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New Frontiers
Lunar Space Architecture

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Abstract

New Frontiers was produced in collaboration between the teams at Skidmore, Owings and Merrill, New York, NY and Lockheed Martin Space, Denver, CO. The project was established to investigate next-generation lunar habitat architecture focused on designing for the human experience and behavioral performance for long duration missions. The teams applied a human centered approach with an emphasis on the influence of environmental variables in design. The design considered parameters such as anthropometry, lighting, temperature, human-machine interactions, comfort and wellness, using design and engineering methods. The habitat was constrained by transportation limits for lunar surface missions that would be available by the late 2020s. The human centered architecture is a key feature in our proposal and results in design strategies that enhance mission durations, and human systems integration. The final concept is characterized by an innovative architectural design, crew systems, and various environmental design features that reinforce a human-centered approach to lunar habitat architecture.

Keywords: (Space Architecture, Human Centered Design, Lunar Habitat)

Acronyms/Abbreviations

TRL	Technology Readiness Level
AE	Architecture and Engineering
NHAB	New Frontiers Habitat
EVA	Extravehicular Activity
ISS	International Space Station
MMOD	Micrometeoroid and Orbital Debris
ISPR	International Standard Payload Rack

1. Introduction

Skidmore, Owings & Merrill (SOM) and Lockheed Martin Space (LMS) established a research collaboration to investigate next-generation lunar habitat architecture focused on designing for the human experience and behavioral performance associated with living and working in space for long-term mission durations. NASA's Artemis program will send astronauts to the lunar surface for longer mission durations than ever before with a focus on long-term sustainable human exploration [1]. The human centered approach applied in this concept emphasizes the influence of experiential variables while applying a paradigm of architectural design, where concepts are evaluated using various design technologies and strategies generally applied in practice of architecture. NASA has developed Human Integration Design Processes previously focused on human centered design methodologies to support human systems integration [2]. We looked to human centered design as one of the key design methods in the development of our concept. We combined this with parametric and computational design methods and architectural design principles. The design considered human-centered parameters such as anthropometry, lighting, temperature, physical and digital interactions, comfort, and wellness, using spatial and environmental simulation technologies. The design was constrained by an assumed mass limit for lunar surface missions and lander capabilities that could be available by the late 2020s. Using a low mass habitat solution was essential to the concept for the purpose of delivery and provided the conceptual limits to integrate all habitat systems (see Fig. 1). The results of this habitat concept study also demonstrated modeling and analysis methodologies that can be used to improve and inform habitat design strategies. These interdisciplinary processes and solutions were applied to the concept in this project but can also be used to extend human mission durations, accelerate the development of mission-driven architectures, and bring new approaches to human systems integration. The resulting concept in this project is characterized by various habitat design strategies, structural elements, and crew system features. It is broken down by systems and supported by analytical models to reinforce a human-centered approach that can improve the influence of human behavior and minimize the adverse effects of long-duration missions on astronauts.

Fig. 1. New Frontiers Surface Habitats & Infrastructure

2. Technical Approach

The New Frontiers Habitat (NHAB) architecture establishes an architectural paradigm for habitat design which adopts human systems integration metrics and leverages architectural design methods applied to human performance challenges. The collaboration between SOM and Lockheed aimed to demonstrate the potential benefits of infusing space sector expertise in habitat design with architecture and engineering (AE) industry expertise by utilizing design technologies to optimize habitation and crew systems. The proposed NHAB architecture is a flexible, adaptable, scalable, and low mass solution. This solution includes various integrated functions for astronauts who will live and work under high stress environmental conditions. Integrated spaces for science, maintenance, medical, and crew operations were designed and allocated using parametric and computational optimization methods that factored in anthropometric, safety, and environmental constraints.

At present, there exists limited empirical data from which to derive habitat design requirements for lunar applications. Although the Apollo missions provided some experience, the longest stay on the moon lasted approximately three days [3] in duration with highly reduced habitat considerations. As mission durations increase, larger facilities, additional hardware, redundancies, and more volume will need to be devoted to long-term surface habitat. Existing design approaches applied in the aerospace industry can benefit from cross-sector collaboration. Multi-objective and evolutionary optimization algorithms were used to solve for volumes taken up by stowage, equipment, consumables, and crew systems. This approach helped us improve calculations for both pressurized and non-pressurized volumes. The multi-objective approach included a set of design parameters (e.g., volume, mass, length, width, height) with the design space distributed across explicitly defined objectives (e.g., free-volume, program, activity, interdependence). These basic objectives combined with discrete parametric constraints produced a range of possible solutions. The solutions were then evaluated based on the relationships between objectives to address human experience factors such as adjacencies, multi-functionality, environmental quality, and level of interaction. Additionally, the habitat design process also included a mission context with a program matrix to develop and design features within the habitat. The technology readiness level (TRL) for each integrated system was considered at a conceptual level in the model to allocate appropriate technologies, locate them and incorporate the required volume. The final habitat design configuration is represented in multiple 3D models (architecture, structure and analytical) with detailed features responsible for habitability and human integration (see Fig. 2). The parametric model was used to estimate and quantify these architectural features which allowed us to visualize the environmental conditions. A mass budget was also derived from this model to optimize the sizing for each system based on the architectural design requirements and performance trade-offs.

Fig. 2. New Frontiers - Workstation Interior View 1

3. Mission Context

The NHAB assumes a long-term mission context including opportunities to explore, conduct science, and test technologies. The design anticipates that crewed missions to the lunar surface will take place in the late 2020’s, with the ability to utilize the Gateway as a staging point. The design was also limited by a landed mass capability of up to 15 metric tons with critical surface infrastructure already in place (e.g., power, consumables, communication). The NHAB will also need to interface with additional elements (habitats, logistics modules, unpressurized and pressurized rovers, etc.) that can be added to the base infrastructure over time. To accommodate long-term human missions, the NHAB will support at least four crew members for mission durations of up to 120 days near the lunar south pole.

Assumptions for Habitat Delivery Mission Capability:

● The NHAB is delivered to the surface using a lander with a landed mass capability of up to 15 metric tons

● NHAB is designed to accommodate a crew of four.

● A lander integrated Lunar Surface Manipulation System (LSMS) will transfer the habitat element from the lander to a surface mobility platform

● Habitat hardware is pre-integrated to the maximum extent possible ● Initial crew transfer to the surface may take place using an HLS architecture (one, two or three-element architecture)

Assumptions for Sustainable Mission Capability

● A crew of four astronauts transfer to the lunar surface using a reusable human landing architecture

● Pre-deployed surface assets are available (power, mobility, etc.)

● The Gateway may be used to transfer crew and cargo to the NHAB

● The NHAB system will be entirely reusable as a habitable architecture

● Gateway may be used as a logistics point for cargo and consumables resupply delivery to NHAB using a reusable lander.

● NHAB will need to operate for extended periods without crew.

3. Habitat Architecture

The proposed lunar surface habitat is designed as a rigid carbon fiber composite structure with an environmental and protection shell system that is an integrated part of the habitat design. The habitat includes two levels with the first level designated for working and science functions. The first level provides two egress doors that connect with adjacent pressurized EVA hatches and tunnels. It also provides the crew with life support, science and working equipment. The first level will be the primary zone for performing mission operations as well as exercise and health monitoring activities. The second level serves as the crew quarters with 4 sleeping units for each crew member. The crew quarters are integrated with personal storage and crew system technologies that monitor temperature, air quality and humidity.

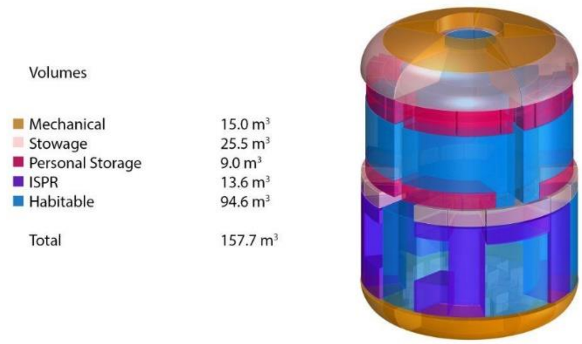

Fig. 3. Habitat Volumetric Analysis

A single habitat unit provides a habitable volume of approximately 100 m3 (3,500 ft3) and a net habitable area of 38 m2 distributed between the two levels (see Fig. 3). To maximize the function of volume and area, the crew functions are co-located along the perimeter which allows for a central zone free of obstructions that is flexible and usable by all crew members for a wider range of common activities. Stowage is located above the second level where there is additional volume as well as underneath the composite floor system. Personal storage is provided within the crew quarters and directly in front of each unit with designated spaces. Locating both stowage and storage away from usable spaces maximizes the use of free space.

Fig. 3. New Frontiers - Workstation Level View 1

A key aspect of this design includes operable and integrated furniture which becomes part of the architecture and utility. At the center of each level is an integrated table that can be deployed remotely or manually. This feature is used only when needed and can be stored at all other times. This is an important part of the design concept since dining and gathering is a critical communal activity. The design positions crew members at an optimal distance for eye-to-eye contact and discussions as well as mobility around the central zone when the table is deployed. The circular design also emphasizes the geometry of the space and the various compartments located on the floor. Access to these compartments is never obstructed even when the table is in the outward position.

On the first level multiple working surfaces are designed as operable elements that are co-located with the exercise zone. This provides an optimal use of working and health monitoring systems that can be activated when needed based on a crew member's schedule. The operable table on this level is intended for meeting and group discussions or for additional working surface area. The central location provides a clear path around the space, where workstations, hygiene, exercise, kitchen, and other features are located. The first level includes dedicated compartments in the floor for tools, equipment, and mechanical systems. At the perimeter are 10 pre-integrated ISPR's.

On the second floor, the crew quarters incorporate an expandable wall system that provides each crew member with additional private space. This system enables the crew to optimize their personal space for sleeping and private working functions as well as needed privacy throughout the mission duration. Environmental quality was considered across various factors. For this we informed the design using environmental drivers such as acoustics, atmosphere, radiation, etc. (see Fig. 4). As a feature of the habitat architecture, increased personal space that is integrated with environmental monitoring and communication technologies helps improve the utility of sleeping spaces typically used for a limited period. When the crew quarters are not being used, they retract to enable a central zone for common functions.

3.1 Human System Drivers

Crew accommodations center on the human element, integrating the required resources and equipment to support various activities set by the habitability requirements (see Fig. 5). The volumetric and area requirements stem from the anticipated crew operations during a mission and individual tasks were combined or co-located within provided zones to determine the total volume required. Anthropometric dimensional constraints such as vertical reach and the required motions for basic human operations such as living, hygiene, working, stationary, stowage, suiting, egress, and translation in a reduced gravity environment function as volume drivers and establishing adjacencies. In this concept we referenced the NASA Space Flight Human System Standards [4].

The crew accommodations also presented several challenges that would rely on an established concept of operations. Rather than focus on a specific schedule, we aimed to provide as much flexibility as possible. Testing of the habitat interfaces, equipment, and accommodation subsystems would need to be performed to reduce human error, increase productivity, and improve overall safety and comfort.

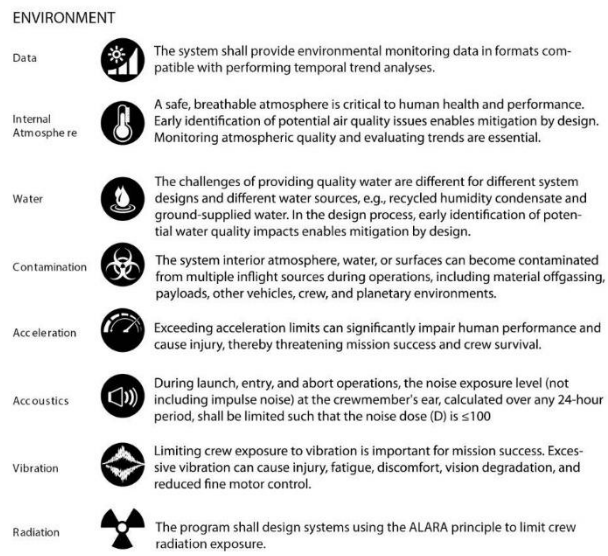

Fig. 4. Human System Environment Drivers

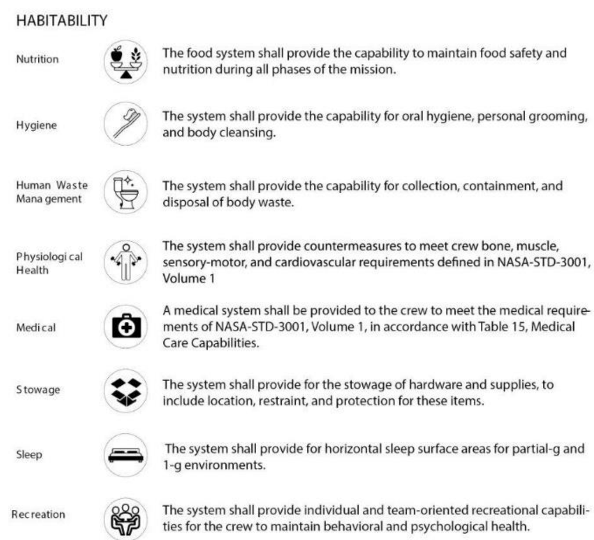

Fig. 5. Human System Habitability Drivers

3.2 Pressure Vessels

Pressure vessel structures on the ISS serve as examples of how LEO space architecture structures are manufactured and the types of materials that are used. For example, the ESA Columbus module pressure shell is fabricated out of solid aluminum 2219 with a maximum thickness of 4.8mm and min thickness of 3.8mm at the end cones [5]. The micrometeoroid and orbital debris (MMOD) protection system is made from AI-6061-T6 aluminum bumpers and a secondary barrier of Kevlar/Nextel panels. This is attached to the exterior and mounted to stiffeners on the pressure vessel shell. The thermal protection or insulation blanket is made from multi-layer aluminized Kapton which protects from high fluctuations in temperature. On the interior there are additional aluminum structures and composites used to support payloads and crew systems.

In industrial applications, pressure vessels are designed and built per the American Society of Mechanical Engineers Boiler & Pressure Vessel Code, Section VIII, Division 1 [6]. The calculation of pressure vessel parameters is driven by the geometry of the vessel, particularly the heads. There are formulae for calculating the size and volume of these vessels with various types of curved ends including: hemispherical, tori spherical, semi-ellipsoidal and bumped ends. Vessels are currently classified into the four types below [7].

- Type I: All-metal construction, generally steel.
- Type II: Mostly metal with some fiber overwrap in the hoop direction, mostly steel or aluminum with a glass fiber composite; the metal vessel and composite materials share about equal structural loading.
- Type III: Metal liner with full composite overwrap, generally aluminum, with a carbon fiber composite; the composite materials carry the structural loads.
- Type IV: An all-composite construction, polymer (typically high-density polyethylene or HDPE) liner with carbon fiber or hybrid carbon/glass fiber composite; the composite materials carry all the structural loads.

3.3 Composite Materials

Carbon fiber is a key material in our design concept. It is a material that offers stiffness and strength at low density which is approx. 40% lighter than aluminum and provides many practical benefits [8]. Weight for weight, carbon fiber offers 2 to 5 times more rigidity (depending on the fiber used) than aluminum and steel. We propose to use carbon fiber as the primary material for the pressure vessel. The design will include other material interfaces that use metals and cores. Carbon fiber reinforced composites will also be considered for various internal elements to reduce weight and exploit specific material properties.

Benefits:
- Design flexibility
- Noise and vibration damping
- Fatigue resistance
- Thermal insulation
- Corrosion resistance

One precedent which served as a key point of departure was the composite crew module developed by NASA Engineering and Safety Center (NESC) [9]. The composite crew module project was initiated in January 2007. The composite crew module's primary structure is constructed of a stiffened honeycomb sandwich of carbon fiber and is composed of an upper and lower pressure shell spliced together. The splicing is accomplished without the use of an autoclave, a large, pressurized oven used to cure composite materials. The module components included the upper shell and lower shell which were fabricated and assembled.

In our concept, we used a similar idea, by identifying 4 distinct areas that could be fabricated and assembled. The top section, two midsections and lower section. Each section had its own distinct geometry which could be fabricated separately. Once these larger elements are built, they can then be spliced together to complete the entire habitat pressure vessel (see Fig. 6).

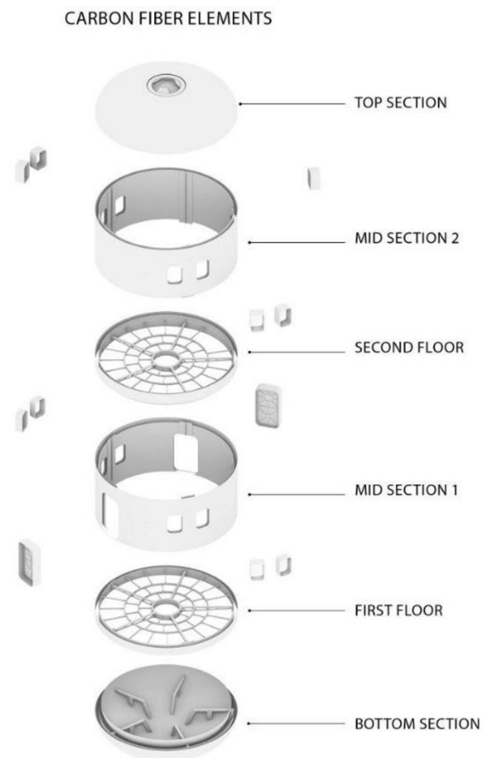

Fig. 6. Carbon Fiber Structural Elements

3.4 Geometry

Several geometric studies were conducted using computational modeling methods. These studies looked at a range of pressure vessel type geometries including multi-lobe options to assess the potential for more complex forms. These studies highlighted some of the challenges associated with multi-lobe forms including reduced volume and increased manufacturing complexity. (See Fig. 7)

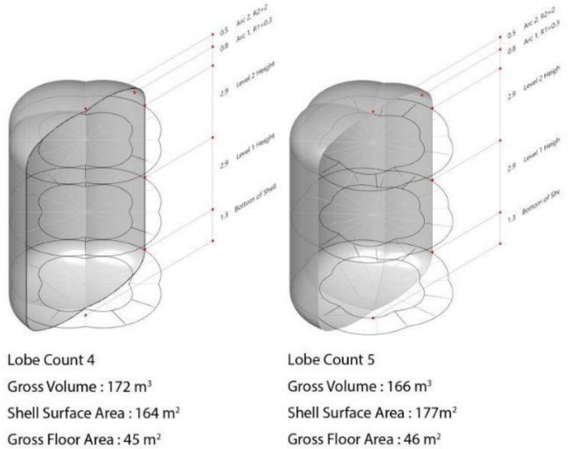

Fig. 7. Multi-lobe Configurations

The basis for the geometry is driven by its size, curvature, and the number of penetrations. Door opening and window openings introduce structural weak zones and require reinforcement. These openings are critical to the design of the habitat for multiple reasons. Multiple penetrations provide egress for working functions, safety and connectivity to other external elements and windows provide visibility, natural light as well as situational awareness. The parametric model was optimized using computational design methods until the selected option met several desired objectives including floor to ceiling heights, dimensional requirements, overall volume, spatial configuration as well as human systems integration mentioned previously (see Fig.8).

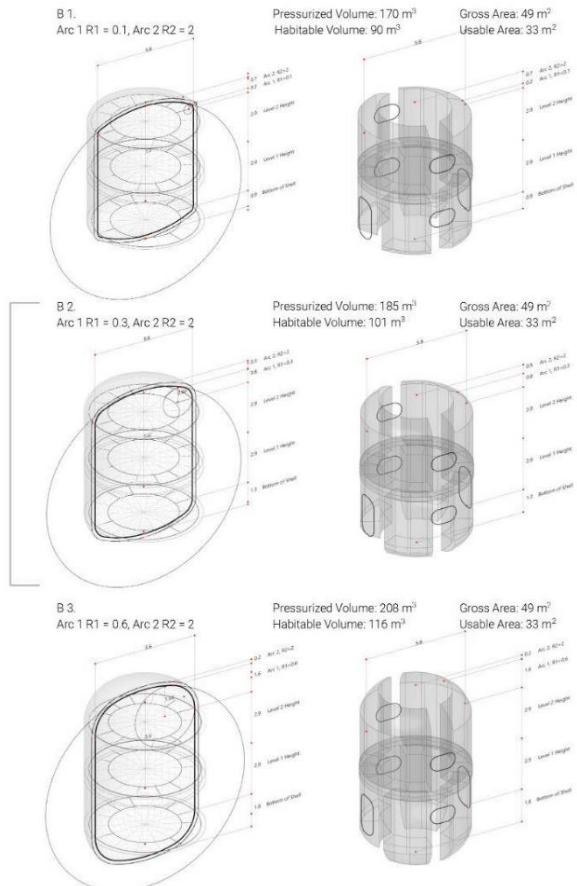

Fig. 8. Habitat Geometry & Computational Design

4. Crew Systems

The first level places all ISPR systems at the perimeter, liberating the central space and maximizing the possibility for collaborative activities (see Fig. 9). Most medical and biological operations would focus on crew health and scheduled medical care. This means that it is optimal to locate exercise and medical functions adjacent to each other for monitoring of health and metabolic information. Working activities also require constant communication which means that preparing for EVA or communal activities are most efficient near workstations.

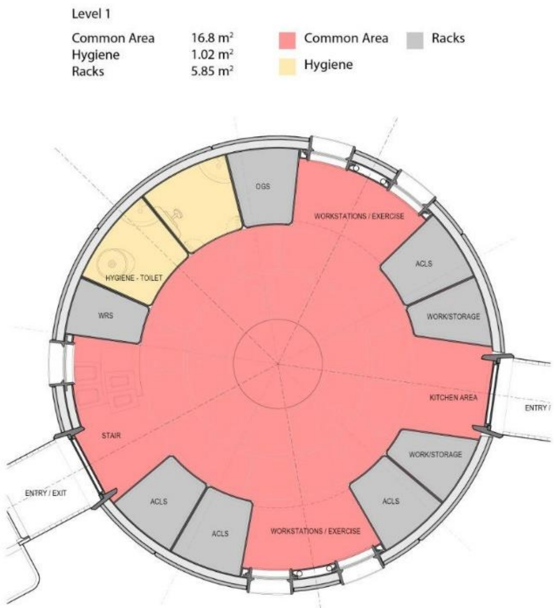

Fig. 9. Level 1 Floor Plan

On the second level private living quarters are provided as individual flexible spaces that open to the common zone (see Fig. 10). The dividing walls expand and contract to increase or reduce the usable area of each crew quarter. The resulting volume and areas are larger than on the ISS and it is desirable for longer term duration missions but more importantly for the health and wellbeing of occupants.

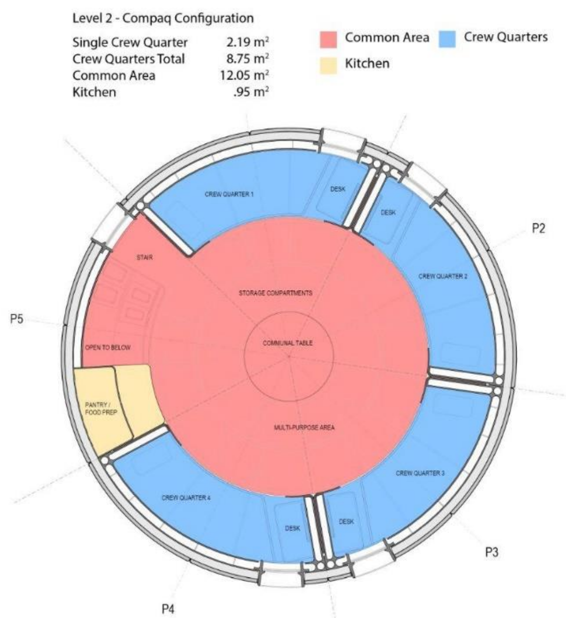

Fig. 10. Level 2 Floor Plan

The crew quarters expand to give each occupant a maximum of 3.3 m2. This flexibility can be used to optimize daily working and living functions. It increases the degree of sleep privacy for each crew member to support long term health and performance (see Fig 11).

Fig. 11. Level 1 Floor Plan - Equipment

Equipment can be located within the floor system, making it accessible and easy to associate with the surrounding ISPR systems. By classifying each compartment in relation to science operations and general storage, management of experiments vs commonly used articles can be efficiently organized. The design proposed grouping these by rings and quadrants from P1 through P5 (see Fig. 12).

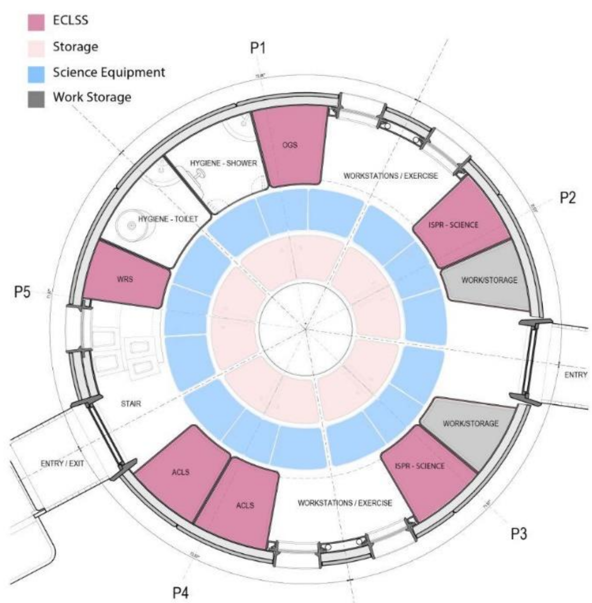

Fig. 12. Level 1 Floor Plan - Equipment

On the second level equipment and storage is organized similarly to the ground level along rings and quadrants from P1 through P5. Within each crew quarter additional personal storage including hygiene, clothing, food, medical and exercise articles can be separated from storage in the common area. One quadrant is dedicated to food preparation storage within P5 where the kitchen area is located (see Fig. 13). This system provides flexibility and efficient use of the underfloor volume. Additionally, long-term stowage is located above the crew quarters, where larger compartments can serve to keep reserves and additional replacement supplies.

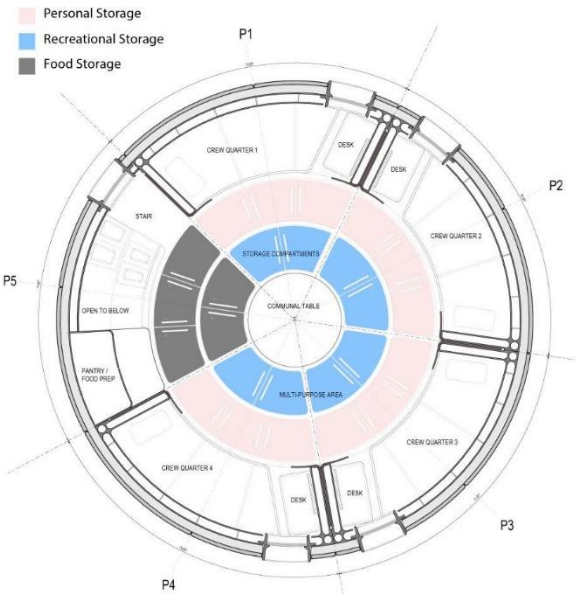

Fig. 13. Level 2 Floor Plan - Equipment

4.1 Environmental Control and Life Support System

In our design, we incorporated various ISPR's on the first level to account for the Environmental Control and Life Support System (ECLSS) (see Fig.13). This is a system of regenerative life support hardware that currently provides clean air and water to the crew [10]. The ECLSS consists of three key components, the Water Recovery System (WRS) and the Oxygen Generation System (OGS) and Advanced Closed Loop System (ACLS). The WRS provides clean water by recycling crewmember urine, cabin humidity condensate, and Extra Vehicular Activity (EVA) wastes. The WRS consists of a Urine Processor Assembly (UPA) and a Water Processor Assembly (WPA). The ACLS is an ESA rack that converts carbon dioxide into oxygen and water [11].

Fig. 13. New Frontiers - Workstation Level View 2

5. Environmental Design

Circadian rhythm is a natural internal process that regulates the 24-hour sleep-wake cycle when exposed to light by inducing physical, mental, and behavioral changes (see Fig. 14). Research has shown that light has a direct effect on both our visual and non-visual systems and that electric light can impact circadian rhythm. Scientists have discovered that long-term exposure to certain wavelengths of blue light at a specific intensity can have a negative impact on melatonin production, which can cause fatigue, insomnia, mood swings, and general anxiety [12].

Circadian lighting is the concept that electric light can be used to support human health by minimizing the effect of electric light on the human circadian rhythm. One day on the Moon is roughly equal to 27 Earth days (or 655.72 hours) long, which means integrating circadian lighting into the habitat is critical for providing a greater human experience and long-term healthy living on the Moon.

Fig. 14. Circadian Lighting Levels

The habitat concept is supported by several strategies to improve lighting conditions but also maximize efficient air movement, communication, visibility, physical mobility and overall human health.

All lighting systems onboard are designed to allow dynamic adjustments of light intensity and color temperature to mimic the day-night cycle of Earth. The light intensity can be controlled with dimmers. Light fixtures are set to a lower intensity in the early morning, transition to a higher intensity as the day progresses, and reduce to a lower intensity in the evening. Cooler color temperatures (ranging from 4000K up to about 10,000K) are used in spaces and during times when it's appropriate to promote alertness and attention. Warmer color temperatures (ranging from < 2700K to 3500K) represent daylight hours when the sun is rising and setting when crew members are falling asleep or waking up. These systems should be automated using sensors and schedules to create a more seamless human experience while also allowing crew members to override settings when necessary.

In our concept, we used simulation methods to identify the location and type of lighting which was distributed throughout the habitat. Each space had its own requirements for lighting and by placing lights at various locations, we were able to provide flexible control and adaptability for unique living conditions (see Fig. 15, 16).

Environmental Lighting Requirements:

- Ambient Lighting - general lighting, provides an area with overall, non-specific illumination.
- Task Lighting - provides increased light for specific tasks in a room that may already have some ambient light.
- Tertiary Lighting - allows you to simulate lighting coming from the surroundings of your Scene. It is common to use environmental lighting to simulate sky lighting.

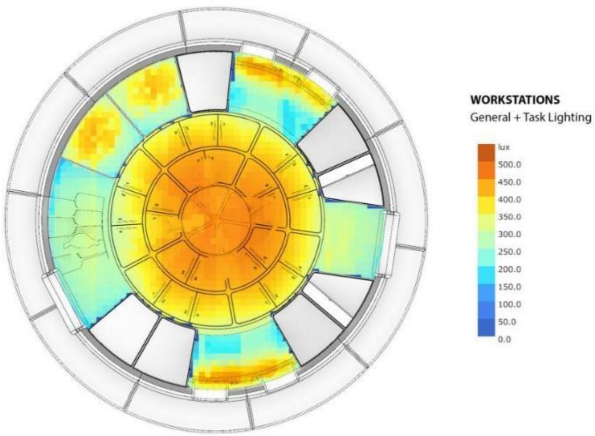

Fig. 15. Level 1 - Illumination Analysis

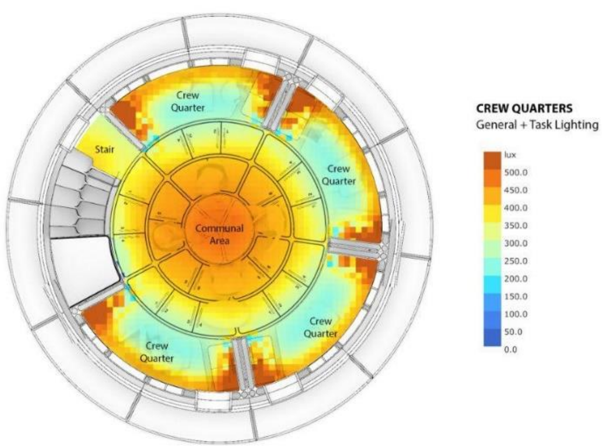

Fig. 16. Level 2 - Illumination Analysis

5.1 Ventilation and Thermal Cooling

The supply locations in the central habitat zone are located on a continuous slot on the floor, at the perimeter of the table, placing it at a central zone in the habitat. We chose to place the return in the ceiling, directly above, within a continuous slot where the light is located to remove hot air that rises to the ceiling and back into the system. The supply location in the crew quarters is below the desk and return above the headrest in the compartments above the bed co-located with the light. The supply locations can be split into the habitat zone and crew quarter zone. The strategy supplies and returns temperature-controlled air and movement for both habitat and crew volumes.

Cabin ventilation and thermal cooling systems provide crew members with efficient airflow and temperature-controlled environments. The crew quarter will require continuous fresh air near the crew members head position while reducing acoustic exposure. This helps remove carbon dioxide, metabolic heat and electronics waste heat. There should be two primary levels for ventilation, temperature control and acoustics, first at the habitat level and second at the crew quarters level. The habitat level system will include an Air Assembly that can be adjusted to reduce the common space temperature to ~18° C (see Fig. 17). The common space will have air intake and exhaust locations centrally located, controlling the primary habitat airflow and temperature. The crew quarters will have a localized ventilation system that includes an air intake and air exhaust to minimize recirculation of air between crew quarters.

The habitat level ventilation requirements are [13]:

- 0.42-5.1 m3 /min of airflow.
- < 76 m/min exhaust air velocity
- average temperature 22°C

The crew quarter ventilation requirements are:

- 0.42-5.1 m3 /min of airflow.
- < 76 m/min exhaust air velocity
- Average temperature 18°C

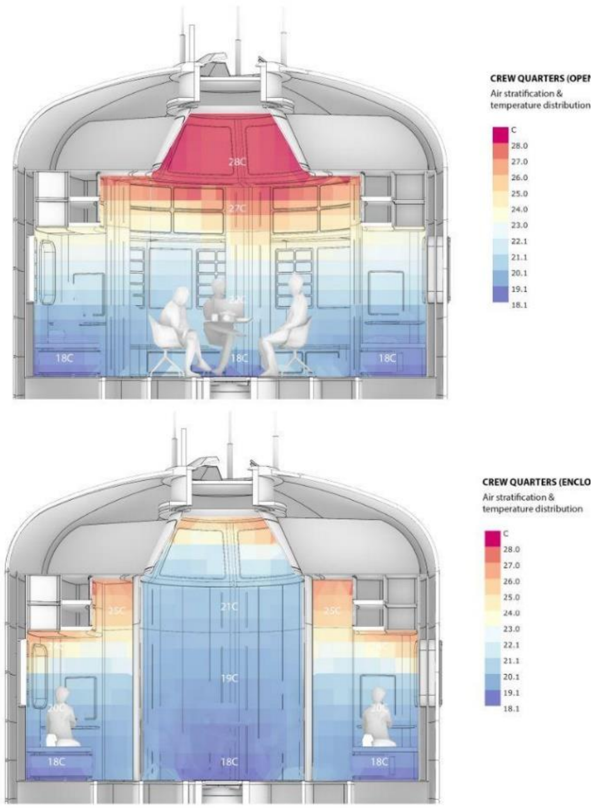

Fig. 17. Level 2 - Air Stratification & Temperature Analysis

Workstation ventilation and thermal cooling systems provide crew members with efficient airflow and temperature-controlled working environments. The workstation level will require continuous fresh air near the crew members head position while reducing acoustic exposure. This helps remove carbon dioxide, metabolic heat, and electronics waste heat. The workstation level system will include an Air Assembly that can be adjusted to reduce the common space temperature to ~18° C. The air intake and exhaust locations are centrally located, controlling the primary habitat airflow and temperature. The supply is in the floor, pushing air outward, toward the perimeter and return will be in the ceiling directly above.

6. Environmental Protection System

Multilayer insulation (MLI) is a high-performance system which implements multiple radiation and heat transfer layers to mitigate the adverse effects of the space environment [14]. We considered several existing materials in our design concept. A major part of the design is the environmental protection system, designed as a multi-layer composite assembly which uses carbon fiber as the structural shell. This shell is responsible for supporting the internal pressure loads and supports a composite floor system. The design includes an inner wall layer which is part of the shell assembly and is intended to function as an augmented part of the life support system – composed of water and other hydrogen-rich materials as a form of passive radiation shielding.

The materials that make up the environmental protection system or enclosure are determined by function, safety, performance, and environmental criteria. The habitat concept makes use of multiple high-performance materials that are divided into two sets. The first set of materials are exposed to the external or space / vacuum environment (where issues of vacuum comparability, dust contamination, micrometeoroids, outgassing, cosmic and ionizing and non-ionizing radiation are key drivers. The second set of materials are lightweight and safe materials that exist on the internal pressurized side and are exposed to the crew. In this set of materials, the drivers are crew safety, flammability off-gassing, toxicity, and permeability.

6.1 Windows

The window design and geometry are optimal for structural efficiency and situational awareness, providing each crew member with a direct line of sight to the surrounding area from their workstation (see Fig. 18). The windows include a shutter on the exterior that is automated and drops down to protect from glare and radiation as well as for micro meteoroids.

Fig. 18. New Frontiers Habitat Configuration

The wall assembly is broken up into two regions, the window area and typical shell. The window assembly is illustrated with the enclosure assembly (see Fig. 19). Each system is designed to perform for impact, thermal control, pressure loads, and radiation. Combined these systems can produce improved performance across each environmental challenge.

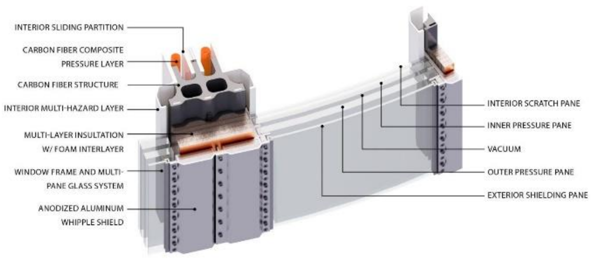

Fig. 19. New Frontiers Habitat Configuration

6.2 Workstations

The workstations are designed as multi-functional zones with both exercise and working equipment integrated into the surrounding walls. Each workstation zone can host two crew members and includes two separate windows adjacent to each other with an exercise machine in between. The flexibility allows a crew to follow multiple daily routines for operations, exercising and living.

6.3 Crew Quarters

The crew quarters expand to give each occupant a maximum of 3.3 sm. This flexibility can be used to optimize daily working and living functions. A degree of sleep privacy for each crew member to support health and performance is provided by this system.

7. Radiation

Dose equivalent vs depth curves and whole-body effective dose equivalent will be computed. It calculates the tissue-weighted sum of the equivalent doses in all specified tissues and organs of the human body. It represents the stochastic health risk to the whole body. These results are expressed in millisieverts (mSv). Radiation limit set by ESA suggests a dose limit of 0.5 Sv (500 mSv) per year and 0.25 Sv (250 mSv) per 30 days [15]. With these dose limits the career of the astronaut will be limited to two years and the average life-time loss can be expected to be more than 10 years.

Radiation Dose Limit & Shielding Requirements

ESA dose limit

Limit	Value	Comment
Career	1 Sv. (1000mSv)	ICRP - No age or gender dependence
Blood Forming	0.25 Sv. for 30d	ISS Consensus limits
Organs (BFO)	0.5 Sv. for annually	
Eye	0.5 Sv. for 30d	
	1.0 Sv. for annually	
Skin	1.5 Sv. for 30d	
	4.0 Sv. for annually	

NASA dose limit

Age in Years	Dose Limit-Male Astronauts (Average Life-Loss Per Death in Years)	Dose Limit-Female Astronauts (Average Life-Loss Per Death in Years)
25	520 mSv (15.7)	370 mSv (15.9)
30	620 mSv (15.4)	470 mSv (15.7)
35	720 mSv (15.0)	550 mSv (15.3)
40	800 mSv (14.2)	620 mSv (14.7)
45	950 mSv (13.5)	750 mSv (14.0)
50	1150 mSv (12.5)	920 mSv (13.2)
55	1470 mSv (11.5)	1120 mSv (12.2)

Fig. 20. New Frontiers Habitat Configuration

6.4 Galactic Cosmic Rays

For this study, the GCR spectra of Matthia 2013 is used. The Effective Dose Equivalent (per day) obtained using M2013 model is presented in graph form and the total values are presented in summary. The dose equivalents are for free-space environments.

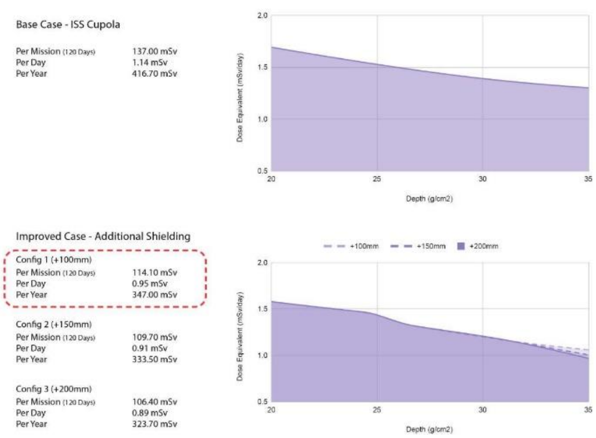

Fig. 21. New Frontiers Habitat Configuration

The International Space Station (ISS) Cupola Module is used as a Base Case to provide baseline results. Improved Cases results are computed by adding additional shielding materials and varying the thickness to observe the effectiveness of radiation protection.

The result shows a significant decrease in radiation dose with the first +100mm shielding material. Subsequent increases in material thickness can provide moderate decreases in radiation dose. As a result, for a 120 days lunar mission, Configuration 1 can achieve well below the annual limit of 500 mSv.

Once landed on the lunar surface. additional protection measures can be done by utilizing local resources. For example, lunar regolith can be excavated and added to the exterior envelope of the habitat. Lunar ice can be extracted and processed to create water skylights.

6.5 Solar Particle Events

For this study, historical SPE is selected to compute dose vs. depth curves. In order to adopt a safe and conservative approach, The Carrington Event (September 1989 hard fit) has been used in this simulation as it represents the worst-case scenario. The dose equivalents are for free-space environments.

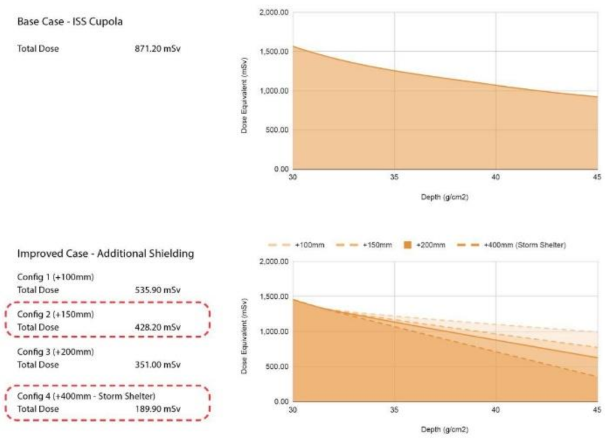

Fig. 22. New Frontiers Habitat Configuration

The International Space Station (ISS) Cupola Module is used as a Base Case to provide baseline results. Improved Cases results are computed by adding additional shielding materials and varying the thickness to observe the effectiveness of radiation protection.

The result shows that with an increased shielding thickness of +150mm (Config 2), the total dose can be within the ESA dose limit of 500mSv, (a 50% reduction compared to base case). Additionally, in the event of an extreme Solar Particle Event, a flexible/ compact storm shelter can be created in a portion of the habitat to increase the radiation absorption capabilities (Config 4), lowering the total dose from 428.2 mSv to 189.9 mSv, an additional 56% reduction of radiation dose.

6.6 Lunar Surface Radiation

The Moon surface will provide a natural shielding on half of the solid angle and the actual dose will be reduced by a factor of 2. The graphs on the right show the estimated effective dose equivalent comparing deep space exposure to Lunar surface exposure.

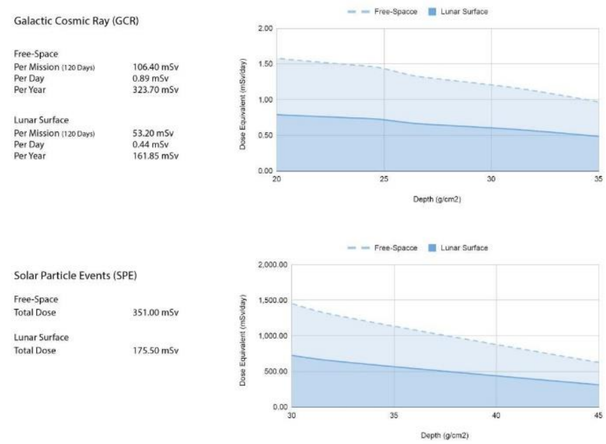

Fig. 23. New Frontiers Habitat Configuration

In conclusion, the result shows that a minimum of +150mm additional radiation shielding must be included in the design of the habitat in order to provide a safe habitat for the crew from both GCR & SPE radiation. It is important to remark that the dose exposure shall always follow the ALARA (As Low As Reasonably Achievable) principle.

To sustain life on the Moon for the goal of long-term habitation, utilizing local lunar resources (such as lunar regolith, water) will be critical to further minimize radiation dosage.

6.7 Shielding Materials

There are two ways to mitigate space radiation. Passive & Active Shielding. Passive Shielding is a physical material placed between a source of radiation and a person, to absorb the radiation energy before it reaches the target. Active Shielding is a magnetic field which serves both to deflect and to trap portions of the incoming space radiation, much like Earth's magnetic field. This study focused on the Passive Shielding approach as Active Shielding technology is still in the early development phase.

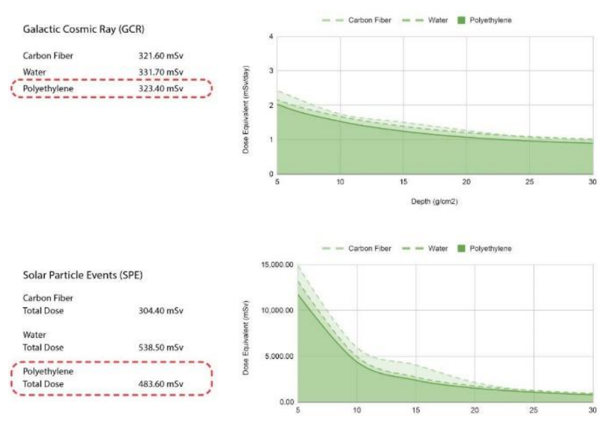

Fig. 24. New Frontiers Habitat Configuration

On the ISS, hydrogen rich materials such as polyethylene help reduce the crew's exposure to radiation. Three materials are tested and compare the radiation dose reduction [16]. These materials will be applied to the last layer of the wall system. The result shows that Polyethylene has the most well-balanced performance in both GCR and SPE environments. Because of its high hydrogen content and low density, it is great at absorbing and dispersing radiation while keeping the wall system lightweight.

Fig. 25. New Frontiers Habitat Configuration

6.8 Integrated Radiation Protection

Exposure to ionizing radiation is a major health risk for upcoming deep-space missions. The space radiation environment includes energetic solar particles emitted during solar flares and coronal mass ejections, as well as GCRs, which are composed of electrons and positrons (2%), protons (85%), helium nuclei (12%), and heavier ions referred to as high-energy and high-charge particles (HZE; 1%). Passive radiation shielding is a mandatory element in the design of an integrated solution to mitigate the effects of radiation during long deep space voyages for human exploration. The crew quarters are an ideal location for augmented radiation protection. This concept proposes a 120mm zone where additional high hydrogen content materials such as polyethylene can be used. There is the potential to use multi-layered materials that work together and exploit multiple material characteristics suitable for radiation shielding.

7. Structural Design

The capsule is subject to two distinct load conditions. One is launch and transfer which is characterized by axial dynamic loads that can reach up to 5Gs depending on the chosen launch vehicle. The other is when the capsule is occupied and fully pressurized at its destination. For this study we chose an air pressure of 60% of sea level atmospheric pressure.

Structural optimization analysis is performed on the geometry for both load cases. Topology optimization is performed on each load case to determine optimal distribution of material through the surface of the pressure vessel (see Fig. 26).

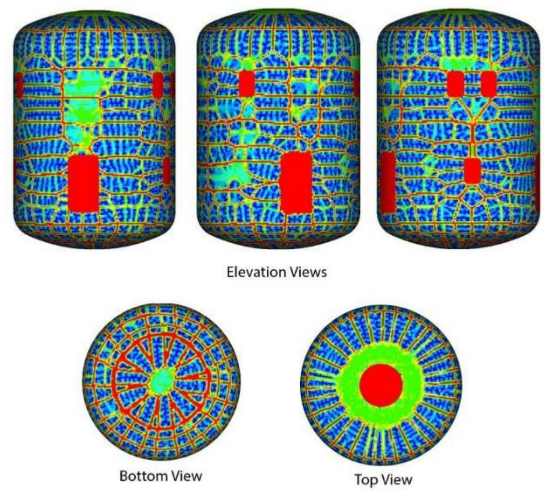

Fig. 26. Habitat Structural Analysis

The results of the optimization can be interpreted differently depending on the manufacturing method and material selection for the habitat. If constructed using traditional aluminum, then the optimization shows the optimal placement of stiffening ribs. Alternatively, if the habitat is constructed using fiber reinforced composites, then the optimization shows areas for increased thickness and potential interlayers on the thin shell to maximize structural performance.

The pressure vessel design also underwent composite optimization cycles. The free-size optimization identifies preferred areas on the model where purported orientations of fiber should be located. The optimization was set up using carbon-fiber material with cover orientations of 0 and 90 degrees. The results show the thickness of plies in each orientation for the given loading conditions, reducing overall structural weight.

7. Floor System

The floor structure is designed as a composite tube with a metal sleeve that connects directly to the pressure vessel (see Fig. 27). The area of connection incorporates metal reinforcement embedded into the pressure vessel. The floor truss members span come together at a central node. The node is a metal structural sleeve that is mechanically fastened to each beam. The floor system reinforces the pressure vessel and supports the dead-live loads, including the compartments embedded below each floor.

Fig. 27. New Frontiers Habitat Configuration

The connection between the floor system and the pressure vessel needs to be reinforced using a metal embed. The reinforcement helps stiffen the zone where there are vertical loads but also serves as a rigid attachment zone for fastening the trusses.

5. Results

The architecture of the habitat placed an emphasis on the need for reconfigurable and automated crew systems such as crew quarter spaces, working functions and collaborative furniture. The idea of movable walls and furniture improves the usability of space. It enables the architecture to co-locate functions and programs within specified spaces so that the crew can maximize performance and interact with their surroundings directly. For example, by locating working functions next to exercise and health functions, the same systems supporting the environment can be utilized to capture and monitor the health of each individual crew member. Using the same strategy, we can also improve the quality of personal space for longer durations by increasing the amount of usable space within each crew quarter. The concept proposed a dynamic wall system that can be configured in an inward or outward position depending on the needs of the crew member. The intention of this system is to improve the overall health and wellbeing of astronauts.

The NHAB concept is presented as a near-term habitat capability that attempts to address the challenges of a highly constrained architecture. The key constraints stem from mass and volume limitations, primarily presented by the need for transportation and delivery capabilities. By constraining the habitat mass to less than 15 metric tons the collaboration focused on the impacts of limited volume, area, and dimension for human occupancy. The reduced volume and scale also posed some interesting challenges in terms of technology integration which were addressed by proposing a structural solution that leverages composite systems to support mechanical, storage and equipment. The idea of a multi-functional structure will be essential not only for integrating mechanical systems but also for improving material use and reinforcing the habitat with radiation shielding.

The New Frontiers collaboration reinforced the idea that there is significant value to thinking about human centered architecture for habitation in highly constrained environments. In the future there will be a need to integrate human to machine principles that improve the use of architectural design for crew accommodations, scientific labs, manufacturing facilities, life support functions, health and medical facilities and the overall human experience of human space exploration.

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