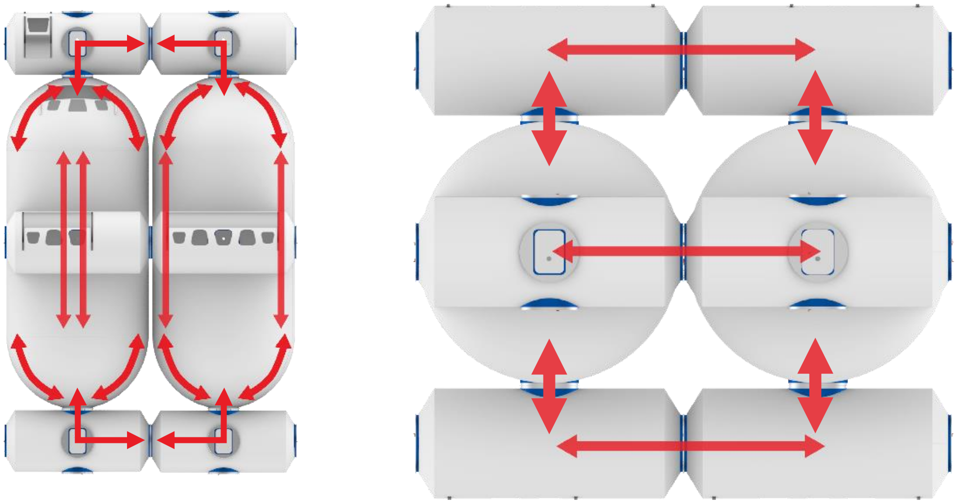


Fig. 2 DSSV Internal Circulation Paths

2. Utilities

The DSSV employs a utilities network with a primary routing that follows the crew circulation path as shown in Fig. 3. The primary routing contains the main, high capacity distribution and can circulate utilities across docking connections. The secondary ducting is primarily in floors/ceilings and node pressure vessel walls, connecting the primary routing to individual components. This utilities network distributes power, potable water, wastewater, high pressure gases, cabin air supply/return, thermal control fluid, and data throughout the DSSV stack.

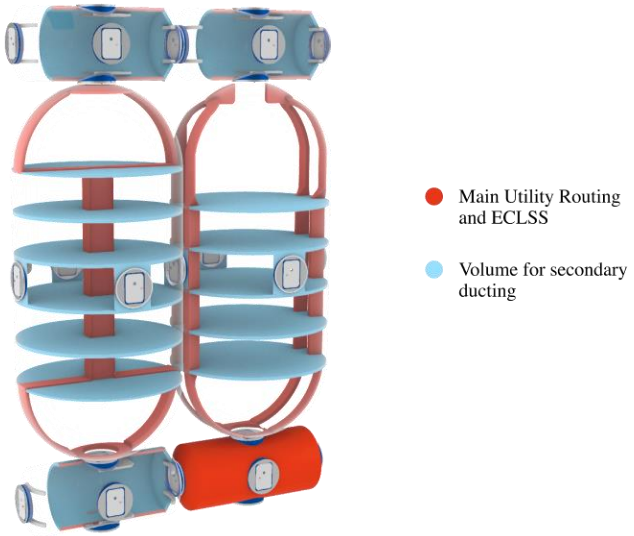


Fig. 3 DSSV Utilities Network

C. DSSV Crew Composition

The DSSV crew are organized into departments, shown in Table 1, based on crew function. In addition to their primary function, some are cross trained as pilots and can operate the microgravity variants of the Pressurized Rover that are docked to the DSSV. Several others are cross trained as paramedics and can supplement the medical staff.

Table 1. DSSV Crew Composition

Department	Primary Work Area	# Crew	# Cross-Trained as Pilots	# Cross-Trained as Paramedics
Operations (11 crew)	Bridge	7	3	1
	EVA, Flight Ops, & Logistics	4	4	0
Food Production (6 crew)	Galley - Food Prep	2	0	1
	Food Production	4	0	0
Engineering (9 crew)	Softgoods & Thermoplastics	3	0	1
	Machining	3	2	0
	Electronics & Software	3	2	0
Physical Science (8 crew)	Combustion & Fluid Lab	2	0	1
	Astronomy & Meteorology Lab	2	1	0
	Materials Science Lab	2	0	0
	Geology Lab	2	2	1
Medical (6 crew)	Surgeon	2	0	0
	Physician	3	1	0
	Counselor	1	0	0
Life Science (8 crew)	Human Research Lab	2	2	0
	Animal Research Lab	2	0	1
	Microbiology Lab	2	0	1
	Botany Lab	2	0	0
		48	17	7

The Operations Department, as its name indicates, are the primary vehicle operators. These are the astronauts who manage all of the spacecraft subsystems, control the DSSV flight path, and interact with visiting vehicles. The Food Production Department is responsible for crew nutrition. This is inclusive of both management of prepackaged food and production of fresh food. The Engineering Department is responsible for the maintenance and repair of DSSV subsystems, payloads, and any visiting vehicles. The Physical Science Department is responsible for the organization and execution of scientific research within various physical science domains. The Medical Department is responsible for the physical and mental well-being of the crew. And the Life Science Department is responsible for the organization and execution of human and all other biological scientific research.

The leadership structure of the crew includes a Vehicle Commander and Executive Officer from within the Operations Department and a head of each of the other five departments. Additionally, when the crew is subdivided into teams for excursions away from the DSSV (e.g. pressurized rover excursions, surface missions, EVAs, etc.) EVA or spacecraft commanders will be designated as appropriate.

V.Hab Module Layout

A. Crew Quarters Decks and Layout

The Crew quarters of the DSSV provide the crew with one of the few private spaces they will have to themselves during a mission. As the future of human space flight develops and longer duration missions are planned it is necessary to understand and adapt to the mental and physical needs of humans. These crew quarters give the crew as much living space as possible while allowing easy egress between decks and their rooms. Having an abundance of space will aid the astronauts on multi-year missions and accommodations have been made to make the spaces feel larger than they are while also expanding on the functionality of the space. The crew quarters are where the astronauts would sleep, stow personal items and communicate with family as well as having the space to work on reports or other digital assignments. The Crew quarters are divided into two areas on decks 3,4, 6, and 7 of the Hab Module. Each deck has 12 private quarters, shown in Fig. 4, housing the entire 48-person crew.

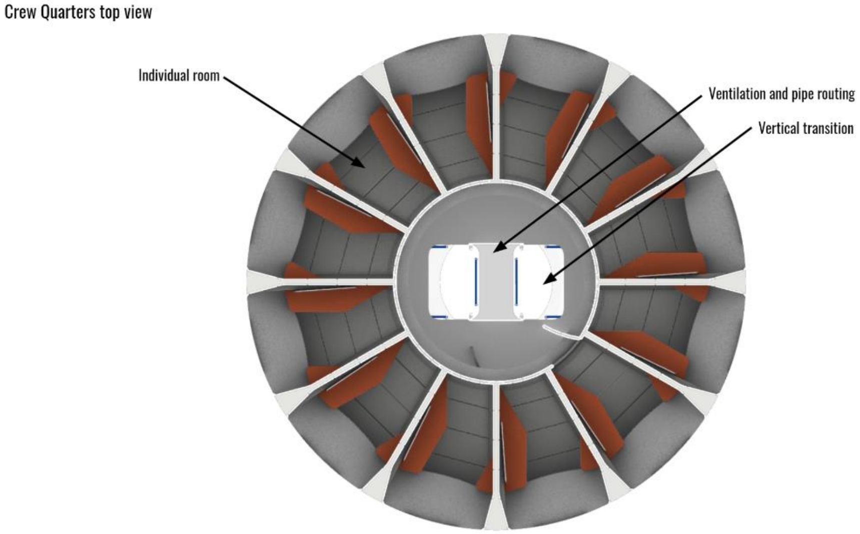


Fig. 4 Crew Quarters Deck Top View

The individual rooms are laid out radially to evenly distribute the rooms around the decks. This also keeps the rooms identical, preventing any rooms from being smaller or “worse” than any other which could create conflict on missions. Each room has a bunk and desk which contain stowage areas for the astronaut’s belongings. Below the bunk are two large pull out drawers for stowing larger items such as clothing. The desk contains a series of smaller drawers which pivot out from a single axis, shown in Fig. 5.

Fig. 5 Open Drawer

This design allows for drawers to take advantage of smaller spaces, giving the room more open floor space. Under the desk is a folding foot bar which would allow the astronauts to anchor themselves to the floor while working and then kick it down when access to the under-bunk drawers is needed. On the wall above the desk is a movable computer monitor allowing the astronauts to adjust between desk work and viewing from their bunk. The cabins also house a "digital window" consisting of a computer screen which would allow each room to have a view out of any area of the vessel or location on earth they would like to see. Computer screens were chosen over actual windows in this location in order to ensure an equal quality of view for each crew quarters. The layout of the crew quarters is loosely amenable to both microgravity and gravity environments, allowing the same design to be used on surface spacecraft. Air circulation was considered in the design of the crew quarters. Ventilation ducts wrap around the top outer corner of the decks, circulating air through each room with return air vents in the floor by the door.

These crew cabins were designed to allow the crew to have some level of customization in their rooms allowing them to swap out the surface color of their desk and bunk prior to launch and during the mission. Fig. 6 illustrates color customization examples.

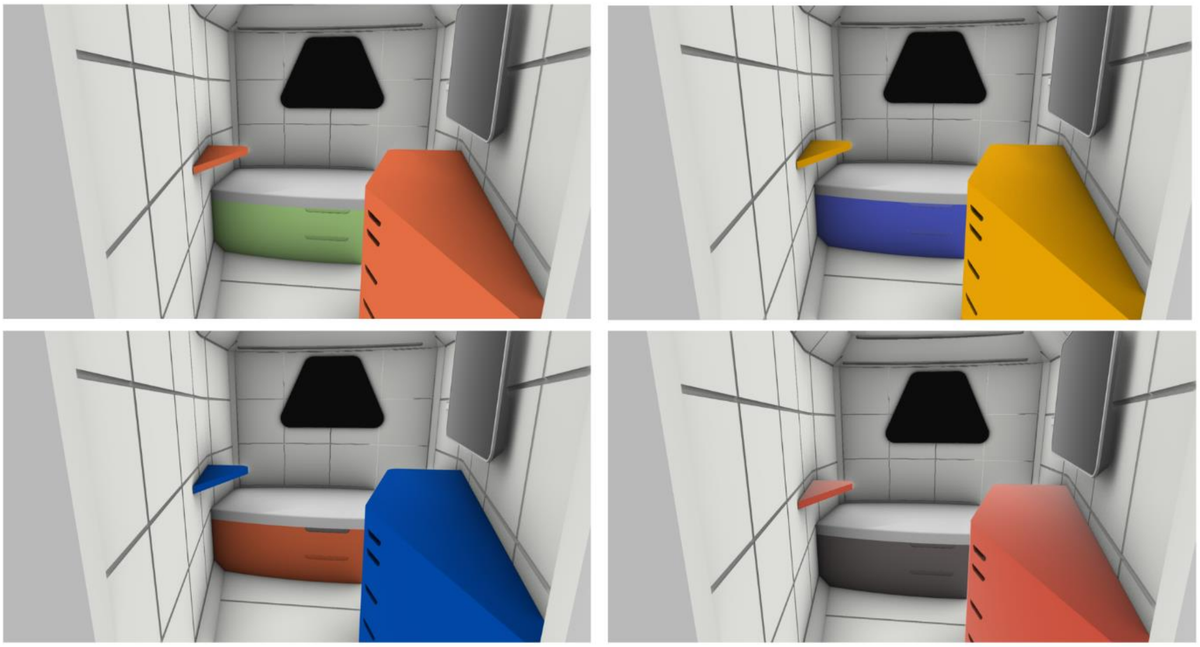


Fig. 6 Color Customization Options

This would allow the crew to truly make these spaces their own and help with feeling more comfortable or more “at home” during long missions.

Outside the cabins is a large common area where astronauts can mingle and talk. Within this volume are two translation ladders to move between decks. A central column lies in-between these vertical transitions, running through decks 3-7 of the Hab Module to accommodates for utilities ducting. This can be seen in Fig. 2.

B. Waste, Hygiene and Exercise Countermeasures

Waste, hygiene, and exercise countermeasures facilities are located primarily in the center of the DSSV. They consist of the entirety of Habitation deck five, a portion of Laboratory deck 5, and the nadir nodes. The central location of these facilities allows for easy and equal access to all crew members. As shown in Fig. 1, Habitation deck five is sandwiched between the crew quarters located on Habitation decks 3,4, 6, and 7. This way, crew members are never more than one or two decks from waste and hygiene facilities after their sleep period. Considerations such as this are vital so that large disparities in amenities do not create tension and frustration between crew members.

In total, there are eight waste collection units with handwashing stations and fourteen full body hygiene units. Additionally, the medical deck (Laboratory deck 5) houses two arm-washing stations. The Hygiene deck, shown in Fig. 7 and Fig. 8, is designed with two concentric circles, with Full-body Hygiene stations occupying the central ring and a portion of the outer ring. This concentric design allows for smooth crew movement throughout the deck and increased privacy since fewer units are directly facing one another. Crewmembers enter the deck from central translation openings. As much as possible these openings face hatches rather than waste or hygiene units so that as the crew move through the translation passages, the privacy of those using waste or hygiene facilities is maintained.

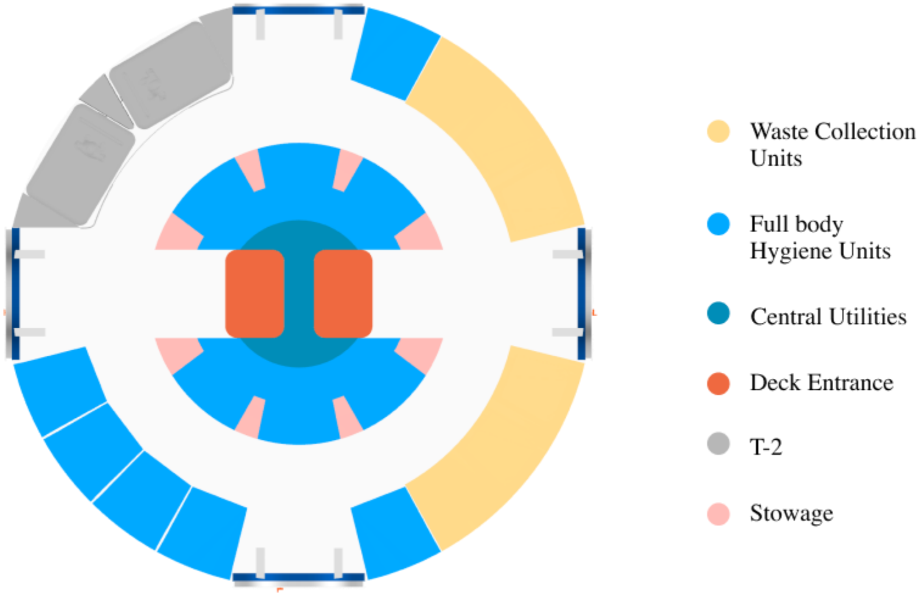


Fig. 7 Hygiene Deck Top View

In addition to waste collection and full-body hygiene units, the Habitation deck five also houses 2 Treadmills (T-2). These machines are located adjacent to the hatchway leading into the exercise nodes, which will be covered in the next section.

Lab deck five houses two arm-washing stations, two of the eight waste collection units, and 2 of the 14 Full Body Hygiene Stations. This provides the Lab Module with some waste/hygiene facilities and allows for accessible collection of fecal or urine samples as needed for medical or scientific purposes throughout the mission.

1. Waste Collection Units & Handwashing

Each of the eight waste collection units is identical. The number of waste collection units is comparable to terrestrial architectural recommendations, with the increase to 8 versus terrestrial standards of 5 or 6 [3] because it takes longer to use a microgravity toilet than a terrestrial one. However, it remains to be seen whether eight bathrooms are sufficient to support a crew of 48 for long durations in 0g.

Fig. 8 Hygiene Deck 3/4 View

Astronauts have described waste facilities in the ISS as difficult to use [4] and accidents occur in 0g that are difficult to clean up. [5] Given the number of crew and waste facilities on this spacecraft, such accidents could pose a health risk. For long-duration missions, adjustments to the design and usability of waste facilities are vital to ensuring crew mental and physical health.

The waste collection units in the DSSV utilize the Universal Waste Management System (UWMS). To increase cleanliness, the UWMS is enclosed in a removable housing. The housing streamlines the unit's appearance and provides a flat surface that can be readily cleaned and is coated with antimicrobial lining. The housing panels are easily removable to support fecal canister replacement and routine maintenance a shown in Fig. 9.

Waste Collection Unit Nominal

Partial panel removed to access fecal canister

Full panel removal

Fig. 9 Waste Collection Units Panel Removal. Cutaway View

Replacement fecal canisters and additional supplies are located in stowage above the seat, identified as such in Fig. 10, for easy access. The foot restraints are adjustable to support crewmembers from a 1% female to a 99% male. In addition, the control panel and wipes are directly beside the armbars. The control panel itself is a touch screen, which avoids the complexity of small crevices in traditional button designs and allows for easy cleaning.

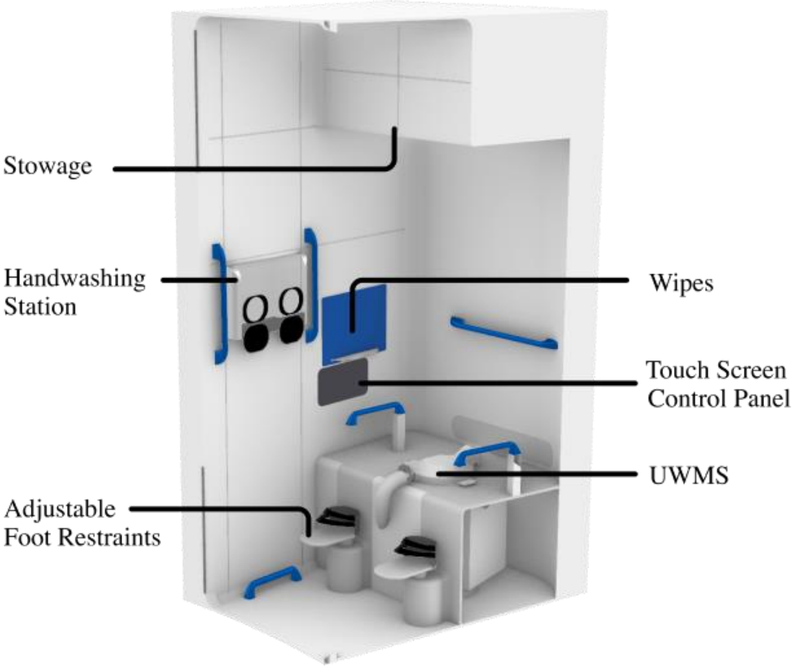


Fig. 10 Waste Collection Unit Labeled. Cutaway View

On the DSSV, each of the eight waste collection units also contains a handwashing station. These stations are a small glove box-like compartment with downward airflow and suction that allows crewmembers to wash and dry their hands with soap and water. Like the control screen for the UWMS, the control for this unit would be a touch screen. It is located inside the station to let crewmembers control water, airflow, and soap with both their hands within the station. To contain the flow of water in microgravity, the handwashing stations and the arm-washing station on Laboratory Deck five are equipped with an adjustable iris that closes around the wrist to provide a seal.

Furthermore, consistent downward airflow and suction from below help push the water into the drainage openings. The use of flowing water as opposed to wipes allows the crew to both *be* clean and to *feel* clean throughout their mission, which is important to boost crew psychological health.

2. Hygiene

Current hygiene practices on the ISS consist of no-rinse solution for the body, no-rinse shampoo for hair, wipes, and deodorant. The routine is brief and utilitarian. For longer-term missions however, a new kind of hygiene routine should be seriously considered. The DSSV Fully Body Hygiene Units (FBHU) shown in Fig. 11 proposes introducing water into the hygiene practices of astronauts.

Introducing more significant amounts of water, akin to a shower on earth, has been attempted in the past. NASA equipped the Skylab space station with a deployable cylindrical zero-gravity showering compartment in the 1970s. This attempt demonstrated that 'bathing' in zero–gravity was possible. However, the complexity and time needed to set up this compartment made it unviable for the crew. Given a choice between taking a towel shower and assembling, drying, and stowing the deployable compartment, crew members chose the option that saved them the most time. [6]

The DSSV full-body Hygiene units are permanent fixtures. In total, there are fourteen Full Body Hygiene Units. This number allows the entire crew of 48 to move through their daily hygiene routine in about 3.5 rotations. The units around the outer circle of Habitation deck five are 2.19m in height, 2.02m in width, and 1.26m in depth, while the six units in the central ring of Habitation deck five are slightly larger in width and depth. Both sizes accommodate the 1st percentile female and 99th percentile male. The triangular shape of the FBHU maximizes freedom of movement given the constraints of space available. "Analysis of the critiques against the shower concept came to support a conclusion that any development effort must focus on usability, rather than on technological and operational aspects -- whose feasibility past missions had largely demonstrated." [6]

In the FBHU, crew members dispense water using a showerhead that has a slight vacuum. This vacuum helps control the water as it is dispensed. The central touch screen can control the temperature of the water as well as the products within the water. This screen also provides controls for the downward airflow that comes from the top of the unit. This airflow helps control the water flow so that it does not simply stagnate or, in the worst case, gather around the crew member's head. Downward airflow alone is not enough to fully dry the unit or the crewmember. After their routine, crew members can use a towel to dry themselves and the unit. Stowage for these towels and clothing and toiletries are in two compartments on either side of the central touch screen.

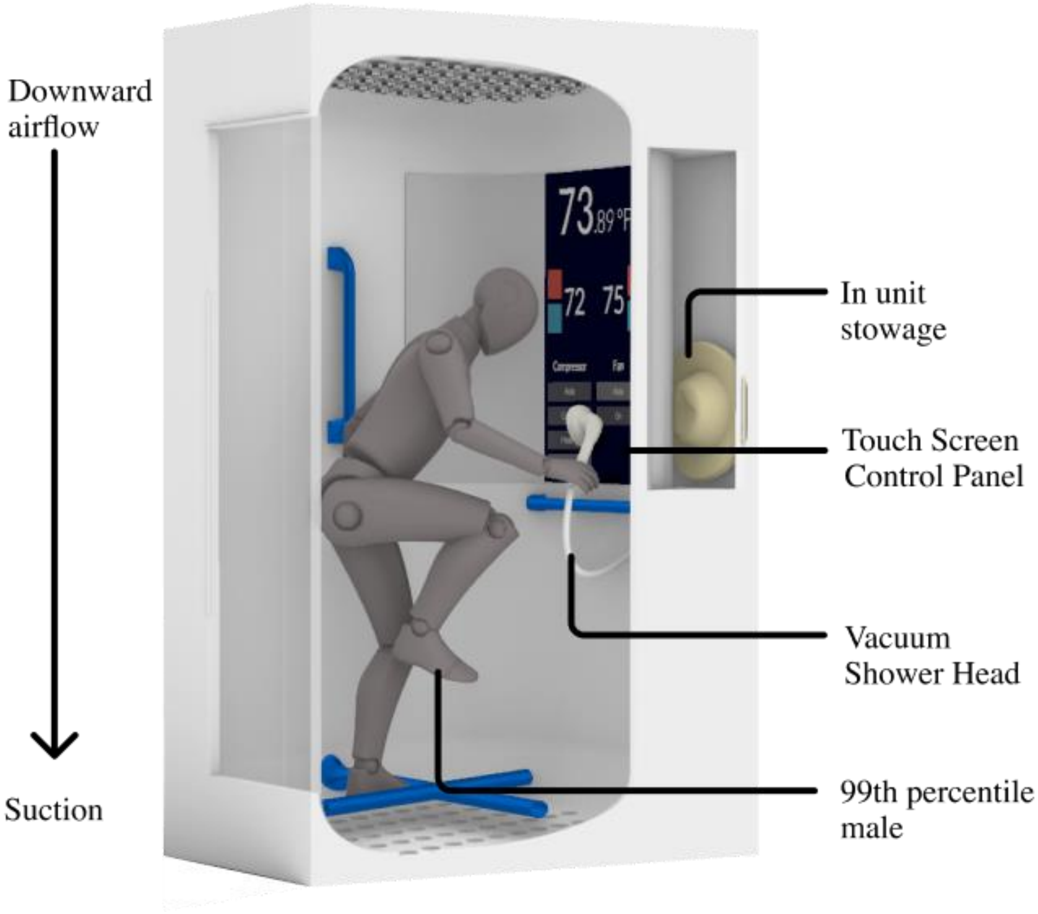


Fig. 11 Full Body Hygiene Unit Labeled. Cutaway View

The overall purpose of the FBHU is twofold, hygiene and personal relaxation. In any mission, both time and space are valuable commodities. However, on a long-duration mission with large crew compliments, these commodities are even more precious. Personal Hygiene and Sleep are rare opportunities for the crew to experience complete privacy. The pleasant visuals and large touch screen in the FBHU provide a relaxing and quiet atmosphere. Through the central touch screen, crew members can access light controls and several visuals. This helps make hygiene time a valuable time for rest, reflection, and rejuvenation. In a multi-year mission, crewmembers will have busy schedules and be operating in close quarters with the other crewmembers. Creating moments of respite within their daily schedule will help alleviate tension and reduce the risk of burn-out.

As human spaceflight progresses into extended duration missions, designing new precedents for how astronaut hygiene and mental health are supported is crucial. The DSSV hygiene deck supports crew physical and psychological health by considering the usability of each unit and prioritizing clean surfaces and smooth workflows.

3. *Exercise Countermeasures*

Exercise is a daily part of an astronaut's routine. To counteract the debilitative effects of microgravity, astronauts must perform 1.5 hours of restive exercise and 1 hour of aerobic exercise each day. In order to house enough exercise devices for all 48 crewmembers to effectively cycle through their 2.5-hour routine exercise, facilities occupy the entirety of both nadir nodes, shown in Fig. 12, and a portion of Habitation deck 5. Crew can enter these nodes from either the Hygiene deck (Habitation deck 5) or the Medical deck (Lab deck 5). This location makes it convenient for crewmembers to clean up after their exercise routine. The ISS exercise systems are used in the DSSV layout because they have extensive performance histories. But if smaller equipment can be developed in the future, that could allow for adding additional waste, hygiene, or exercise facilities.

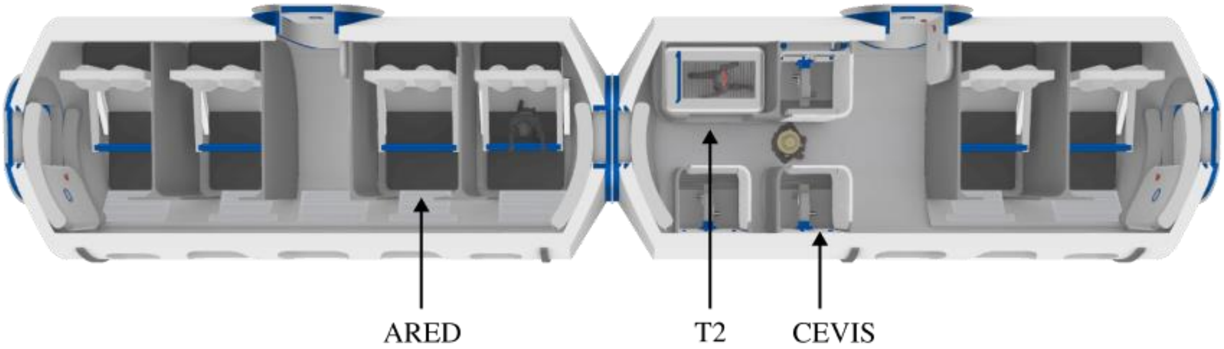


Fig. 12 Exercise Nodes Top View

In total, the DSSV exercise facilities contain six Advanced Resistive Exercise Devices (ARED), three Cycle Ergometers with Vibration Isolation Systems (CEVIS), and three second generation Treadmills with Vibration Isolation Systems (T2). Each exercise device is housed in its own stall. This provides the crew with privacy and helps contain sweat particles that are ejected from the body during exercise. Booths for the CEVIS and T2 are fully enclosed and internal screens provide instruction and entertainment. The booths for the ARED, on the other hand, are open at the front to allow crew members to look out of the windows, visible in Fig. 13, during their routines. While structural engineers often prefer to minimize windows because of their added weight, it is essential to consider the psychological health of crew who are confined to an enclosed and cramped interior space for years. Furthermore, the opportunity to look beyond the walls of the DSSV provides the crew with added motivation to consistently take part in their rigorous daily exercise protocols. Two of the treadmills are placed on the Hygiene deck (Habitation deck 5) because of space considerations.

Fig. 13 Exercise Nodes External View

Airflow within the nodes is designed to reduce the spread of odor. Each stall has air supply near the top and air return below. This lets fresh air circulate near the crew's face as they are exercising and stale air to be pulled downward away from their faces as shown in Fig. 14.

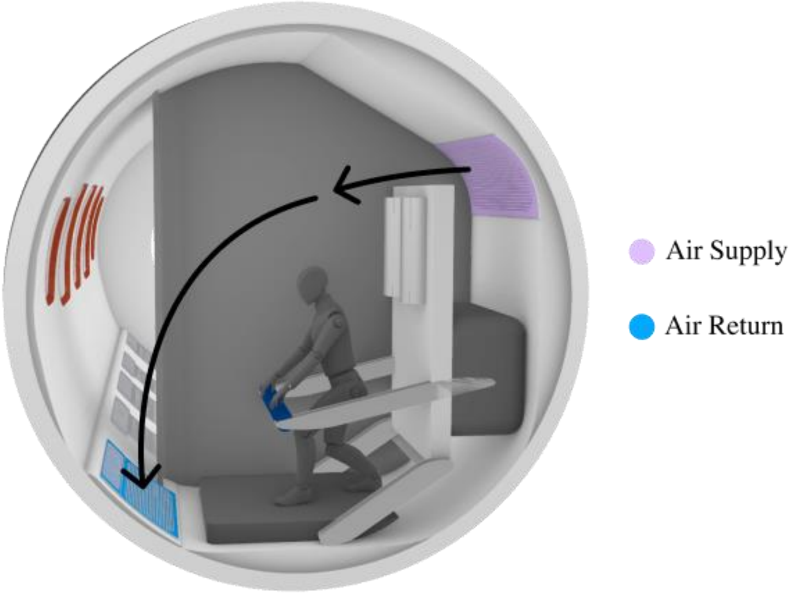


Fig. 14 Airflow Diagram - ARED Booth in Exercise Nodes

The design of the DSSV exercise facilities maximizes privacy, odor mitigation, and crew motivation while also providing adequate space for freedom of movement. Astronauts' daily exercise routines are lengthy and demanding, so designing systems to improve the overall experience will help keep crew members healthy throughout their mission.

C. Recreation Dome

The Recreation Dome occupies the entire lower dome segment of the Hab Module and provides the crew with a large, open space for solo or group crew “play” and overall enjoyment of weightlessness. This space, shown in Fig. 15, provides options for crew on very long missions to burn off steam and is an important psychological countermeasure. Inspired by the crew use of open space on the Skylab space station, the Recreation Dome is intended specifically for crew physical activity.

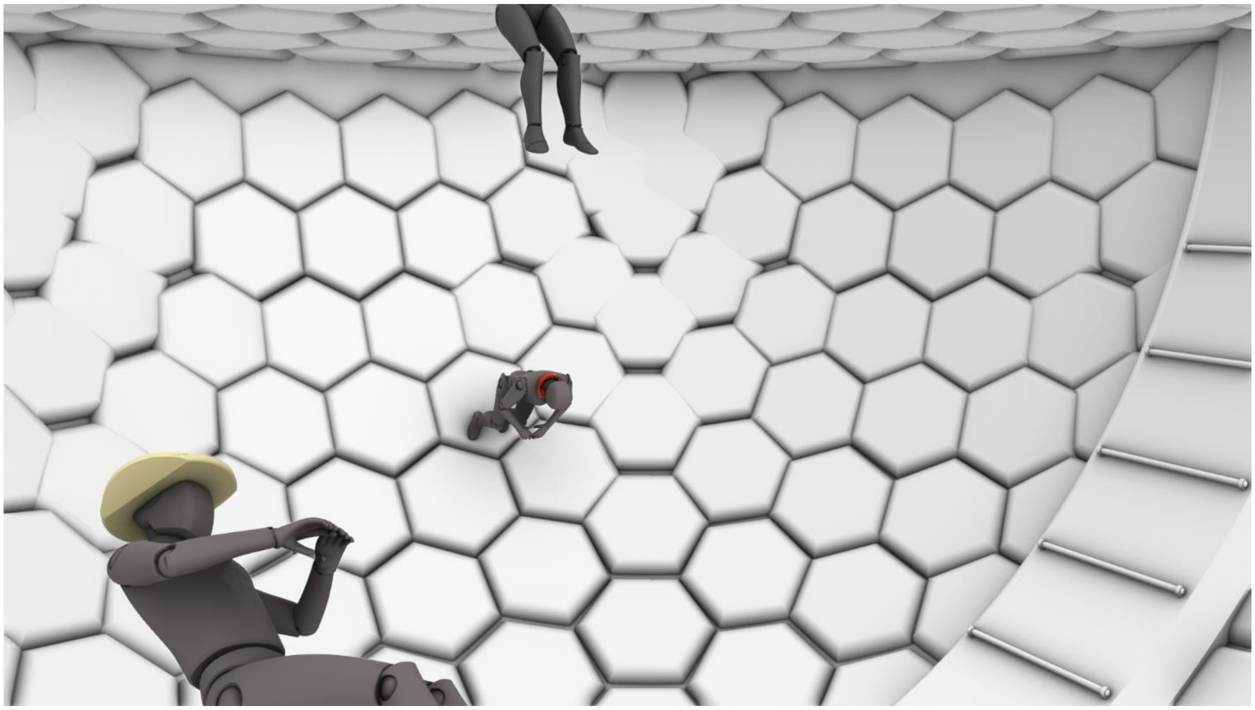


Fig. 15 Recreation Dome

Variations on terrestrial sports and games can be played in the dome, but it is expected that the uniqueness of microgravity will quickly lead to the invention of new activities that would be impossible on Earth or any gravity environment. A notional group game is illustrated in Fig. 16.

Fig. 16 Notional Group Recreation in Dome

The surfaces of the Recreation Dome are padded, for crew protection, and also house stowage lockers, shown in Fig. 17, that can be used to house game equipment. These hexagonal lockers can be subdivided to store small items and in select instances oversized items are stored in large lockers that are multiples of the hexagonal locker form.

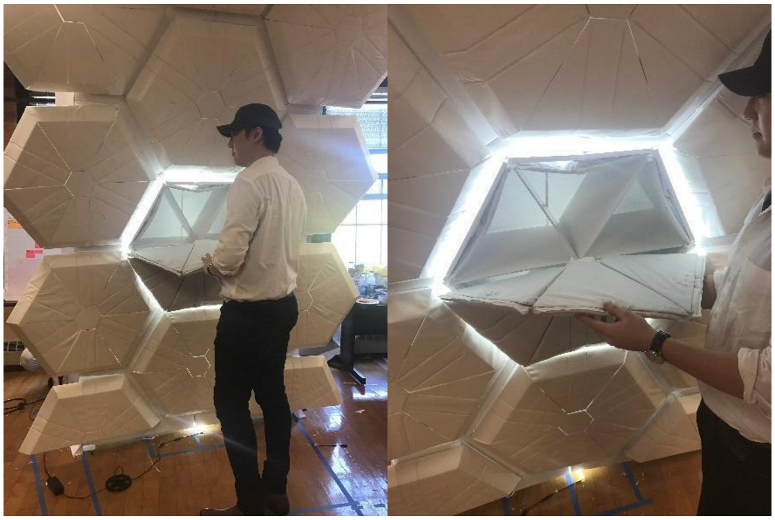


Fig. 17 Mockup of Recreation Dome Stowage Lockers

Some hexagonal units are not lockers but instead are mounting and/or sensor units associated with various forms of game play. Most of the hexagonal units are removable as demonstrated in Fig. 18 and can be repositioned to create custom gaming environments.

Fig. 18 Removable Stowage Locker

Access to the dome is provided by a single 1m x 1.5m passageway at the base of the dome leading down to the Stowage Node and two 1m x 1.5m passageways at the top of the dome leading up to the Crew Quarters decks.

D. Galley

The Galley is located in the upper dome of the Hab Module. This large open area also acts as a wardroom and movie theater. The primary goals of this galley design are to support full 48 crewmember meals, promote a positive eating experience, enable a smooth food pickup flow, and act as a community hub and bonding space. To achieve these goals, as well as the multiple functionalities of the space, the galley has transformable dining surfaces, an overall concentric design, and easily deployable restraints.

To enter the Galley from below, crew enter through the central translation corridor. To exit at the top of the dome, crew move to the sides of the Dome where handrails lead up the sides of the dome to the Mission Operations hatchway. There are two areas for food pickup, preparation, and assembly. As can be seen in the top view in Fig. 19, these areas are identical and run along the perimeter of the dome. The dining surfaces are two faceted arcs in the middle of the deck. Crew can gather along both the inside and outside edges of these tables. The facets allow the multiple crew members on the inside and outside to directly face one another when eating as shown in Fig. 20. The essentially concentric design of this deck allows for a smooth flow through food prep and 'seating'.

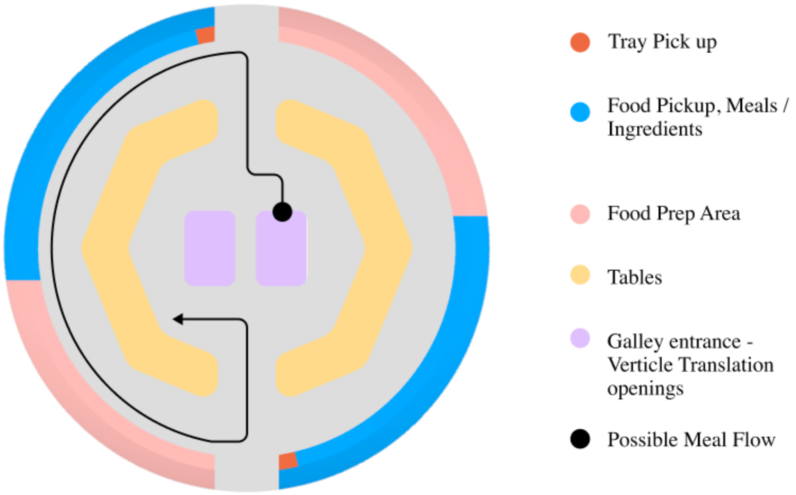
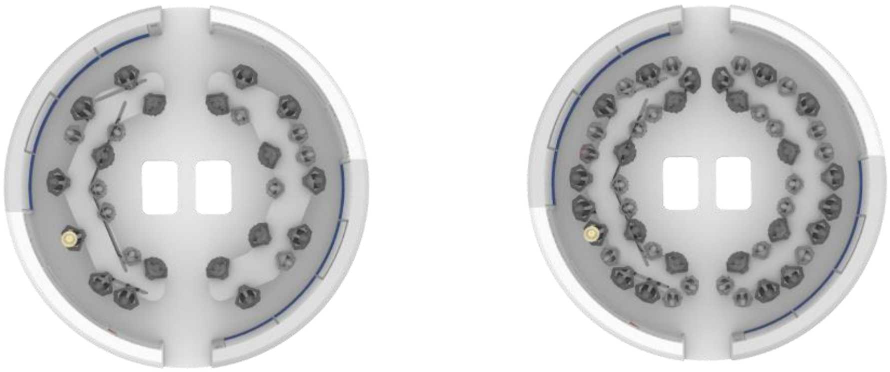


Fig. 19 Galley Color Coded Top view



Nominal Crew Meal (28)

Full Crew Meal (48)

Fig. 20 Galley Top view Crew Meal Density

During meal ops, when crewmembers enter the galley from either above or below, they can make their way to either side to pick up their tray and move along the perimeter of the deck for food pickup, rehydration, and heating, shown in Fig. 21. Each side of the deck has 48 rehydration spouts (96 total) and 40 heating chambers (80 total). These numbers let all 48 crewmembers move through the food preparation process quickly during full crew meals. Waste disposal is in the center of each section and at the ends so that crew can dispose of packing during food prep and after consumption. In the center of each food preparation section is an area for fresh herb growth. Crew members can use these herbs to season food. These areas work in conjunction with two large plant growth panels on the port side of the dome to provide aromatic and visual stimulation. In addition, these panels could help invoke the passage of time or seasons by varying the types of herbs and produce grown throughout the year.

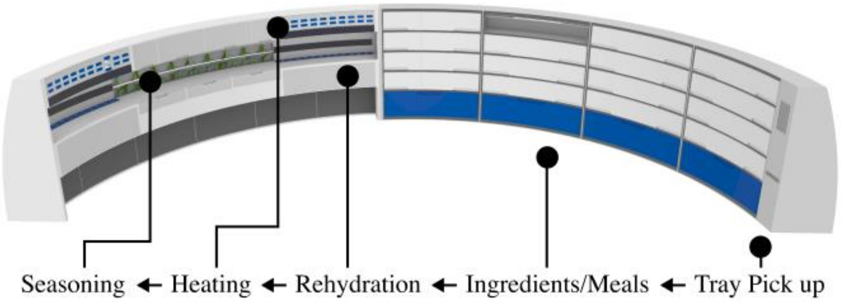


Fig. 21 One of Two Meal Preparation Sections

When considering a long duration mission with a large crew complement, creating an infrastructure that facilitates community and communication is essential as it will ultimately allow the crew to work together more efficiently, form bonds, and develop collective identity throughout their mission. The galley can transform into a wardroom as well as a full crew movie theater for this purpose. While the details of these transformations are notional, the goal is to comfortably accommodate all 48 crewmembers in a way that allows simultaneous viewing of entertainment and presentations. The collapsing table and rising restraints can be seen in Fig. 22.

On one side of the dome, the dome surface houses a large projection screen. This screen is used for crew movie nights, large presentations and provides an opportunity for ambient visuals during meals.

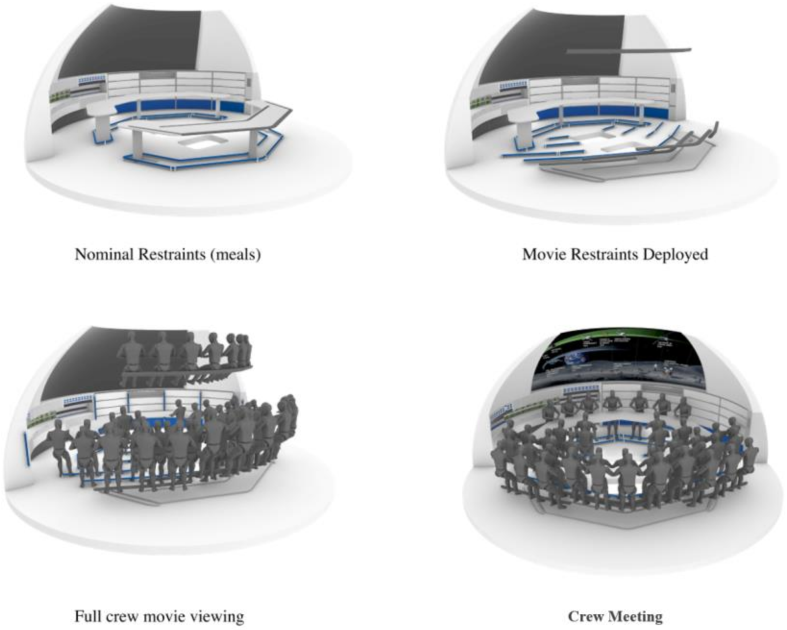


Fig. 22 Galley Movie and Wardroom Configurations

Across from the screen, on the opposite dome wall, are three large windows. From here, crew can have a collective experience of looking beyond the borders of their vessel. The Cupola on the International Space Station (ISS) is one of the most popular locations on the station because of its windows and the windows in the DSSV Galley, shown in Fig. 23, are similarly expected to be popular with the crew.

ISS Cupola

DSSV Galley Interior

Fig. 23 ISS and Galley Windows

The DSSV proposes windows in this large gathering space because of the unique opportunity for social reflection and community building. Community celebrations and gatherings are central to the human experience, and as human spaceflight expands beyond short-term missions, it is vital to consider how to provide infrastructure to meet these needs. On the DSSV, gazing into space is not a limited or solitary experience. It is an experience that the entire crew can share.

VI.Lab Module Layout

A. Food production

The food production dome, located at the top of the Lab Module, cultivates crops in space for consumption and research. As humans expand into the solar system, we will need to understand how to provide more resources than we can bring on a vessel or in resupply missions. The food production dome would supplement the supplies on the DSSV and give the crew the opportunity to eat fresh food. This will ultimately have a positive impact on the mental and physical health of the crew. The Veggie experiments were sent up to the ISS for the same reason [7]. The Food production area occupies decks 7 and 8 of the Lab Module and houses agricultural equipment, cultivated meat equipment, aquaculture, and a flight technology testing area with routing for utilities wrapping around the sides of the dome. A top view is shown in Fig 24.

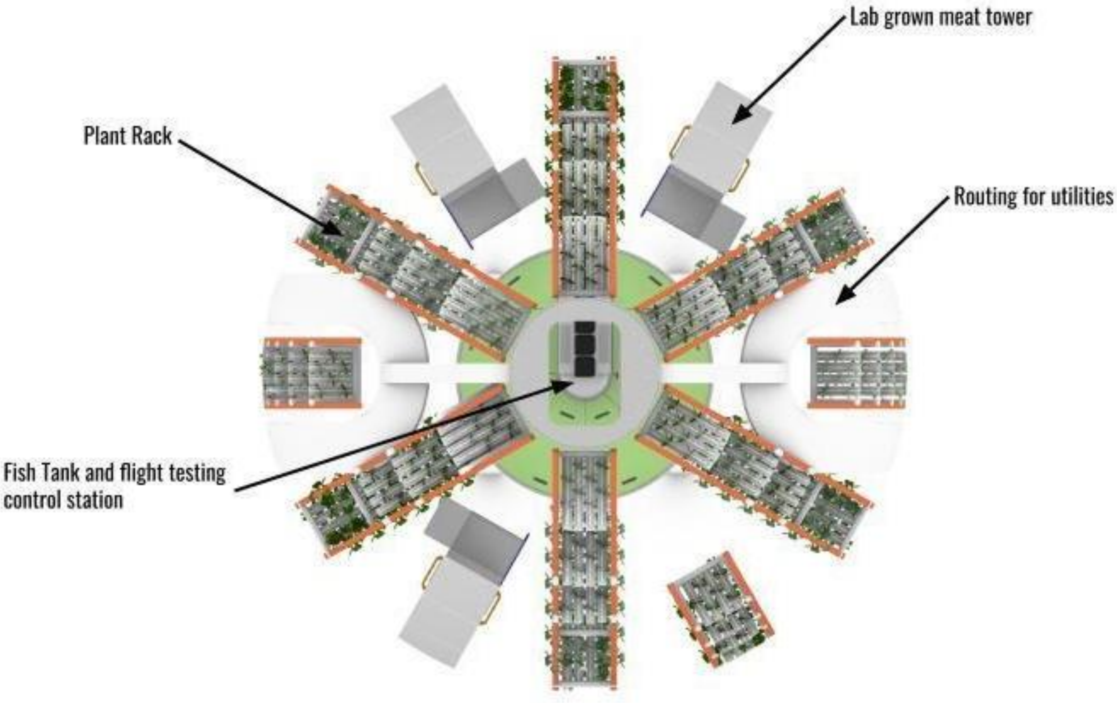


Fig. 24 Food Production Dome Top View

There are three towers that produce cultivated meat in the food production dome. Each tower holds 24 50-liter bioreactors, for a total of 72 bioreactors in the dome. In personal communication with Uma Valeti, the CEO of Upside foods, he confirmed that these numbers could provide somewhere around 5oz of meat per week for each crewmember. [8] These numbers are still notional and further work would need to be done to establish the power needs of this system as well as whether the nutrients needed to grow the meat could be produced onboard or would need to be brought along with other logistics supplies.

The aquaponics system on the DSSV pipes nutrient rich water from the central fish tank through each of the 9 plant racks which surround the room. These racks, shown in Fig. 25, are modular in height, allowing the crew to adjust the spacing between levels (1.8m, 1.2m and 0.6m spacing) depending on the plant being grown. This allows the system to be more flexible with the plants it can grow and would allow for plants to be grown more efficiently by arranging based on size or the stage of growth. Nutrient water from the fish tank would be pumped up these plant racks and through the pipes which contain the roots of the plants, feeding the plants and cleaning the water which is cycled back into the fish tank. Each level of plants has a series of grow lights attached to the bottom of it which provide artificial sunlight for the plants below.

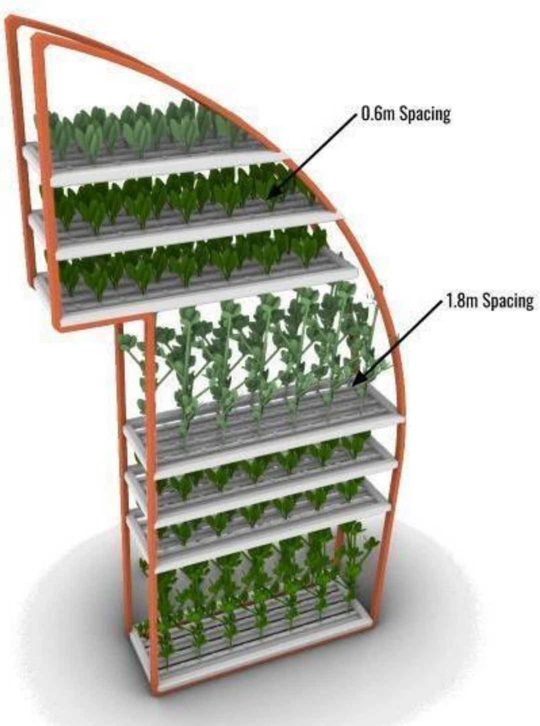


Fig. 25 Modular Plant Rack

The central fish tank, which supplies nutrients to the whole system, is a single 6600-gallon tank which is stocked with tilapia, a commonly used fish in aquaponics due to their hardiness and fast growth rate. Tilapia are capable of living in very high stocking densities (1 pound of fish to 3 gallons of water) and have a fast growth rate under ideal circumstances [9]. Going with more conservative numbers the tank could support 1,100 12oz fish at a stocking density of 1 pound of fish to 8 gallons of water. Tilapia have a 34-week growth cycle (spawn to harvest) and mature fish spawn every 3-5 weeks . We estimate that this would allow the crew to harvest enough fish to provide a quarter pound of fish per person per day. Harvesting would be done autonomously, preventing any dangerous spills of water or escaped fish. The fish would be filtered into a smaller isolation chamber. Once the desired number of fish is collected this smaller chamber would seal itself off from the rest of the tank and evacuate the water from the chamber. Once the majority of the water has been removed the automated fish processor would collect the fish and send them though the system to be processed. The system functions similarly to industrial fish processing on earth, which moves the fish through a modified conveyor system while preparing the meat for consumption. The output is clean fish fillets that would be taken to the galley for cooking and crew consumption, and waste byproducts that would need to be disposed of or potentially reconstituted into feed for the fish.

Above the fish processor is a control station for flight tech testing, shown in Fig. 26. Six drones comparable to the ISS Astrobee free-flying robot [10] dock at the top of the station with monitors below for remote operation of the drones or diagnostics to be performed.

Fig. 26 Flight Tech Testing Control Station

The primary objective of the drone units is to experiment with flight operations in microgravity to provide operational support to food production. Tasks that the drones could be programmed to perform range from monitoring plant growth within the food production dome, plant harvesting, item retrieval for astronauts throughout the vessel, and transportation of prepared fish, cultivated meat, and harvested fruits and vegetables to the galley, all of which would aid the crew and save time.

B. Life Science

The DSSV mission is to advance human knowledge using the unique vantage points of interplanetary trajectories and planetary orbits in the inner solar system. Lab deck 6 is a life science research lab. This research includes human research, animal research, plant growth research, and microbial research. This Lab is home to laboratory freezers, science payload stowage, ambient environment and environmentally controlled glove box workstations, general staging/open areas, and team meeting space. Life science is already a central part of the research done on the ISS because the extreme conditions of space provide a valuable setting to conduct research. The DSSV's scale offers a novel opportunity to accommodate large, diverse science equipment.

The Life Science Deck is directly below the Food Production Dome and directly above the Medical Deck. The design of this deck prioritizes open sightlines, smooth workflows, ample work surfaces, individual computer stations for each section, and ample room for full team meetings. The floorplan is split into quadrants, shown in Fig. 27, with each section dedicated to a research focus.

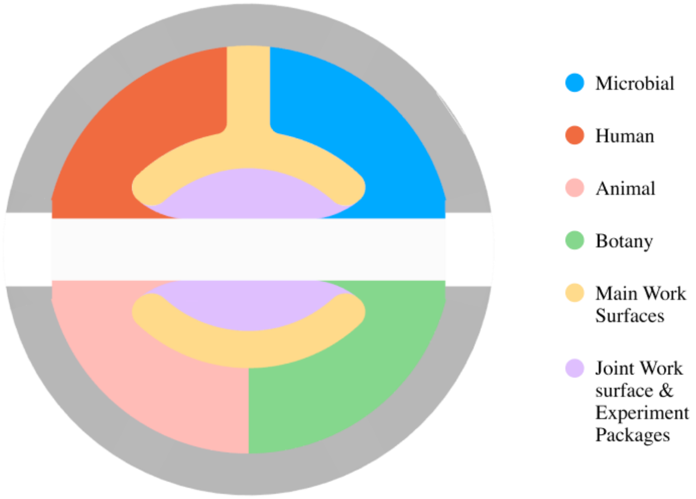


Fig. 27 Life Science Deck Color Coded Top View

In the Life Sciences Deck, worksurfaces, visible in Fig. 28, split up the deck rather than walls. This provides additional working surfaces while also having the benefit of maintaining open sightlines. This freedom of sight prevents the room from feeling enclosed while also encouraging teamwork and communication between scientists. These large work surfaces enable flexible use of bench-top science equipment (e.g. mass spectrometers, microscopes, centrifuges, etc.). This flexibility is beneficial in staging experiments or preparing samples for analysis. This equipment can then be placed in stowage below the work surface when it is not needed. Additionally, there is stowage directly above the work surface. This placement allows easy access to materials and tools so that crew does not have to leave their work area as they are preparing and conducting their experiments.

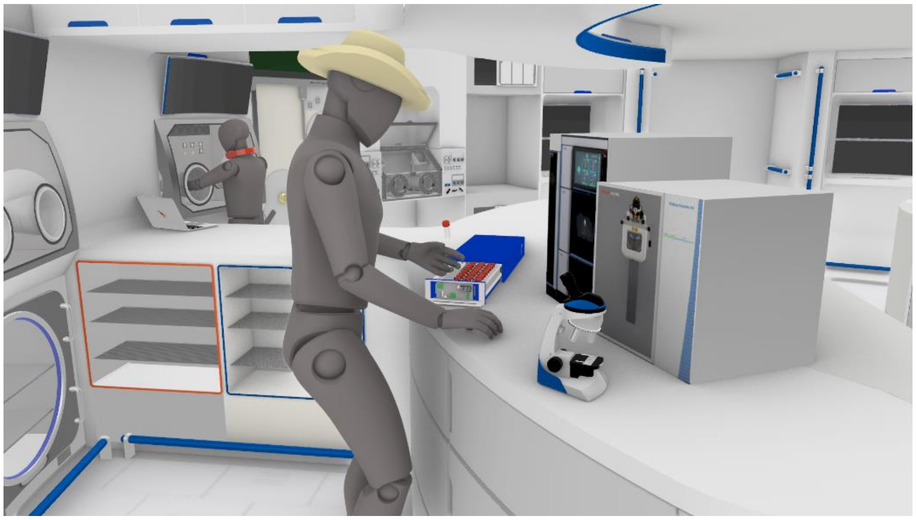


Fig. 28 Life Science Deck Crew Members at Work

Around the outer walls of this deck are several rack structures that house mid deck lockers or science payloads. These racks are inspired by ISS racks, but are taller with greater capacity. Some of these ISS rack-inspired structures have been modified to have an open volume that serves as a work surface between glove boxes or other payloads. This adjacent surface allows for a smooth workflow between a preparation area and an execution area. Furthermore, each glovebox is equipped with an overhead screen so that the user can easily view results, instructions, or videos about work in the glovebox.

In addition to the mentioned ISS-inspired rack structures, instrumentation, laboratory freezers, autoclaves, vivarium, plant growth, gloveboxes, and computer stations are placed around the deck perimeter as seen in Fig. 29.

These additional structures are slightly curved so that they flow smoothly around the deck perimeter. In this way, the architecture of this deck is in harmony with the geometry of the cylindrical laboratory module. Ultimately designing for clean workflows between activities and integrated appearance will benefit the long-term mental health of the crew.

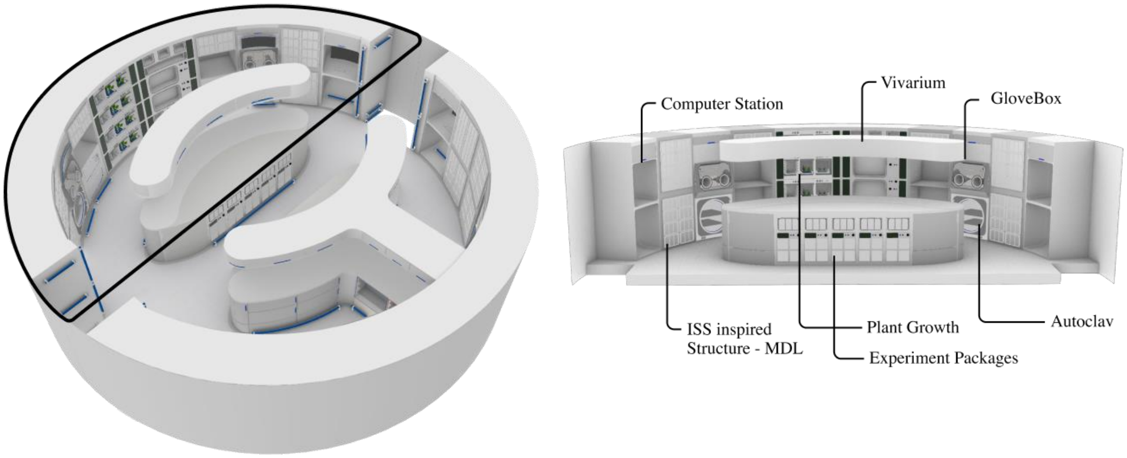


Fig. 29 Botany and Animal Research labeled

As seen in the deck top view in Fig. 27, two additional surfaces face the central 'hallway'. These surfaces are a shared workplace for the life science team. Below these surfaces is another space for experiment payloads.

Above the joint work surface on the human and microbial research side is a pull-down projector screen that helps facilitate group meetings for all ten members of the life science team. Team members can gather around the plant and animal worksurface to face the screen and one another, shown in Fig. 30.

Fig. 30 Life Science Full Team Meeting

Despite the presence of meeting areas in other sections of the DSSV, designing this deck in a way to provide a method for full team meetings was a key priority. Like in any business or joint venture on earth, team cohesion and communication are vital parts of mission success. Opportunities for discussion, stand-ups, and even joint calls back to earth will also assist the development of team culture and community.

C. Medical

To provide comprehensive and independent medical capabilities, the DSSV has a dedicated medical deck and team. The Medical deck is located on Lab deck 5, directly below life science and above physical science. This deck provides both physiological and psychological health care for the DSSV crew. The DSSV medical team consists of two surgeons, three general physicians, and a counselor. In addition to this core team, seven other crew members aboard the DSSV are crossed trained as paramedics, including at least one within each crew department, to increase medical presence while the crew is spread throughout the vessel and to provide surge medical care capacity in the event of a serious contingency.

If there is a medical emergency on the ISS, astronauts can return to earth and be treated within 6 to 24 hours [11]. This would not be possible for the crew of the DSSV. In addition, real-time telemedicine, or other consultation with medical professionals on earth, is generally impractical due to communication delay. A DSSV crew near Ceres would experience a round trip communication delay of 60 min.[12] Given the crew size and potential durations of DSSV missions, there must be an assumption that medical emergencies will at some point occur. However, facilities that support the regular monitoring of crew health could help catch some conditions before they become serious. In addition to regular monitoring, the medical deck would also need to support emergency surgery, routine dentistry, and psychology. To ensure the health and safety of the crew, the DSSV must be capable of independent medical intervention and support.

The medical deck contains four radial hatches and is a point of transition between the Lab and Hab Modules. As a result of incorporating these translation paths, providing sufficient space posed a significant challenge when designing the Medical Deck to support general checkups, dentistry, surgery, psychology, stowage, and check-in. Some core considerations in the design of this deck were ensuring privacy and enabling maneuverability within each medical room. In addition, designing 0g operating rooms presented the challenge of surgeon restraints, hygiene, and surgical containment units.

The volumes used for the DSSV operating rooms and general medical examination rooms are influenced by a Cross-cutting Computational Modeling Project: Exploration Medical Station Analysis performed at the Glenn Research Center. In this project, three medical professionals, one male in the 90th height percentile, one female in the 26th height percentile, and one female in the 94th height percentile, performed medical procedures on a medical manikin. They found that, “Restricting the volume with an external barrier did not necessarily affect the completion of the task or the time required to perform it, with the exception of intubation procedures. Intubation requires visual access to the subject’s airway, looking down the throat from behind the head. Restricting the volume to limit this access makes the procedure more difficult for the caregiver and likely riskier for the patient.” [13] They also found the most restricting factor when the medical professional had their feet restrained was how far away supplies were located. [13] The design of the DSSV medical deck takes these findings into account by prioritizing head room in the operating rooms as well as stowage and active tool placement in both the operating room and general medical examination room designs. However, forward work testing these designs and volumes at increasing fidelity leading up to eventual microgravity testing would be needed to verify their efficacy.

The DSSV Medical Deck contains three general examination rooms, two operating rooms, a psychological interview lounge, a check-in area, two arm washing stations, two full body hygiene units, and two waste collection units. This floor plan is visible in Fig. 31.

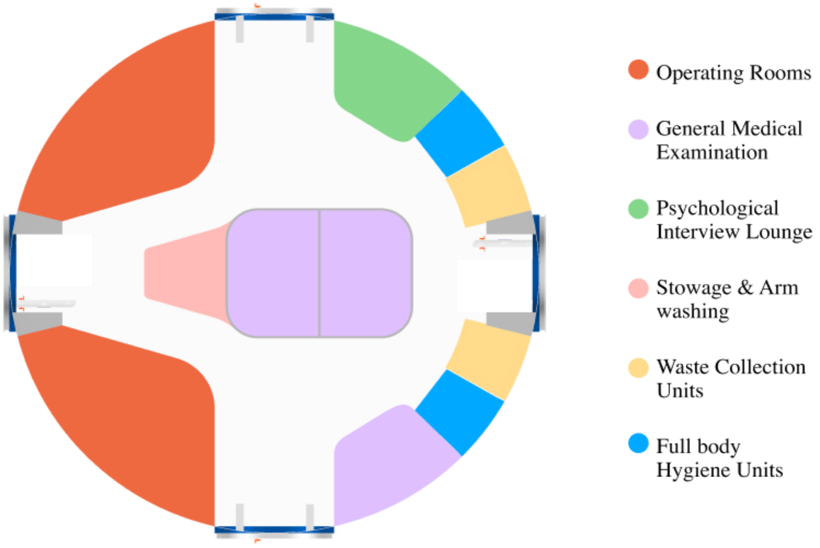


Fig. 31 Medical Deck Color Coded Top View

The two operating rooms are symmetrical and are designed to be as large as possible while not intruding on translation paths in the deck. Shown in Fig. 32, these rooms facilitate surgery, dentistry, and routine imaging. Up to three caregivers can attend to a patient in each of the operating rooms. The teardrop shape allows enough room at the head of the patient for comfortable patient intubation and routine dentistry work. To provide advanced imaging capabilities the operating rooms contain c-arm structures that follow a track on the operating room ceiling and can scan along the entirety of the patient's body. C-arms are commonly used in hybrid operating rooms on Earth and support fluoroscopic intraoperative imaging and real-time x-ray imaging, allowing caregivers to monitor progress in real-time. [14] Forward work remains to see if these devices could be made lighter and if additional instrumentation could be mounted to support minimally medical procedures.

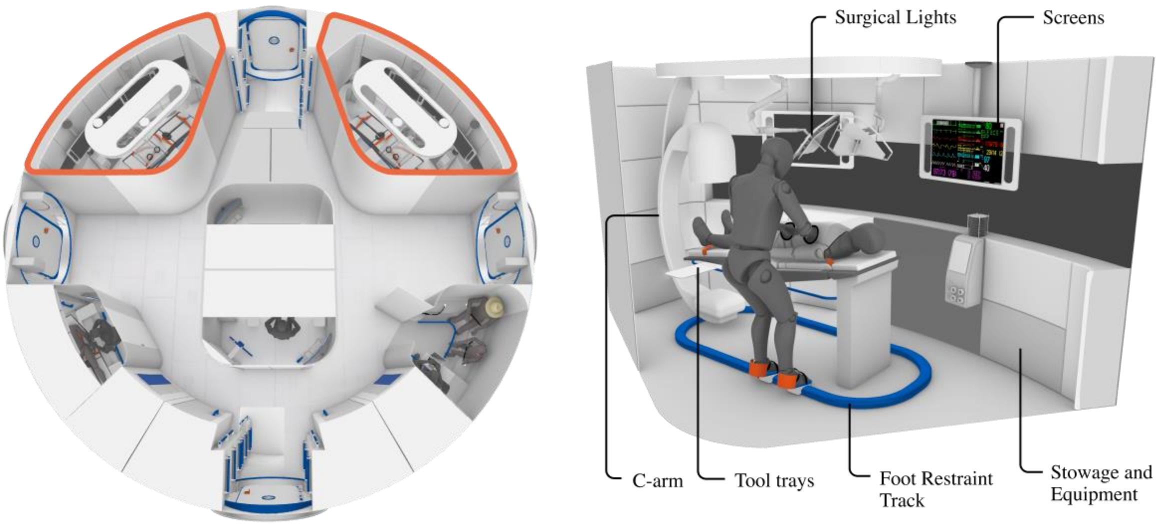


Fig. 32 Operating Room Labeled

Stowage follows the exterior perimeter of the room and would house sanitized surgical tools and equipment like ventilators and cardiac monitoring. In many Earth operating rooms, this machinery is free and moveable, however, because of limited space and the difficulty of maneuvering large equipment in 0g these machines are fixed. Associated wires and tubing could be run along the ceiling to drop down over the patient or below the deck and rise up through the column at the head of the patient bed. Wire/tubing organization in this space is vital to ensure that caregivers can move around the patient freely without entanglement. Free movement is also supported by a restraint track around the base of the patient's bed. Here surgeons can slide along a rail while remaining in comfortable and stable foot restraints. Surgery in 0g would likely be as non-invasive as possible. In non-invasive surgery, screens allow the surgeon to see the surgical field.[11] In the DSSV operating rooms, four adjustable screens can be linked to the c-arm and display patient vitals. In addition, two adjustable surgical lights help illuminate the surgical field.

The two arm washing stations on the medical deck are directly outside the operating rooms. They provide a place for surgeons to conduct thorough hand/arm washing without using a FBHU. These stations work similarly to the handwashing stations that are outlined in the hygiene section.

The three general examination rooms, identified in Fig. 33, support regular crew health monitoring and diagnostics. Long-duration missions provide an opportunity to learn how microgravity can affect the human body. As such, crewmembers would likely have regular checkups to monitor health and gather data on long-term effects of living in 0g. Each room is fully enclosed to ensure patient privacy and is designed with an adjustable horizontal examination bed. Commonly used instruments like ultrasounds and electrocardiograms (EKGs) can be placed in compartments above the patient so that the associated wires and tools can be pulled downwards and used. This allows wires to take up vertical space rather than horizontal space, allowing for more unrestrained doctor movement within the room.

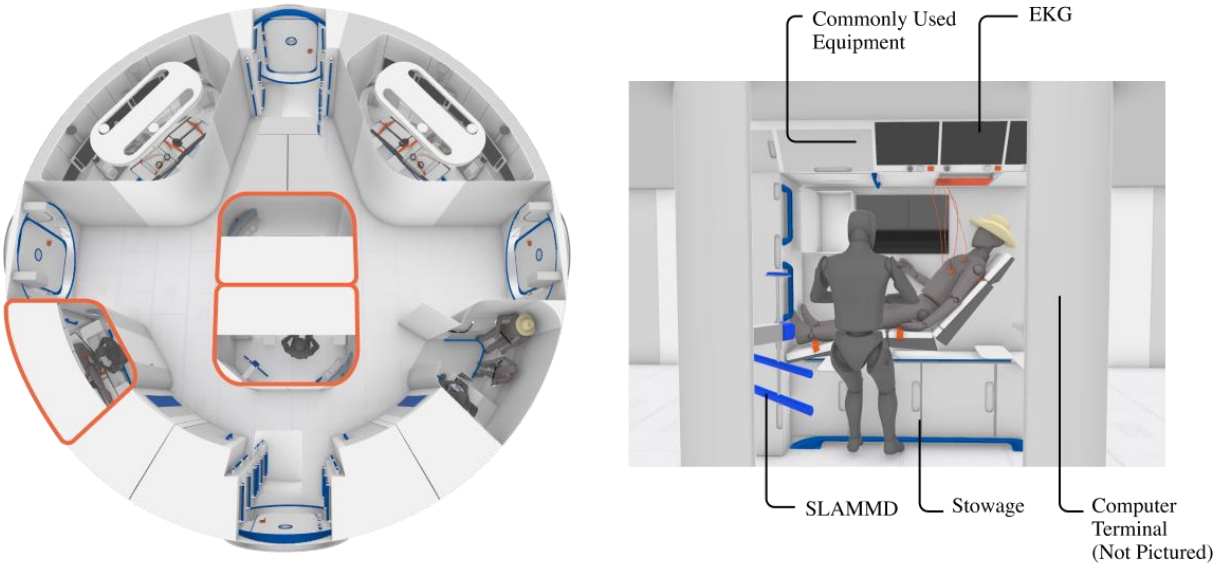
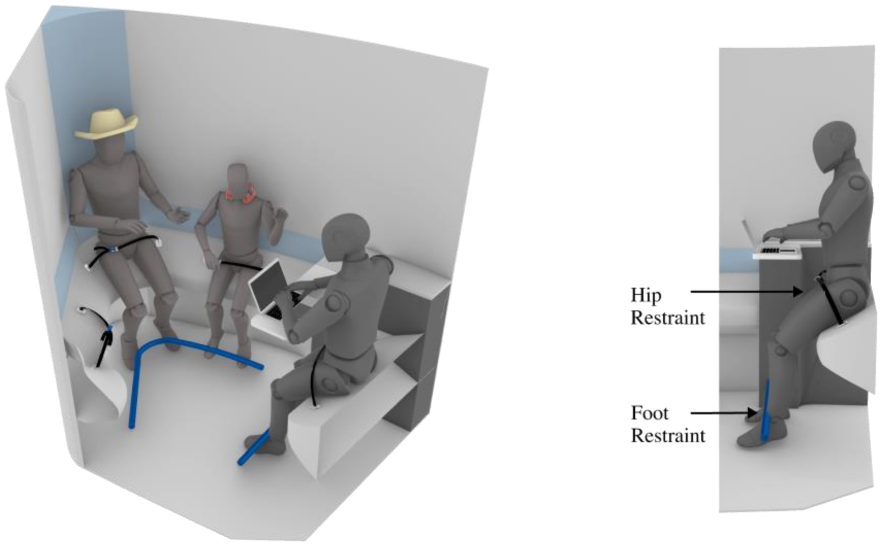


Fig. 33 General Medical Examination Room Labeled

Psychological support is also an integral part of maintaining overall crew health. On any space mission, crew will experience high-stress and close quarters. On long-duration missions in particular, this stress can build over time and lead to personal and interpersonal distress. The Medical Deck's psychological interview lounge shown in Fig. 34 is a space dedicated to individual therapy, psychological checkups, and mediated group conflict resolution. The room accommodates up to three patients and a counselor. To create a relaxed atmosphere, 0g seating wraps around the perimeter of the room. This seating has two restraint points, a belt across the hips and a bar for the user to brace their toes against.



Partial Occupancy

Seating side view

Fig. 34 Physiological Interview Lounge

Developing comprehensive 0g medical facilities is vital as missions grow longer and more complex. The DSSV medical deck proposes designs that can start the discourse. However further work needs to be done to address the specifics of surgical containment, bleeding control, and the mass of imaging equipment.

D. Physical Science

The physical science area located on deck 4 of the Lab Module houses sufficient equipment for Geology, Materials Science, Combustion and Fluid Science, and Astronomy. Each science has a designated area, indicated in the floor plan in Fig. 35, designed to accommodate the equipment and workflow of each science. Each area is semi-isolated from one another, branching off a central corridor in order to contain different workflows and experiments.

Fig. 35 Physical Tech Testing Deck Top View

The Astronomy and Meteorology Laboratory is the smallest of the four, due in part to the majority of its equipment being mounted externally on the DSSV which allows this laboratory to be geared towards data presentation and collaboration. Three computer stations with several monitors each give the crew ample resources to make observations and command external sensors. In the center of the lab is a planetary projection system that allows for a 3D visualization of a planetary body similar to how it is done with the Science on a Sphere® (SOS) system developed by NOAA [15] as well as a large display screen behind this for displaying other information or images. The DSSV planetary projection system and NOAA SOS system are shown in Fig. 36.

Fig. 36 DSSV Spherical Projection System and NOAA Science On a Sphere®

The Geology Lab, shown in Fig. 37, occupies a quarter of the working area of the Physical Science Deck and houses ample resources for sample preservation and experimentation. Much of this area will focus on experimenting with samples taken from surface EVAs performed during a planetary, moon, or asteroid surface mission, or delivered to the DSSV by sample return spacecraft. This laboratory has several freezers, lockers, and sealed sample stowage modules occupying the area above and below the glove boxes and flat work surfaces which would be used to stow collected samples and supplies for testing. Mounted to the opposite wall is larger equipment such as surface polishers, vibration polishers, and locations for ISS inspired payload racks. Special transfer containers are used to move samples between freezers, glove boxes, and other instruments without exposing the sample to the cabin environment.

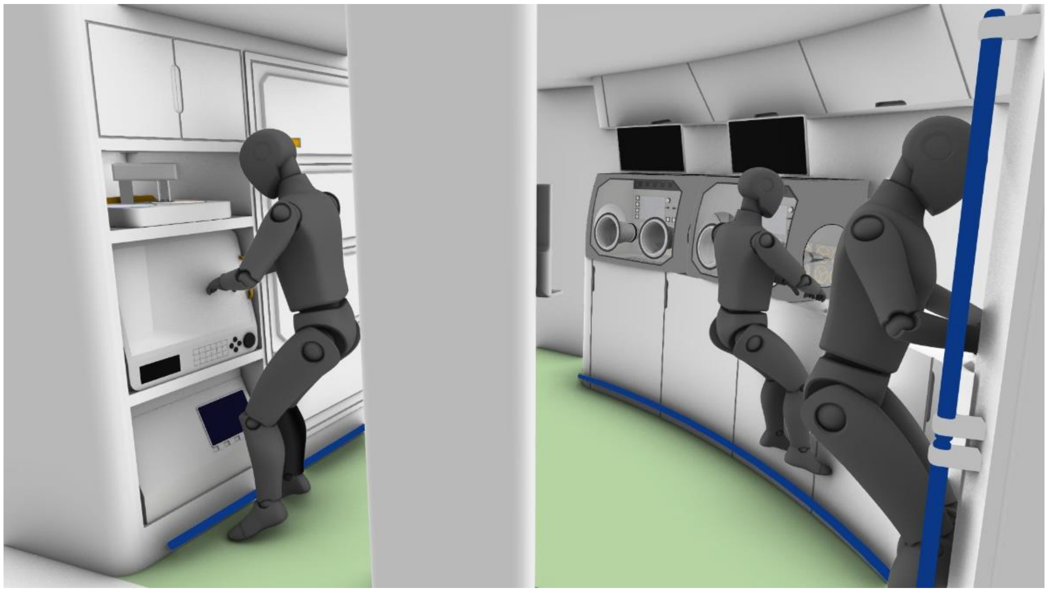


Fig. 37 View of Geology Lab

The Materials Science Laboratory in Fig. 38 is very similar in layout to the Geology Laboratory due to each facility having similarly sized equipment and workflows. During a mission the Materials Science Laboratory would be used to analyze and test locally produced materials, collected samples, spacecraft components, and experiment samples placed outside the vessel for exposure to the ambient environment, similar to MISSE on the space station [16].

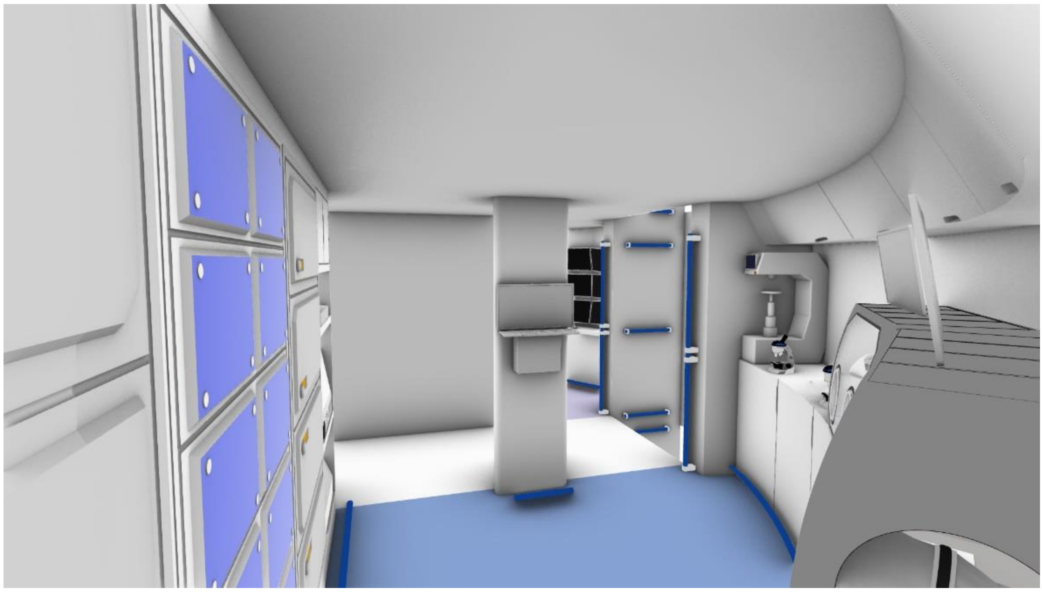


Fig. 38. Materials Science Laboratory

The Combustion and Fluid Science Laboratory in Fig. 39 is the largest of the physical science labs, housing six payload racks that would house equipment similar to the space stations FIR and CIR [17]. Additionally, there is locker stowage above and below glove boxes and flat work surfaces in the back of the lab. Combustion and fluid science will continue to be an important topic of research across inner solar system destinations.

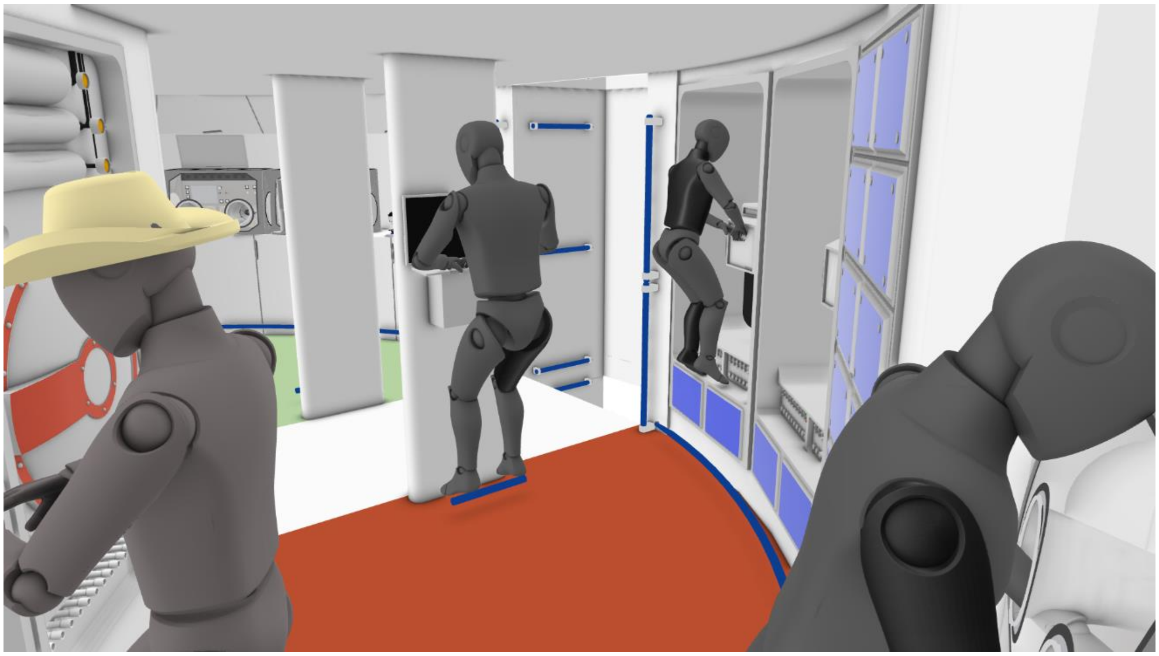


Fig. 39 Combustion and Fluid Science Laboratory

E. Repair Dome

It will be essential to have adequate means of repairing the DSSV with onboard resources as neither aborts nor immediate return to Earth are options. The Repair Dome is the lower dome of the Lab Module. It occupies Decks 2 and 3 and contains areas for fixing a wide variety of maintenance issues that could arise during a mission. Deck 3, shown in Fig. 40 is home to large equipment such as CNC milling machines, the ship's laundry system and smaller rooms designed around specific tasks such as welding, softgoods / thermoplastics, and electronics / software. Deck 2, shown in Fig. 41, is a large workspace color coded to identify “walking areas”, assembly areas and tool areas. The color coding on deck 2 indicates how a machine shop capability is accommodated within this dome volume. The fabrication areas indicate volumes where various tools are mounted and the mechanical / assembly areas indicate work surfaces where equipment can be assembled or disassembled. Neither of these include the volume occupied by the crew member. “Walking areas” do not necessarily indicate actual walking, but instead indicate the working volumes occupied by crew members accessing the fabrication or assembly areas. These volumes are configured such that the fabrication and assembly areas are within the working envelope of a crew member in the walking area. This is illustrated in three dimensions in Fig. 48.

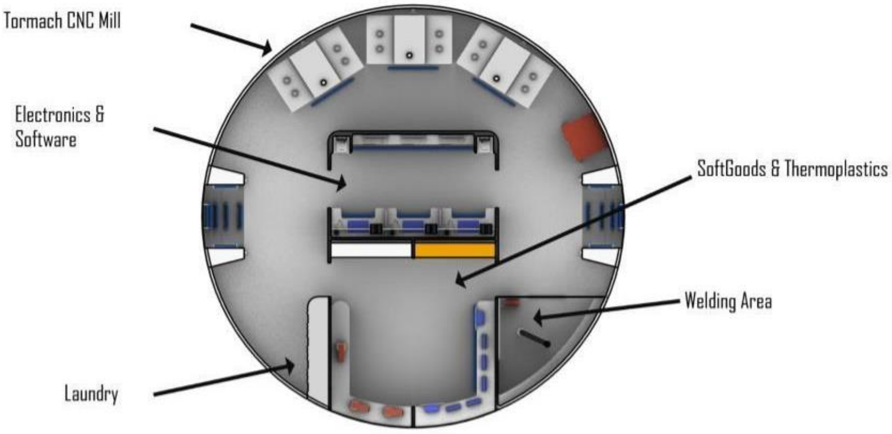


Fig. 40 Repair Upper Deck Top View

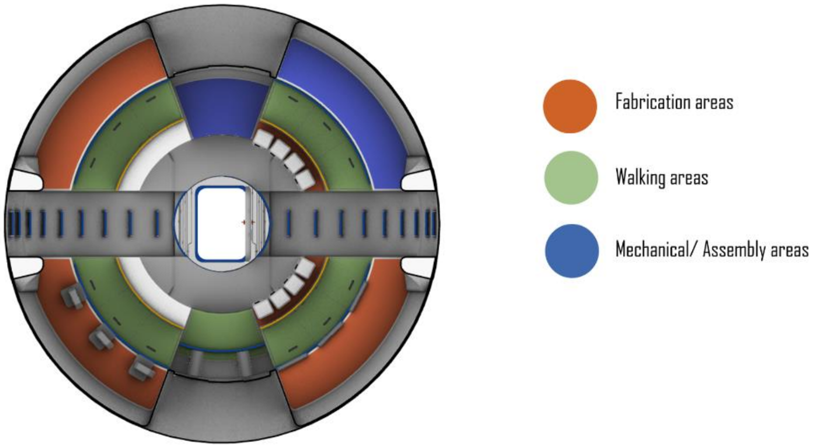


Fig. 41 Repair Lower Deck Top View

The soft goods and thermoplastics area, shown in Fig. 42 and Fig. 43, is used for any fabric or sheet plastic repairs ranging from basic maintenance of stowage bags and crew garments up to major restoration of space suits or inflatable sections of docking adapters. The room has wall storage for up to ten 1.9-meter wide rolls of material and ample cabinet room under the work surfaces which surround the room. The work surface on the port side can pivot out and unfold into a larger work surface allowing the crew to lay out large projects and help keep them contained while in microgravity.

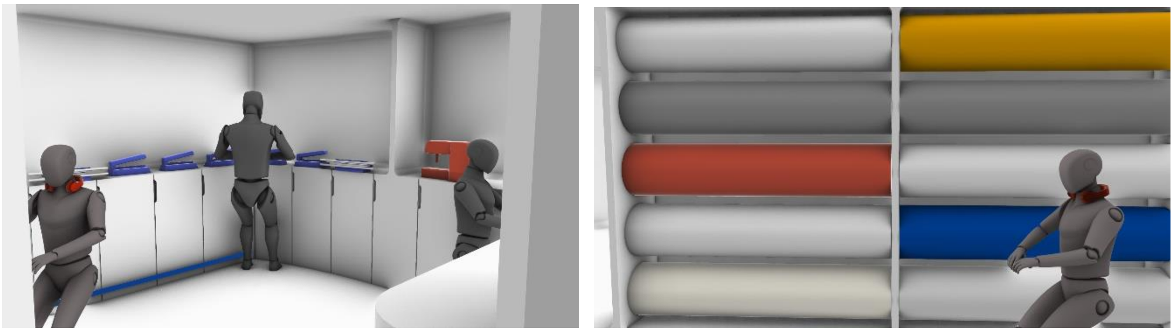


Fig. 42 Thermoplastic Machinery and Material Rolls Stowage

Fig. 43 Unfolding Work Surface in the Soft Goods and Thermoplastics Area

The electronics and software area, shown in Fig. 44, has several stations for assembling electrical components as well as stations for working on software. Flanking the software areas is an assortment of PCB printing machines which would be used to fabricate custom electrical boards during the mission.

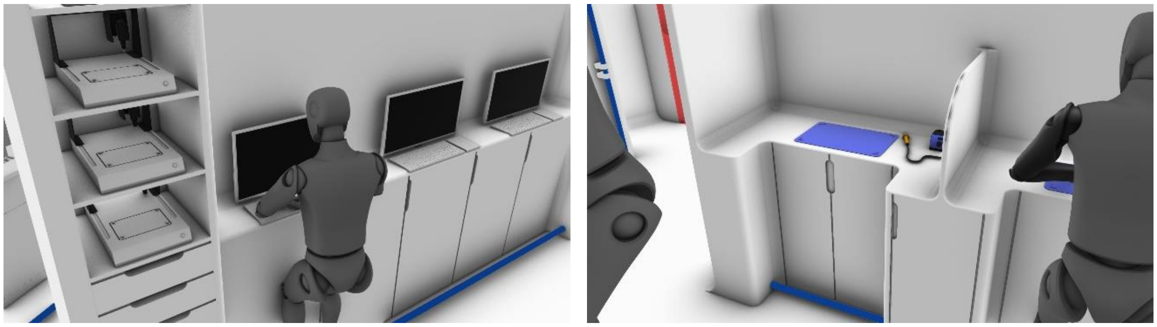


Fig. 44 Electronics and Software Area

The welding area, shown in Fig. 45, allows for more intensive repairs to be achieved while in space. The primary concern with welding is outgassing of materials which would quickly contaminate the vessels air supply, The DSSV welding area isolates itself behind tinted curtains that block ultraviolet light while allowing others to keep an eye on the process. A ventilation and filtration system separate from the DSSVs ECLSS removes dangerous contaminants from the air and keeps a negative pressure on the welding chamber, preventing leaks. Multiple adjustable fixturing arms are mounted to the ceiling and are used to hold components together and supported in microgravity. Actual welding activity can be performed manually, robotically, or through teleoperation of robotic systems.

Fig. 46 Welding Area

In the upper Repair Dome, large fabrication equipment (notionally shown as three Tormach 1100M CNC machines) enable large/ complex repairs to be made. This outer area is also home to the vessel's laundry system (16 units), shown in Fig. 47, allowing the crew to wash their clothing and reduce the amount of apparel needed for multi-year missions.

Fig. 47 Sixteen Laundry Units

The lower Repair Dome, as previously mentioned, is color coded in Fig. 48 to identify where crew can maneuver and work versus where repair equipment can be positioned. These spaces are organized by color, green represents areas that are safe for people to stand or move through, blue is areas where projects can be laid out and held down while working in microgravity, and the orange/red is areas reserved for small and medium size equipment that may create debris or have the potential to injure crew. Considerations will need to be made in the future to contain debris from activities such as drilling or sawing as the generated debris would otherwise pose a serious hazard.

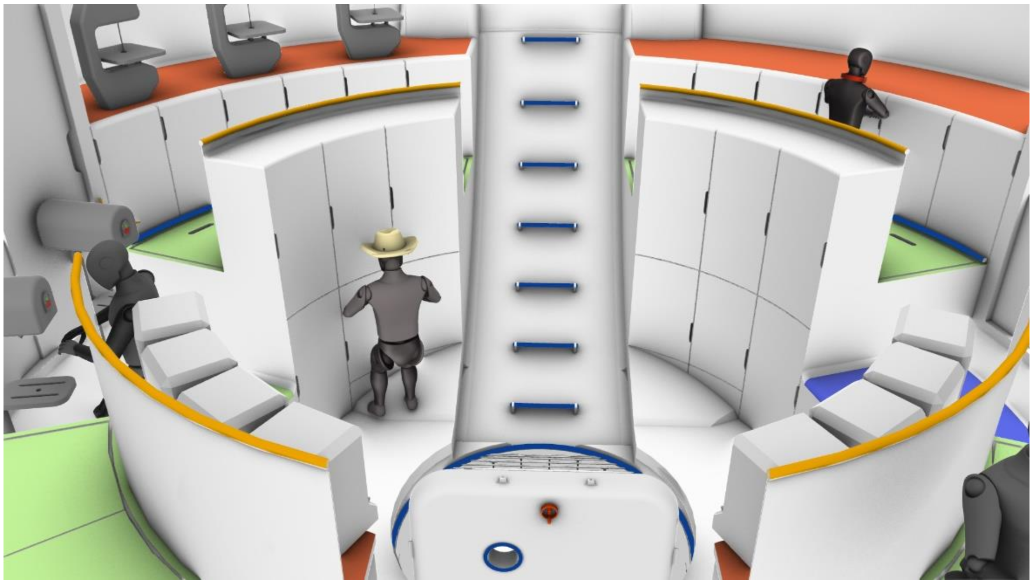


Fig. 48 Interior View with Example Equipment

A key part of the lower deck assembly area is contained on the ceiling in the form of a large, deployable panel that forms a vertical work surface that greatly increases the usable space for laying out and disassembling equipment as part of DSSV maintenance and repair activities. When not in use the panel folds flat against the ceiling, creating a more open working environment. Figure 49 shows this assembly panel deployed and stowed. Numerous stowage compartments are located throughout the Repair Dome, housing materials and supplies necessary for a mission of this scale and duration.

Fig. 49 Assembly Panel Deployed and Stowed

Additive manufacturing is a key component of the DSSV fabrication, maintenance, and repair capability. Twenty-four 3D printers can be found on the inner ring of the lower deck, shown in Fig. 50. These include a mixture of plastic and metal printers. With the printers, certain fabrication activities are automated, reducing the repair times.

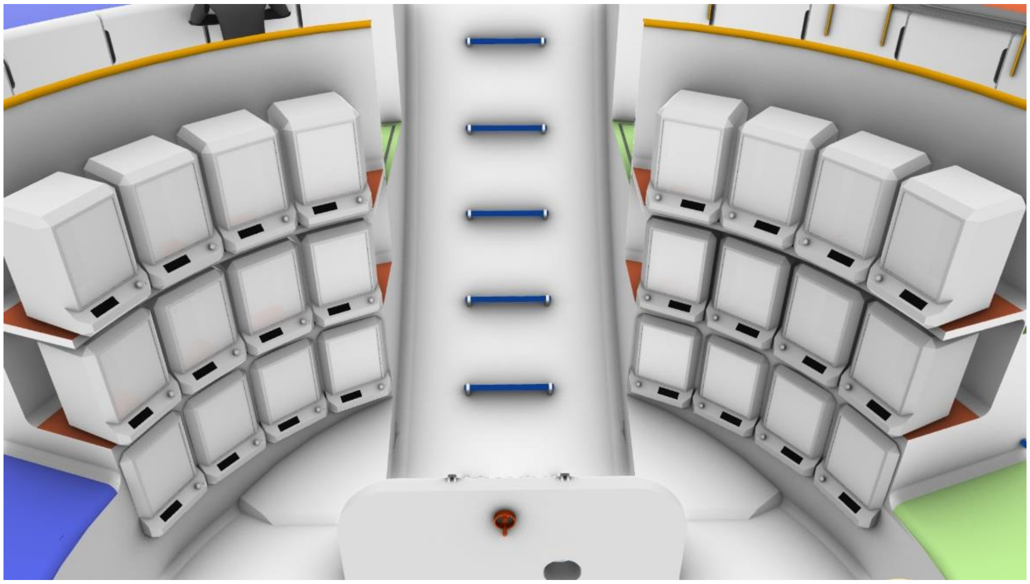


Fig. 50 3D Printers in the Repair Dome

VII.Node Module Layouts

A. Observation Deck / Space Café

The crew of the DSSV will have to endure being confined in a relatively small space for years at a time. Thus, it is important to design features that will reduce the astronauts stress and aid them in successfully completing the mission. The observation deck and space cafe provide the crew with an open, windowed area that allows them to “step outside” the vessel. The observation deck in that way functions similarly to the Cupola on the ISS, a place where many astronauts choose to go in their free time. The observation deck consists of two node modules located on Deck 5, The space would primarily function as a relaxation space while also providing additional pathways between the HAB and LAB modules.

The cafe function, like at a cafe on earth, provides refreshments to the crew that can be enjoyed within the Observation deck or taken with them as the crew moves through the spacecraft. Each node of the Observation deck contains two refreshment stations (4 total) along either side of the entrance to the HAB and LAB modules, visible in

Fig. 51. Stocked by the Galley, they include a potable water dispenser and food warmer, as well as a cache of dehydrated, thermostabilized, shelf stable, and fresh foods.

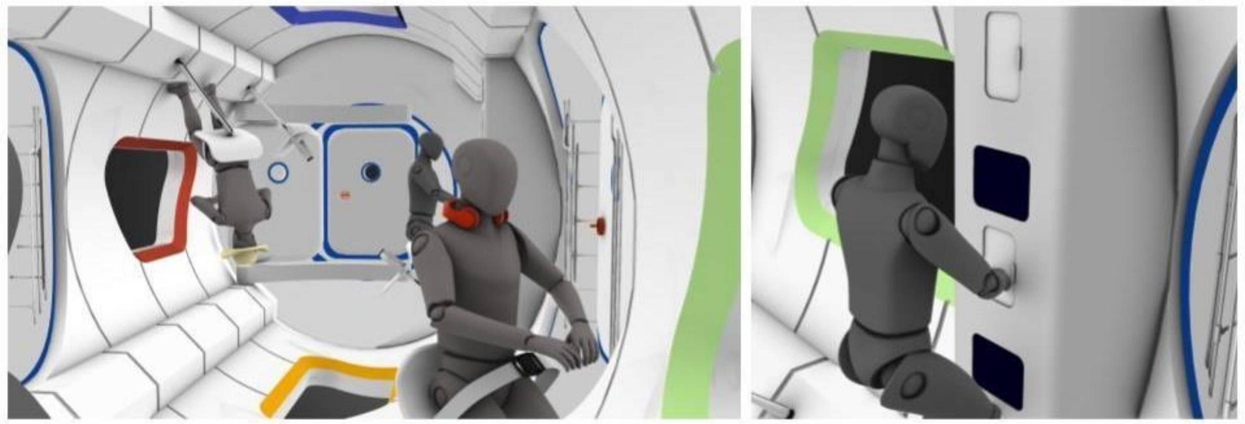


Fig. 51 Observation Deck Interior View / Crewmember Accessing Station

Having a basic refreshment dispensary located centrally in the vessel will allow crew members to grab food or drink more easily while on a break or when moving between tasks. Without such an option the crew would need to travel all the way to the galley located on deck 8 to achieve the same goal. Having the space cafe takes some load off the galley and saves the crew time when seeking out refreshments.

Being able to effectively position yourself and fix yourself in space will be especially valuable to crew members on the DSSV. In the Observation deck the crew will have a number of windows to look out of in order to view the cosmos and feel like they have temporarily left the vessel. The restraints or effectively “chairs” in the observation deck, shown in Fig. 52, will help the crew to relax more easily instead of having to hold on to railings.

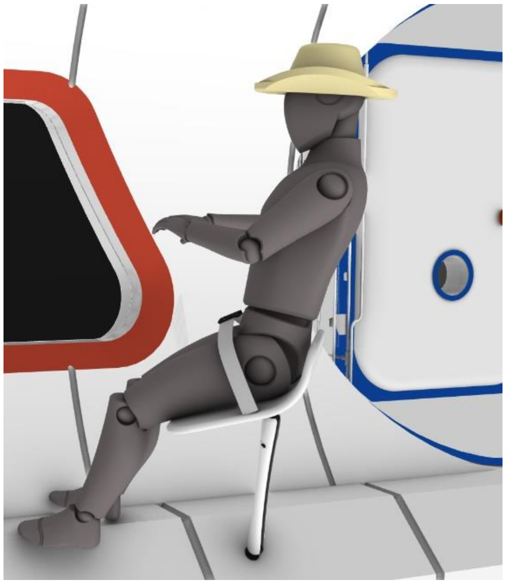


Fig. 52 Crew Member Seated

The restraints consist of two ball joints, a long arm/ connection piece and the “seat” component which can allow the crew to restrain their motion if desired. The human body assumes a certain position while in microgravity and thus a zero G chair would not need to support the astronauts like it would on earth. The restraints in the observation deck will hold the astronauts down at the thighs to a shallow seat preventing them from floating away. The seat is attached to the vessel with a long positioning arm similar to a commercial ball grip positioning arm such as the one shown in Fig. 53. [18]

Fig. 53 Positioning Arm Example from McMaster-Carr [18]

The Observation deck fulfills many roles on the DSSV, but it is primarily a rest and relaxation space designed to allow the astronauts the ability to step “outside” and escape the vessel for a time. It also functions as a much-needed additional pathway between the Habitation and Lab modules reducing the traffic through other paths. It further provides a direct visual of the exterior zenith side of the vessel should camera systems fail or become obscured.

B. Mission Operations Node

Located on Deck 9 above the Hab Module, the Mission Operations Node is subdivided into two operational sections, separated by the radial docking ports. The starboard side of the node, shown in Fig. 54, is a crew breakout meeting space. This is a reconfigurable meeting center. With partitions fully deployed, the center is separated into a central passageway and two small conference booths, each of which can accommodate 4-5 crew. With the partitions opened, the three spaces combine into a larger meeting area that can accommodate 15-17 crew.

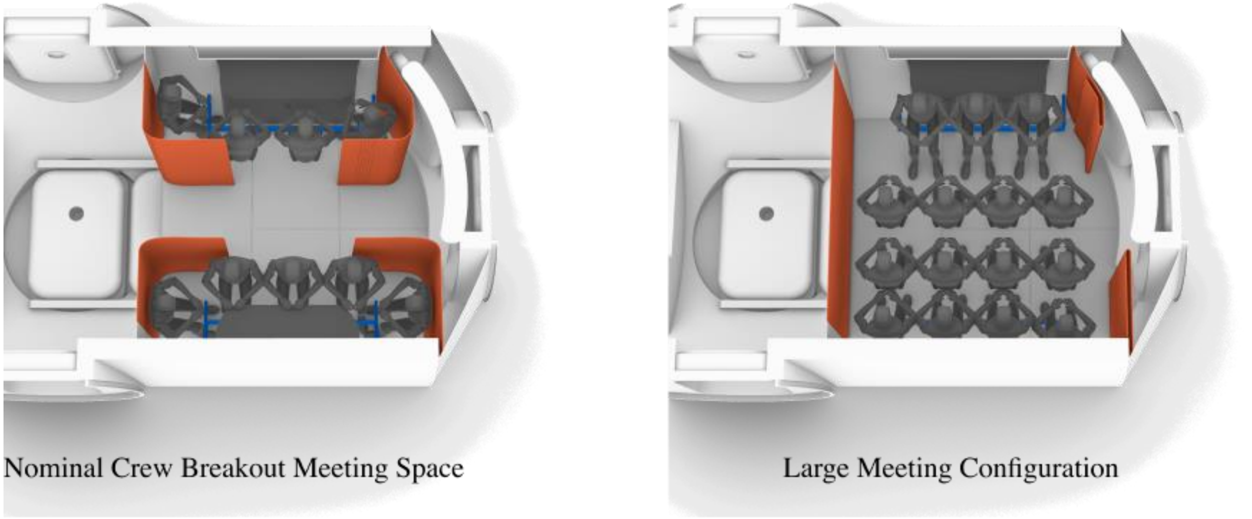


Fig. 54 Mission Operations Node Crew Breakout Meeting Space Configurations

The DSSV may one day become the first human spacecraft to contain an actual “bridge” or mission operations center, located on the port side of the node. Due to the distances the DSSV will travel from Earth, real-time mission control support will be limited. There will still be Earth-based mission control centers (MCCs) supporting each DSSV, but a dedicated onboard team will be responsible for real-time operations of the spacecraft. This onboard team will still coordinate with and rely on Earth mission control for activities whose response times are measured in days but will take more immediate action locally. Most of the core mission control positions used today for the International Space Station map to bridge positions on the DSSV. Table 1 matches ISS MCC console operators to the equivalent DSSV bridge operator and Fig. 55 shows the relative positioning of each bridge operator within the Mission Operations Node.

Table 1 Comparison of ISS Mission Control Console Positions with DSSV Bridge

ISS Mission Control Console Positions	DSSV Bridge / Mission Operations Center Positions
• CRONUS • PLUTO	• DARTH (Data Archive, Relay, and Transmission Handler)
• FLIGHT	• VADER (Vessel Administrative Director and Expedition Regulator)
• EVA (Extra-Vehicular Activity Officer) • VVO (Visiting Vehicle Officer) • ISE (Integration and Systems Engineer) • ROBO (Robotics Officer)	• SITH (Space Integrated Traffic Handler)
• OSO (Operations Support Officer) • Ops Plan • ISO (Inventory Stowage Officer)	• VULCAN (Vehicle Utilization, Logistics, and Crew Activity Negotiation)
• ETHOS (Environmental and Thermal Operating Systems)	• TRIBBLES (Thermal Regulation, Integrated Berthing, and Biochemical Life and Environmental Systems)
• SPARTAN (Station Power, Articulation, and Thermal Control)	• PHASER (Propulsion, Heat rejection, Active cooling, Secondary power, Electrical systems, and Reactor)
• ADCO (Attitude Determination and Control Officer) • TOPO (Trajectory Operations Officer) • Pointing	• WARP (Waypoints, Attitude, Rendezvous, and Pointing)

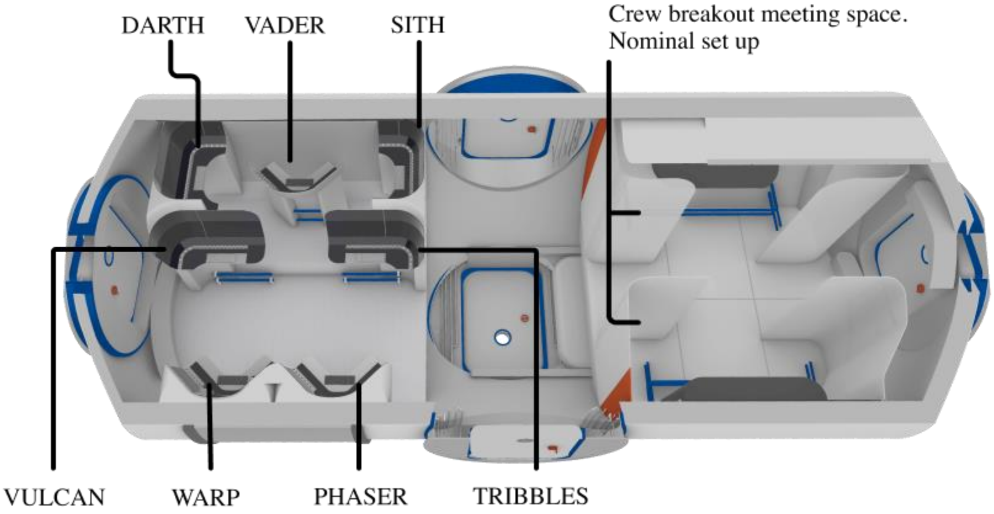


Fig. 55 Mission Operations Center Top View

As illustrated in Fig. 56, these consoles are designed to maintain a proper viewing distance of 20 inches and angle of 15 degrees for the crew while in the neutral body position. Each console display is a touchscreen but also contains edge keys to provide haptic feedback for critical commands.

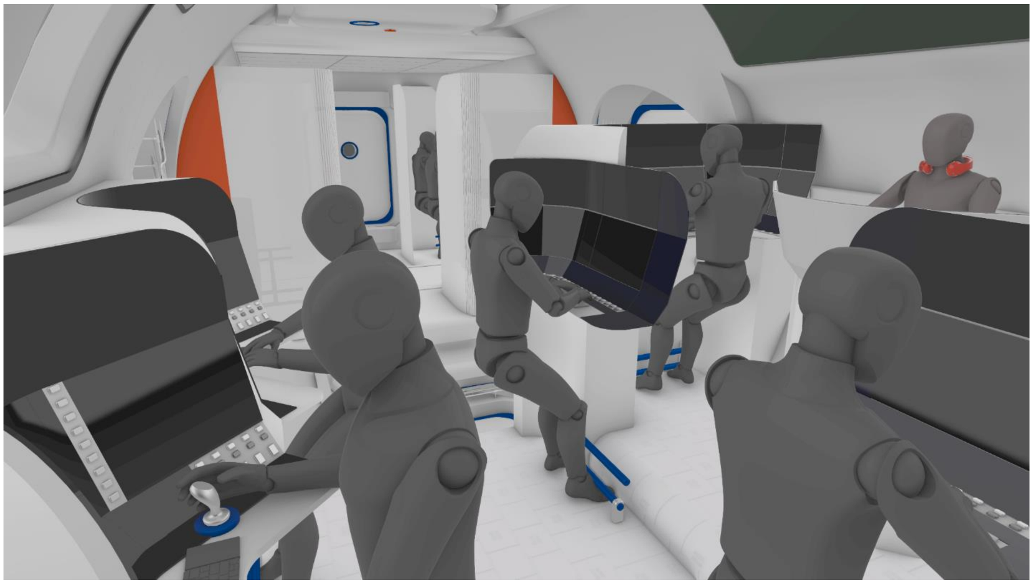


Fig. 56 Mission Operations Internal View

The bridge is fully staffed during the primary work shift and depending on vehicle activity may also be fully staffed during a second shift. At other times it is minimally staffed with only two operators. All of the DSSV crew are cross trained to serve an off-duty shift for at least one bridge position. Any display may be brought up on any console to enable varying staffing levels. However, controls for piloting or teleoperations are only available at the WARP and SITH consoles. To maintain a sense of hierarchy the VADER console is centrally located, and all aft consoles are slightly raised. This raised rear section also increases line of sight and the perception of space for crewmembers working in a relatively small area.

C. EVA Node

The EVA Node is the location for all preparations for EVAs as well as for basic spacesuit maintenance. The node, shown in Fig. 57, is located on deck 9 above the Lab Module and directly attached to Mission Operations. It is divided into two areas, an EVA maintenance area, and an EVA prep area. The EVA Node does not contain an airlock. Spacecraft ingress/egress, can be achieved through a variety of means – airlock, suitport-airlock, single-person spacecraft, etc. Variations of these are also compatible with specific types of spacesuits. The DSSV can dock one or more of these elements to itself as needed, enabling a mission-specific customization of EVA capabilities.

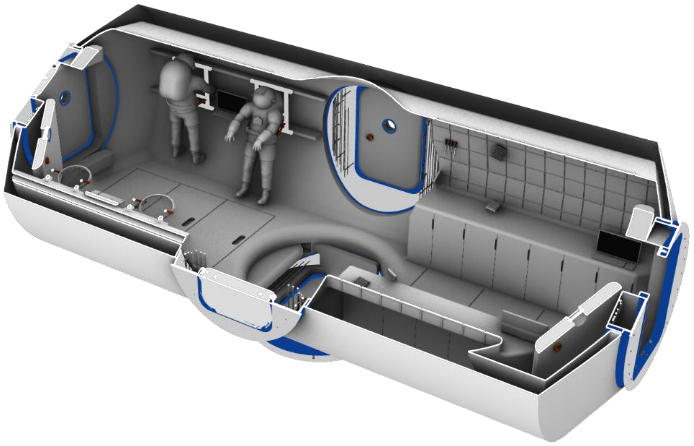


Fig. 57 EVA Node ¾ View

The EVA maintenance area consists of two large mounting vertical surfaces with attached horizontal table space that can be used for disassembling components and spreading them out while being worked on. Below these are stowage lockers that provide primary stowage for EVA consumables . These lockers are resupplied as needed.

The EVA prep area contains adjustable suit stands that allow the crew to service the spacesuits before and after missions. Nearby computer stations are available to support suit diagnostics, display procedures, and provide real-time support to EVAs in progress. The EVA prep area also provides volume for suit donning and doffing.

D. Stowage Node

The Stowage Node is located on Deck 1 below the Hab Module. The Stowage Node could be viewed as analogous to a loading dock in a terrestrial building. It does not contain the bulk of the long-term stowage for the DSSV, but instead serves as a staging area for distribution of incoming stowage and outgoing trash and waste. It can also be used as an assembly/disassembly area for incoming or outgoing items. Shown in Fig. 58, the port side of the node contains a series of nine large and six small stowage bays. The starboard side is an open volume. The node can accommodate up to 432 Cargo Transfer Bags (CTBs).

When not filled with stowage, the starboard side of the Stowage Node can be used as a crew breakout area and can accommodate meetings of up to 22 crew. It can also be subdivided into two meeting spaces, each with room for 3-6 people.

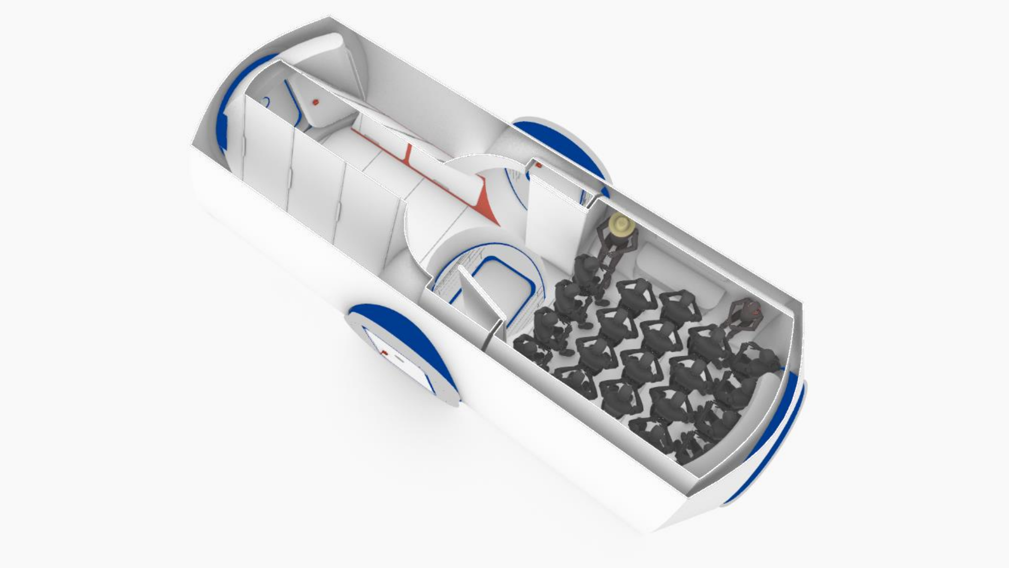


Fig. 58 Stowage Node

The Stowage Node is docked to the propulsion element, Hab Module, and Subsystems Node, leaving three open ports to dock to logistics modules. However, recent analysis suggests this may not be the optimal DSSV configuration from a stowage perspective.

A very rough, preliminary stowage estimate using merged parameters from multiple NASA Moon and Mars studies suggests total stowage needs for a five-year mission (a credible duration for some of the more distant destinations) to be on the order of 430 tons and 1000 m^3 (17,750 CTBs). This suggests that the initial approach of ISS node-derived modules may be an inefficient logistics solution as two dozen or more of those modules would be required. Clearly, cycling 24 logistics modules through three ports is a nonstarter. Alternately, two modules the size of the SLS Core Stage Liquid Oxygen Tank would be more than sufficient with additional growth margin for longer missions. Or a single module equal in size to the Habitation and Lab modules would be sufficient to carry five years of stowage.

Future work will explore alternate DSSV configurations that incorporate large logistics modules, with one option based on the use of two SLS LOX tank derived modules and a second option based on a single logistics module equal in size to the Habitation and Lab modules. This reconfiguration will also reassess the purpose of the Stowage Node and may move it into the logistics module(s). The resulting shift in vehicle configuration may also result in changes to the other node elements and even changes in deck layouts within the Habitation and Lab modules. Future logistics studies will also explore options for cold storage for perishable food and pharmaceuticals.

E. Subsystems Node

One node has been notionally designated for DSSV subsystems, including ECLSS, avionics, thermal, and power subsystems. The associated components have not been sized and there are presently no mass and volume estimates. The node is merely a placeholder in the current architecture. The design intent is that subsystems will be centralized in one or more node elements with the previously discussed utilities network used to provide services to the individual modules within the DSSV. This placeholder node is the aft starboard node, docked to the propulsion element, Lab Module, and Stowage Node. This node is retained in the DSSV as a placeholder, but it is expected that when future work sizes the subsystems it will be found that the node is not large enough to contain all needed systems. The intent of this project was to begin with the working and living spaces and expand in future work to the enabling subsystems.

VIII.Power and Propulsion Considerations

While no power assessments have been performed at this time, it is likely that the non-propulsive power needs for the DSSV will measure in the hundreds of kilowatts to singles of megawatts. While solar arrays could be large enough to generate this level of power at solar distances of 1AU, the intent to operate the DSSV as far away as the asteroid belt suggests that solar energy is not a practical solution and nuclear fission is a more viable power source given the DSSV's expected operating environments.

A future propulsion study is needed to determine if any conceivable propulsion systems can move the DSSV through its intended mission profiles, but it is currently assumed that either a nuclear electric or hybrid nuclear electric solution will be required, with fission power needs in the singles to tens of megawatts.

This multi-megawatt power generation will require corresponding heat rejection capability, but it is assumed that the heat rejection in the vicinity of Mercury and Venus will be greater than that required in deep space or in the vicinity of Mars or main belt asteroids. A radiator solution is forward work, but it is likely that such a solution will include the ability to increase radiator surface area when in higher heat environments. This might be achieved with deployable or expandable radiator wings, perhaps actuated with some form of motorized rigging.

Future propulsion studies will determine the true operating range of the DSSV. The initial intent is for the DSSV to conduct orbital missions throughout the inner solar system. However, some initial analysis suggests it may be more difficult (from a delta-v perspective) to achieve a Mercury orbit than it is to orbit Jupiter. The previously mentioned future logistics study will set a stowage capacity and thereby define the longest mission duration and total vehicle mass (excluding that of the propulsion system). A propulsion study can then use this mass and duration data as inputs to calculate which destinations can be reached by the DSSV and the associated flight times. Some iteration may be required to reach a reasonable solution.

A hybrid solution is expected, with one system providing high specific impulse (Isp) but low thrust, and another system providing low specific impulse but high thrust. High Isp options include xenon electric propulsion. Note that DSSV propulsion studies will not consider low TRL exotic propulsion systems as the intent is to identify solutions that could be implemented with reasonably current technology. Low Isp options include both chemical and nuclear thermal propulsion.

Hypergolic propellants are the most reliable chemical propellants because they ignite on contact and are liquid at room temperature, making them easy to store. However, their Isp is low enough that they often do not trade well in main propulsion system studies. Methane is a potentially favorable chemical propulsion option as there is existing commercial activity in high thrust, in-space methane propulsion. However, its Isp is not much greater than hypergolic storables. Some potential exists for methane production from in-space resources, to some extent offsetting its low Isp.

Hydrogen propulsion options will always have an appeal because of the high Isp of hydrogen. No other chemical propulsion system will achieve the performance offered by hydrogen. Hydrogen can also be produced from local resources at many places in the solar system. The Moon, Mercury [19], Mars, Vesta [20], and Ceres [21] are known to have substantial amounts of hydrogen. Automated propellant production facilities at these locations could possibly produce hydrogen to refuel an arriving DSSV. However, hydrogen's low boiling point potentially negates its advantages. Presently, no cryocooler is capable of maintaining hydrogen in liquid form indefinitely. And given the durations expected for DSSV missions, any boiloff is a potential showstopper. It is possible that rapid electrolysis could be used, such that propellant is stored long term as water, and is electrolyzed into liquid oxygen and liquid hydrogen shortly before use. However, this will undoubtedly require very high levels of electricity. More study is needed to determine if this is within the credible performance of a fission reactor system.

Nuclear thermal propulsion offers the highest Isp of the high thrust propulsion systems. However, it uses hydrogen as a propellant and thus shares the storage disadvantages of hydrogen chemical propulsion.

IX.Conclusion and Forward Work

This work has established, from a human centered design perspective, how forty-eight crew might live and work in the DSSV. A next step is to expand on the stowage estimates and redefine the habitable volumes based on either integrated or modular stowage systems. This will also include identification of conditioned stowage requirements, such as for frozen food and medicines. As previously discussed, this may add additional large diameter modules, perhaps equal in size to the Hab and Lab modules and may replace some of the nodes. Solar particle event shelters have not been incorporated into the vehicle design and should be added in conjunction with the stowage systems development as the stowage forms a natural radiation barrier. Next, vehicle subsystems will be defined with mass and volume estimates and CAD placement, particularly ECLSS, avionics, structures, and internal thermal control. The utilities already identified at a high level in this work will also be more thoroughly defined. This may lead to additional subsystems modules. EVA and visiting and attached spacecraft architectures will also be more fully developed. A complete mass estimation of all components within the habitable elements of the DSSV will be conducted.

With the habitable segment of the DSSV sized, the power, propulsion, and thermal systems design can begin. The control moment gyros (CMGs), reaction control system (RCS), main, and electric engines will be selected. This inherently will include decisions on propellant types and propellant storage capabilities, ruling in or out, for instance, liquid hydrogen or methane systems. Trajectory determinations will be completed, sizing the vehicle for the upper ends of its performance envelope. A starting position will assume a maximum mission duration of seven years, chosen to match a likely flight time for one of the more distant potential destinations. Based on the Isp of the selected engines this will bound the delta-v envelope of the DSSV, which when matched with potential trajectories will bound the potential destinations. Propellant tanks sizing can then be completed, including any necessary cryocooler selection. The primary and secondary power usage will then be estimated for the DSSV, leading to selection of the appropriate nuclear fission reactors and any secondary power generation or storage systems. This will then allow for sizing of reactor shields. Finally, based on the thermal energy generated by the DSSV and the thermal environments at different locations in its operating envelope, a heat transfer and heat rejection system can be sized.

Several campaign analyses will then be conducted to explore the operation of the DSSV. A launch vehicle analysis will be performed to identify an assumed launch architecture to support DSSV operations. Based on this, a manifest for initial assembly of the DSSV and outfitting it for its first expedition, including crew launch, will be prepared. Another analysis will examine options for mid-cruise resupply at specific destinations and identify which logistics are appropriate for delivery after the DSSV has departed Earth. Surface and atmospheric expeditions will be briefly assessed, primarily focusing on NEA, Venus, and Mars destinations. Additional analysis will explore artificial gravity campaigns that can be launched from the DSSV, using its visiting vehicles as tethered artificial gravity platforms. Finally, crew and logistics exchanges will be modeled, assessing how the DSSV will be resupplied and how crews will be exchanged between missions.

A Vehicle Architecture Analysis (VAA) will be used to compare the DSSV to its theoretical predecessor, the Deep Space Exploration Vehicle (DSEV). [22] This analysis will identify areas of commonality and will contrast key technology developments needed for each spacecraft. This can help define a development path from the eight-person DSEV to the forty-eight person DSSV.

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