

# Study for a Rigid/Inflatable Greenhouse Module to Integrate Bio-regenerative Life Support Systems into Orbital Facilities and Deep Space Transfer Vehicles

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A recurrent issue in concepts for future Deep Space Transfer Vehicles (DSTVs) and space habitats is the need for a large provision of consumables necessary to crew's vital sustainment during prolonged missions without any external supply. The integration of ecological bio-regeneration into the environmental control and life support system (ECLSS) seems now an appropriate solution to reduce the amount of storage, favoring a circular economy of vital elements. The goal is to create a closed loop of oxygen, water, and food through recycling and regeneration of a given quantity, reducing the dead mass of consumables stored for backup and emergency supply only. The concept of Bio-regenerative Life Support System (BLSS) has been extensively tested by ESA, NASA, and Roscosmos since the late 1980s. Projects like MELiSSA (Micro-Ecological Life Support System Alternative) financed by ESA have been tested both in ground facilities, as fully closed biological lifecycle, and in a series of orbital spaceflights to test the system's performance in conditions of microgravity. However, the reduction of consumables in terms of dead mass, using a closed-loop paradigm, can come at a cost. Increased system complexity, greater energy usage, and more possible failure modes are all possible consequences of BLSSs. This paper explores the feasibility of a hybrid rigid/inflatable module based on the Cygnus cargo module by Northrop Grumman Space Systems, assumed as the standard module for the Cislunar Gateway station. The expandable module would host an experimental greenhouse for plants, microalgae's photo-bioreactors, and necessary BLSS hardware, adding capability to the ECLSS of the station. Its scope is to evaluate the capability of carbon sequestration, oxygen regeneration, humidity condensation, waste processing, wastewater recycling and food production of the BLSS in prolonged conditions of microgravity. Furthermore, it increases the habitable volume and introduces an element of tangible natural bond with the home planet for crew's psychological support.

## Nomenclature

BEAM	=	Bigelow Expandable Activity Module
BLSS	=	Bio-regenerative Life Support System
CES	=	Closed Ecological System
DSTV	=	Deep Space Transfer Vehicle
ECLSS	=	Environmental Control and Life Support System
GCR	=	Galactic Cosmic Rays
HALO	=	Habitation and Logistics Outpost (Gateway station)
ISRU	=	In Situ Resources Utilization
ISS	=	International Space Station
MELiSSA	=	Micro-Ecological Life Support System Alternative
PPE	=	Power and Propulsion Element (Gateway station)
SM	=	Service Module
SPE	=	Solar Particles Event
TLI	=	Trans-lunar Injection

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## I. Introduction

THE study presented in this paper explores the feasibility for a hybrid rigid/inflatable greenhouse lab module as a testing facility operating in conditions of microgravity, i.e. orbital stations and deep space transfer vehicles (DSTV). The concept at its basis is the integration of bio-regenerative lifecycles to be paired with the life support systems installed onboard of these spacecrafts, like the International Space Station (ISS) or the future Cislunar Gateway station. The main purpose of the lab module is to test in extended real conditions the potential capability of biological systems to improve air and water regeneration, waste and wastewater recycling, and food production onboard a spacecraft with limited or no opportunity for resupply from external resources.

In general terms, the Environmental Control and Life Support System (ECLSS) is the core system around which would rely on the entire architecture of a manned spacecraft, since it provides all the essential vital elements to sustain biological life onboard, like breathable air, water, temperature, and humidity.<sup>1</sup> These elements need continuous regeneration and revitalization in order to be kept at a constant level and scrubbed by any toxic byproduct. Consequently, the ECLSS assumes a pivotal role in spacecraft design in terms of pressurized habitable volume occupied, energy use, and system complexity.

The first generation of orbital facilities, like Skylab, Mir, and Salyut stations, had some limitations in hosting crews for a prolonged time, due the relatively small amount of resources stored onboard these stations, and the limited cargo capability of Apollo and Soyuz capsules.<sup>2</sup> Russia tested a resupply system on January 2, 1978, sending an automated capsule called Progress, a Soyuz scrapped of crew accommodation and heat shield, towards the Salyut-6 orbital station. Loaded with a cargo of essential consumables, the Russian space program experimented for the first time with a regular ferry service of cargo for their orbital stations, being capable of extending crews' permanence in orbit.

The Progress spacecraft was conceived as expendable, hence discarded to burn into the atmosphere once unloaded, a procedure which is still in use today, making this resupply system efficient but still economically expensive. With the Space Transportation System (STS) entering service in 1981, the goal of an almost fully reusable spacecraft to go back-and-forth from Earth-to-orbit carrying crew and cargo seemed fully accomplished. Indeed, the Space Shuttle was an extraordinary machine, allowing the construction of the ISS, the largest human-built object currently in space, and being the backbone of NASA's human exploration for thirty years. However, the excessive costs for maintenance and refurbishment of orbiters and boosters after each flight, and the tragic loss of crews in the Challenger and Columbia disasters, made the overall system economically unsustainable.

After the retirement of Shuttles' fleet from service in 2011, the transfer of crews from Earth-to-orbit returned to old-fashioned ballistic capsules like the evergreen Soyuz, but at the same time paved the way for a new generation of innovative reusable capsules like SpaceX's Crew Dragon, NASA's Orion, and Boeing's CST-100 Starliner. Instead, resupply missions for oxygen, water, food, equipment, spare parts, and fuel never ceased to rely on a regular service provided by a fleet of expendable spacecraft, like Progress, Cygnus, former ESA's ATV, and Tianzhou, developed for China's Tiangong-1 orbital station. Despite this resupply system has proven to be efficient, the early concept of orbital stations as empty tanks requiring continuous refueling of vital consumables from a close source represents per se an added cost and a limitation in keeping these facilities permanently inhabited without this constant supply.

A different scenario is presented once the crew would be in condition of remoteness and isolation, like onboard a transfer vehicle travelling toward a distant celestial body or operating in habitats on a planetary surface. In such cases, all the needed necessities must be carried onboard, like early pioneers travelling towards remote and unknown destinations. Such vessels were configured to carry the essential supplies for crew survival, using the available space between cargo and habitat, often with the latter drastically reduced. This scenario would be unsustainable, both physiologically and psychologically, for a crew travelling in deep space. In the case of a mission to Mars, for example, a crewed mission should carry all the necessary consumables for a period of almost two years. Once this stored mass would be added to the systems, structure, fuel, etc. the whole spacecraft would be extremely heavy at lift-off, and almost impossible to launch directly from the Earth's surface. However, it would not be a problem of load alone, but of precious pressurized volume occupied by the dead mass of storage, which would drastically hamper the livable space and therefore limit the spacecraft's habitability.<sup>3</sup> Moreover, once reached the destination and set up the first habitat on planetary surface, the choice for In Situ Resource Utilization (ISRU) would be practically unavoidable.<sup>4</sup> The mission's duration, the impossibility for resupply from Earth on regular basis, and no chances for evacuation in the event of an emergency, would necessitate complete self-sufficiency. The extra-terrestrial settlement would need, to be arranged as a closed, introverted ecosystem where all resources should be continuously produced, recycled, regenerated, and reused from the scarce raw materials locally available, in an almost perfect circular economy.

Studies in this field are not current and originate from military research since late 1950s, known as *cabin ecology*,<sup>5</sup> about the possible adoption of Closed Ecological Systems (CES) in submarines and nuclear fallout shelters

underground. These early findings, which coincided with the first attempts at space exploration, raised multiple questions regarding physicochemical mechanisms of planetary life and how they may artificially be reproduced. Indeed, the concept of a spacecraft as a closed artificial ecosystem date to the dawn of human spaceflight, as depicted by Vernadsky and Tsiolkovsky in 1926, although this branch of research associated with space exploration would not develop until the Moon missions of 1960s and 1970s. The concept of Bio-regenerative Life Support System (BLSS) is relatively more recent and has been extensively evaluated by ESA, NASA and Roscosmos since late 1980s, based on precedent studies conducted separately in USA, the former USSR, the European Union, and Japan. Manmade closed ecosystems, like CELSS (Controlled Ecological Life Support System) and ALSP (Advanced Life Support Program) by NASA at Johnson Space Center; Bios-3 at the Institute of Physics in Krasnoyarsk, Russia; CEEF (Closed Ecology Experiment Facility) at the Institute of Environmental Sciences in Japan, and MELiSSA (Micro-Ecological Life Support System Alternative) by ESA at Universidad Autonoma de Barcelona, Spain, are running since several decades now, and have been extensively tested in ground facilities and partially in a series of orbital spaceflights.<sup>6</sup> However, a fully integrated BLSS has not been tested yet in space, mainly due to technical and economical constraints.

Therefore, the focus of this research is on a proposal for a fully a dedicated lab module, based partly on available technologies and partially on the opportunity to test new technologies in real conditions, such as the hybrid configuration rigid/inflatable, which will be necessary for human exploration beyond the Earth orbit in the future. This lab and test facility would allow for extended research and experimentation of BLSS in steady-state microgravity, defining the multiple parameters to maintain an effective closed-loop ecosystem and proving an opportunity to test new materials and technologies in extreme conditions in real time. In turn, the gained knowledge would ease the system integration in terms of hardware, mass, and energy use of these bio-mechanical regenerative systems into the ECLSS of future spacecraft, including habitats on planetary surfaces. Once properly parametrized and dimensioned in relation to crew's size and allocable space, the integration of bio-regenerative ecosystems would increase the complete self-sufficiency of the crewed spacecraft or planetary habitat from other resources externally supplied.

The proposed rigid/inflatable BLSS laboratory module is based on the dimensional standards of the Habitation and Logistics Module (HALO) for the Cislunar Gateway station.<sup>7</sup> Its scope is an additional capability to the future Gateway station for testing and experimentation of bio-regenerative systems, in order to define an ecological closed loop of air, water, and nutrients onboard. Furthermore, it represents a test bed for inflatable technologies and mitigation strategies for the protection of the crew against radiation hazards. It is supposed that integration of BLSS and greenhouses into the ECLSS of future DSTVs will be of fundamental importance not only for biophysical support, but also as psychological comfort for crews in extreme isolation for extended periods, adding a tangible natural element.<sup>8</sup>

## **II. Cislunar Gateway Station**

Different and opposing viewpoints have been expressed regarding the utility of the Cislunar Gateway station as a necessary intermediate step for humans to reach the lunar surface, and discussions are still ongoing.

Many professionals and space experts advocate a series of Apollo-like direct lunar missions, where progressively a permanent lunar outpost would be settled and predisposed for future growth, thereby saving time and additional costs in developing an orbital facility. Others perceive an orbital outpost where lunar science and experiments would be conducted, offering an intermediate haven for crews before landing on the lunar surface or configured as fuel depot for further exploration. However, the scope of this paper is not to discuss the different motivations raised by one part or another. From our point of view, the Cislunar Gateway project offers the opportunity for additional research in the field, anticipating a permanent outpost on our satellite's inhospitable surface and hopefully, paving the necessary knowledge to reach other destinations beyond.<sup>9</sup>

Once completed, the Cislunar Gateway will not be larger than an approximate twenty percent of the current ISS and will not be permanently inhabited. However, the challenges that transient crews will face while aboard this tiny outpost will be greater than those encountered while aboard the ISS. Above all, the greater distance from our home planet and its reassuring presence outside the window, the multiple difficulties in keeping the station efficient during the uncrewed intervals, and lastly, but not least, the missing protection of Van Allen Belt against hazardous cosmic radiation. A place extremely challenging, for humans and systems, but a fundamental and unavoidable step forward for a better understanding of systems, procedures, materials, training, mission designs, and future vehicles' features, once human exploration sails toward other destinations like Mars.

With the expected retirement from service of the ISS within 2030, the ongoing research on human health risks associated with long permanence in microgravity would be further delayed, if not replaced by an alternative research

platform in space beyond this date. As per NASA's Office of the Inspector General, Report No. IG-22-005, issued on November 30, 2021:

"Microgravity research that is not completed by 2030 would shift, according to NASA's plans that are in development, to alternative platforms such as a commercial destination in low Earth orbit, the Lunar Gateway, the Human Landing System, and the surface of the Moon. If none of these destinations are available in time to complete this critical research, the Agency will have to accept a higher level of health risk for deep space missions or delay those missions until adequate mitigation strategies are developed."<sup>10</sup>

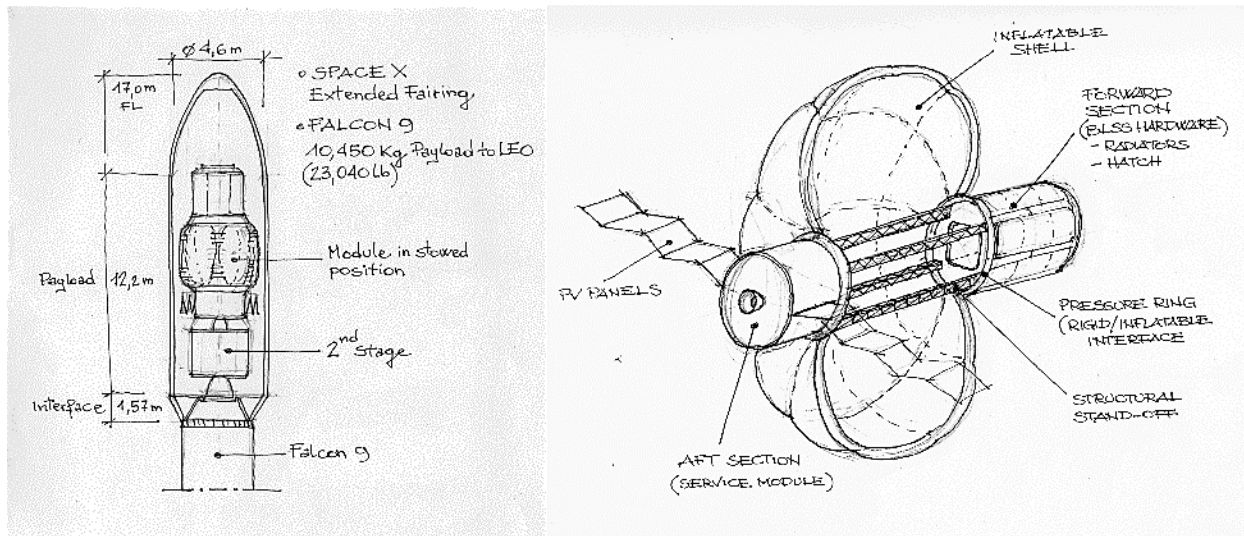
About this aspect, the Cislunar Gateway could offer a tremendous opportunity to accrue further knowledge and experience about limits and performances of humans and systems beyond Earth orbit, like research stations in Antarctica are still contributing to a better understanding of human psychophysiology in conditions of extreme isolation.<sup>11</sup> In this scenario, the inclusion of a greenhouse module into Gateway station's architecture is an opportunity to test BLSS' reliability in extreme conditions, to enhance further analysis of growth behavior in plants and microalgae exposed to microgravity for prolonged periods, to test and assess the performance of inflatable structures, materials, and components exposed to galactic cosmic rays (GCR) for extended time, and a further definition of protection protocols to safeguard human health and spacecraft integrity in deep space. The high levels of GCR occurring outside the protecting Van Allen Belt, paired with potentially dangerous solar particle events (SPE) due unpredictable solar activity, would expose crews stationing there to high doses of radiation. Future crews travelling towards distant destinations will be permanently exposed to such a risk, therefore a careful experimentation and assessment of protection systems, shielding materials, and emergency protocols needs to be assessed before any supposed crewed mission in deep space. In this regard, the opportunity for a research facility which could be operated also remotely, like the Gateway, would offer a privileged test bed for systems and technologies which until now have been simulated in ground facilities or Earth orbit only.<sup>12</sup>

If a permanent crewed lunar base would benefit from shielding against radiation from raw materials available on site, like a structure buried underground or covered with protective layers of lunar regolith, an efficient shielding for future DSTV is still needed for further research, experimentation, and testing in real conditions. The effects of long exposure to space environment for spacecrafts' components are well known, especially in Earth orbit, but the effects of a long exposure in deep space to GCR and ionizing radiation from SPEs are still unknown for crewed spacecrafts.

### III. Module Overview

The dimensional standards and structural frame are derived from the Cygnus cargo spacecraft by Northrop Grumman, which is the main contractor awarded the Artemis Contract for Gateway Crew Cabin in July 2020. Northrop Grumman is proposing the structural frame of Cygnus for the HALO, 3.07 m in diameter and 6.1 m long, one meter longer than standard Cygnus cargo in order to meet the habitable volume needs for future Gateway crews.<sup>13</sup> The adoption of Cygnus structure and integrated ECLSS systems has been suggested by its proven reliability as pressurized vehicle and reduced launch mass, once paired with the Power and Propulsion Element (PPE) which will provide energy and maneuverability to the Gateway station once fully assembled.<sup>14</sup>

In our study, the original Class I structure of the HALO module has been modified into a hybrid rigid/inflatable Class II module, keeping the same dimensions once in closed configuration at launch with an internal pressurized volume of 27 m<sup>3</sup>. Following the same minimalist design philosophy of the original Cygnus project, the study evidenced the modular adaptability of this spacecraft. Moreover, the pressurized module will be equipped with a service module (SM) for power and propulsion, similarly to Cygnus cargo spacecraft, properly dimensioned to thrust the module autonomously in cislunar orbit to rendezvous with the Gateway station. Power generation is provided by two gallium arsenide solar arrays extended to four modules each, instead of the two Ultraflex arrays installed in latest Cygnus to avoid geometric interference with the inflatable shell. Once docked to the station, the SM will provide additional power to greenhouse's systems, and could be used as a thruster for orbital maneuverability and backup energy source in case of an emergency (Figures 1 and 2).

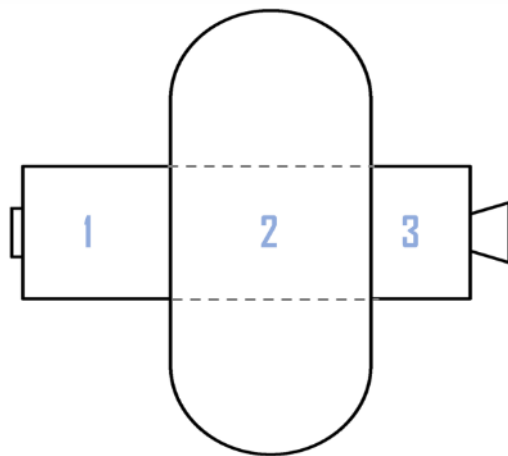


**Figure 1. Concept Sketches.** (Images by authors)

### **Cygnus Rigid/Inflatable BLSS Module**

Launch Mass (estimated): 7700 kg

Internal Volume: 27.16 m<sup>3</sup> (closed configuration) 222.64 m<sup>3</sup> (deployed configuration)



#### **1 Rigid Section**

- Pressurized Volume: 11.78 m<sup>3</sup>
- Life Support System (BLSS)
- Internal Thermal Control Systems & Radiators
- Water Recovery
- Waste & Wastewater Management
- Docking System

#### **2 Inflatable Section**

- Volume: 15.38 m<sup>3</sup> (closed, unpressurized), 195.48 m<sup>3</sup> (deployed, pressurized)
- Greenhouse Racks
- Photo-bioreactors
- Photosynthetic Lighting System

#### **3 Service Module**

- Electrical Power System (PV Panels)
- Communications Systems
- RCS and Attitude/Trajectory Control
- Propulsion System
- Thermal Control

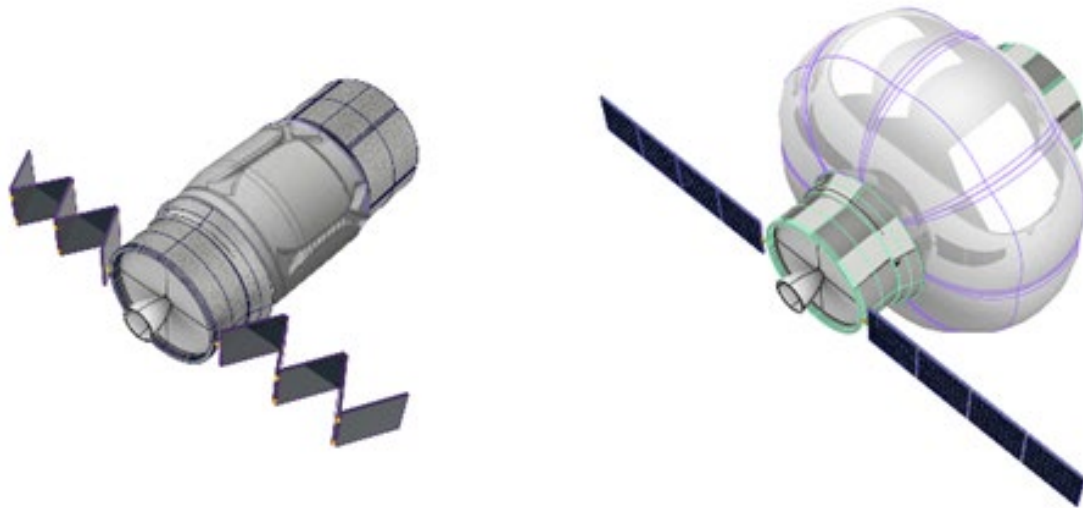
**Figure 2. Module diagram.** (Image by authors)

The overall length of the module is 7.58 m, with a standard axial hatch positioned in the forward rigid section 2.25 m long, equal to one section and half of the original Cygnus structure. This arrangement has been necessary to dedicate enough internal space to the BLSS hardware, which includes water and gas pumps package, O<sub>2</sub> and N<sub>2</sub> tanks, nutrients collectors, reactors, heaters, condensed water recovery, water tanks, backup filters, and a crew toilet, allocated into racks disposed along the main axes, fully accessible from the central aisle for maintenance, and connected to the ECLSS of the Gateway. This section is sealed by two hatches, one forward connected to the station and one aft with

the inflatable section. Due to biological items present in the digester and reactors stored in BLSS hardware this section needs to be launched pressurized. Moreover, the second hatch would act as an emergency shutter in case of accidental decompression of the inflated section. Furthermore, the forward rigid section hosts six radiators for heat dissipation, radially disposed on the external surface.

Following a similar concept to NASA's TransHab<sup>15</sup>, the remaining inflatable section of the module is shaped in a toroidal of 3.4 m long and internal diameter of 7.4 m, revolved around the internal structural core formed by four structural standoffs, and connected with pressure rings at forward and aft section of the module. Pressure rings are critical elements since represent the interface between the rigid parts of the module and the inflatable shell. As experimented in the TransHab project, the two pressure rings are designed as conical compression rings wrapped by the restraint layer. As the load in the restraint layer increases, the pressure in the ring increases as well. Once inflated at 14.7 psi, the inflatable section would increase the pressurized habitable volume of approximately 195 m<sup>3</sup>, hosting the greenhouse for plants and microalgae's photo-bioreactors. The shell has a thickness of 30 cm once deployed, composed of multilayered insulation, four bulletproof layers separated by open-cell foam for micrometeoroid protection, a main restraint webbing, redundant air-containment bladder layers, and a scuff-barrier interior wall. This composite technology recalls the one proposed for the former TransHab project and successfully tested on the ISS with the BEAM (Bigelow Expandable Activity Module).<sup>16</sup> The folded inflatable shell is estimated to have a diameter of approximately 4.0 m once in stowed configuration, hence within the internal tolerances of 4.6 m for Space X, or 4.57 m for ULA (United Launch Alliance) fairings.

The module is launched partially pressurized in closed configuration, meaning that during launch phases the rigid section and racks in the inflatable section only are sealed and stowed at minimal pressurization to keep plants and bacteria alive. In order to avoid any uncontrolled expansion of the compressed packed shell once still in the fairing during the ascension stage, the entire inflatable section is kept unpressurized, except for the mentioned pressurized racks hosting plants and bioreactors (Figure 3).



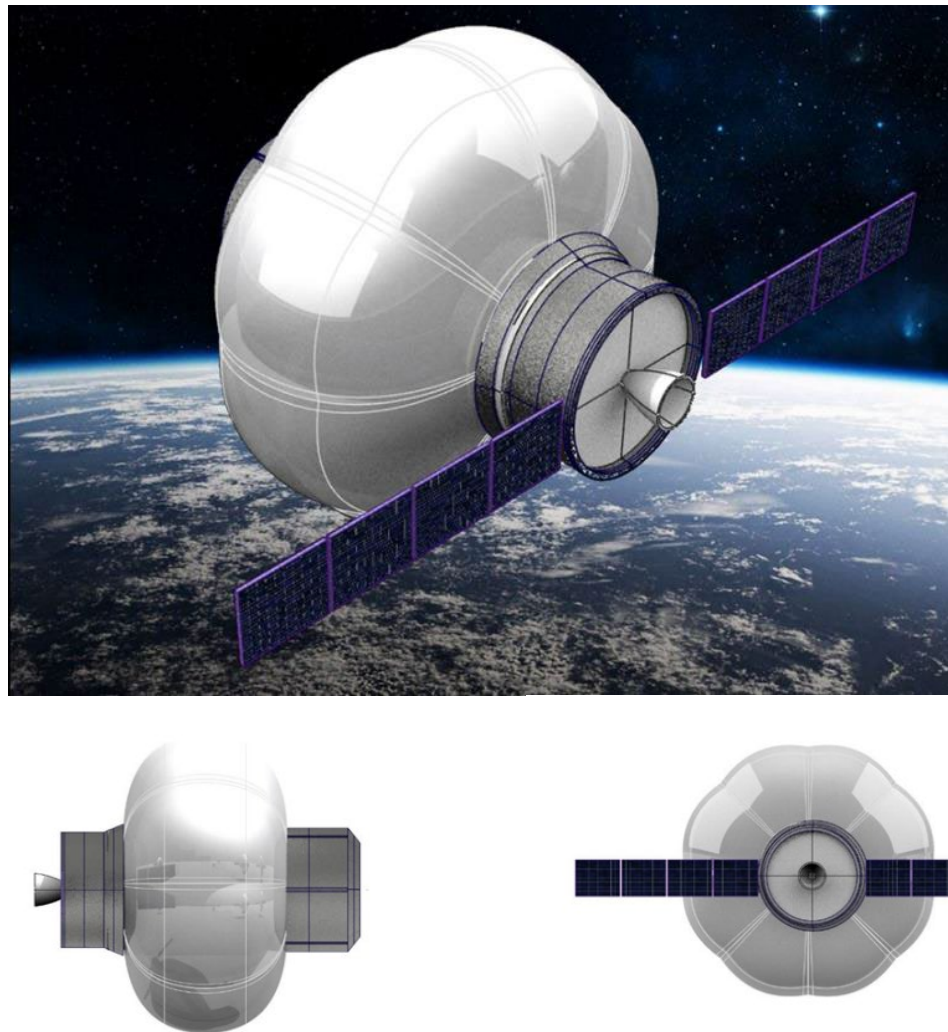
**Figure 3. Module in Closed and Open Configuration.** (Image by authors)

Once parked in Earth orbit, the two PV panels and the inflatable section are deployed, with internal pressurization stabilized at nominal operative level. This phase would allow the ground control to monitor the operation in real time and verify that all systems are ready before the ignition for TLI (Trans-Lunar Injection). A second stage would provide the necessary acceleration for TLI before being discarded, then the main engine of the SM would provide the thrust to rendezvous automatically with the Gateway station in cislunar orbit (Figure 4).

The TLI phase is autonomous until final approach, then the module is captured with the Canadarm installed on Gateway to secure the docking, similarly to the current cargo docking on the ISS. On this regard, the module will be equipped with 12 hypergolic thrusters for RCS (Reaction Control System), positioned in the SM and oriented not to intercept the inflated shell or PV panels with their jets. The integration with RCS is necessary to transform the spacecraft from orbital module to an autonomous spacecraft with full maneuverability through automated controls.



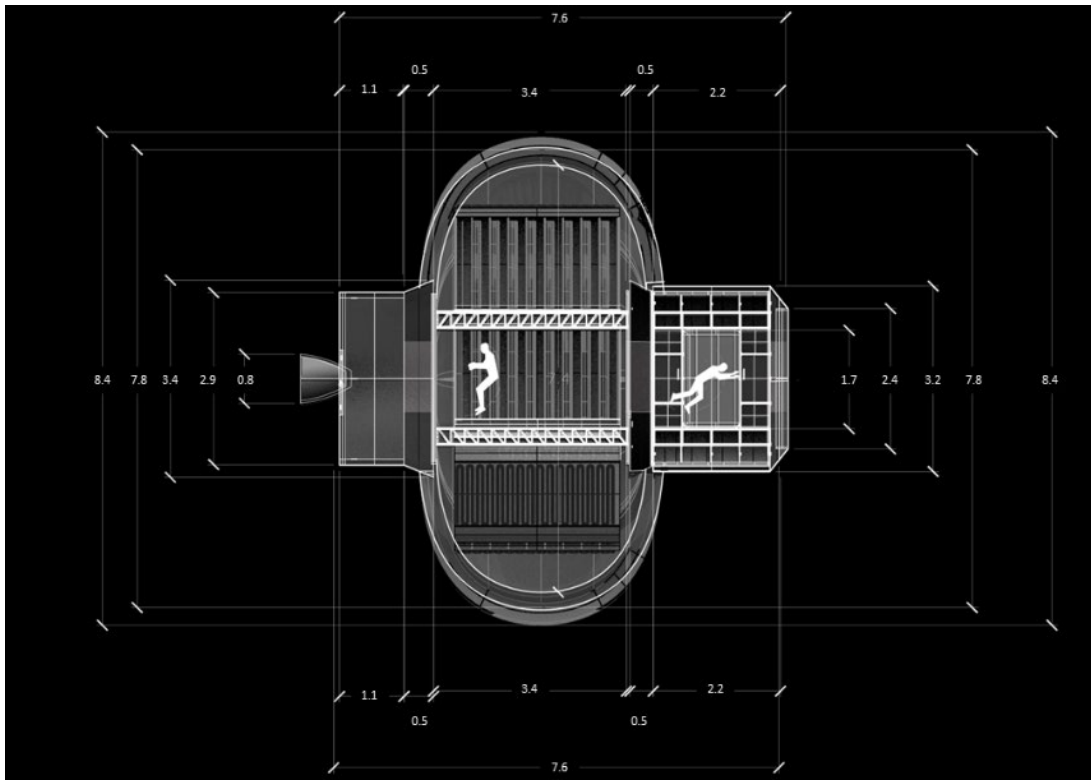
During the uncrewed travel to cislunar orbit, internal systems will be activated and monitored from ground, giving time to plants and living bacteria stored in bioreactors to adapt to the new microgravity environment at nominal pressure, temperature, and humidity levels.



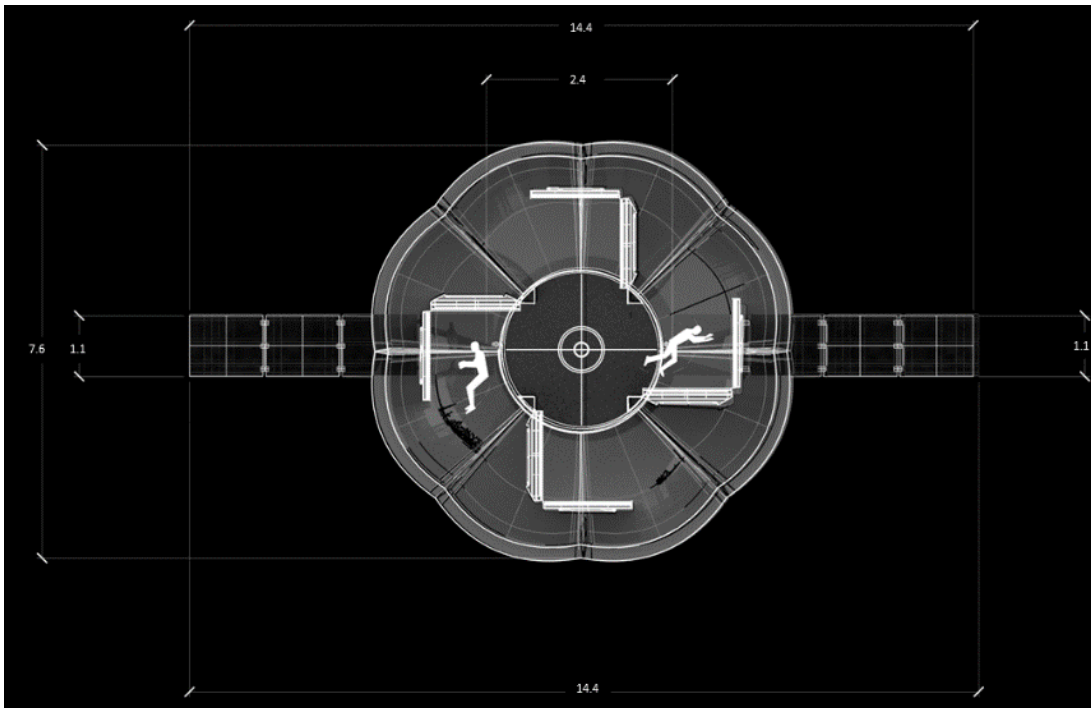
**Figure 4. Visualization with inflatable shell deployed.** (Image by authors)

#### **IV. Internal Configuration**

The concept for internal configuration follows the traditional arrangement as already experienced in ISS modules, with a central aisle surrounded by racks connected with hinges to standoffs.<sup>17</sup> This configuration offers an optimal degree of adaptability, since racks can be easily removed and changed depending on the mission and the specific function assigned to the module. The configuration proposed in this study shows the adoption of four double-face foldable racks for aeroponic system and microalgae's photo-bioreactors, with LED lighting panels in between, providing the necessary amount of light to activate the biosynthesis process. After being launched and parked in Earth orbit, the module will deploy the PV panels and inflate autonomously, which means the four folded racks will remain in stowed position, equalizing the internal pressure and activating the systems for lighting, water feeding and recovery. After docked autonomously to the station, and internal pressure of the two spacecrafts equalized, the final internal configuration would require a minimal intervention from the crew onboard in securing the racks in open position and complete the operational setting of systems (Figures 5 and 6).



**Figure 5. Longitudinal Section.** (Image by authors)

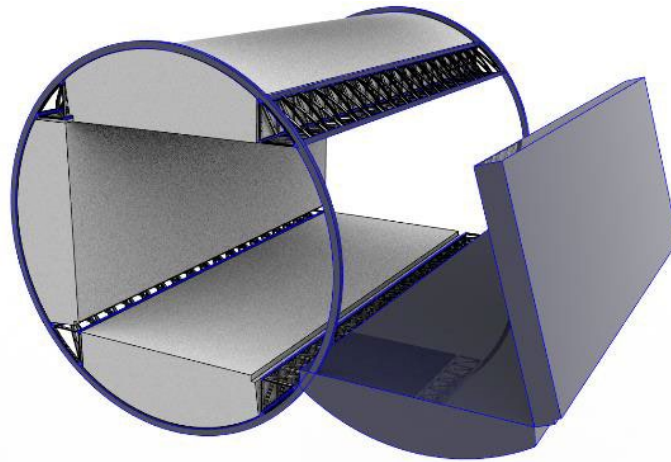


**Figure 6. Transversal Section.** (Image by authors)



### A. Structural Standoffs

These structural parts support the distribution of various utilities, structurally connecting the end cone attached to the SM and power plant to the rigid forward section of the module, hosting the BLSS systems and the main hardware. Differently by standoffs as normally used in ISS's modules, these elements are structurally loaded with tension and sheer forces acting internally on aft and forward sections by the pressure of the inflated shell. Therefore, these standoffs have the multiple function of structural girders, utilities connectors, support for additional lighting system, and hinged points for the four folded racks rotating outward the central aisle once the shell is inflated. Due their double function as structural elements and utility connectors, they are dimensioned to withstand torsional and sheer forces during launch and autonomous propulsion phases (Figure 7).

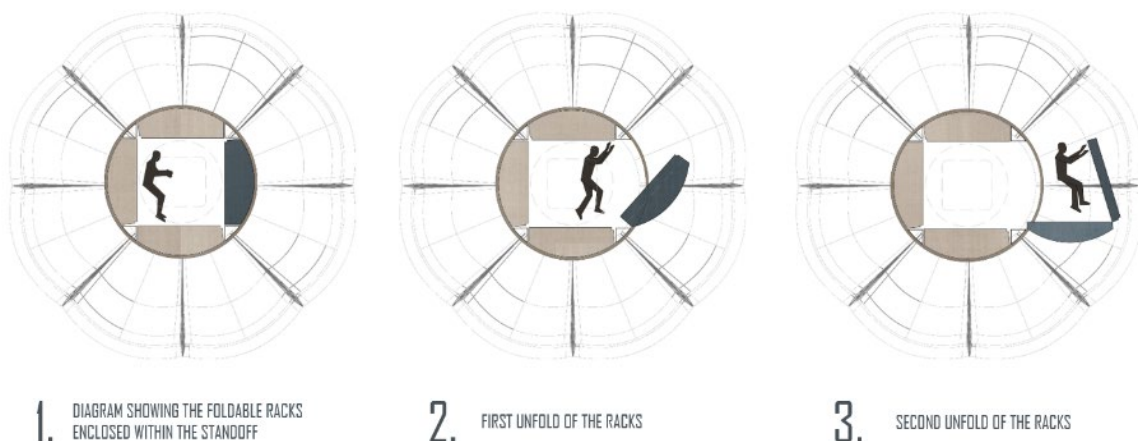


**Figure 7. Structural Standoffs detail.** (Image by authors)

### B. Racks

The forward rigid section of the module is equipped with racks on both sides and deck, leaving the ceiling partially free for the closing mechanisms of the two hatches. These racks host the BLSS hardware and are fully accessible for maintenance from the central aisle, with one side hosting an extensible toilet for the crew. The toilet is an integral part of the BLSS, since it collects the human waste and wastewater necessary to activate the anaerobic digester and source of carbon and nitrogen as nutrients for the plants.

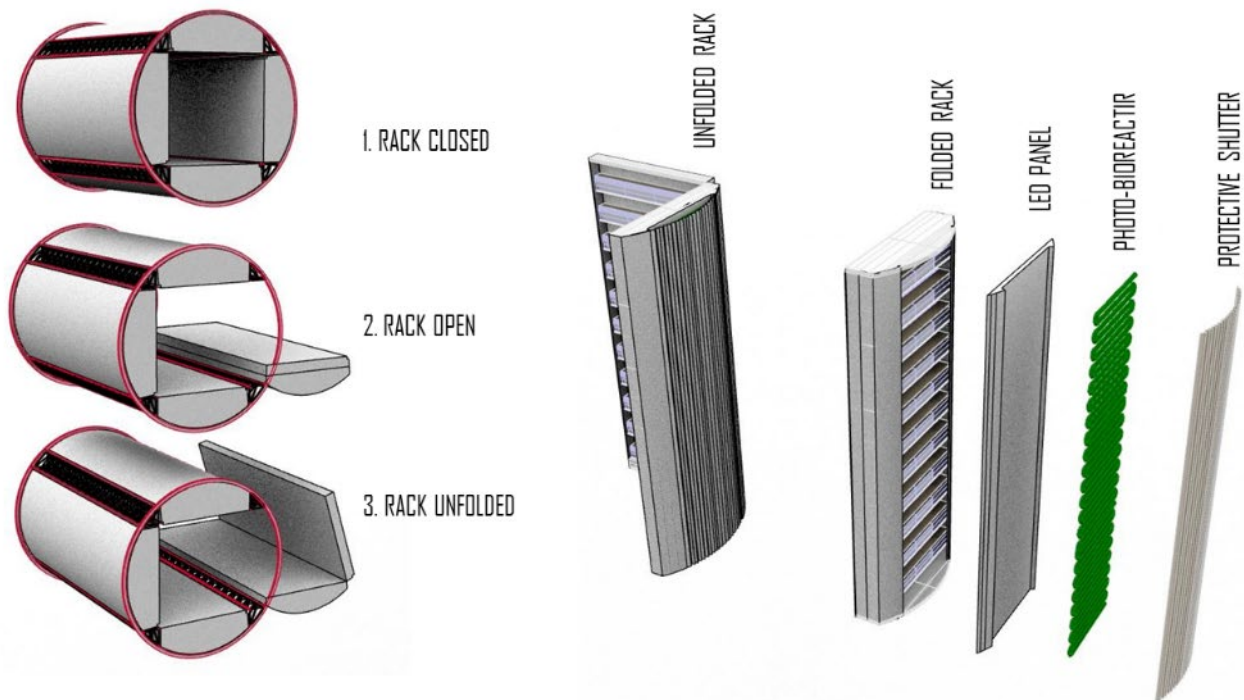
The four hinged and folded racks present in the inflatable section are the main components of our concept, expanding the usable surface approximately four times that of fixed racks due to the increased diameter of the inflatable shell, and offering a greater degree of adaptability for alternative uses (Figure 8).



**Figure 8. Foldable Racks Configurations.** (Image by authors)

With different racks' typologies configured at ground, the same module could be fitted for alternative functions such as crew accommodation or logistics module, instead of greenhouse, extending its commercial usability. For example, with other racks integrating sleeping pods and cabinets, the module can be configured as crew accommodation quarters with a high degree of privacy.

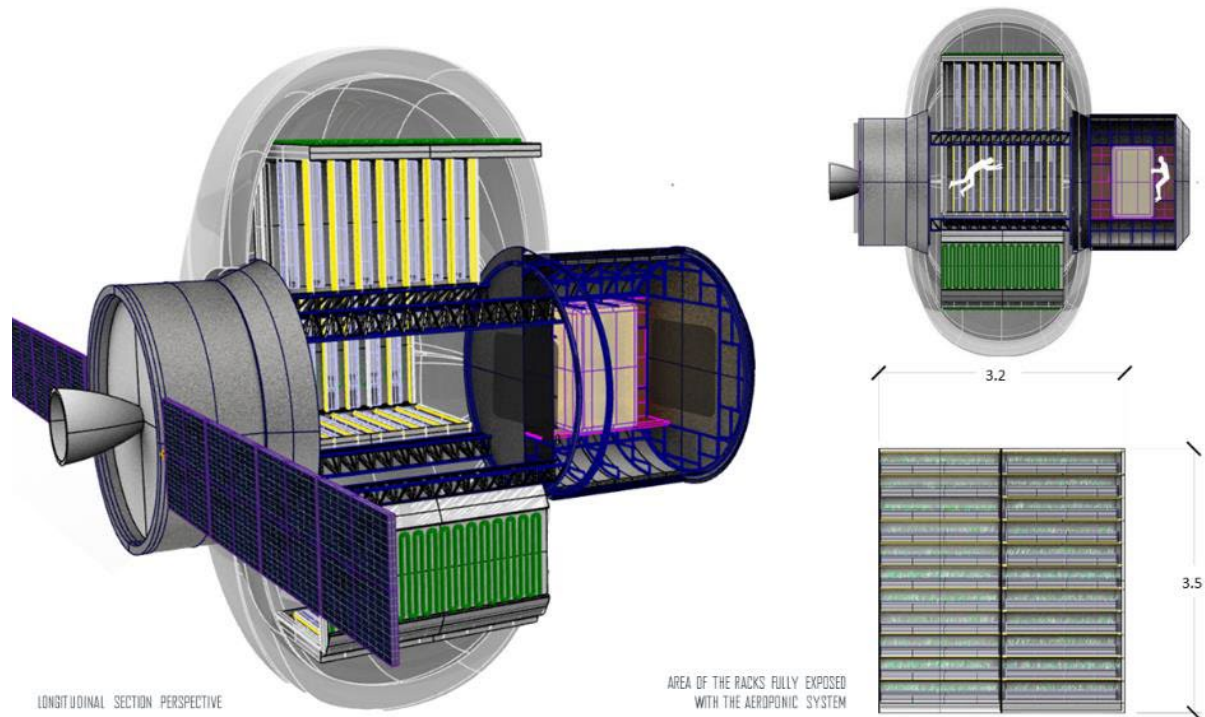
In this study the module is configured as greenhouse and BLSS lab, with racks designed to host two photo-bioreactors for microalgae on the external sides, and two higher plant aeroponic compartments in the internal sides. During launch phase in stowed position, racks are sealed and individually pressurized at low pressure, hence both plants and bioreactors are padded with plants' shelves normal to vertical axis (Figure 9).



**Figure 9. Foldable Racks Components.** (Image by authors)

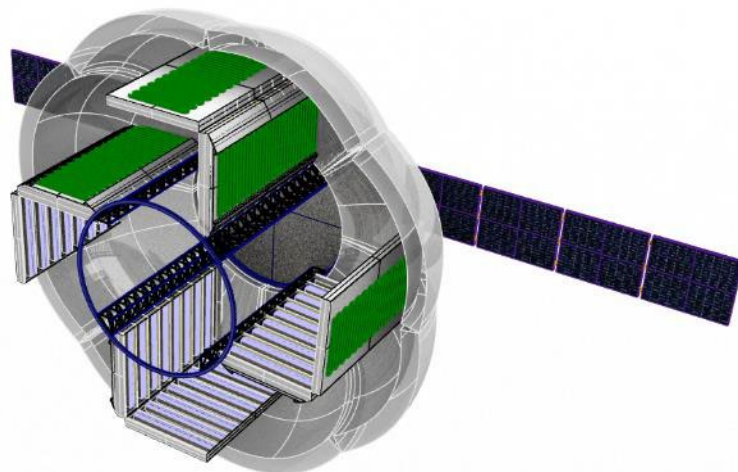
The outer side of the racks, facing the compacted mass of deflated shell during launch and hosting the flat photo-bioreactors, are protected by metallic shutters to prevent damage during the folding and compressing phase of the shell at ground, once the module is stowed in the fairing. Once in operation, with the inflatable shell fully deployed and pressurization restored at nominal level, the four racks are rotated outward on hinges and opened like a book, exposing all sides to the internal atmosphere to maximize the  $O_2$  and  $CO_2$  exchange of plants.

The final configuration, with racks fully open, would roughly divide the inflated space into four sectors; each one could be separately dedicated to different crops, microalgae treatment, lighting intensity, or specific lab functions as micro-environments. Textile dividers can be manually extended from the racks to the inflated shell, and rolled shutters installed on standoffs can separate the four separate micro-environments from the central aisle (Figures 10 and 11).



**Figure 10. Longitudinal Section with Foldable Racks open.** (Image by authors)

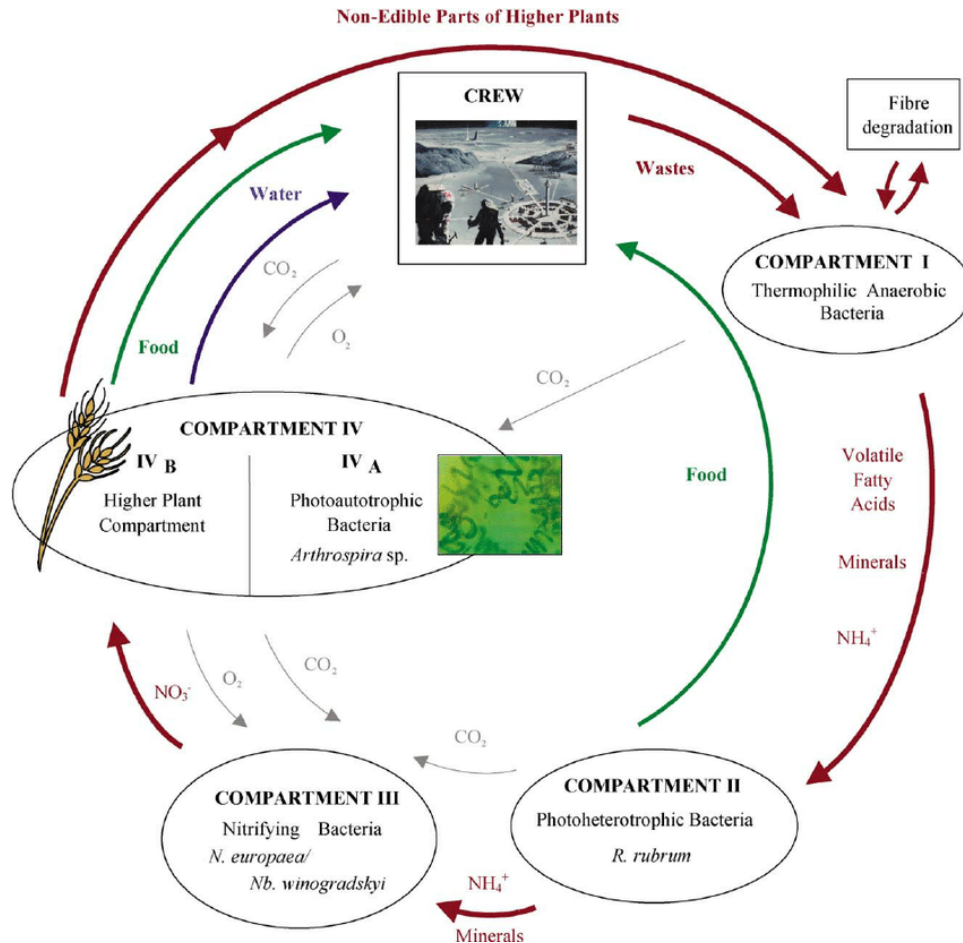
Each rack is equipped with adjustable LED lighting system for the backlit photo-bioreactors, and the necessary aeroponic hardware for water and nutrient feeding. These lines are connected to the main treatment systems, allocated in the rigid forward section, and running through the standoff girders. Dedicated water pressure and humidity level sensors monitor the four racks' micro-environments, allowing remote control from ground during uncrewed periods. The combination of bioreactors, water lines, and recovery tanks tied inside the racks would also offer the opportunity for crew shielding in case of a solar flare, creating a water-intensive protective barrier to ionizing radiation. In case of a SPE warning, the crew could temporarily shelter in the central aisle of the module with the four racks folded in closed position.



**Figure 11. Transversal Section with Foldable Racks open.** (Image by authors)

### C. BLSS Systems

The proposed BLSS of the module is connected to the ECLSS of the station and arranged into four treatment compartments using biological processes, similar to the loop scheme experimented in MELiSSA project (Figure 12).

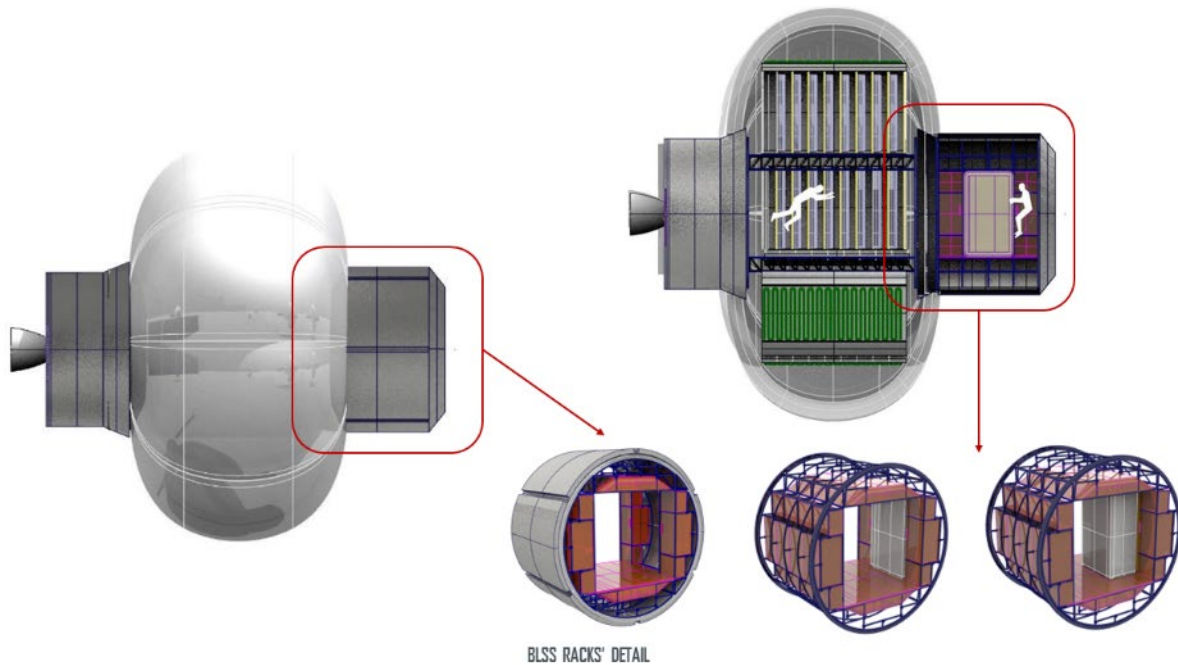


**Figure 12. MELiSSA loop scheme.** (Image by Hendrickx et al)<sup>18</sup>

- Compartment 1 - Plants and Human Waste Treatment (thermophilic anaerobic digestion)
- Compartment 2 - Low Molecular Carbon-compounds Treatment (volatile fatty acid, CO<sub>2</sub>, H<sub>2</sub>, and H<sub>2</sub>S)
- Compartment 3 - Nitrifying Treatment (NH<sub>4</sub> and minerals)
- Compartment 4<sub>A</sub> - Higher Plants
- Compartment 4<sub>B</sub> - Photoautotrophic Bacteria (*Arthrospira Platensis Spirulina*)

Compartments 1, 2, and 3 are distributed in the module's rigid section and integrated with a toilet to collect human waste and wastewater, as previously explained. This section also treats water recovered from air recirculation and sludge's oxidization from fiber degradation in Compartment 1. Other organic and solid waste, like non-edible parts of the higher plants, biodegradable packaging derived from soybeans etc. can be recycled in Compartment 1 and used as nutrient feeder for higher plants. Consequently, systems in these compartments must be fully accessible for periodic maintenance due to contact with biological byproducts and risk of clogs and kept constantly monitored to avoid any leakage of contaminants (Figure 13).





**Figure 13. Detail of BLSS Racks in Rigid Section.** (Image by authors)

Compartment 4<sub>A-B</sub> is represented by the inflatable section, with the four double-sided racks, hosting the higher plants in aeroponic shelves and flat photo-bioreactors for *Arthrospira Spirulina*. The exchange of O<sub>2</sub> and CO<sub>2</sub> mainly occurs in this section via photosynthesis. Therefore, this compartment needs a sufficient volume of air and a good ratio of exposed surface for plantations and illumination. Once fully deployed, each rack has an exposed surface of approximately 22 m<sup>2</sup>, hence the four racks would provide an overall internal surface of 88 m<sup>2</sup>, half for higher plants (e.g. wheat, rice, oats, soy, etc.) and half for *Arthrospira Platensis Spirulina* in photo-bioreactors. This cyanobacterium possesses a high nutritional value in protein (55 to 65%) and CO<sub>2</sub> reduction characteristics, since it is a photosynthetic bacterium, which makes it a good candidate as a food source, oxygen regenerator, and an efficient carbon-scrubber. Since a human diet requires a proper balance between proteins and carbohydrates, the *Arthrospira Spirulina* could represent an integrative protein source, as successfully tested in ground tests.

Lighting is an important aspect of a plant's natural lifecycle and the primary activator of photosynthesis and biological processes of carbon reduction in photo-bioreactors. Researches have demonstrated that the optimal photosynthetic efficiency is achieved with an irradiation intensity of 100-120 W/m<sup>2</sup> of photosynthetically active radiation (PAR), achieved in lab testing using six-kilowatt xenon lamps with a spectrum close to sunlight.<sup>19</sup> In order to maximize lighting efficiency, the internal layer of the inflatable shell could be covered by an aluminized reflective surface to diffuse the artificial light from the systems installed on standoffs, since the photo-bioreactors are backlit by LED panels embedded in the racks.

Additionally, the internal surface of the inflatable section could be covered with Forward Osmosis (FO) passive system like the Water Walls Life Support Architecture (Cohen, 2014), composed of translucent bags that can be adapted to the internal geometry of the shell. Furthermore, the adoption of Water Walls would add further protection to crew against SPEs since the hydrogenous qualities of the content act as an additional shield from highly ionizing atomic nuclei.<sup>20</sup>

## V. Conclusions

The scope of this study is the design of a minimal configuration module which would be useful for testing and experimentation while utilizing off-the-shelf technologies that are widely available but must be tested in extreme conditions. Most of the current knowledge about regenerative processes has been extensively verified in closed environments in ground testing facilities, but only partially in prolonged conditions of microgravity. Several sample tests have been conducted onboard Salyut, Mir, and ISS with encouraging results, but a complete closed-loop bio-regenerative process in space has yet to be assembled and thoroughly tested yet. Currently, the only research and testing platform in space is represented by the ISS, but its scheduled retirement would pose an unquantifiable delay in this type of research. Quoting the already mentioned NASA Office of Inspector General Report on November 2021:

“As of June 2021, 27 technology demonstrations for Mars missions require a microgravity test environment—8 of those demonstrations are individual components of the ECLSS, which will be integrated into a single system for testing on the ISS by 2026. ECLSS and three other technologies—plant production, food system supporting health and performance, and radiation shielding—will need to be tested in microgravity after 2030, when the ISS is expected to retire”.<sup>21</sup>

To date, the Gateway cislunar station appears to be the sole orbital facility scheduled to be operational before the ISS is decommissioned, providing enough time to gain knowledge and pursue further research about these systems to support deep space travel, including a full assessment of bio-regenerative closed-loop ecological systems for spacecrafts. For this purpose, this study proposes a dedicated module for the Gateway station as test bed for research and experimentation on bio-regenerative systems in permanent microgravity conditions, mitigation of long-term space radiation exposure, and changed electromagnetic fields, which are still not fully experienced in deep space for humans, plants, and microorganisms. It is supposed that the knowledge and experience accrued during the experimental and operational phases could be easily scaled up to be applied into larger facilities and different configurations, like habitats on planetary surfaces. Furthermore, it would represent a driver for the development of a closed-loop technology with the highest level of reliability, particularly in terms of potential bio-contamination in case of failures.

Since bio-regenerative systems are primarily composed by filters and reactors reducing plants and human waste into nutrients, minerals, and gases, the human fecal material which is part of the process may introduce micropollutants, such as heavy metals, hormones, or transformation products of pharmaceutical drugs. At the current state of research, insights into the behavior and effects of these compounds in bio-regenerative closed loop systems operating in space are still largely unknown and need to be tested in operational conditions.<sup>22</sup> Other incognita are represented by potential genomic modifications of crops induced by long exposure to microgravity or ionizing radiation, including potential side effects of spores and micropollutants on humans, plants, and systems exposed to microgravity environments.

Furthermore, the overall dimensioning of the system, its compactness to be installed onboard spacecrafts, and its full accessibility for routine maintenance and repair are all aspects that need to be verified, preliminarily at ground with full scale mock-ups during design stage, then operatively in real conditions.

Following and paraphrasing the research and experimentation goals set by CELSS and ALS programs,<sup>23</sup> and the targets set by NASA’s Human Research Program (HRP),<sup>24</sup> the BLSS research module in this study has the scope of pursuing this type of experimentation in space to:

- Validate regenerative life support technologies (e.g., air revitalization, liquid and solid waste recycling, active thermal control, shielding against ionizing radiation) through long term testing of integrated biological and physicochemical life support systems.
- Validate the use of crops and microalgae to perform life support functions under the restrictions of optimizing volume, mass, energy, and labor, with the goal of a complete or nearly complete closure of the regenerative process.
- Advance the technology readiness level of regenerative life support components, thermal system components, and protective barriers against radiation hazards from GCR and SPE.
- Advance the studies about hazards of radiation, isolation, and confinement, distance from Earth, lack of gravity, and closed habitat in an extreme hostile environment.
- Identify terrestrial applications of life support technologies as spin-ins and spin-offs from space.



## References

- <sup>1</sup> Häuplik-Meusburger S., Bannova, O., *Space Architecture Education for Engineers and Architects*. Springer, 2016, pp. 227-229
- <sup>2</sup> Häuplik-Meusburger S., *Architecture for Astronauts: An Activity-based Approach*. Wien: Springer, 2011.
- <sup>3</sup> Sforza P.M., *Manned Spacecraft Design Principles*, Oxford, Elsevier, 2016, pp. 453-460
- <sup>4</sup> Seedhouse E., *Mars via the Moon: The Next Giant Leap*, London, Springer-Praxis, 2016, pp. 86-92
- <sup>5</sup> Anker P., *From Bauhaus to Ecohouse: A History of Ecological Design*. Baton Rouge: Louisiana State University Press, 2010.
- <sup>6</sup> Gitelson I.I., Lisowsky G.M., MacElroy M.D., *Manmade Closed Ecological Ecosystems*, London: Taylor & Francis, 2003, pp. 33-62
- <sup>7</sup> <https://news.northropgrumman.com/news/releases/northrop-grumman-completes-preliminary-design-review-for-nasas-gateway-crew-module>
- <sup>8</sup> Esfandabadi M.M., Bannova O., "Designing A Martian Greenhouse as A Habitable Space: Feasibility Studies and Design Approach." In *70<sup>th</sup> Int. Astr. Congr., IAC-19-B3.8-GTS.2.3*. Washington, DC: 2019.
- <sup>9</sup> David L., *Moon Rush: The New Space Race*, Washington DC: National Geographic, 2019, pp. 139-148
- <sup>10</sup> NASA Office of the Inspector General, Office of Audits, Report No. IG-22-005, "*NASA's Management of the International Space Station and Efforts to Commercialize Low Earth Orbit*", November 30, 2021, p. 18
- <sup>11</sup> Stuster J., *Bold Endeavors: Lessons from Polar and Space Exploration*. Annapolis, MD: Naval Institute Press, 1996.
- <sup>12</sup> Banik J.A., Jenkins C.H., *Testing Large Ultra-Lightweight Spacecraft*, Reston, VA: AIAA, 2009, pp. 211-216
- <sup>13</sup> <https://www.nasa.gov/press-release/nasa-awards-northrop-grumman-artemis-contract-for-gateway-crew-cabin>
- <sup>14</sup> <https://www.nasaspaceflight.com/2020/08/northrop-halo-plans-gateway/>
- <sup>15</sup> Kennedy, K.J., "TransHab Project." In Howe, A.S., Sherwood, B. (eds.). *Out of this World: The New Field of Space Architecture*, Reston, VA: AIAA, 2009, pp. 81-88
- <sup>16</sup> Seedhouse E., *Bigelow Aerospace: Colonizing Space One Module at a Time*, London, Springer-Praxis, 2015.
- <sup>17</sup> Howe, A.S., Sherwood, B. (eds.). *Out of this World: The New Field of Space Architecture*, Reston, VA: AIAA, 2009, pp. 31-43
- <sup>18</sup> Hendrickx L. et al. *Microbial ecology of the closed artificial ecosystem MELiSSA (Micro-Ecological Life Support System Alternative): Reinventing and compartmentalizing the Earth's food and oxygen regeneration system for long-haul space exploration missions*. Research in microbiology. 157. 2006, pp. 77-86. 10.1016/j.resmic.2005.06.014.
- <sup>19</sup> Gitelson I.I., Lisowsky G.M., MacElroy M.D., *Manmade Closed Ecological Ecosystems*, London: Taylor & Francis, 2003, p. 238
- <sup>20</sup> Häuplik-Meusburger, S., Bannova, O., *Space Architecture Education for Engineers and Architects*. Springer, 2016, pp. 214-216
- <sup>21</sup> NASA Office of the Inspector General, Office of Audits, Report No. IG-22-005, "*NASA's Management of the International Space Station and Efforts to Commercialize Low Earth Orbit*", November 30, 2021, p. 20
- <sup>22</sup> Hendrickx L. et al. *Microbial ecology of the closed artificial ecosystem MELiSSA (Micro-Ecological Life Support System Alternative): Reinventing and compartmentalizing the Earth's food and oxygen regeneration system for long-haul space exploration missions*. Research in microbiology. 157. 2006, p. 83
- <sup>23</sup> Gitelson I.I., Lisowsky G.M., MacElroy M.D., *Manmade Closed Ecological Ecosystems*, London: Taylor & Francis, 2003, p. 43
- <sup>24</sup> NASA Office of the Inspector General, Office of Audits, Report No. IG-22-005, "*NASA's Management of the International Space Station and Efforts to Commercialize Low Earth Orbit*", November 30, 2021, p. 17