AIAA SPACE 2013 Conference and Exposition
September 10-12, 2013, San Diego, CA

AIAA 2013-5433

Internal Layout for a Cis-Lunar Habitat

Brand N. Griffin[1]
Gray Research, Jacobs Engineering and Science Services and Skills Augmentation Contract, 655 Discovery Drive, Ste. 300, Huntsville, AL 35806 U.S.A.

David Smitherman[2]
NASA, Marshall Spaceflght Center, Huntsville, AL 35812 U.S.A.

and

A. Scott Howe[3]
NASA, Jet Propulsion Laboratory, Pasadena, CA 91109 U.S.A.

The distance between Orlando, FL and Miami, FL is 377 km (234 mi.). This is the approximate orbital altitude of the Russian Salyut and MIR space stations; Skylab and the existing International Space Station (ISS). With the exception of the Apollo missions, virtually all human space flight has occurred within the distance between Orlando and Miami. In other words, very close to the Earth. This is significant because NASA's goal is to explore Beyond low-Earth Orbit (BEO) and is building the Space Launch System (SLS) capable of sending humans to cis-lunar space, the surface of the Moon, asteroids and Mars. Unlike operations in low-earth orbit, astronauts on BEO missions do not have rapid emergency return or frequent resupply opportunities and are exposed to potentially lethal radiation. Apollo missions were by comparison short. The longest was 12.5 days compared to cis-lunar missions currently being sized for 60 and 180 days. For radiation, one of the largest solar particle events (SPE) on record (August 4-9, 1972) occurred between the Apollo 16 and 17 flights. This was fortunate because the magnitude of this SPE would likely have been fatal to astronauts in space suits or the thin-walled Lunar Excursion Module. A cis-lunar habitat located at one of the Earth-Moon Lagranian points (EM L2) is being studied. This paper presents an overview of the factors influencing the design and includes layout options for the habitat. Configurations include ISS-derived systems but there is an emphasis on SLS-derived versions using a propellant tank for the habitat pressure vessel.

Nomenclature

BEO	=	Beyond Earth Orbit	*L*	=	Lagrangian Point
CTB	=	Cargo Transfer Bag	*LEO*	=	Low-Earth Orbit
CO2	=	Carbon Dioxide	*MMOD*	=	Micrometeoroid Orbital Debris
DDT&E	=	Design, Development. Test & Evaluation	*MPCV*	=	Multipurpose Crew Vehicle
DSH	=	Deep Space Habitat	*MPLM*	=	Multipurpose Logistics Module
ECLSS	=	Environmental Control Life Support	*NDS*	=	NASA Docking System
EML2	=	Earth-Moon Lagrangian Point 2	*RF*	=	Radio Frequency
EVA	=	Extravehicular Activity	*SLS*	=	Space Launch System
GCR	=	Galactic Cosmic Ray	*SPE*	=	Solar Particle Event
ISPR	=	International Standard Payload Rack	*WMC*	=	Waste Management Compartment
ISS	=	International Space Station			

[1] Senior Engineer, Gray Research, Jacobs Engineering ESSSA Group, Huntsville, AL, Senior Member.
[2] Architect, Advanced Concepts Office, Mail Code ED04, Senior Member
[3] Architect, Mission Systems Concepts, Mail Code 312E.

I. Introduction

TO provide a low-cost deep space habitat within a short period of time, attention was concentrated on residual International Space Station (ISS) ground assets. For this approach, the Node 1 structural test article and a Multipurpose Logistics Module (MPLM) were considered the most favorable candidates. These modules were designed for a Shuttle delivery and configured with hatch openings and an interior layout based on modular interchangeable racks connected to utility standoffs. Using these modules as pressure vessels, two layout grouping were studied. One was constrained to the ISS rack-standoff concept and the other repackaged ISS systems into a "non-rack" solution. Both concepts required multiple expendable vehicle launches to assemble and resupply the cis-lunar habitat.

The new Space Launch System (SLS) inspired another concept similar to the post-Apollo Skylab project. Like Skylab, an empty upper stage hydrogen propellant tank is converted into a deep space habitat. This too was considered low-cost because SLS pays for the design, development, test and evaluation (DDT&E) and as designed, the tank accommodates all launch loads and exceeds cabin pressure requirements. Furthermore, because SLS delivers heavy lift, large diameter payloads, the single launch Skylab model is a very attractive option.

II. Cis-Lunar Space – Not Low-Earth Orbit

Cis-lunar refers to the space between the Earth and the Moon, however for the purposes of this paper; it also includes the Earth-Moon Lagrangian points such at EM L2 which is beyond the Moon (Figure 1). Cis-lunar space is different than Low-Earth Orbit: 1. It is further away from Earth which means a longer transit time (8 days to EML2), has a significant communication delay (2.6 sec) and does not offer a rapid emergency Earth return. 2. Unlike orbiting Earth, the trip requires more energy for escape velocity and orbit insertion which means an upper stage translating into less payload and costly, less frequent resupply. 3. Being outside the Earth's magnetosphere means a more severe radiation environment and therefore crew protection is required in the event of a Solar Particle Event (SPE) and there is an imposed 180 day limit due to Galactic Cosmic Ray (GCR) exposure. 4. It is colder which means additional mass for the thermal control system. Combined, these differences call for a more autonomous habitat with an interior layout designed for reliability, maintainability and infrequent resupply.

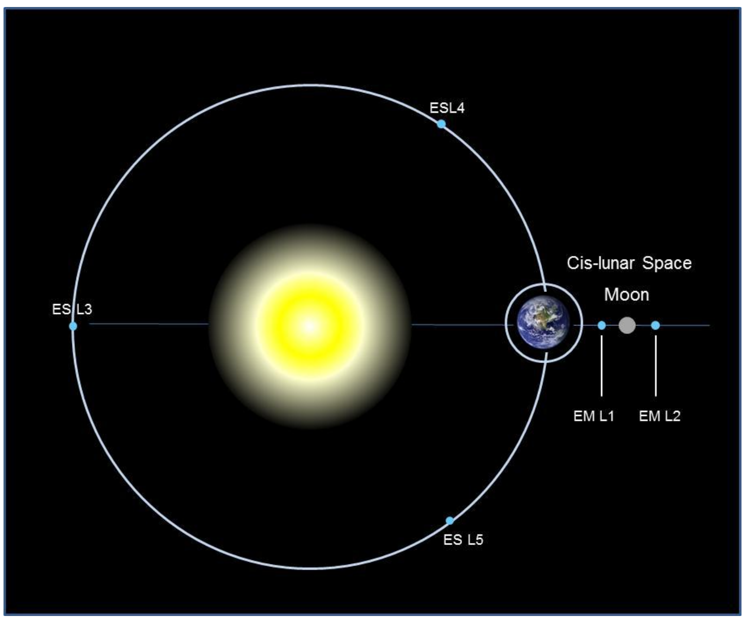

Figure 1. Cis-lunar space includes Earth-Moon Lagranian points.

III. Mission Objectives and Internal Systems

A. Mission Objectives

The objectives for the EML2 location are to provide a microgravity environment for physical sciences and accommodations for life science research necessary for the planning and design of a human mission to Mars. In addition, this location offers near real-time teleoperations of lunar operations such as robotic rovers or *in-situ* resource utilization. It also serves as an assembly/servicing platform for spacecraft and telescopes.

B. Internal Systems

The internal layout of the cis-lunar habitat integrates mission, support, and crew systems. Mission systems include: the workstations, tools and equipment necessary for conducting science and lunar teleoperations. The support systems include secondary structure, environmental control and life support, thermal control, electrical power control and distribution, and avionics for data management, guidance, navigation and control as well as communications. Crew Systems include: galley, wardroom, crew quarters, exercise equipment, food and food storage, personal hygiene/waste management, storage, and accommodations for extravehicular activity (EVA).

C. Crew Size and Mission Duration

All internal layouts were sized for 4 astronauts with no accommodations for overlapping crews. For the EML2 location, initial missions were assumed to run for 60 days then growing to 180 days.

IV. Weightless Habitats-Guiding Principles

A. Neutral Body Posture

A cis-lunar habitat operates in weightless space and therefore is designed for astronauts in the neutral body posture as shown in Figure 2. This is the form that humans assume without the influence of gravity and it is important because not only is it dimensionally different than 1-g anthropometry, but so are orientation, translation and stabilization. The design population for the cis-lunar habitat ranged from the 5th percentile female to the 99th percentile male.

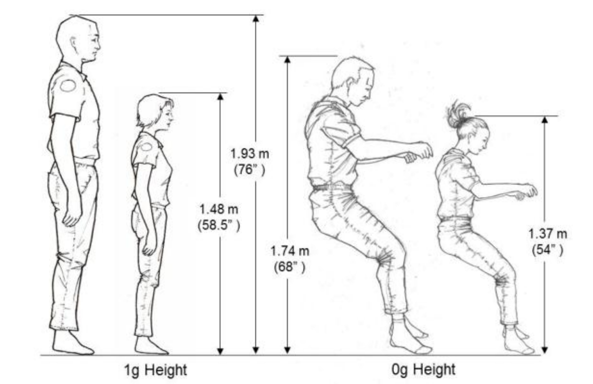

Figure 2. Designed for Neutral Body Posture.

B. Local Vertical

Without the natural orientation of gravity, a local vertical is imposed to provide a common up and down across the spacecraft. This establishes the orientation for controls and display, labeling and is useful in face to face communication. Like sunlight and overhead lighting, spacecraft illumination is used to imply an "up" direction and because there is no convection, a head-to-toe airflow provides a reinforcing cue while washing away exhaled carbon dioxide (Figure 3). Without foot restraints, weightless astronauts must stabilize themselves using their hands. Because this prevents two handed operations, having floor mounted foot restraints allows stability with two free hands. The local vertical provides a reference but does not restrict the crew from assuming different orientations out of personal preference or improved accessibility.

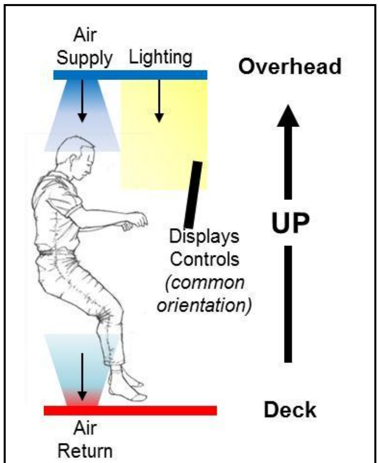

Figure 3. A common local vertical across all elements.

C. Zoning and Functional Adjacency

Zoning and functional adjacency are guiding principles that provide constraints for positioning internal systems. Zoning is the grouping of elements that share common attributes or resources (Figure 4). Typically, this includes separating quiet and noisy activities, placing crew access function such as galley/wardroom and personal hygiene in the wall location, positioning subsystems in the overhead and floor locations, and grouping microgravity science at the best location within the spacecraft. Functional adjacency refers to a proximity assessment determining which activities prefer to be next to one another, separated or are indifferent. These guiding principles provide a point of departure for the internal layout; ultimately the final arrangement is the result of an iterative process that integrates other factors including mass, volume, cost, schedule, technology level and maintainability.

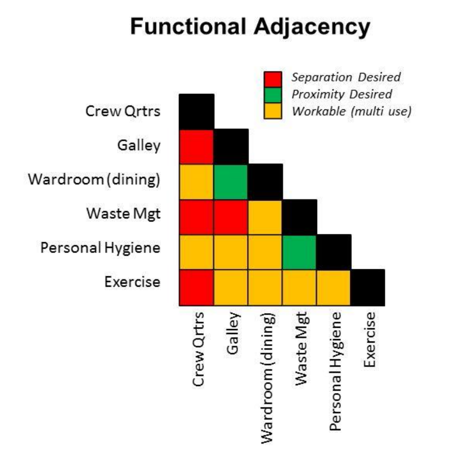

Figure 4. Collocation and separation helped by adjacency matrix.

V. ISS-Derived Layouts

The motivation behind ISS-derived solutions is the potential of lower cost using ISS elements that are on the ground, specifically the structural test article for Node 1 and the MPLM. These elements were designed to fly on the Shuttle and use a rack/standoff internal layout. The rack/standoff approach refers to an internal arrangement that packages systems into International Standard Payload Racks (ISPR) then attaches these to 4 structural standoffs for restraint and access to utilities (Figure 5). Because the Shuttle delivered modules partially outfitted, follow up logistics flights were required to complete the configuration. Consequently, translation paths and hatch openings were sized to accommodate transferring and placing racks into the on-orbit modules. For the cis-lunar habitat layout, ISS module pressure shells were configured using either conventional rack/standoff or systems repackaged into a non-rack/standoff layout.

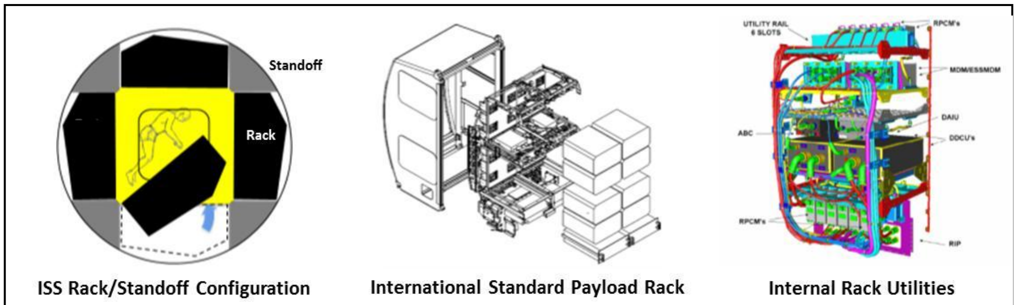

Figure 5. Additional packaging mass and utility complexity with rack/standoff.

Subsystem	N 1	MPLM 1	MPCV	Rack Equiv
Atm Revitalization		*		1/2
Oxygen Generation				1
Water Recovery				2
Waste/Hygiene				1
Crew Health Care				1
Fire Detectn/Suppress		**		
External Thermal Cntrl				
Atm.Cond./Sup. Sys				2
Internal Therm. Cntrl				1
Elec. Pwr Supply				
Pwr Distribution				1
External Comm.				
Avionics				1.5
Crew Quarters				4
Galley				1
Wardroom				2

*A 2nd AR rack is included for long missions
** ACSS in endcone; long missions 2 racks of contingency air added

Figure 6. Subsystem rack equivalent volumes used for cis-lunar habitat.

A. Rack/Standoff

For rack/standoff layouts, subsystem experts first assessed the ISS racks for applicability to the cis-lunar habitat mission. Duration, crew size, technology level, redundancy, mass and volume were all considered in the assessment. Based on the identified functions (racks) an initial layout was generated according to the guiding principles listed above. Because Node 1 and the MPLM have fewer rack bays than the US Laboratory, layouts were compressed lacking the separation provided by most on-orbit elements. Another factor affecting what racks went into which module was the delivery sequence (Figure 6). Ground rules stated that the first three missions would each be 60 days and use only Node 1, a commercial pressurized logistics element and an MPCV. After this series of missions, the MPLM element would be added to the assembly providing accommodations for a 180 day mission (Figure 7). Although not ideal, the concepts appeared workable. Surprisingly, accommodating exercise surfaced an under-appreciated challenge. This is because ISS exercise equipment is heavy with masses ranging from 100 to 1000 kg and a 2 ½ hour daily workout is recommended for each astronaut. The result is 10 hours continuous use producing an unhappy adjacency between the crew work stations and exercise within the 4 available rack bays of Node 1.

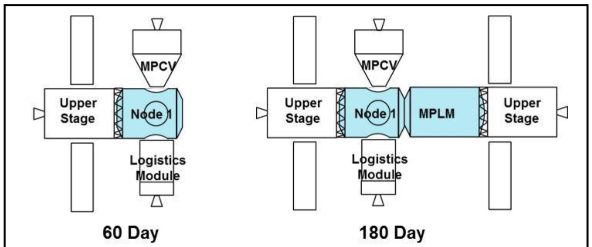

Figure 7. Growth from 60 to 180 day mission.

The buildup plan for the ISS-derived habitat is to first deliver the Node to EML2. Later, a pressurized logistics module will be launched and autonomously dock to the Node making the assembly ready for the crew arriving in the MPCV. All three elements are functionally interconnected and necessary to support the 60-day mission. This arrangement is possible because the MPCV provides most of the ECLSS and habitation functions while the Node accommodates workstations, exercise and doubles as an EVA airlock. Figure 8 shows the Node topology with the associated functions for each of the attached pressurized elements. Because of the rack/standoff cross-section symmetry, internal layouts are displayed in "rolled-out" topographic representation. To accommodate the 180-day missions, the MPLM provides both functional subsystems and habitation elements for the longer missions. This mission is accomplished by adding an

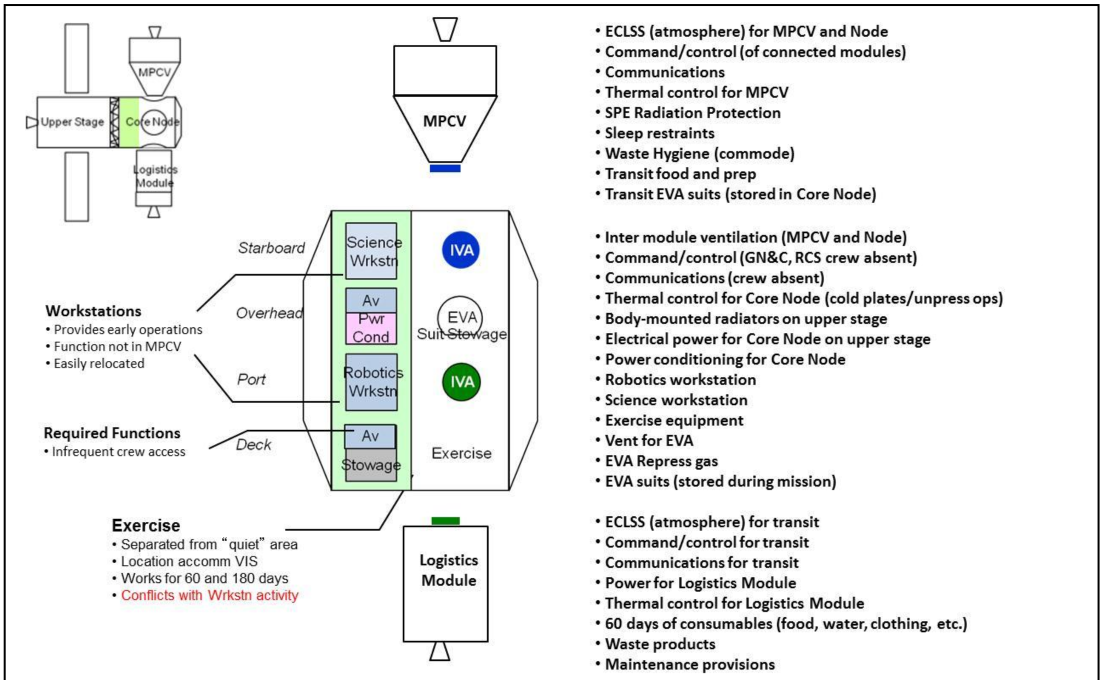

Figure 8. Node 1 connects with MPCV and Logistics Module for 60 day missions.

MPLM module configured with subsystems and crew accommodations.

The overall arrangement (Figure 9) follows the active/quiet gradient with the galley wardroom at the entrance and crew quarters at the far end. Also located close to the entrance is a maintenance work station that takes

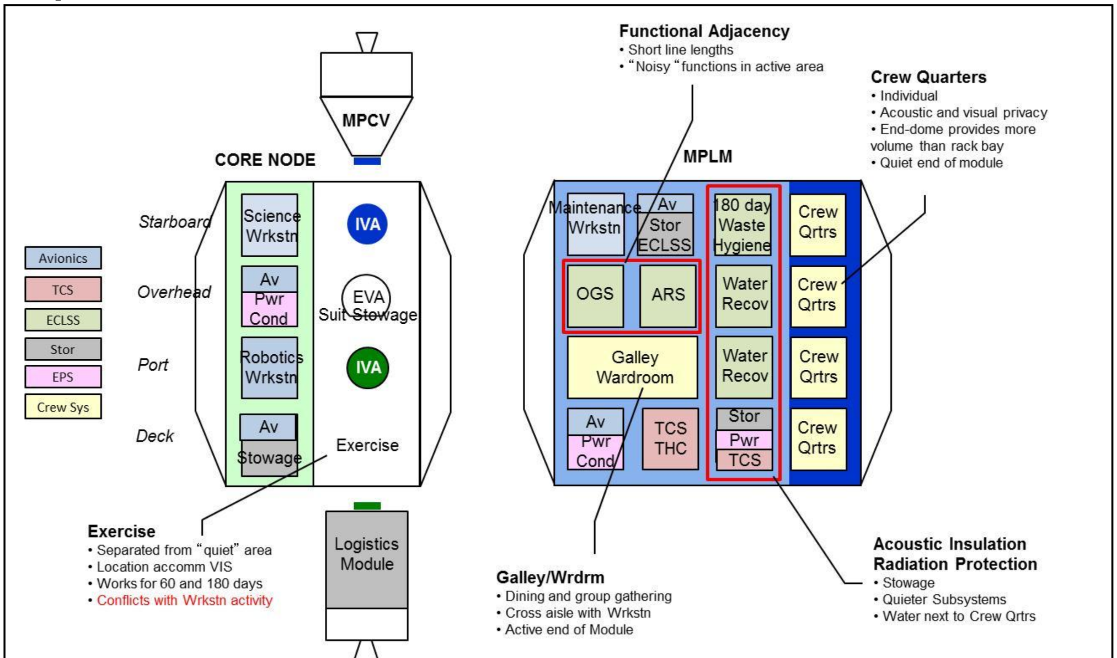

Figure 9. An MPLM with subsystems is added for the 180 day missions.

advantage of the open galley wardroom space across the aisle. In addition to being at the quiet-end, the crew quarters location offers additional radiation protection by being sandwiched between adjacent subsystems and the mass of the attached upper stage. For rack-based consistency, the crew quarters use the ISS bump-out design and are positioned in each of the far end rack stations. To the extent that subsystem adjacency is beneficial, the ECLSS racks are grouped together. An ISS type waste/hygiene compartment provides greater volume and privacy than the commode in MPCV and is more suitable for longer duration missions. Thermal control, avionics and power conditioning equipment are located in deck and overhead rack locations.

B. Non-Rack/Standoff (within ISS pressure shells)

The non-rack/standoff approach arranged systems within ISS pressure shells using different restraint and equipment packaging concepts. Rack-packaged hardware is not easily accessed so one objective of this approach included single-layer packaging of equipment thus avoiding having to remove one component to get to another. Furthermore, the symmetry of the ISS rack/standoff cross-section resulted in a combined aisle way work space. Non-rack/standoff geometries provided the opportunity to tailor aisle ways and work spaces into a more efficient and responsive layout. Figure 10 compares a number of non-rack/standoff cross sections to the ISS configuration.

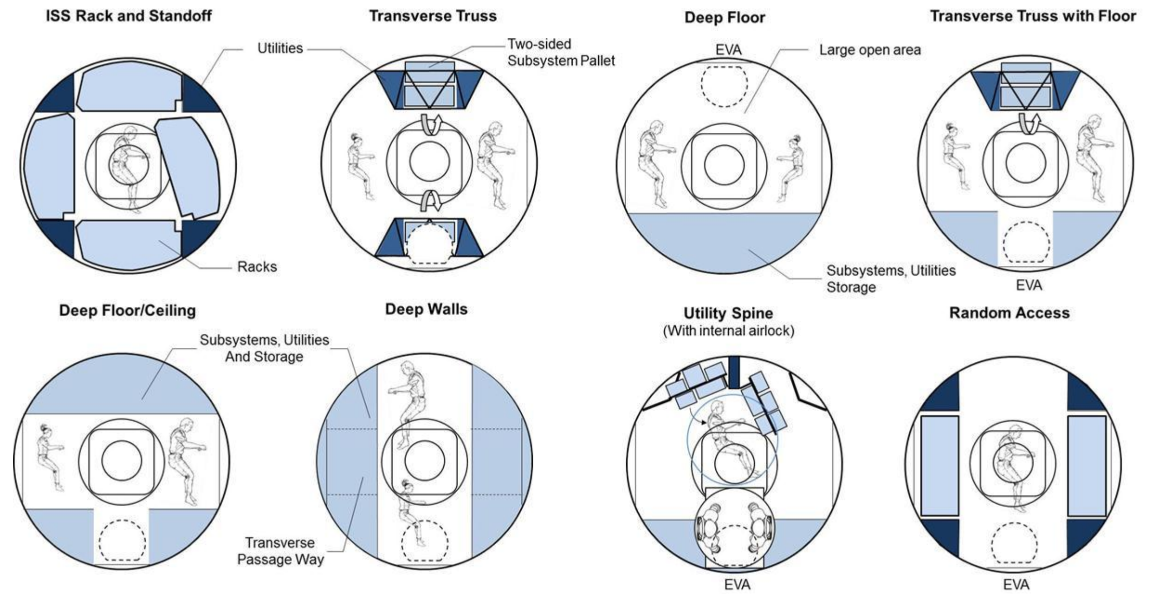

Figure 10. Options for non rack/ standoff outfitting within the ISS pressure shell.

One option called Four Longerons (Figure 11) proved particularly well suited for an ISS-sized deep space habitat. ISS utilities are densely packed in standoffs making inspection or repair difficult and time consuming. To improve the design, four open-web longerons were used for structural support and also as cable trays. The benefit is the longeron depth affords single-layer mounting of utilities with direct visual and physical access for easy maintenance. A two-sided equipment pallet is another improvement over the rack/standoff approach. By allowing utilities to cross over in the middle of the module, the Four Longeron reduces line length, power requirements, and noise producing a lighter, more efficient distribution system than the ISS rack/standoff solution. Furthermore, rather than the complicated distribution required for interchangeable rack, the Four Longeron solution provides for simple direct connections.

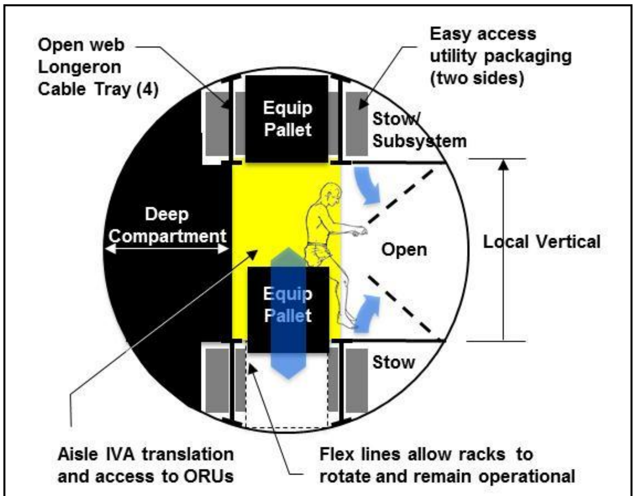

Figure 11. Four Longeron configuration.

Pallets double the equipment mounting area and when rotated, provide access to equipment mounted on both sides, the utility trays and the pressure vessel hull. Flex lines connect the pallet to the utility tray allowing the system to remain operational while rotated for servicing. In contrast to the large aisle way produced by the rack/standoff configuration, the Four Longeron approach provides a smaller (1.5m x 2m) multi-use aisle way allowing larger compartment volumes for habitation functions such as private crew quarters, waste/hygiene, full body cleansing, group meals/meetings, and exercise.

The topology shown in Figure 12 is packaged within the shell of the ISS habitat module located at NASA's

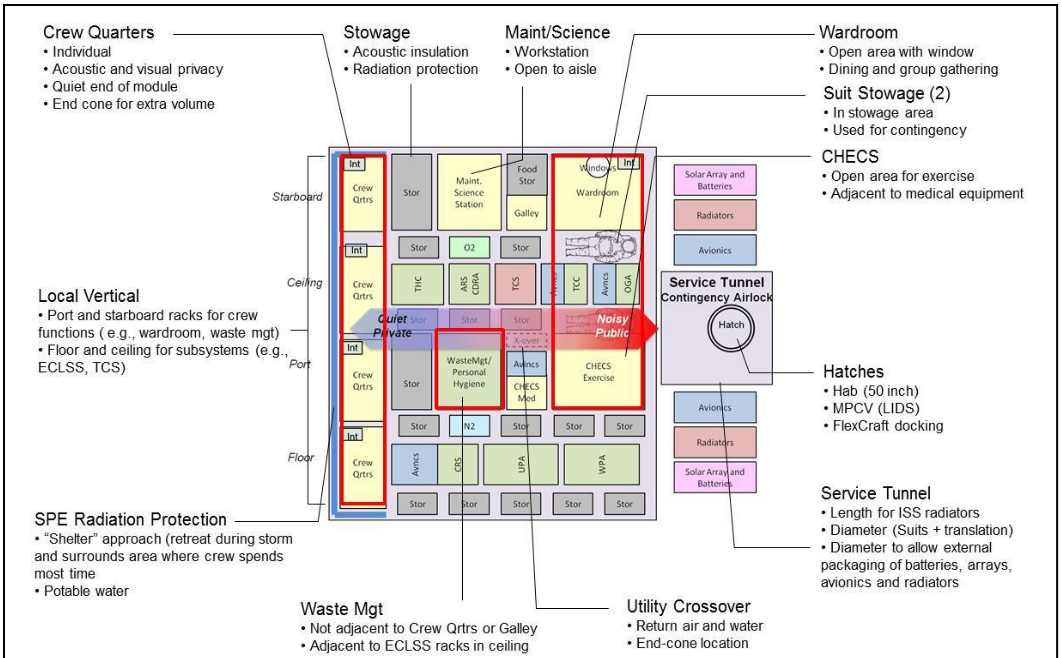

Figure 12. Topology of Four Longeron non rack/standoff configuration.

Marshall Space Flight Center along with plan and sections in Figure 13. The active subsystems are located in the floor and ceiling allowing the habitability functions to be positioned in the wall locations for direct access consistent with the local vertical. The active end of the module opens to the full 4.3 m diameter and includes a

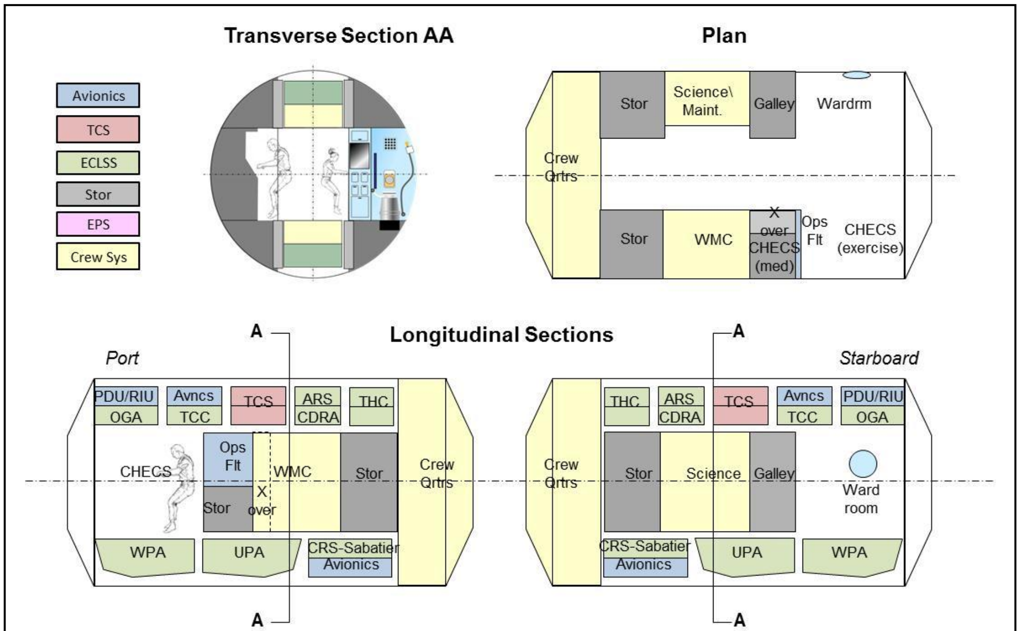

Figure 13. Plan and section views of the Four Longeron configuration.

galley/wardroom on one side with accommodations for Crew Health Care (exercise) on the other. This open area is a multi-function space and also includes storage for medical provisions and a work station for flight operations. Events in this area are time shared so that exercise does not interfere with the common meal time.

Crew Quarters

The Four Longeron configuration provides each crewmember with about twice the volume as the ISS crew quarters. This is beneficial because the crew quarters are used as a radiation storm shelter sometimes requiring multi-day confinement during a Solar Proton Event (SPE). Storage is placed adjacent to the crew quarters to provide acoustic insulation and add to radiation protection. They are equipped with sleep restraints, power and data ports, and controls for lighting, temperature, and air flow. In addition to sleeping, crew quarters are used for changing clothes, private communications, and off-duty activities. The concept for the crew quarters is shown in Figure 14.

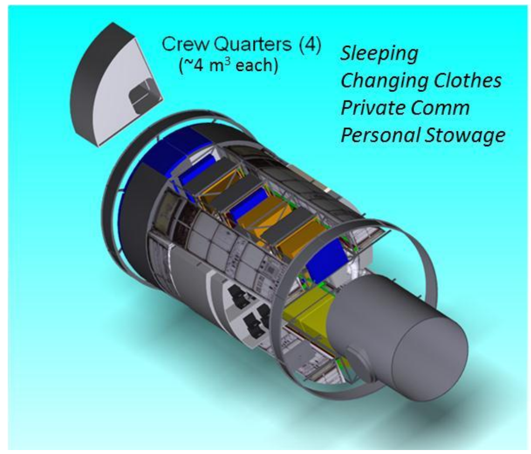

Figure 14. Larger crew quarters for DSH.

Waste Hygiene Compartment

The waste/hygiene compartment (WHC) is in the middle of the module convenient to both the active and passive ends of the module. For ISS, the WHC equipment takes up most of the rack volume requiring users to extend privacy partitions into the aisle way. The Four Longeron architecture offers a much improved design that includes adequate internal volume for waste management as well as whole body cleansing (Figure 15). If the compartment is occupied, crew members use the aisle way hygiene station to brush teeth or wash hands. The configuration allows easy access to both the hull and commode hardware for servicing. Rather than take up internal volume, hygiene provisions are in the adjacent stowage rack, yet accessible from inside the compartment. Like the crew quarters, the compartment has controls for lighting, temperature, and air flow.

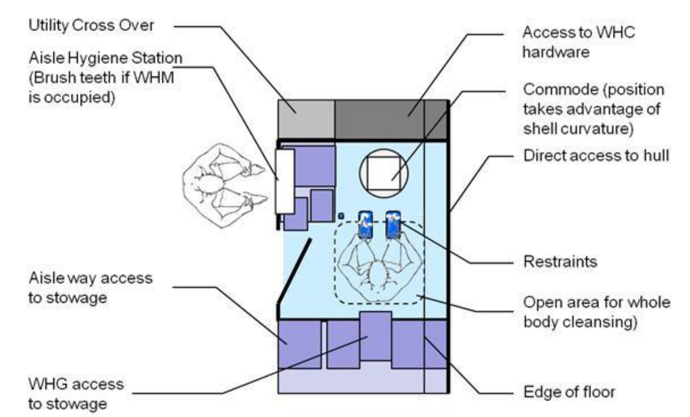

Figure 15. More volume for waste/hygiene compartment.

Prioritized Access

The Four Longeron configuration uses zoning for accessibility. As shown in Figure 16, items that require immediate physical and visual access are placed in zone A. These may include frequently used hardware or emergency items. Zone B provides indirect access for items that may include filters or clothing. Items used only on the return leg of the mission or spares could be located in Zone C. Locating stowed items is always a challenge, so the goal is to use a Radio Frequency (RF) identification system with a tailored software search engine to find items even if they are misplaced. Dimensionally, the aisle way is wider than the compartment partitions. This allows the partitions to be transported down the aisle way without disassembly.

VI. SLS-Derived Layouts

The size and heavy lift capability of the Saturn V enabled a large diameter habitat, solar telescope, multiple docking adaptor, and airlock to be placed on-orbit in a single launch. The Space Launch System (SLS) offers similar size and lift capabilities that are ideally suited for a Skylab-type mission to cis-lunar space. An envisioned Skylab II employs the same propellant tank concept; however in this case, the SLS upper stage hydrogen tank is used as a deep space habitat (Figure 17). The tank is light weight, designed for SLS launch loads and because it is a propellant tank it is capable of accommodating a one atmosphere pressure with human

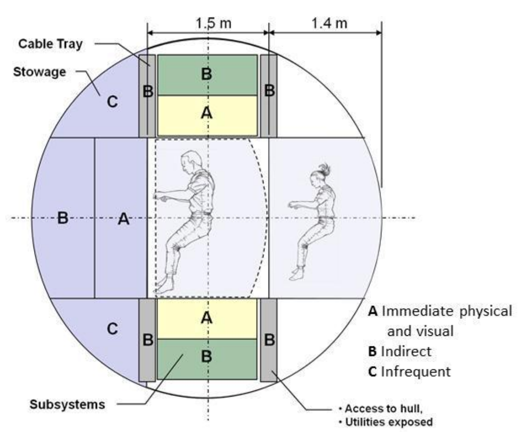

Figure 16. Prioritized stowage access.

rated safety margins. Furthermore, it is large with an outer diameter of 8.5 m (27.6 ft.) and an overall height of 11.15 m (36.1 ft.)which is taller than a two story house.

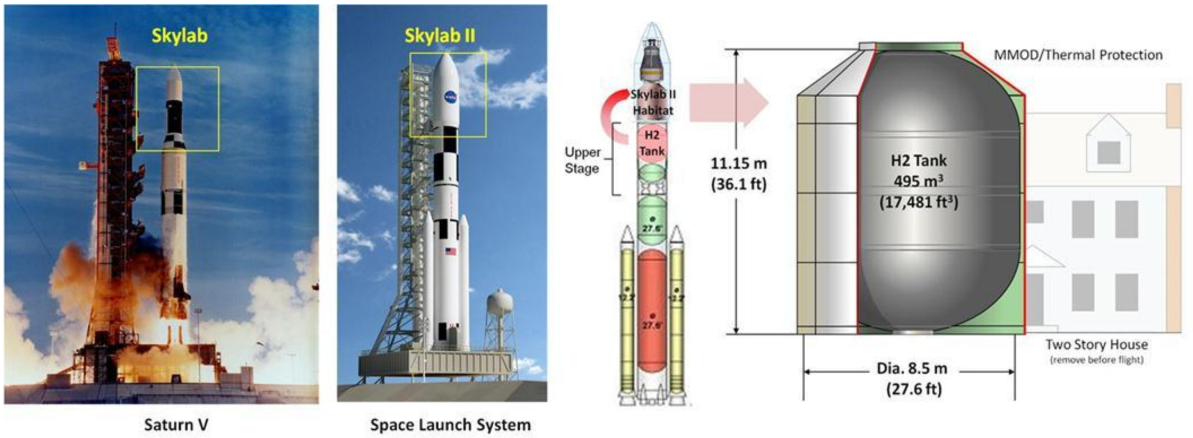

Figure 17. Like the Apollo Saturn V, SLS offers heavy lift and large diameter for single launch payloads.

Design Approach

Although design is rarely sequential, a step-wise approach helped to structure the analysis leading to a point of departure. Each step identified assessed features affecting the internal layout which meant rather than an infinite number of solutions, the problem was progressively constrained. Figure 18 shows the 10 steps used for developing the SLS-derived internal layout.

Internal Layout Approach

1. **Identify deck orientation options**
2. **Establish deck separation (floor/ceiling height)**
3. **Position decks within pressure vessel**
4. **Assess deck options with respect to docking port options**
5. **Analyze dimensional and geometry sensitivities (equipment, stowage)**
6. **Explore structural options for deck arrangements**
7. **Assess structure/utility routing**
8. **Analyze functional location based on "passive" radiation protection**
9. **Create layout diagram**
10. **Generate example layout(s)**

Figure 18. Step-wise process used to produce internal layouts.

1. Deck Orientation

Because ISS modules have a small, 4.3 m diameter, there are few options for floor (deck) orientation. A transverse (pancake) arrangement does not lend itself to rack modularity, has inefficient packaging and requires disproportionate volume for crew translation. This is why both the rack and non-rack-based configurations were configured using the ISS-like longitudinal orientation. For a large 8.5 m SLS propellant tank, the deck orientation is not so obvious. Deck orientation was classified as either transverse or longitudinal (Figure 19) and used to separate activities, mount equipment and distribute utilities. Geometries would allow for crew translation between decks and be tailored for air flow, acoustics insulation, visual privacy and radiation protection.

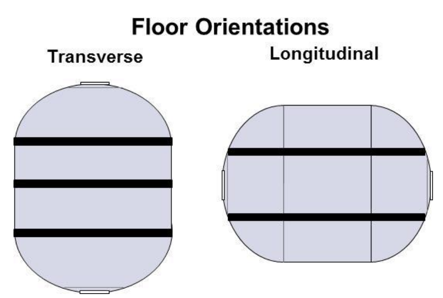

Figure 19. Two floor orientations

2. Deck Separation

Understanding the two orientations, the next step was to assess the location and number of decks that could be placed within the SLS tank size and geometry. This started with the projected height of neutral body posture astronauts in a local vertical environment. It was assumed that there was a common "up" for the entire volume. However, the deck separation should remain the same even for a back-to-back floor arrangement. Clearly, the separation distance is dominated by the tall end of the design population which is 1.74 m (68 in.). Beyond this minimal dimension, what should the deck separation be? Two conditions were considered: one free floating and the other with floor-mounted foot restraints (Figure 20). For free floating, a space of 12.7 cm (5 in.) above and below was assumed to be acceptable, considering that most astronauts are not that tall. The result is an approximately 2 m (78.7 in.) distance between decks which gives 25.4 cm (10 in.) above the tallest restrained astronaut and 63 cm (24.7 in.) above the shortest. Deck thickness is another dimension necessary for determining the number of decks. It was assumed that a .3 m (12 in.) thickness would accommodate launch loads for both floor orientations and provide the necessary depth for utility routing within the floor. In addition, temporary bracing was considered an option to improve stiffness for launch.

3. Deck Positioning

With the separation and deck depth established, options for positioning the decks within the pressure shell were compared. The transverse orientation was arranged with 3 and 4 floors and the longitudinal with 2 and 3 floors.

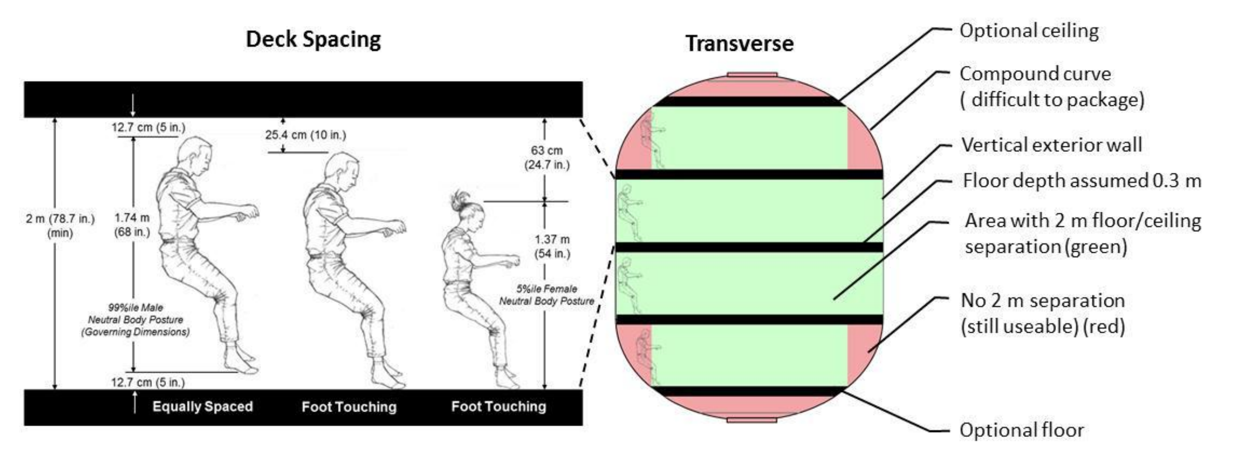

Figure 20. Deck spacing based on weightless anthropometry.

Because of the hull curvature, not all of the floor area provides a clear 2 m separation. Therefore, as shown in Figure 21, the floor area that provided the 2 m clearance was coded green with the other area in red. The 4 floor transverse arrangement offered the greatest area with the 2 floor longitudinal the least. Interestingly, this difference

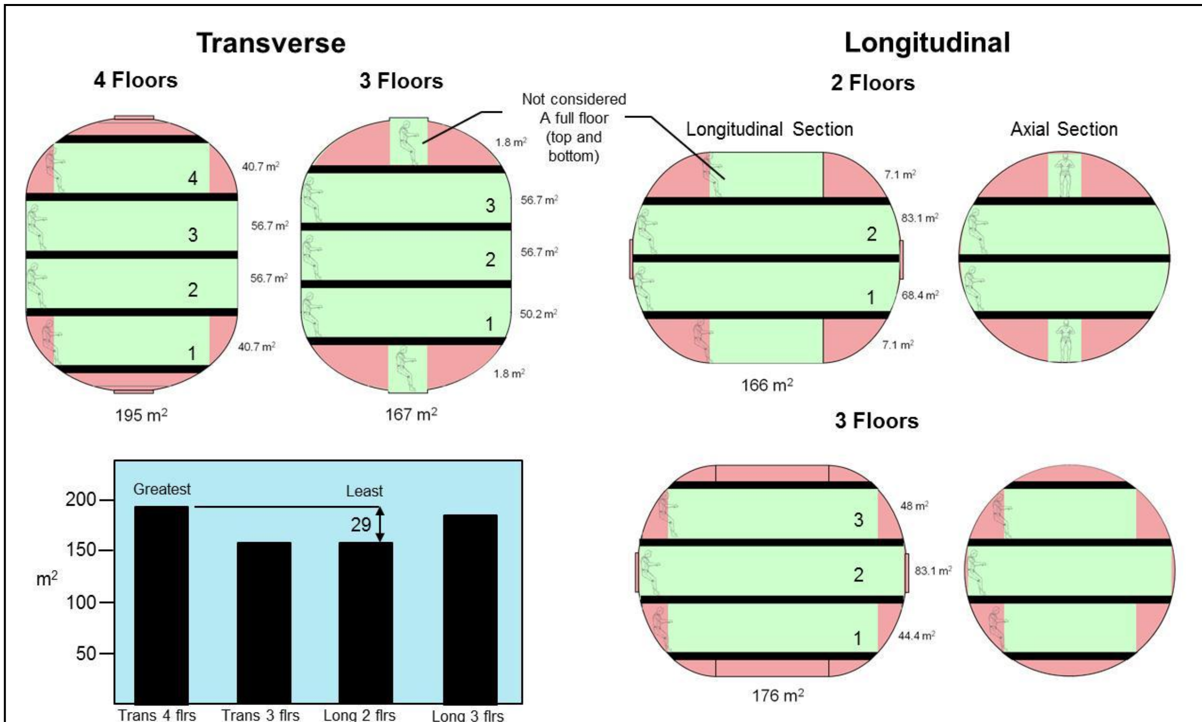

Figure 21. Comparison of area for the floor options per orientation.

alone was not a significant discriminator because more area may be offset by the complexity of additional floors.

4. Effect of Docking Port Locations

Docking ports determine crew ingress/egress influencing translation corridors and deck arrangement. Four options were considered each including a NASA Docking System (NDS) port for vehicles and an EVA airlock

(Figure 22). The nomenclature for port location refers to the number of ports on top over the number on the bottom. Therefore, Two/One represents two NDS ports over one EVA hatch. Note, the airlock can be designed with an NDS allowing both docking and EVA as shown in the Two+EVA/One option. Because all concepts require EVA, only

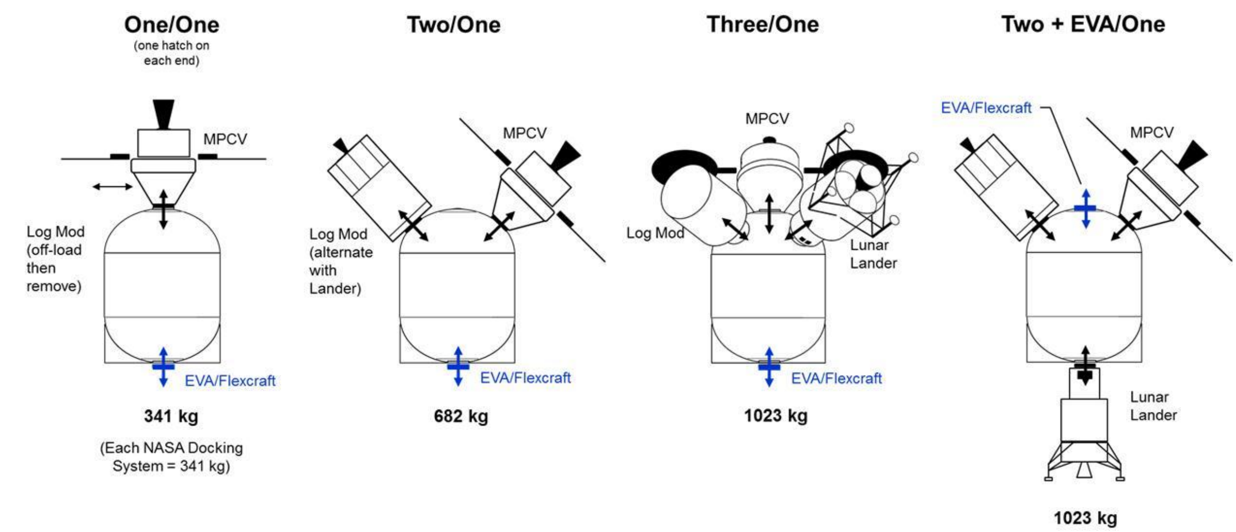

Figure 22. Location options for external elements.

the number of NDS ports was considered as a discriminator across the options. Furthermore, the reason the NDS ports are shown on the upper dome is to have them protected by the nose cone during ascent. Other locations are possible.

Each docking port option was analyzed for interference with the different floor options for both the transverse and longitudinal orientations. The summary of the analysis is shown in Figure 23 with the most promising options

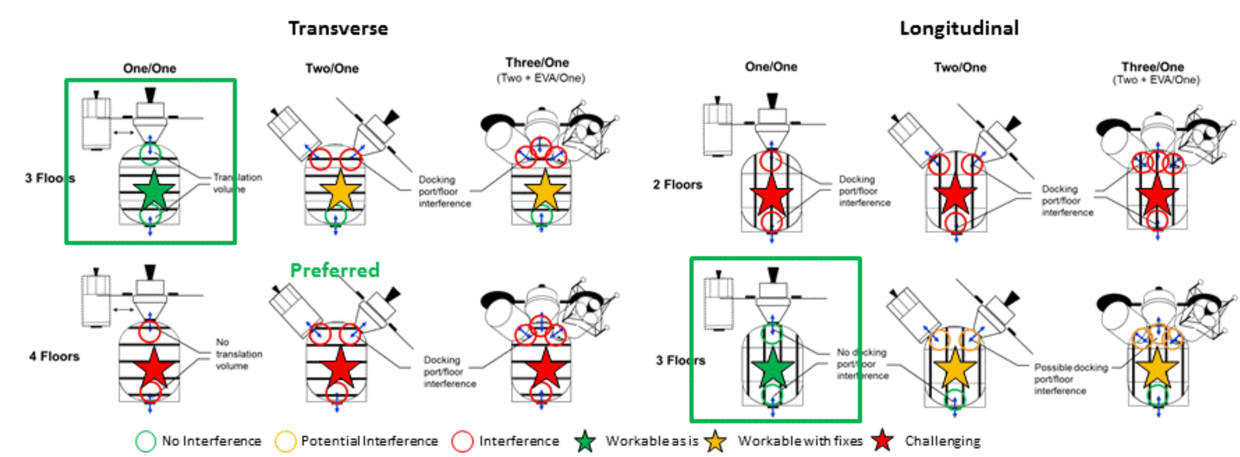

Figure 23. Assessment of options for externally attached elements.

identified with green boxes. It should be noted that the favored options serve as conditional decisions in order to move to a solution. Based on discovery or imposed requirements, the decision would be revisited and potentially changed.

5. <u>Dimensional and Geometric Sensitivities</u>

Further guidance for the SLS-derived internal layout is provided by applying sensitivities for human activities, subsystem equipment, stowage and utilities.

Weightless anthropometry is the source for human activities. Earlier, the distance between decks was established using the 99th percentile male. A similar logic is used to determine the width of translation corridors, and enclosed areas such as crew quarters and the waste hygiene compartment. It was determined 1 m (39 in.) was a good width for corridors because it provided 14 cm (5.5 in.) on either side of the extended elbows of the largest male and provided easy reach of wall mounted handholds (Figure 24). The size of the hatch opening plays a role in the width of the corridor. For ISS, moving racks between modules resulted in a 50 in. "square" hatch opening. The 50 in. opening is neither compelling nor efficient for a cis-lunar habitat. Instead, the 30 in. hatch way on the MPCV is the governing "bottle neck" for the crew and anything returning to Earth. Therefore, a 1 m corridor was determined to be more than adequate for crew and equipment. Furthermore, EVA hatches are 1 m in diameter, so if required, this width would allow passage of a suited crew member.

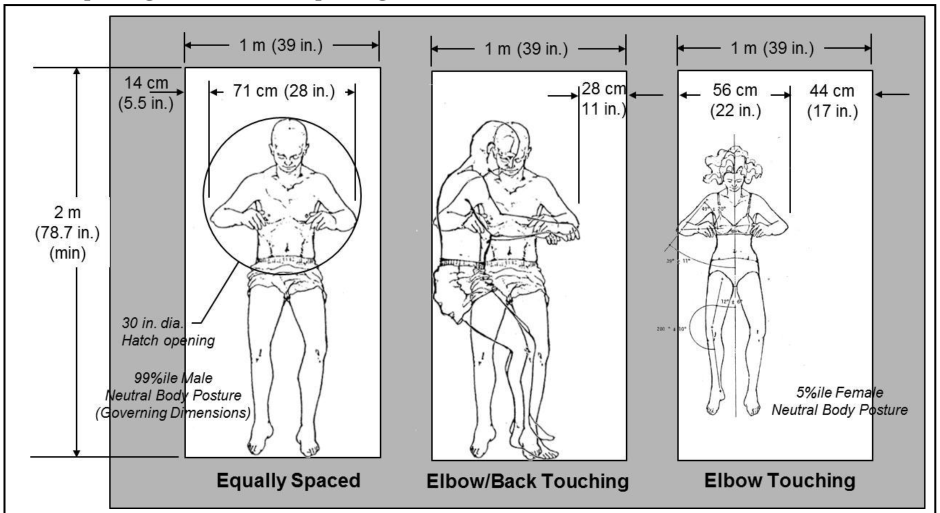

Figure 24. One meter width selected for translation corridor.

Much of the same thinking is applied to the sizing of crew enclosures. For crew quarters, a 1 m by 1 m footprint within the 2 m height allows convenient reach with an astronaut in a wall-mounted sleep restraint. This volume is also considered a minimum open volume for hygiene and full body cleansing compartments.

Packaging depth can vary widely and this is why it is important to understand the sensitivities before developing an internal layout. Shown in Figure 25 are the four areas that were examined which include drawer depth, reach, depth of cargo transfer bags and standard equipment racks. Note, the representation of ISS rack profiles and cargo transfer bags is not to imply a packaging concept and used for reference only. For equipment and bulk stowage, deeper is not necessarily better. Drawers that are too deep require more volume when extended limiting placement and access, and racks that are too deep inhibit reaching embedded fasteners, connectors and equipment. Dimensions have been established for modular Cargo Transfer Bags (CTBs) used as soft stowage for ISS logistics and ISPR were developed using dimensions from Earth-based standard equipment racks. The point of this dimensional survey is to see if there is an efficient packaging depth that can guide the layout of the cis-lunar habitat (Figure 26). No single depth is correct, but it was observed that 1 m accommodates all four areas and for a point of departure, this was used as a maximum dimension for stowage. Like the ISS non-rack based concept, single layer packaging is recommended for functional

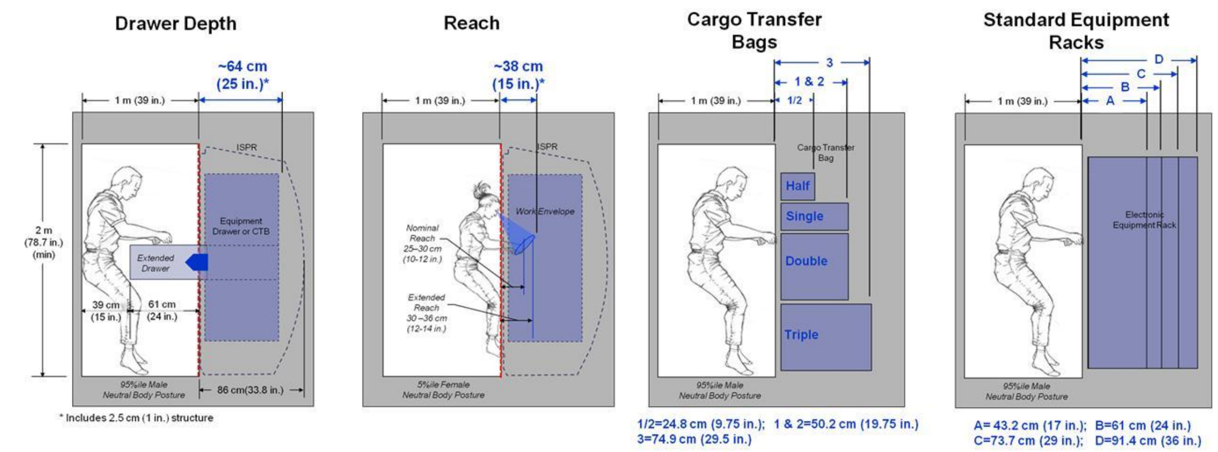

Figure 25. Four assessments used to determine maximum stowage depth.

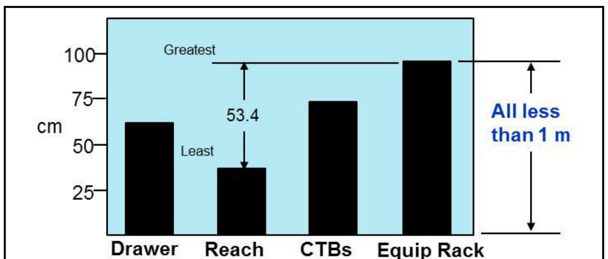

Figure 26. Stowage depth less than one meter.

equipment that requires access for servicing.

With a large volume, crew translation is integrated with other functional elements to enable access with a minimum of wasted space. It was observed that there are fundamental differences in translation between longitudinal and transverse deck orientations; yet the approach to the end-domes was similar (Figure 27). This is because the end-domes are the logical location for docking ports and the EVA airlock, which means dedicated translation pathways to connecting elements and outside. Furthermore, the compound curve of the end dome makes it complex and inefficient for equipment mounting and therefore is better used for crew translation between decks.

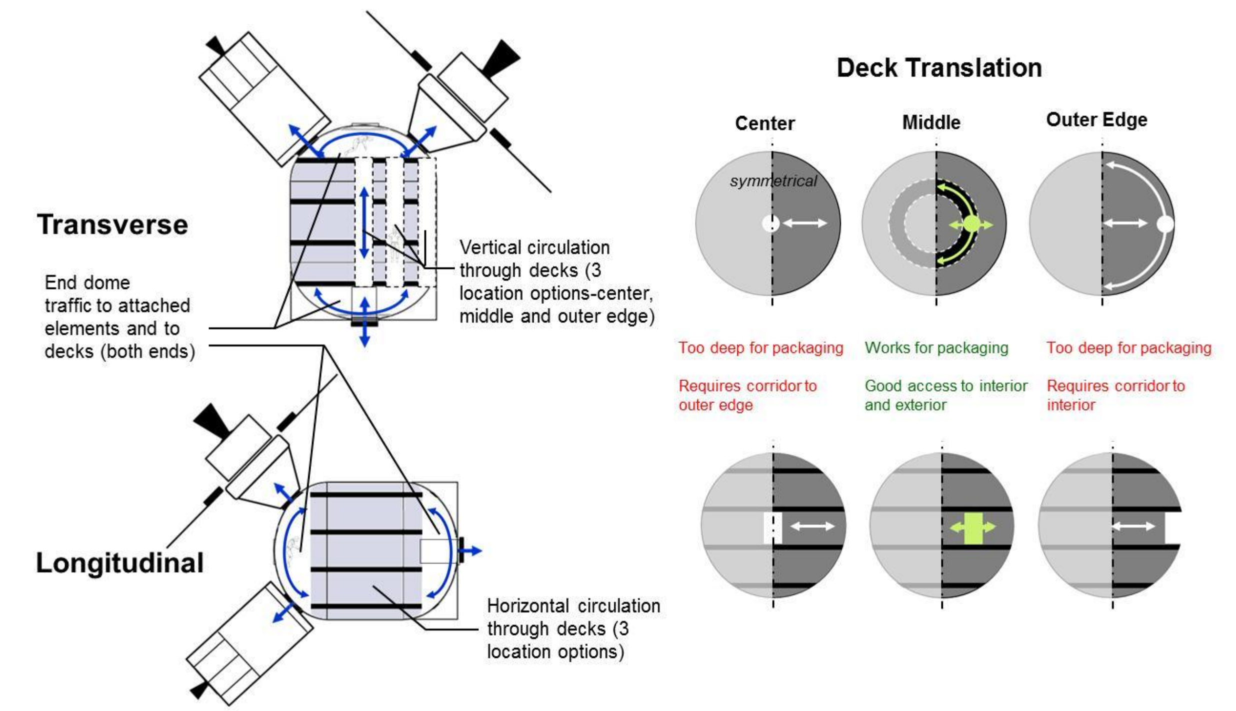

Figure 27. Options for transverse and longitudinal crew translation.

The key translation difference is that the transverse geometry requires at least one additional perpendicular corridor connecting the floors, whereas the longitudinal uses the end-dome. This penetration through the decks not only takes up space, but it's location through the deck plays a major role in layout. A single, central 1 m translation path results in 3.75 m depth to the hull which is too deep for packaging (equipment, compartments and stowage). A penetration located between the center and edge works better, but still requires a corridor around the center to access inner and outer packaging. The edge location is the least desirable because it requires either a peripheral or radial corridor while still having deep packaging.

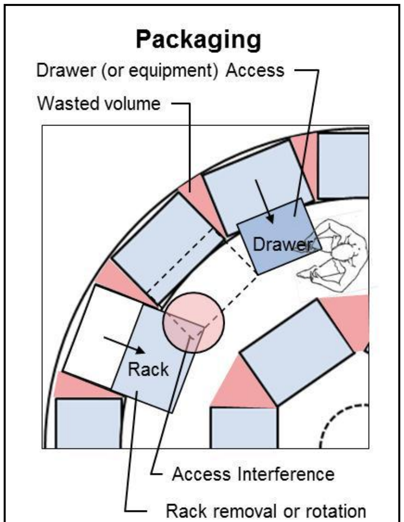

Figure 28. Wasted volume.

The longitudinal deck orientation proved to be more efficient because the end-dome circulation between floors and an axial corridor located between the center and edge provided good access to the interior and exterior packaging.

The plan-form geometry was another factor affecting the efficiency of the layout. Transverse decks are circular whereas the longitudinal decks are rectangular. Either can be made to work, but the circular geometry is difficult to outfit and less efficient. Most packages are rectilinear and when formed in a circle leave unusable wedges (Figure 28). This of course can be fixed with radial/concentric packages but the keystone geometry prevents removal.

6. <u>Structural Options for Deck Arrangements</u>

More than supporting equipment, the deck structure is important because it serves as the organizing element for systems integration including packaging modularity. For most of its life, the internal structure provides restraint for

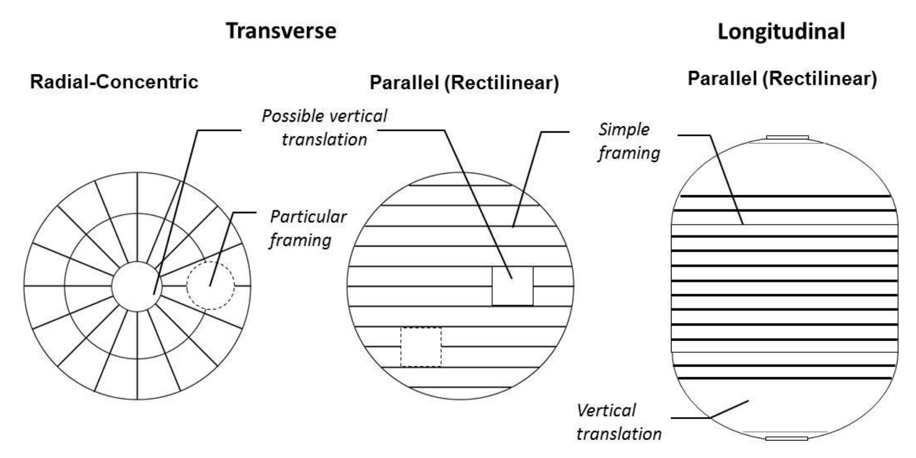

Figure 29. Geometric options for deck structures.

packaging, utilities and the crew in the weightless environment; however, the design is dominated by launch loads during the first 10 minutes. So, to avoid the excessive mass penalties while preserving layout flexibility, the structural approach integrated 1 g loads for Earth assembly with removable bracing for launch loads.

Figure 29 shows the basic geometries for the two deck orientations. The circular decks of the transverse orientation are radial-concentric and parallel (rectilinear). For the longitudinal deck structure, a parallel geometry of open web joists (or space frame) is the simplest solution and allows two-way distribution of utilities routed through the depth of deck structure. For both orientations, the parallel geometry is preferred.

7. Structure/Utility Integration

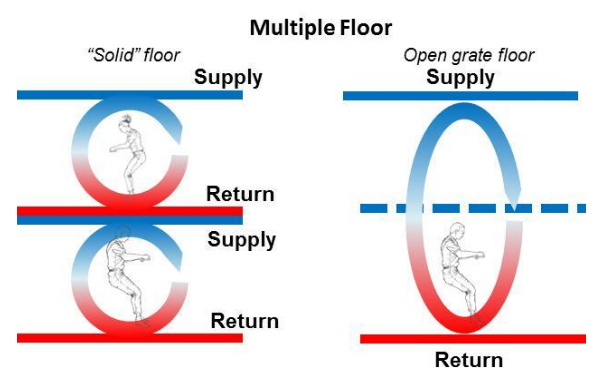

Figure 30. Air handling influences layout.

Efficient layouts coupled the structural system with utilities and air handling is one of the more demanding integration functions. Without convection, positive air flow is not only necessary to remove the buildup of exhaled carbon dioxide (CO_2), but it provides cooling for crew and equipment and is used for fire detection. The larger air handling ducts place more requirements on the structure than wires or plumbing as do the location of supply registers and return air filters. Furthermore, as represented in Figure 30, the complexity increases with multi-deck habitats. Floors that are "solid" or impervious have floor-by-floor return air ducting. However, a grated or open floor may allow return air ducting for two or more floors.

The utility distribution for the radial-concentric geometry in the transverse orientation is more complex than the parallel geometry (Figure 31). The reason is the concentric geometry has either curved or straight segments that are very sensitive to dimensional changes and because of this geometry, it is more difficult to manufacture and integrate. The purpose behind the parallel structure is to provide for a flexible layout with easily integrated utilities.

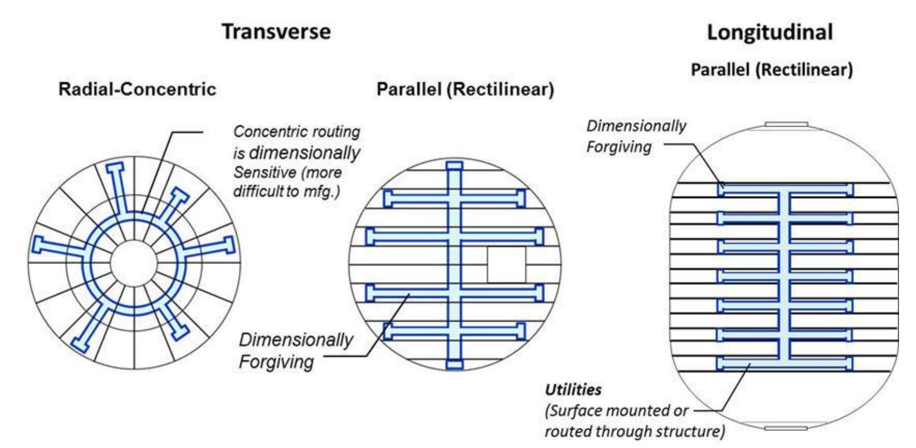

Figure 31. Integrating air handling ducts into structural options.

The benefits of the transverse parallel structure apply to the longitudinal orientation as well. The difference is the orientation of launch loads. The longitudinal decks are perpendicular to the axial load which means a slightly different load path.

8. Passive Radiation Protection

Radiation protection for the crew is one of the most challenging issues facing long-term human exploration beyond the Earth's magnetosphere. As discussed earlier, the ISS-derived layouts included additional storm shelter mass for SPE protection. Because of the SLS 8.5 m diameter there is the potential to provide this protection without dedicated shelter mass. This protection comes from a layout that strategically locates the existing equipment, food (water content) and stowage between the crew and the outer diameter. In order to have the most effective protection the long duration activities, in particular the crew quarters, are located at the centroid (Figure 32). Using the

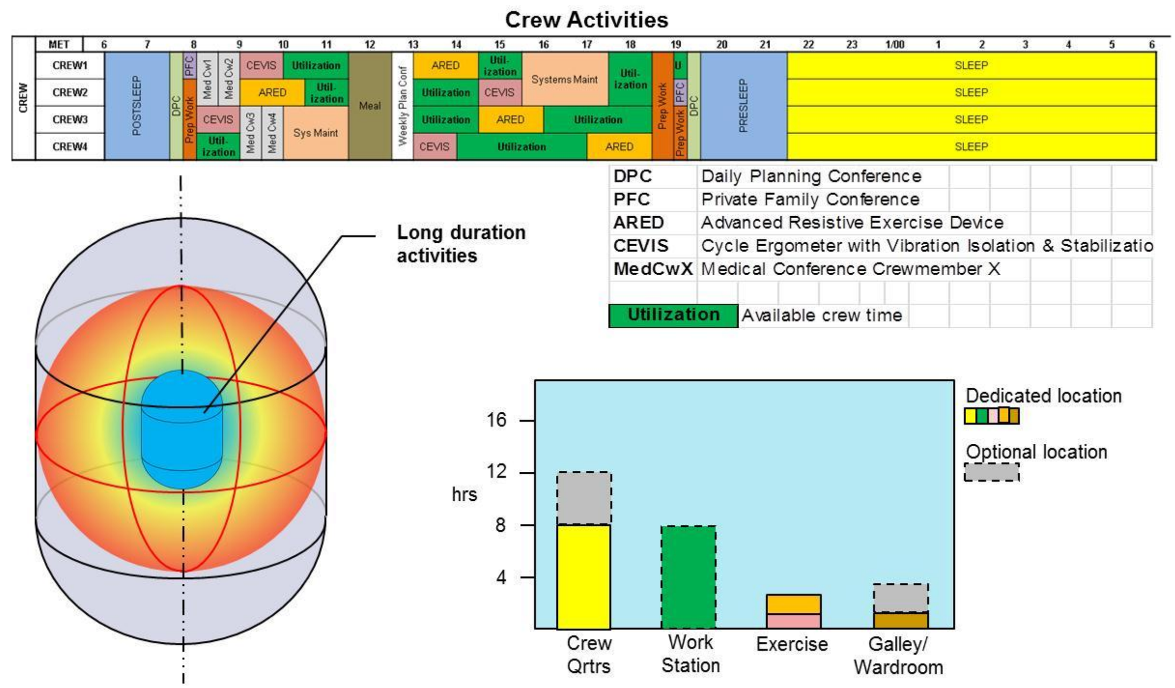

Figure 32. Passive radiation protection couples large SLS diameter with crew activity time.

duration of crew activities, this same strategy is used for gaining the maximum benefit from the passive radiation insulation.

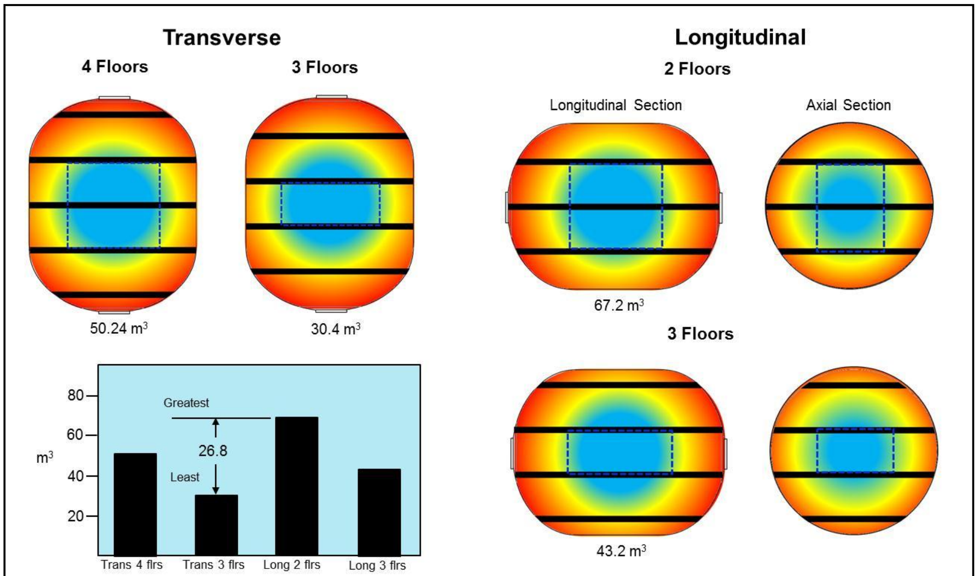

Figure 33. Comparison of radiation protection volume per floor option.

A passive radiation map was created in order to compare the volume captured within the insulated "sweet spot." Figure 33 shows contour mapping and a graph for the different floor options for the two orientations. The two floor longitudinal arrangement contained the most insulated volume while the transverse three floor contained the least. It is important to note that having the crew quarters in the middle affects the internal layout options. It precludes a central open area or translation corridor. The large SLS diameter is seen as an opportunity for radiation protection, but this cannot be verified until the design matures providing actual geometry and material properties for analysis.

9. Create Layout Diagram

Now, it is time to move from analysis to synthesis. By definition, the integrated solution does not focus on optimizing individual contributing elements. Rather, the contributing elements are organized for total overall solution efficiency. The first step of this iterative process is to select elements from the preceding 8 steps to create reasonable points of departure for both the transverse and longitudinal orientations. The green arrows in Figure 34

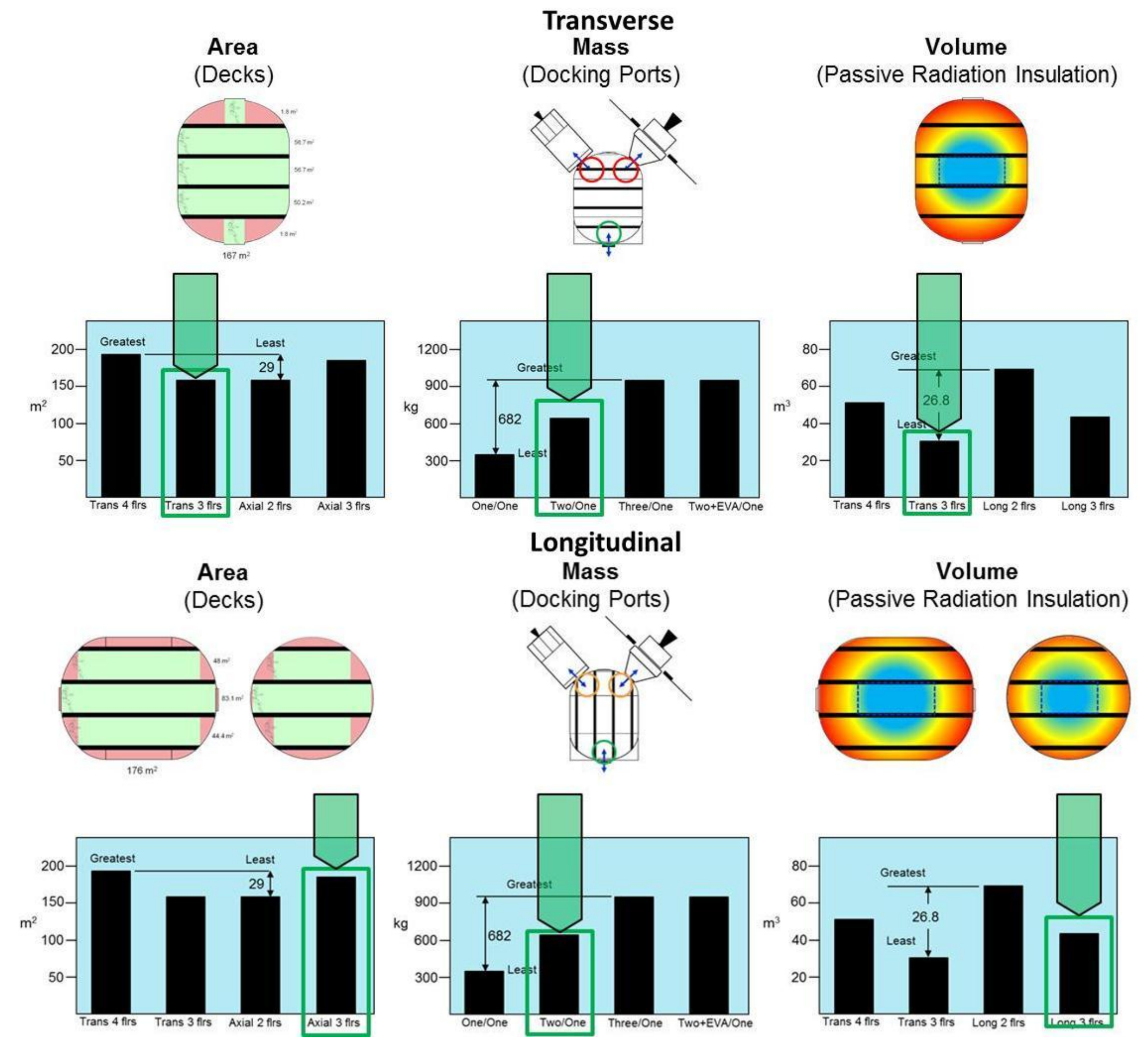

Figure 34. Selections for transverse and longitudinal points of departure.

identify the elements selected for these points of departure. Both the transverse and longitudinal points of departure include three floors with two upper/one lower docking port. As a transitional step to the layout, the major habitat functions are organized into a diagram (Figure 35) describing the approximate physical location. The diagram precedes the layout and is guided by the following: 1. Double loaded corridors (1 m minimum), 2. One meter or less packaging depth, 3. Parallel/Rectilinear deck structure (vs. radial-concentric), 4. Single layer equipment packaging, and 5. Accommodations for vertical and horizontal air handling.

Because radiation protection is essential for deep space habitats, both transverse and longitudinal diagrams placed the crew quarters at the center to benefit from the maximum passive insulation thus reducing dedicated mass. Adjacency relationships served to locate other functional elements. Externally, this included the access to attached

MPCV and the Logistics Module along with the airlock and EVA. Internally, the emphasis on radiation protection influenced functional location based on the time estimated for the crew to be in that area (Figure 32). In addition, habitation functions were either collocated or separated based on adjacencies shown in the matrix in Figure 4 and using a (noisy)/private (quiet) gradient. Also, subsystems such as ELCSS and TCS were collected in a common

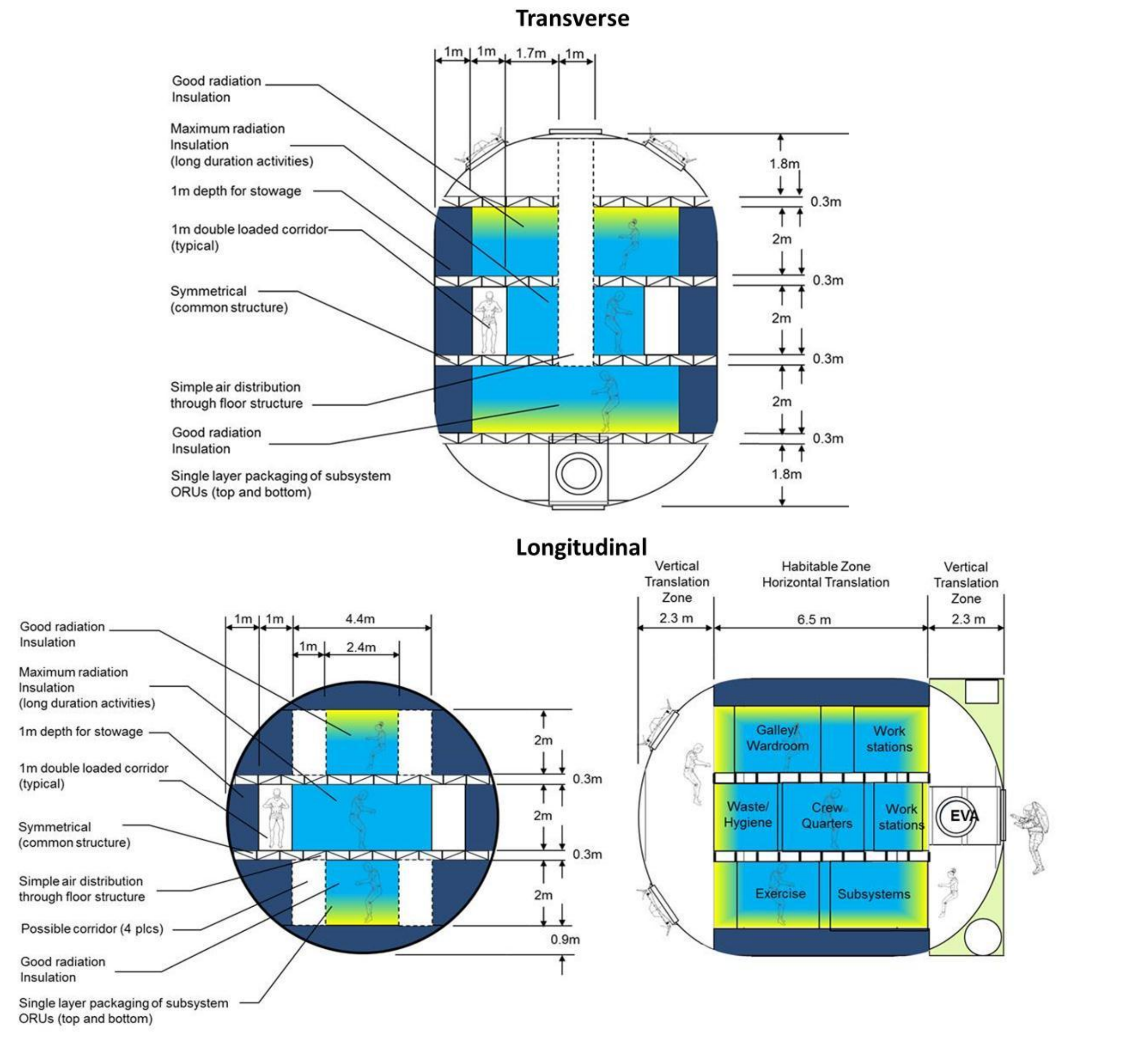

Figure 35. Incorporating the selected features into a transverse and longitudinal diagrams.

utility location arranged for efficient and maintainable support of spacecraft functions with adjacency to external hardware minimizing utility line length to heat exchangers, solar arrays and antennas. One major difference between the two floor orientations is how the crew moves from floor-to-floor. For the transverse orientation, the minimal solution assumed a one meter, off-axis vertical shaft connected to a step off "landing" and circulation corridor. Although minimal, this consumed a large fraction of the floor area. For the longitudinal orientation, it is possible to use end dome volume to translate between floors. This is an efficient use of space because it does not take up floor area, provides access to the attached external elements and is better suited for translation than mounting equipment or habitation functions. On the main deck, there are two axial double-loaded corridors that allow end-to-end translation and access to the centrally located crew quarters.

10. Example Layouts

This last step is used to translate the relationships in the diagram into an example layout. Different diagrams will produce different layouts and a single diagram can also produce different layouts. The point is that the commitments made to produce a layout often expose issues not revealed in the diagram. It is assumed that many layouts will be created based on revised priorities and "discovery" as more elements are brought under the umbrella of integration.

Figure 36 shows the example layout for the transverse orientation. Surrounded by stowage (radiation insulation), the upper deck contains three workstations, a waste/hygiene compartment and the galley/wardroom. Crew

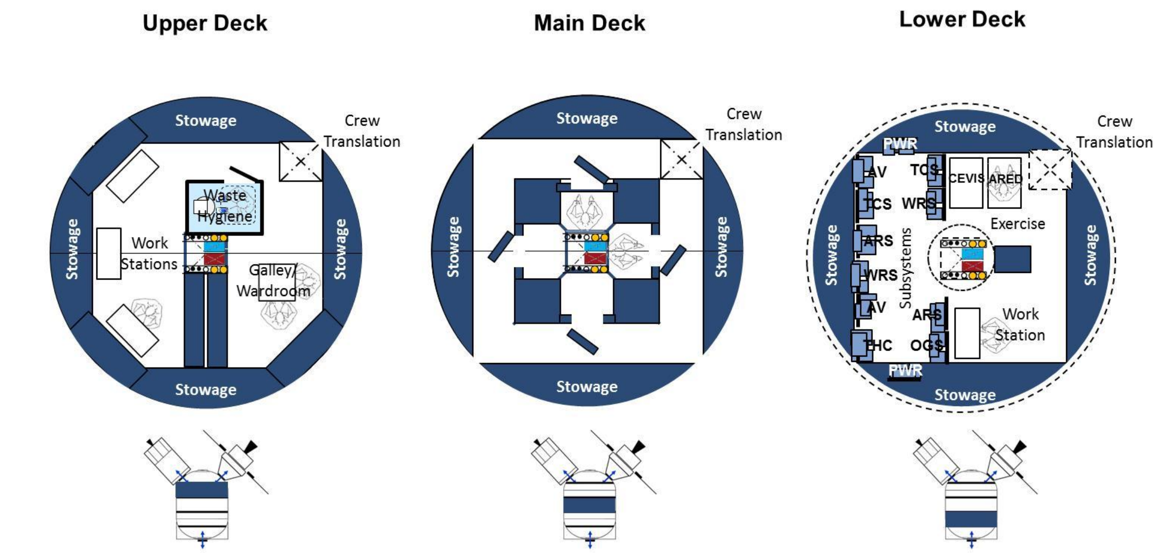

Figure 36. Example floor-by-floor layout for the transverse orientation.

translation is peripheral because of the centrally located crew quarters; however, the utility chase works well in this location minimizing utility line length on each floor. Four crew quarters surrounded by a double-loaded corridor and stowage make up the main deck while the lower deck includes a fourth workstation, exercise and the pallet-mounted (single layer) subsystems.

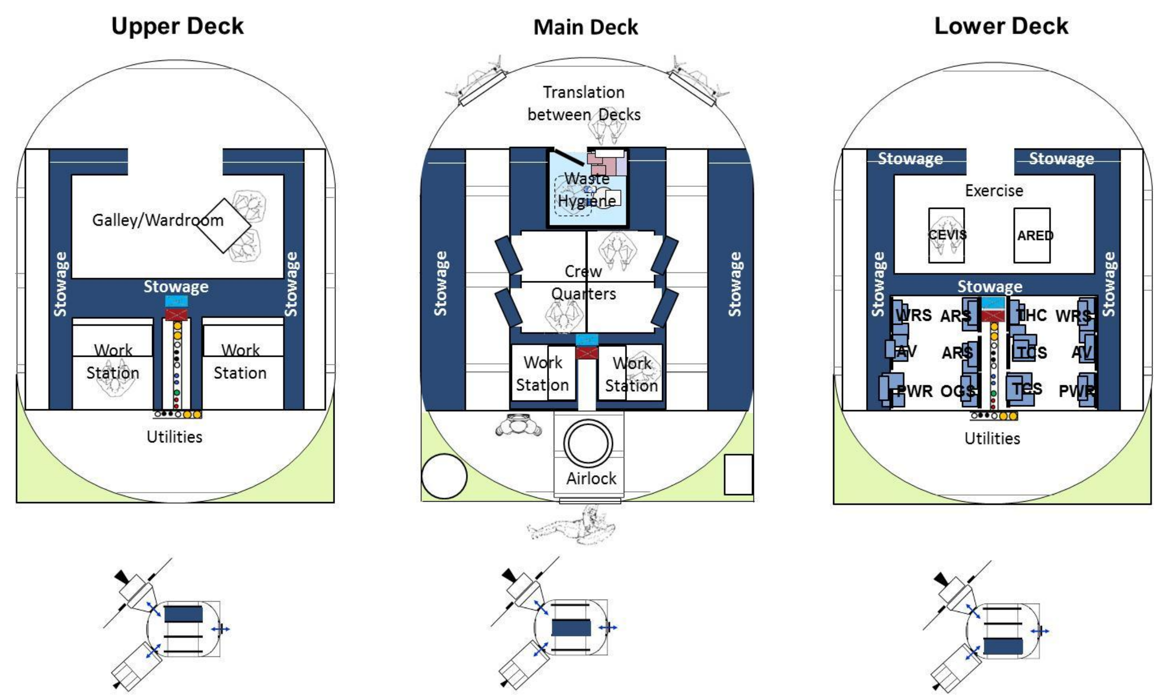

Figure 37. Example floor-by-floor layout for the longitudinal orientation.

The example longitudinal layout is shown in Figure 37. Similar to the transverse, the layout has a galley/wardroom and workstations on the upper deck surrounded by stowage. It can be seen that crew access to these spaces is from the translation space in the end dome. The main deck includes the crew quarters, the waste/hygiene compartment and two workstations. Note, the stowage wall facing the docking ports is envisioned to be pantry-like providing rapid physical and visual access. The lower deck contains an area for exercise and the subsystems mounted on single-layer pallets.

To provide the access required for long duration missions, a concept for pallet-mounted systems is being

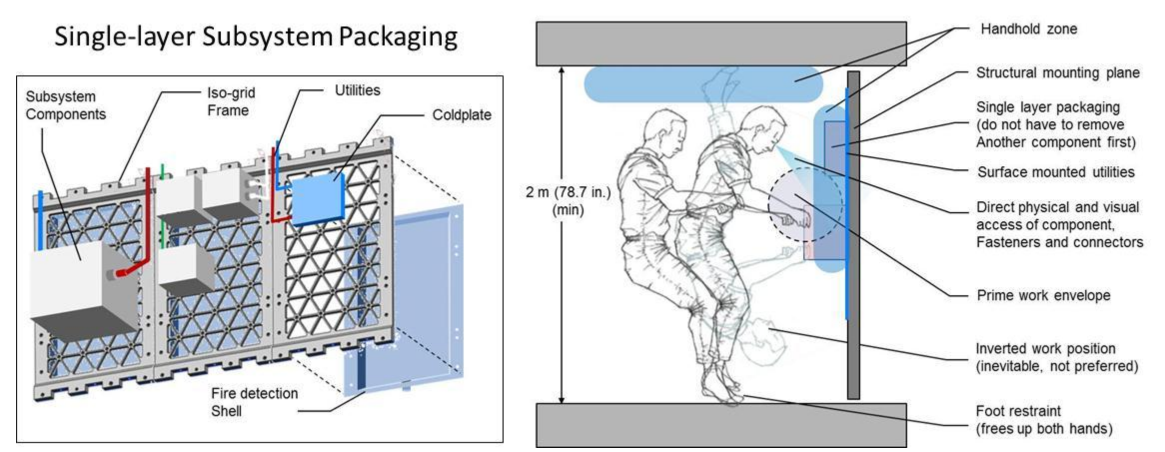

Figure 38. Concept for single-layer mounting of subsystem equipment.

explored. As shown in Figure 38, an open structural frame like iso-grid is used to restrain equipment and mount interconnecting utilities. Ideally, all fasteners and connectors are to be directly visible and accessible by hand or tool. All labeling and test ports for diagnosis are to be on the front face to allow servicing in place while operational. The open frame not only supports equipment, but allows cabin air to pass over/through the boxes for cooling and fire detection. A light weight shell is attached to the backside of the frame to direct the airflow over sensors and return it for conditioning.

VII. Conclusion

Amongst the options, the SLS-derived habitat with the longitudinal floor orientation is preferred. The ISS-derived solutions are heavy, volume-constrained, require structural modifications for launch and docking, depend on multiple launches to put in place, rely on additional launches to sustain, and have limited extensibility. It is doubtful that using the existing Node 1 and MPLM will save money while offering refurbished 30 year old designs based on delivery by a retired launch vehicle to low-Earth orbit.

The SLS-derived habitat not only realizes DDT&E cost savings, but is compatible with the system intended to take humans beyond low-Earth orbit and thus extensible to Mars missions. Layouts for both the transverse and longitudinal floor orientations can be made to work, but the longitudinal offers more efficient packaging, better use of floor area and improved crew translation.

VIII. References

"Skylab II, Making a Deep Space Habitat from a Space Launch System Propellant Tank," B. Griffin, D. Smitherman, K. Kennedy, L. Toups, T. Gill, and S. Howe, AIAA Space 2012 Conference, Pasadena, CA, September 11-13, 2012, AIAA 2012-5207

"Deep Space Habitat Configurations based on International Space Station Systems," Smitherman, D., et al, Global Space Exploration Conference, Washington, D.C., May, 2012, GLEX 2012.01.1.8x12219

"Issue and Design Drivers for Deep Space Habitats," Michelle A. Rucker and Molly Anderson, Global Space Exploration Conference, Washington, D.C., May, 2012, GLEX-2012.05.3.3x12247