Habitat of the Future: Design, Materials and Construction of Deployable Space Habitats

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The imperative to develop inflatable habitats as a viable alternative to rigid/non-deployable structures is underscored by their demonstrated efficiency in terms of mass and volume, yielding substantial cost savings. NASA's seminal research on inflatable habitats dates to 1961, exemplified by the space station design initiative undertaken by Goodyear. Although this particular design did not materialize in space, persistent innovation has characterized the trajectory of this industry. Moreover, private sector entities, including Bigelow Aerospace, Sierra Space, Lockheed Martin, and numerous others, have entered the fray, driving significant advancements in inflatable habitat technology. The engagement of these companies signals robust plans for the utilization of inflatable habitats across a spectrum of applications, encompassing commercial, private, and governmental space stations. Within this landscape, our studio has made notable contributions with a concept poised to emerge as a leading innovation in inflatable habitat technology. Our concept exhibits potential for docking with the ISS or serving as an extension to India's ambitious space station plans within the private sector. The paper is delineated into two principal sections: the first section meticulously delineates the development process from the launch payload fairing to the deployment mechanism, leveraging empirical data and technical specifications. The second section offers a comprehensive examination of ancillary services and interior habitat functions, elucidating practical implementations and anticipated outcomes.

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Nomenclature

ACS	=	Atmosphere Control and Supply
ACBM	=	Active Common Berthing Mechanism
ATM	=	Standards Atmospheric Pressure
BEAM	=	Bigelow Expandable Activity Module
CE	=	Cryogenic Engine
CM	=	Crew Module
c*FS*	=	Core Flight System
DIDS	=	Distributed Impact Detection System
DDS	=	Deployment Dynamics Sensor
ECLSS	=	Environment Control and Life Support System
ft	=	feet
HM	=	Habitat Module
HVI	=	High Velocity Impacts
IAE	=	Inflatable Antenna Experiment
ISRO	=	Indian Space Research Organization
ISS	=	International Space Station
LASH	=	Low-cost Affordable Space Habitat
LIFE	=	Large Integrated Flexible Module
LVM III	=	Launch Vehicle Mark III
LEO	=	Lower Earth Orbit
ms	=	Millisecond
MM/OD	=	Micro Meteoroid/Orbital Debris
NASA	=	National Aeronautics and Space Administration
RAM	=	Radiation Area Monitor
REM	=	Radiation Area Monitor
RTD	=	Resistive Temperature Device
SM	=	Service Module
SMI	=	Stretchable Module Interconnect
UTCP	=	Ultra-Thin Chip Package
UWMS	=	Universal Waste Management System
WTS	=	Wireless Temperature Sensor
WSN	=	Wireless Sensor Networks
WCS	=	Waste Collection System

I. Introduction

Deployable habitats for space represent a pioneering frontier in human space exploration, serving as pivotal components in facilitating sustainable and extended missions beyond Earth's confines. These innovative structures, designed with compactness for launch and expansion capabilities in orbit, redefine the possibilities for creating habitable environments in the harsh realms of space, minimizing so many factors. Utilizing advanced materials, intricate deployment mechanisms, and sophisticated life support systems, deployable habitats offer a promising solution to accommodate astronauts, support scientific endeavors, and lay the foundation for long-term human presence on celestial bodies such as the Moon, Mars, and beyond. This paper aims to delve into the design principles, technical intricacies, and the transformative significance of deployable space habitats within the context of India's future space infrastructure and exploration endeavors.

II. Survey of Inflatable Concepts

A deployable habitat, designed for portability and rapid assembly, serves as a versatile solution for various environments. Its modular and collapsible features make it suitable for emergency response, military operations, and exploration, offering temporary living and working spaces with a focus on both portability and efficiency. The core focus of this survey is to understand a historical evolution of Deployable/Inflatable structures in the world. The Survey parameters focus on *form, function, layout/infrastructure, materials & smart systems.*

Note: The data presented under the survey section is limited to the brief of the complete study made.

A. Study of Existing Inflatable Systems

1. TransHab by NASA

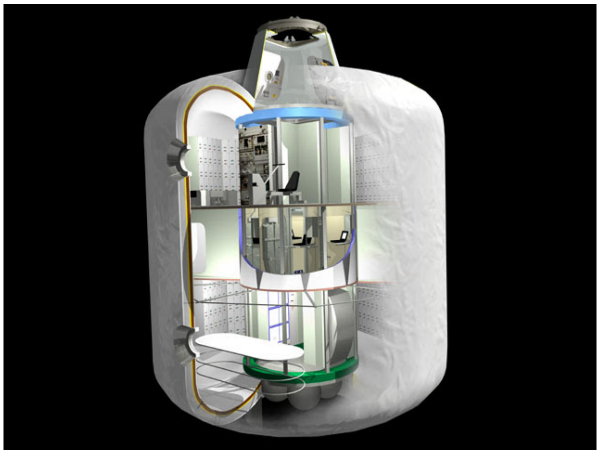

Figure 1. TransHab Internal Cross Section View. *Image Credit: NASA*

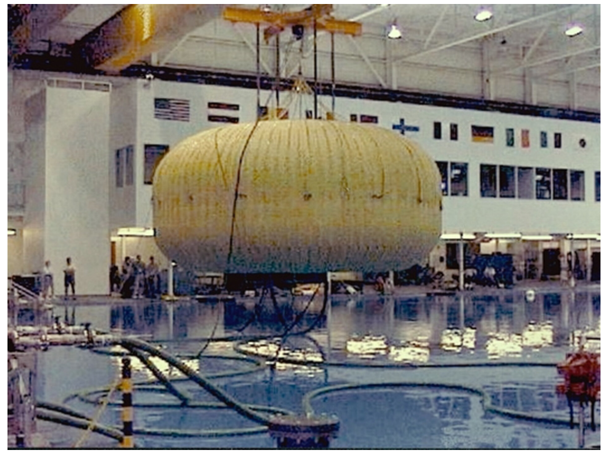

Figure 2. TransHab 23ft diameter Development Unit used for Hydrostatic Pressurization Test. *Image Credit: NASA*

NASA's TransHab – the starting point of deployable space systems, introduces a revolutionary approach to space exploration through its design, optimizing interior space by addressing launch volume constraints. The use of advanced materials like Vectran proves crucial in withstanding the rigors of space, making TransHab a conceptual model for potential Mars missions. The lessons learned from TransHab underscore NASA's commitment to continuous innovation, emphasizing interdisciplinary collaboration, risk mitigation, and rigorous testing.

2. BEAM by Bigelow Aerospace

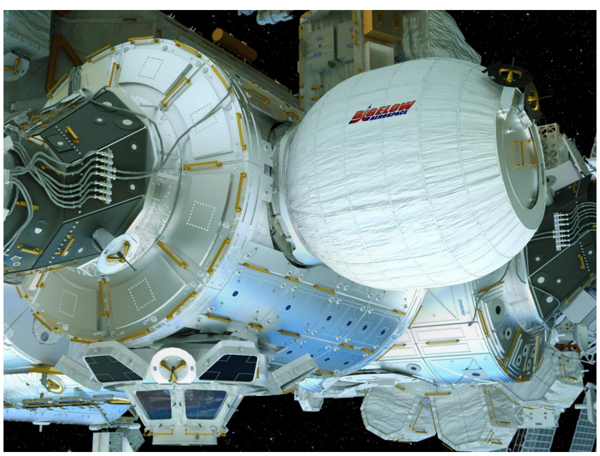

Figure 3. An Artists Impression on *BEAM* deployed in *ISS*. *Image Credit: NASA/Bigelow*

Figure 4. Undeployed BEAM Habitat at the Test Facility. *Image Credit: NASA/Bigelow*

The Bigelow Expandable Activity Module (*BEAM*) represents a significant advancement in inflatable habitat technology, demonstrating practicality on the *ISS*. With layers of soft goods and a Vectran outer shell, *BEAM* ensures compact storage during launch and resilience in space's harsh environment. Scientific insights from *BEAM*'s thermal performance, pressure maintenance, and structural integrity contribute valuable data, highlighting the adaptability and durability of inflatable habitats. The collaboration with Bigelow Aerospace showcases the potential for public-private partnerships in advancing space exploration technologies.

B. Upcoming Inflatable Systems

3. LIFE by Sierra Space

Figure 5. Fully Deployed View of LIFE Habitat. *Image Credit: Sierra Nevada Corporation*

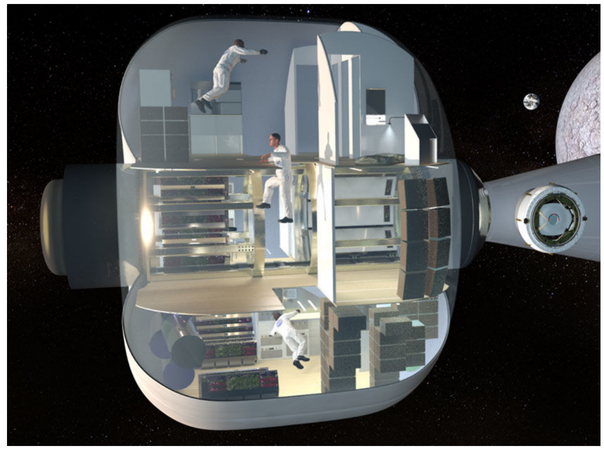

Figure 6. Visual Representation of LIFE Habitat Interior. *Image Credit: Sierra Nevada Corporation*

Sierra Space's LIFE habitat, particularly LIFE 1.0, stands as a groundbreaking development with its three-story inflatable structure. Launched conventionally and expanded in orbit, it accommodates astronauts and supports various space businesses. The Vectran fabric weave - inflatable pressure shell, surpassing NASA's stress tests, ensures safety and comfort for extended human habitation. The adaptability demonstrated by LIFE, along with plans for enhanced capabilities in LIFE 2.0 and LIFE 3.0, contributes significantly to the future of commercial space exploration. With the completion of design phase LIFE habitat has progressed towards facility development of the habitat in the prototyping phase and conducting the *UBP* test has proven that their LIFE habitat has surpassed the standards fixed by NASA for Deployable systems. The Orbital reef by Sierra is among the few upcoming Space Stations that NASA is looking up for.

4. Development of Inflatable Habitat by Lockheed Martin and its testing

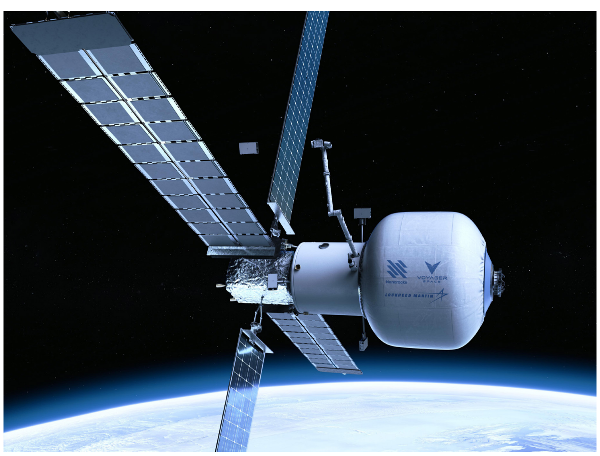

Figure 7. Artists Impression of Lockheed Martin's Deployable Habitat in Space.[24] *Image Credit: Lockheed Martin*

Figure 8. Lockheed Martin's Deployable habitat undergoing Burst Test (the test achieved validation by getting up to 253 psi – 6 times the maximum operating pressure).[21] *Image Credit: Lockheed Martin*

Although not officially named, Lockheed Martin's Inflatable habitat, utilizing Vectran, redefine the landscape of space missions. With their In-house Manufacturing facility and Burst test facility, Lockheed Martin is focusing more on analyzing & studying the Structural Integrity of their Inflatable Habitat, as a part of which the Burst test proved the performance of their habitat in correspondence to Internal pressure. It is documented that the habitat withstood six times the maximum operating pressure necessary at 253 psi before bursting.[21] This test allowed them to understand the creep nature of their fabrics made of Composites with base fabric made of Vectran. This highlights the importance of stress analysis and breakage point of the Inflatable fabrics, failure of which otherwise could prove a fatal incident in the history of space.[21]

C. Inferences

The study of existing and proposed Inflatable/Deployable Space Systems has proved the development of the space industry towards sustainable, human centric and space friendly habitable systems. The size and scope of the subject research was limited due to the access to graphic materials.

Beginning with the *geometrical parameter,* all the space systems from the survey display the essential need for smooth and curvy-linear forms, the derivatives of curves (example: toroid/torus, Cylindrical, Spherical) with uniform & symmetrical topographical variations of the skin. This aspect is focused on all the above systems since these provide high performance towards pressure distribution and deployment ensuring safety while reducing significand amount of weight.

Speaking about the *functionality* and intent of the design, all the surveyed habitats had the intent of minimized payload fairing volume and increased habitable volume in space. The major aspects focused here are the – type of core /deployment system, enclosure layering to dissipate various issues faced in space including radiation, temperature, humidity, *HVI* mitigation, Internal Pressure Distribution, Gas diffusion etc., This allowed us to understand which areas of design is critical for the development of *LASH*. All these existing sources are limited to deployable systems development, which gives us very minimal support data of interior systems integration, demanding customization of all the systems & subsystems necessary for the habitat.[16] Which will not be a focus of this paper.

Every Space Habitation System proposed so far has focused on all the basic amenities necessary for a complete mission crew necessity, but only limited to mission crews, allowing for limited range of supporting crowd. The key areas focused are the Control center/workstation, Hygiene Module, Galley & Crew Quarters. This provides a basic requirement necessary to develop *LASH*.

The *materials* as studied under each deployable system constantly replicated the standard forms of Kevlar, Vectran & Mylar modified under parameters like weave pattern for pressure distribution and adding composite layers of different materials for dissipating various factors as stated in the functionality, arriving at an understanding that there limited materials that can meet the performance requirements of a deployable habitat. This identifies the layering of the fabric as an exploratory zone for *LASH*.[16]

Focusing on the *smart systems* integration, BEAM has displayed a wide variety of smart systems that enhance the performance, maintenance and serviceability of the deployable fabrics which include systems like wireless sensor grids integrated as thin layer in the deployable fabric, giving constant feedbacks on the health and performance status of the habitat.

The Low-Cost Affordable Space Habitat (*LASH*) concept developed & presented by AAKA Space Studio in this paper is envisioned to be a pioneering innovation in space habitat development and is focused on being a cost-effective yet robust solution for sustainable human habitation beyond Earth. With Multiple Inflatable concepts developed & proven to be efficient for future space missions, LASH delves into the focus of studying prototypes using advanced geometries and comparing their performance to the existing Inflatable models in structural, technological & architectural aspects utilizing materials like Vectran™, embedded fabric health monitoring technologies, followed by developing Modular Interiors using human-centric design principles & studying their impacts. Standing at TRL1, with the basic principles being studied, AAKA Space Studio aims to develop *LASH* as a demonstration prototype (at TRL7) to be docked and studied with the ISS.

III. Concept Design - Architecture

This research paper exhibits the conceptual development of *LASH* & aims to comprehensively explore the architectural intricacies of space, technical underpinnings, human centric development, and transformative potential of the *LASH* concept within the broader landscape of space habitat design and future space infrastructure.

D. Introduction to HÜGELSCHÄFFER EGG CURVE

Proceeding with the inference under the Survey of deployable habitats made in this paper, Identifying Models forms/concept that align well with the factors for space deployment and aligning with the architectural characteristics was also essential, leading to the development of the form from the famous Hügelschäffer Ovoid form.[13,14]

The egg-shaped curve construction devised by German mathematician Fritz Hügelschäffer in 1948 is essentially a reinterpretation of the conventional method for constructing ellipses using concentric circles (as depicted in Fig 10).[13] To apply this method, two circles with diameters matching the major and minor axes of the ellipse are drawn concentrically, labelled GH and MN respectively. An arbitrary radial line is then established, intersecting both circles. Points of intersection on the smaller circle (referred to as P2) are used to draw lines parallel to the major axis, while points on the larger circle (labelled P1) are utilized for drawing lines parallel to the minor axis of the ellipse.[13] The points of intersection between these two systems of parallel lines yield the points (E) defining the ellipse.[13]

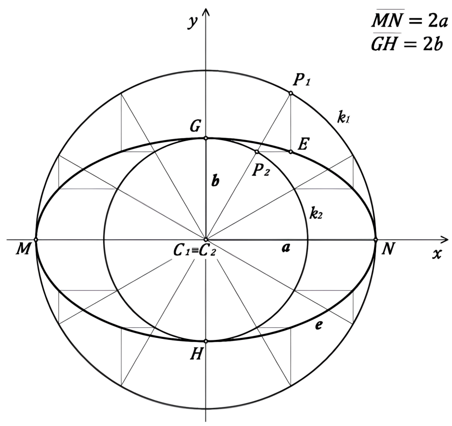

Figure 9. Ellipse Construction Principle.[13]

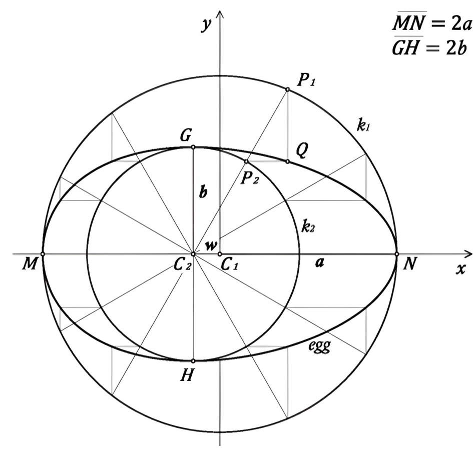

Figure 10. Hügelschäffer shifted the minor circle from the concentric position with the major one, along the x axis for the parameter w, so that intersection points of the corresponding parallels form the egg-shaped curve.[13]

E. Architectural & Technical Significance of the Geometry to LASH

It has been demonstrated that certain egg-shaped curves, such as those developed by Hügelschäffer, hold potential utility in engineering design, particularly within architecture. Few characteristics of the Ovoid geometry that prove beneficial to the LASH development are: Optimized Volume-to-Surface Ratio, Optimized Internal Volume/Efficient Use of materials, Enhanced Structural Integrity, Enhanced Radiation and Thermal Distribution factors, Aerodynamic stability.[13] Although the engineering capabilities of the ovoid is clearly established, but with minimal architectural points to be considered, this paper presents the comparative study of the Architectural Characteristics involving Material Consumption to Internal Volume Utilization, spatial distribution & Modular capabilities of the Ovoid geometry to the studied models.

5. Optimized Volume-to-Surface Ratio:

The ovoid shape has advantages in terms of structural stability because of its continuous curvature. To provide inherent strength against collisions and structural failure, the fabric can be tensioned across the ovoid surface, dispersing stress uniformly.

6. Optimized Internal Volume/Efficient Use of Materials:

The ovoid shape makes better use of available space. The ovoid geometry's tapering ends enable maximum use of the available volume while eliminating underutilized or unused areas which are referred to as the negative spaces within the geometry. By adjusting to the ovoid geometry's curvature, the fabric may minimize internal Volume to material ratio and save wasted space. "*Dwellings based on a circular ground plan, the dome, cone, and cylinder, are more stable and resistant to physical and mechanical forces. These dwellings enclose the maximum available volume* *with the smallest structure, using the minimum number of materials which reduces the amount of surface exposed"*[22] as quoted by Arwen L Feather indicates the possibilities of Spatial Optimization.[21]

*7. **Enhanced Structural Integrity:***

Because the egg form equally distributes tension throughout its surface, it is naturally resistant to external forces like debris or micrometeoroids strikes. Because of its structural integrity, less reinforcement material is required.

*8. **Thermal & Radiation Shielding:***

Radiation is more likely to scatter or be absorbed on a curved surface than on a flat one, such as the surface of an ovoid shape. This is due to the surface's curvature, which raises the possibility of multiple interactions between radiation particles and the habitat's substance. As a result, less radiation enters the living area since more of the incoming radiation is either absorbed by the material or diverted away from the habitat. The crew can live in a more stable and comfortable environment since there are fewer hot or cold patches inside the habitat due to the regular distribution of thermal energy over the curved surface.

F. Formula Derivation

To develop a 3D ovoid geometry using Hügelschäffer's ovoid curve, we can start with the parametric equations for the ovoid curve in 2D and then extend them into 3D space. The parametric equations for Hügelschäffer's ovoid curve are as follows[13]:

$x(t)=a\cdot\cos(t)$

$y(t)=b\cdot\sin(t)$

$z(t)=c\cdot\cos(t)\cdot\sin(t)$

where,

a is the semi-major axis,

b is the semi-minor axis,

c is the scaling factor for the height, and

t is the parameter ranging from 0 to 2π.

These equations describe the ovoid curve in 3D, where x and y represent the horizontal plane and z represents the vertical plane. Adjusting the parameters, a, b, and c allows for the generation of ovoid geometries of varied sizes and proportions.[13]

G. Mathematical Comparison of Existing Systems

The utilization of egg-shaped curves in Habitat design offers multifaceted benefits across various engineering aspects. Aerodynamically, these curves contribute to reducing drag and enhancing habitat efficiency. Few examples of the geometry's performance are displayed as shown in the figures.

9. Example one

Mathematical model for suitability analysis shown in the below section is now applied to several different facilities which have listed some of their major features as: high energy efficiency, high aerodynamic qualities, and minimal consumption of materials.[13]

$$R = \begin{bmatrix} X \\ Y \end{bmatrix} = \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} + \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} \pm \dfrac{x_2}{\sqrt{\dfrac{b^2.\,(a^2-x_2^2)}{a^2+2\,.w\,.x_2+w^2}}} \end{bmatrix}$$

Equation 1. Equation for Determining the compatibility of the existing ovoid forms with mathematical derivative.

Analyzing this expression, it can be concluded that the cubic egg-shaped simply referred to as a 3rd degree ellipse or hyperbola curve in the coordinate system is defined by the following parameters: a, b, w, p1 and p2. These parameters will be obtained as the result of maximization of the coefficient of determination. expression for Coefficient of determination is:

$$R^2 = \frac{SS_{reg}}{SS_{reg} + SS_{err}}$$

Equation 2. Expression for Coefficient of Determination

Figure 11. National Center for the Performing Arts, Beijing (The Egg), by Architect Paul Andreu (2007). *Photo Credit: National Centre for Performing Arts*

French architect Paul Andreu was responsible for the design of *"The National Centre for the Performing Arts"* in Beijing, which comprises three halls: The Opera Hall, Concert Hall, and Theatre Hall. Opened in 2007, this iconic structure is commonly referred to as *"The Egg"* due to its distinctive shape. Through the application of a mathematical model outlined in the preceding section, it was determined that "The Egg" can be effectively approximated by a cubic Hügelschäffer's egg-shaped curve. Values of unknown parameters of cubic egg-shaped curve and coefficient of determination shall have the following values: *a = 95.5m, b=46.3m, w=10m, θ = 0°, R2 = 0.99. The* contours of objects can be approximated by a cubic egg-shaped curve obtained because of the construction of Fritz Hügelschäffer quantified by the coefficient of determination.[13]

10. Example two

Figure 12. Gherkin Tower, London by Norman Foster.[25] *Photo Credit: The Gherkin London*

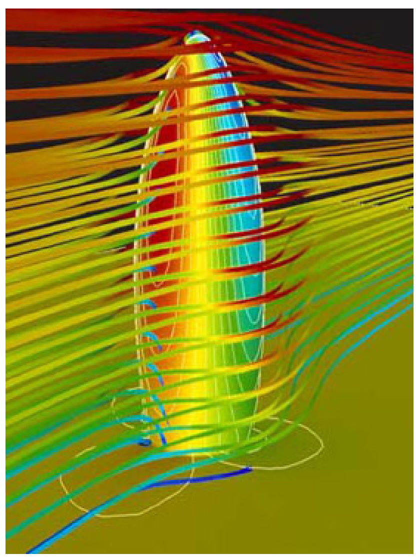

Figure 13. Air Flow Model around Gherkin Tower Geometry. [25] *Image Credit: Foster + Partners*

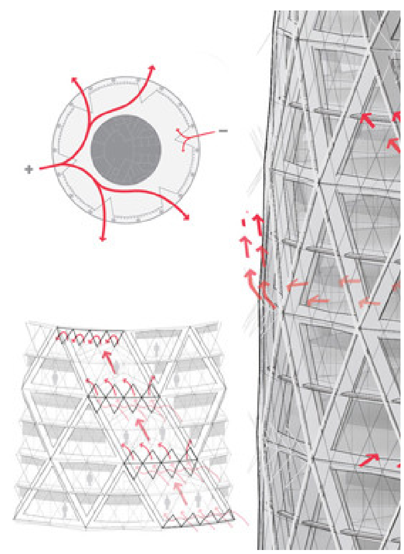

Figure 14. Architectural Illustration of air flow though & around the building.[26] Image *Credit: Jonathan Massey & Andrew Weigand*

Designed by English architect Norman Foster, "The Gherkin" building stands at a height of 180 meters. Its base is circular, and through aerodynamic modeling, it has been determined that optimal natural ventilation occurs when each floor is rotated slightly from those below it. Among the 40 stories, the 16th floor boasts the largest base with a circular cross-section. The distinctive shape of "The Gherkin" has been developed based on simulations of its aerodynamic properties. The analysis conducted in this study confirms that “The Gherkin” can be approximated by cubic Hügelschäffer’s curve, with coefficient of determination 0,992 which is very close to 1 (the coefficient of absolute match)[13]:

a = 102.9m, b=29m, w=14.8m, $\theta = 90°$, *R2 = 0.992*

The examples & research on this subject is limited to minimal study materials as not all the data on such advanced geometries get published.

IV. Architectural Design Development

H. Payload Functionality and Selection

The Habitat Docking & Deployment Systems module is designed with the consideration of payload capabilities of rocket systems, currently considering the *LVM III* Launch Vehicle of *ISRO*, as our key focus is to transport our Habitat Module to space without compromising the payload capabilities, as it is essential when we design a robust, lightweight & Deployable system. Also considering the capabilities of the *LVM III* launch vehicle with its cryogenic engine system & human space flight rating, it would prove the interfacing & launch capabilities of the rocket along with *LASH.*

I. Payload Fairing Compatibility

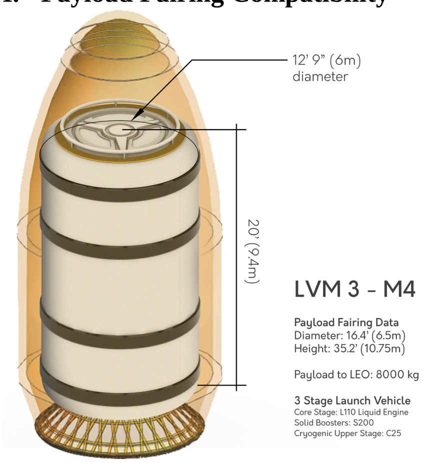

Figure 15. Payload Fairing Compatibility of LASH with LVM III.

Launch vehicle compatibility is a critical aspect of mission success. It revolves around ensuring the seamless integration of a payload with a designated rocket. This involves meticulous assessments to align the payload's size, weight, and structural requirements with the capabilities and design specifications of the chosen launch vehicle. Factors like payload fairing dimensions, adapters, and interface connections are carefully considered in the compatibility evaluation. Achieving compatibility is paramount for a safe and efficient launch, ensuring the payload's resilience during liftoff and its effective operation in the challenging space environment.

J. LVM 3 and the CE-20 Cryogenic Engine

The *CE*-20, cryogenic engine developed by *ISRO*, is integral to the *GSLV Mk III & IV*, now referred to as the *LVM-3* launch vehicle. Representing an advancement over the *CE*-7.5 cryogenic engine, the *CE*-20 is a key component in *ISRO*'s successful realization of human spaceflight, particularly the Gaganyaan mission.[3,4] Its enhanced capabilities contribute to the efficiency and reliability of space missions.

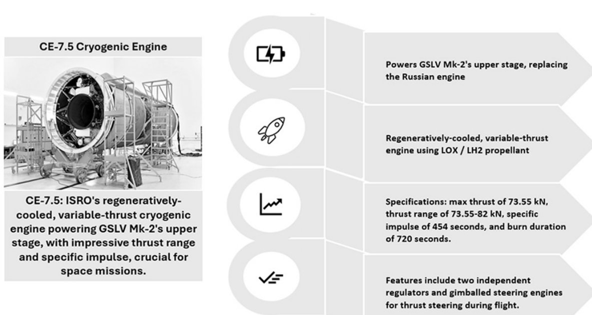

Figure 16. Technical Specification of CE-7.5 Engine.[4]

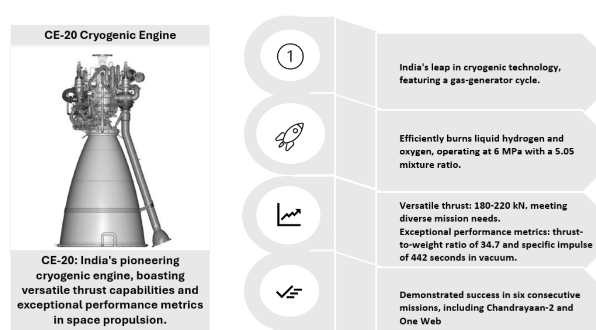

Figure 17. Technical Specification of CE-20 Engine.[3]

K. LVM 3 in our Mission & Deployment Stages

The LVM 3, chosen as the launch vehicle for our mission as it boasts a substantial payload capacity of 8 tons to LEO, the region where the ISS is located. This capability positions the LVM 3 as an ideal choice for carrying the habitat module, which has a volume of 80.4 cubic meter.[23] The selection of the LVM 3 underscores its capacity to support crucial aspects of space exploration and human spaceflight missions. The deployment of LASH has a volume change from Just 5.7 m^3 (Figure 19) to a 448% increase in volume of 31.4 m^3 (Figure 21).

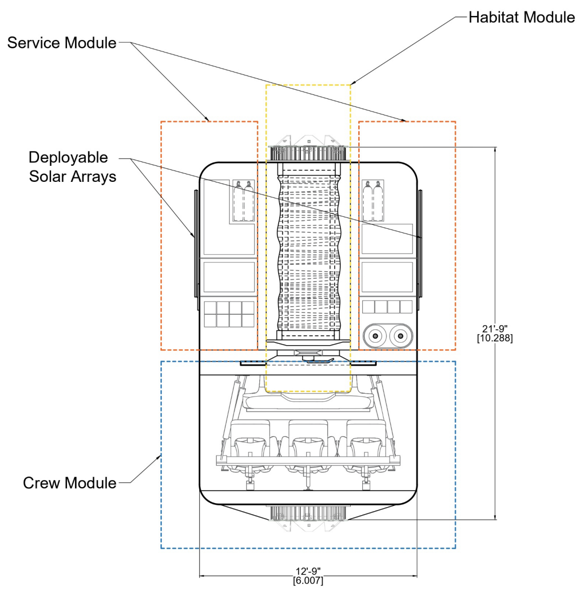

Figure 18. The Inflatable Habitat Capsule – 3 Zones.

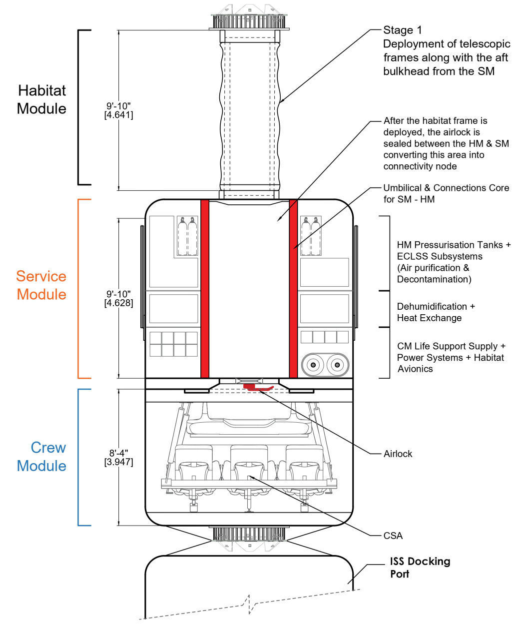

Figure 19. Stage I_Deployment of HM after docking with ISS.

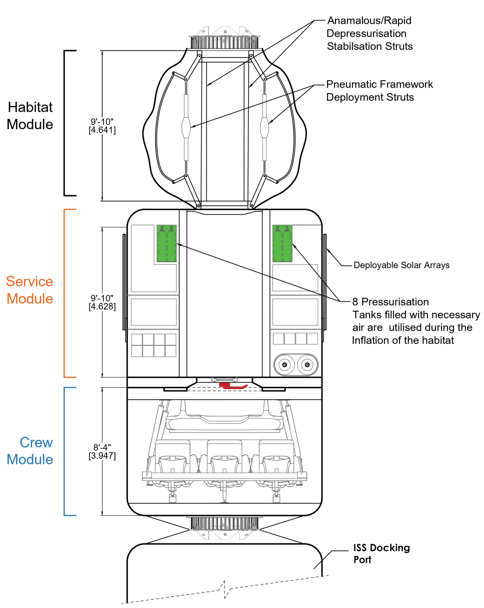

Figure 20. Stage II_Pressurization of Inflatable Habitat & Frame Deployment.

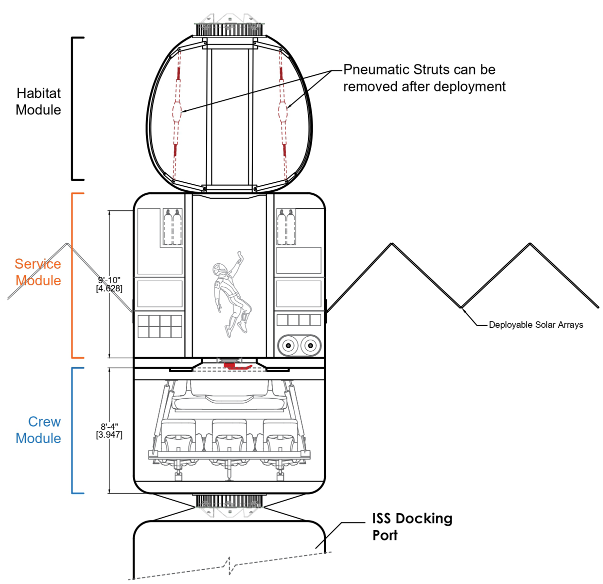

Figure 21. Stage III_Pressurization Complete & Stabilization of Internal using Flexure Frames.

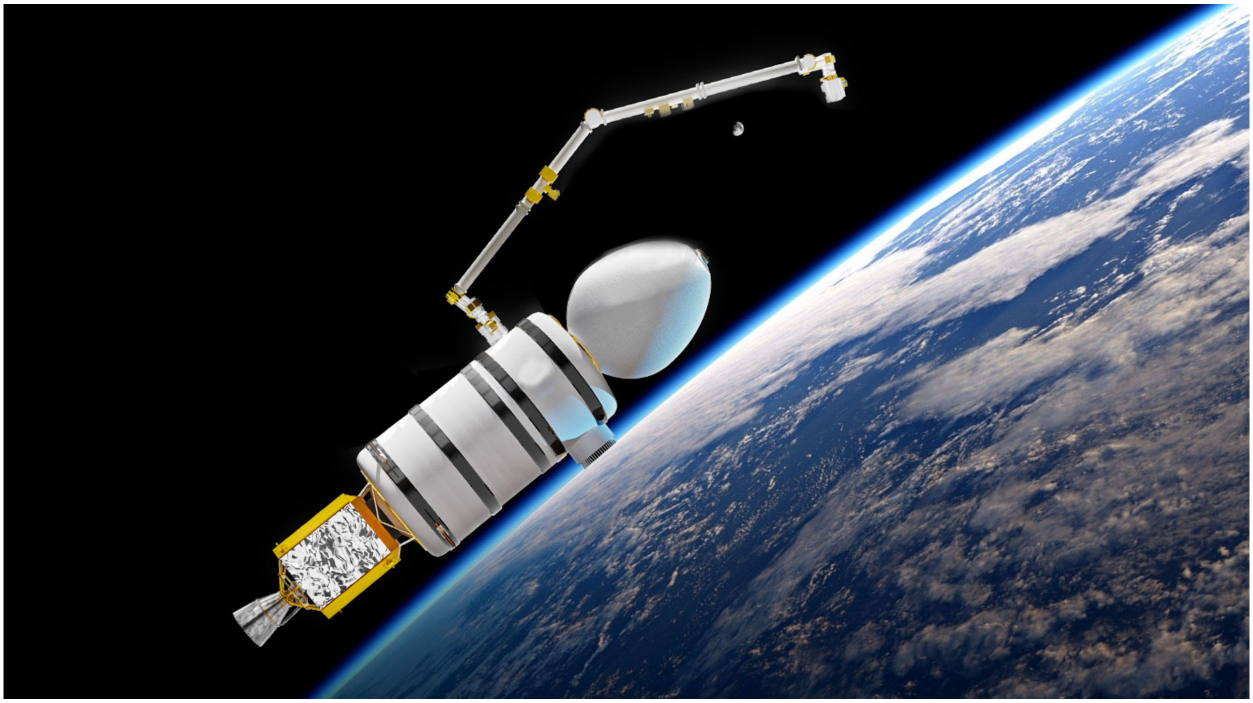

Figure 22. Conceptual Visualization of LASH Habitat with CM, SM, and HM along with the propulsion.

V. Habitat Ancillary Systems

This section briefs on what possible technical innovations or advancements inspired from the survey of deployable habitats can be utilised or replicated to make the habitat as per the conceptualisation & limiting to proposal of such technical systems usage in *LASH*. Since LASH will be designed for accommodating two crew members, & considering the volume of the habitat, LASH has explored the possible solutions for Inflation Techniques as analysed from the survey.

The deployment procedure begins with the initiation of Inflation tanks, & fabric monitoring system. Upon Partial Inflation, the flexural Longerons will be deployed using the pneumatic struts. The Longerons will lock in position using the flexural locking. This Separate Deployment gives variable control of the Fabric and the Framework, as it will be useful during servicing.

Pressure variations or drops during the deployment will be monitored using a range of *DDS* networks with data recording in short intervals which can be stored in the on-board computers of ISS & downlinked to the Earth Monitoring Station. Since *LASH* is to be deployed in the LEO, & designed for various operational platforms, and understanding from the survey it is essential for the Inflatable Systems to Qualify a Burst/Creep test rating.

L. Power Systems

The LASH habitat is developed with the intent of being a self-sustaining module with its own power supply system. The active components of the *LASH* including embedded avionics and health monitoring systems will be powered by the ISS, leveraging its robust power infrastructure. This arrangement ensures reliable operation and seamless integration with existing space infrastructure. However, to optimize efficiency and ensure autonomy, passive subsystems within the habitat will be powered by custom-made Replaceable Modular Battery Packs housed inside the SM of the *LASH*. These battery packs, specifically designed for the unique requirements of the habitat, will provide essential power for non-active systems such as *DIDS, DDS, WTS, REM & RAM*.[17] By utilizing a modular design, the *LASH* can easily replace or upgrade battery packs during utilizing the consecutive missions from earth, ensuring continuous power supply and operational flexibility throughout its mission duration. This hybrid power approach combines the reliability of external power sources with the adaptability and autonomy afforded by on-board battery systems, making the *LASH* a self-sustaining and versatile habitat for long-duration space missions.

M. *ECLSS* Subsystems

ECLSS plays a vital role in maintaining the internal atmosphere characteristics under desired levels. LASH will use the Existing ECLSS systems of ISS as the primary supply and monitoring system using the umbilical connection between ISS & SM, while keeping an emergency ECLSS system in the SM, which can take over the supply for LASH during Emergency Scenarios and allowing for the safety of the crew acting as a buffer.[15]

N. Avionics & Monitoring

Progressing towards a self-sustainable system, the habitat is integrated with *UTCP* which are advantageous.[1] The Avionics of *LASH* is broken down to three core categories:

11. Habitat Health Monitoring Systems (WSN & SMI Technology)

Since the Habitat is a deployable fabric, it is necessary to monitor the health & Integrity of the habitat with a network or wireless data sharing systems which Include the Following Sensor Grid Systems distributed around the Habitat, and are also equipped with Stretchable Electronics using the SMI technology which can be embedded as a layer of the bladder itself, allowing for increased functional density in a reduced or application-specific form factor.[1]

DIDS detects *MM/OD* impacts on inflatables. Each recorder monitors in power-saving until a trigger surpasses a present g-force threshold. It then saves a 270 ms, 30 kHz sampled data window per channel into internal memory.[17] This system can monitor multiple *MM/OD* and ensure that in any case of Impact to alert the crew & prevent the System from *HVI.*

The *DDS* technology utilized in the *BEAM* Deployable System for monitoring deployment, employing accelerometers, is integrated into this design due to significant developmental similarities. Components comprise a triaxial accelerometer affixed to the aft bulkhead of the Deployable Habitat.[17]

Wireless temperature sensor is installed to monitor the internal temperature of the bladder. Each *WTS* data recorder samples four *RTD* channels once per minute and stores the data locally.[17] This system can be utilized to understand the development of Insulative layers necessary to maintain the temperature passively with minimal usage of the active systems.

RAM's (Passive System) & REM's (Active System) can be employed in tandem through the utilization of Distributed Stretchable Electronics Technology for networking, facilitating comprehensive radiation monitoring and analysis of the radiation doses within the habitat.[17]

12. Emergency ECLSS (ECLSS, Humidity Control, Microbial & Fungal Monitoring on the Interiors.,)

Being the first human space flight system for India, the organization encountered challenges in obtaining detailed information for the development of key components, particularly the *ECLSS*. Consequently, an Indigenous *ECLSS* and other life support system has been developed, with limited information to be represented in this paper.[20] The *LASH* serves as a potential test bed for evaluating the performance of this ECLSS as part of emergency backup systems for *LASH* as these systems are designed to assist short mission periods, allowing for studying the standalone capabilities of *LASH* during emergency scenarios. The core support for *LASH* would be the *ACS* Subsystems of *ISS*, only transferring the load to Emergency *ECLSS* for the *SM* during critical scenarios.[15]

13. Flight Monitoring, PCBM Controls & Deployment Framework Controls

The Flight Monitoring System for the entire module comprises a hardwired circuit integrated within the *SM*. This system continuously monitors the live positioning of the habitat within *LEO* and transmits this data to Ground Monitoring Stations post-launch. This capability enables manual error corrections essential for successful docking procedures. Additionally, it actively monitors the health status of the habitat pre-deployment.

And using the core Flight System(cFS) platform for the integration of the Mechanical components with the Electrical components providing a dynamic run-time environment, layered software & component-based design.[9,19] This allows for integrating future technologies with the existing counterparts without any issues in platform support & communication across the existing systems & sensor networks. All these systems are powered by hybrid power supply networks which include on-board modular high-performance batteries, Deployable Solar Panels & Supply from the ISS power grid. Again, the usage of Hybrid system here defines the presentation of failsafe capabilities of LASH.

VI. Habitat Material Selection & Fabric Layering Consideration

Inflatable Systems being a developing concept requires innovative & smart materials that should perform on a wider range of parameters than the traditional space systems. Looking into the chronological data, gives the evolution of materials developed for inflatable systems, allowing us to understand the limitations & restrictions faced in each phase of development.

The evolution of material technology for inflatable space systems showcases a progression towards lightweight, durable, and cost-effective solutions for spacecraft design. Initiatives like *NASA*'s *ECHO* 2 satellite utilized Mylar sandwiched between aluminium foil layers to maintain structural integrity while withstanding *MMOD* impacts.[8] Similarly, the Inflatable Antenna Experiment (*IAE*) during the *STS*-77 mission employed neoprene-coated Kevlar for booms and aluminized Mylar for the reflector, demonstrating lightweight yet robust materials.[8] The Mars Pathfinder mission introduced innovative landing techniques using airbags made of silicone coated Vectran fabric, emphasizing the importance of abrasion tolerance.[8] Although the Erectable Torus Manned Space Laboratory faced challenges with *MMOD* and *HVI* concerns, it highlighted the potential of inflatable structures for inducing artificial gravity.[8] *NASA*'s TransHAB project overcame previous setbacks by emphasizing the importance of bladder, restraint layer, and *MMOD* protection. Similarly, *BEAM* by Bigelow Aerospace demonstrated successful deployment and operation of multi-layered inflatable structures on the ISS.[8] Integration of such advancements in material technology into low-cost, affordable space habitats holds promise for enabling scalable and sustainable solutions for future space exploration endeavours.

As observed from above all the materials that have been used in the Inflatables have been developed with simple layered & coated fabrics. Meaning that the materials developed had only limited focus and did not have embedded intelligence, which are readily available systems in the current trend.[5] So, incorporating those systems could make the habitat integrated with systems that are developed for function specific form factors without losing any of its intended characteristics. The below image provides a reference of how smart materials can be integrated into the inflatable system, using the Inflex Systems.[5]

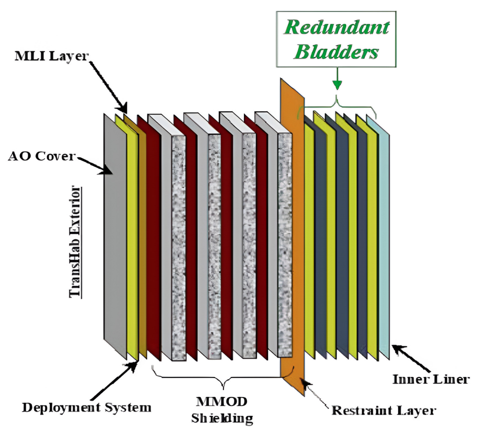

Figure 23. Necessary Layers for Inflatable Fabric Development.[5]

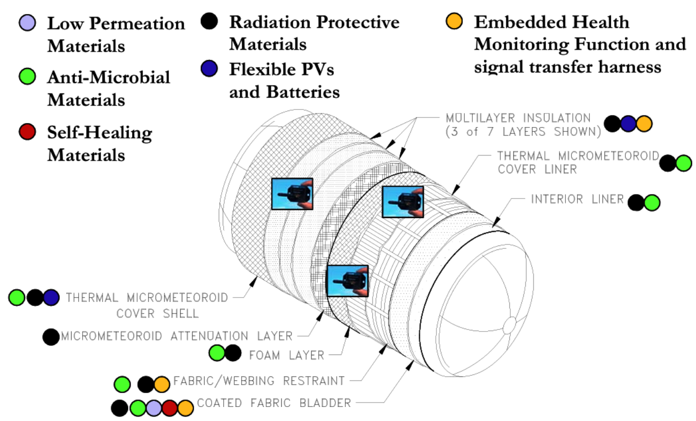

Figure 24. Possible Insertion Points for Smart layers in an inflatable Structure.[5]

Based on the Stress Analysis of Inflatable systems as provided in the research paper. The Hugelschaffer 3-Dimensional Ovoid developed is symmetrical about its axis of rotation which passes through its poles. If we dissemble the geometry along its meridians, the resulting doubly curved surface segments can be individually developed and recombined to give a closed shell. The edges of the doubly curved segment which are given as gores in two dimensional aspects can be increased to reduce the faceted nature & reduced seams during assembly.[7]

	Bladder		Restraint		TML	
	Description	Mass % of Bladder Layer	Description	Mass % of Restraint Layer	Description	Mass % of TML Assembly
Base Material (s)	Urethane coated Nylon, ~ 0.5mm thick	94%	Vectran Webbings (5cm x 0.01cm), over 500d 40x40 Vectran fabric	99%	FEP coated fabric shell, ~16 layers of VDA coated 1 mil polyester, several layers of nextel fabric and PE foam	99.80%
Sensor & Interconnects	Printed conductive ink ~0.01mm thick, 50% area coverage circuit on exterior of bladder	1%	Surface applied conductive polyester fibers on exterior of restraint	0.05%	Printed conductive ink ~0.01mm thick, 50% area coverage circuit on inner MLI layer	0.01%
Communications	2 RF nodes per 16 area circuits ($1m^2$ each)	5%	2 RF nodes per 16 x and y circuits ($1m^2$ each)	0.95%	2 RF nodes per 16 area circuits ($0.25\ m^2$ each)	0.02%
ESTIMATED TOTAL AERIAL DENSITY	2-4 g/cm^2		15-20 g/cm^2		60-80 g/cm^2	

Table 1. Mass Assessment of the Parasitic Smart Layer that will be Integrated with the Inflatable Fabric.[5]

14. The Bladder layer of the Habitat will be made up of Nomex, followed by consecutive redundant layers of CepacHD200, separated by an embedded bladder health monitoring sensor layer. This bladder zone will also be equipped with a radiation shielding layer & Antimicrobial Layer for health concerns.[5,7]

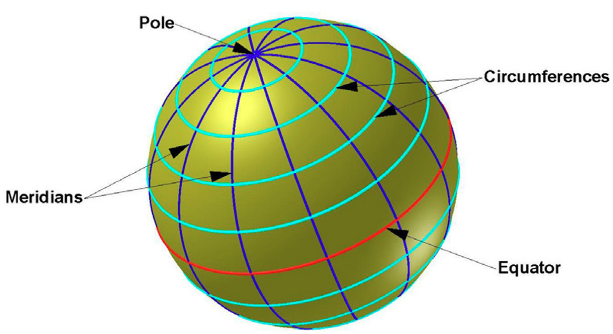

Figure 25. Fabric Seam Development.[7]

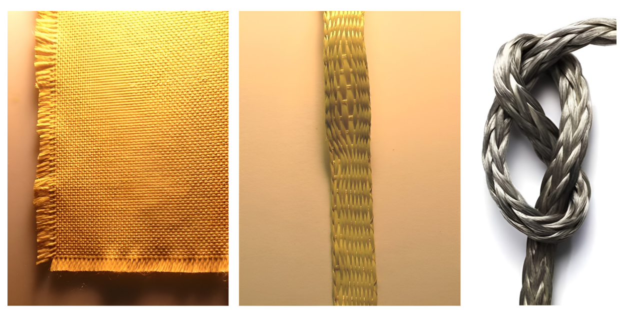

Figure 26. Weavability & Patterning of Kevlar for the Restraint Layer.[7]

15. To increase the geometric stability of the inflatable, the restraint layer uses a narrow weave Kevlar webbing system to weave the restraint tendons running along the meridian converging at the poles to the circumferential tendon hoops which lie perpendicular to withstand the bi-directional Stresses.[5] *The Kevlar weave will be composited with Flexible Textile Breakpoint detection systems developed by InFlex allowing to accurately monitor the health of each tendon using conductive fibers & woven polymer fiber Optics. The Intermediate Layer will contain Form Redundant Tendons encapsulating low permeable membrane layer to reduce gas diffusion to the atmosphere.*[5,7]

16. The outermost MMOD *Zone is composed of a Whipple Bumper Layer Separated by Micro Inflatable Tendons which inflate and provide a buffer zone between the Whipple Layer & the Actual MMOD protection layer (Nextel) containing microencapsulated healing materials, enhancing the performance of the inflatable towards HVI. The* *innermost layer of the MMOD Zone will have radiation shielding. This multi-layered radiation shielding gives us the possibility of securing the bladder from external radiation at varying thickness of the fabric.* [5]

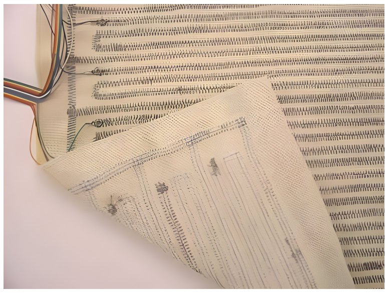

Figure 27. Flexible Textile Breakpoint Detection System.[5]

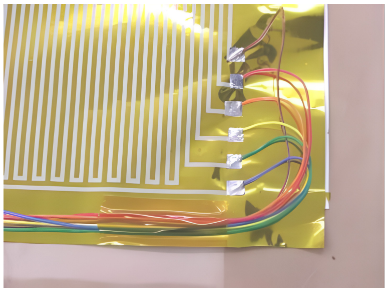

Figure 28. Flex Circuit Layer made of Printed Conductive Ink on Aluminized Kapton™.[5]

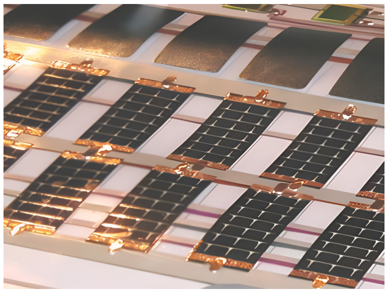

Figure 29. Flexible PV's and Battery Simulators Mounted on a Thin-Film Circuit Membrane.[5]

Now coming to the structural framework of the deployable system, it is essential that the material can provide a high performance to weight ratio to be a lightweight system. Since the Habitat is going to be fitted with a central telescopic core that houses the structural system of the entire inflatable habitat, the core is to be designed with Space Grade Aluminum allowing for lightweight structures while using titanium composites for micro joineries & connections, as the Aluminum also has the ability to reflect the incoming radiation to certain degree, without any interiors components present. As the radiation results vary significantly by the interaction of interior components.

VII. Cost & Sustainability

Table 2. Rapid Mass Based Cost Estimate using available data for LASH.[2,23,10]

Description	Chandrayan 3	Gaganyaan	LASH
Country	India	India	India
Organisation	ISRO	ISRO	AAKA Space Studio
Mission type	Un manned	Manned	Manned
Mission goal	Follow-on mission to Chandrayaan-2 to demonstrate end-to-end capability in safe landing and roving on the lunar surface.	Demonstration of human spaceflight capability by launching crew of 3 members to an orbit of 400 km for a 3 days mission and bring them back safely to earth	Demostration of docking & Inflation of repurposable Inflatable Systems on board ISS and study the performance of the habitat and analyse the human performance based on the architecture
Mission Category	Planetary	Orbital - LEO	Orbital - ISS
Mission Timeline (Pre Launch)	4 Years	17 Years (if launched as per schedule)	With Existing Technologies as perceived from Gaganyaan & Chandrayaan, The focus would be on the customisation and development of Interior Units based on Architectural Characterisitcs, development of Inflatable & deployment Solutions & Fabric Research, with standrads set to TRL 9 as this would be fully functional Habitable system - the developmental period would be around 8-10 years
Mission Timeline (Post Launch)	40 days + 1 Lunar Day	3 Days	Study period of 2 Years on Board ISS
Extended Mission Time period		3 Years	Keep a buffer of 3 years
Manufacturing cost	215 Cr	~ 9023 Cr	With Expectations to TRL 9 and Transfer of existing Technologies to further Optimise the development a suggestive figure of 8000 Cr can be suggested as most technologies & solutions are existant/ready to integrate while the geometry specific systems moficiations are necessary to accomodate those systems
Launch services	365 Cr	500 Cr	~ 500 Cr
Overall Cost Involved (Crore Rs.)	~ 615	~ 9523 Cr	~ 8500 Cr
Project specification	Rocket : LVM3 M4 Vikram Lander Mass : 1752 Kg Launch mass : 3900 kg (8600 lb) Dimensions : 2.54 x 2 x 1.2 m Volume : 6.1 cum	Rocket : LVM3 M4 CM Mass : 4520 Kg Launch Mass : 8200 Kg (including SM) Dimesnions : 3.1m dia x 2.97m - CM Volume: 22.43 cum	Rocket : LVM3 M4 Launch Mass : N/A Dimensions : 6.7m x 3.9m Volume including the SM (attached throughout the mission) : 80.4 cum
TRL	TRL 9	TRL 7 - 8	TRL 7-8
System Density	287Kg/cum	201.5Kg/cum	N/A
Cost/ per cubic volume	100.8 Cr/cum	424.68 Cr/cum	105.7 Cr/cum
Note: This Cost Only Exhibits the simplisitc projectable figures based on the space systems compared			

LASH is being developed with the primary focus on low cost and affordability, allowing a wide range of consumer platforms to utilize the habitat as per their demands. Although the pre-development costs of such a design can be higher, AAKA aims to make this habitat cost-effective by using high cost-efficiency, weight-performance ratio materials, allowing the habitat to be lightweight while satisfying the necessary standards for space habitation. AAKA focuses on the cost-effective nature of the habitat in mass manufacturing by employing simpler, efficient design solutions and effective methods of manufacturing, modular assembly systems, thus reducing manufacturing time, minimizing time consumption for assembly and pre-launch payload integration, and post-launch deployment. This allows the overall mission time to be reduced, which is a major part of resource and capital conservation, thus rendering LASH cost-effective and affordable for various organizations seeking to be a part of space programs requiring infrastructure for space. The base of manufacturing also plays a significant role, being in the Indian Sub-Continent with cost effective manufacturing & laboring support also adds to the advantage. Apart from manufacturing and launching processes, LASH also aims to be cost-effective by using minimal and simpler design solutions with a prominent level of optimization factors, as LASH has proved its efficiency in various aspects such as geometrical performance, material consumption, modularity, and deployment techniques. The following Table provides an overview of figures that could be necessary for the development of LASH on a mission-based format comparing to the existing Missions as shown in Figure 30.

VIII. Interior Concept Development

Beginning with the understanding of the proposed form in volumetric distribution in comparison to the surveyed geometries simulated for the same amount of volume, as shown in the figures, displays the advantage of the form architecturally and technically. Upon this inference the project moves towards creating the Interior Architectural Aspects

The interior configuration of the LASH (Low-Cost Affordable Science Habitat) Module is proposed to be a lightweight & modular system with wide range of functionality, and replicate earth style eco-system through interior designing. One key aspect that has been considered is the clear distinguished floor & ceiling representation as the general space infrastructure has functionality distributed based on available volume only. This clearly distinguished representation of Floor & Ceiling and achieving the clear height entirely changes the experience of the interior by astronauts. Followed by the arrangement of the zones. Furthermore, the module integrates circadian lighting systems

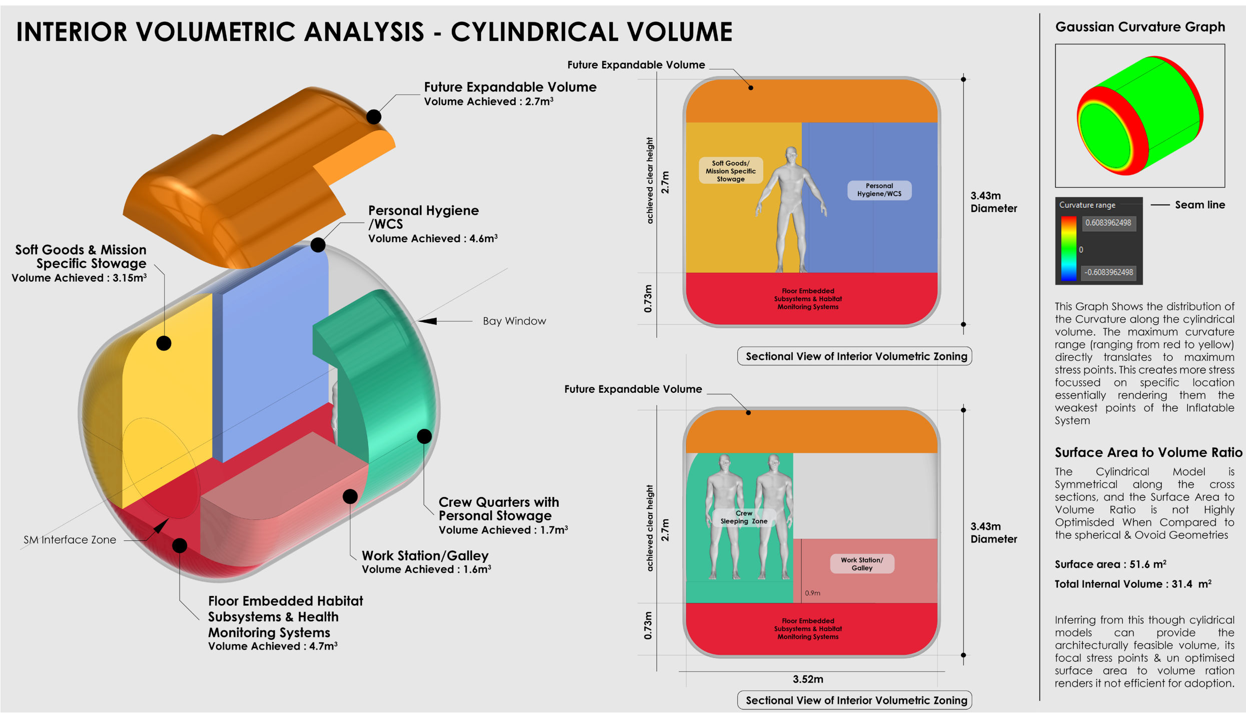

Figure 30. Interior Volumetric Arrangement Study 1 – Cylindrical model.

engineered to replicate the natural day-night cycle of Earth through sophisticated lighting simulations. This system enhances the sleep-wake activity cycle of astronauts.

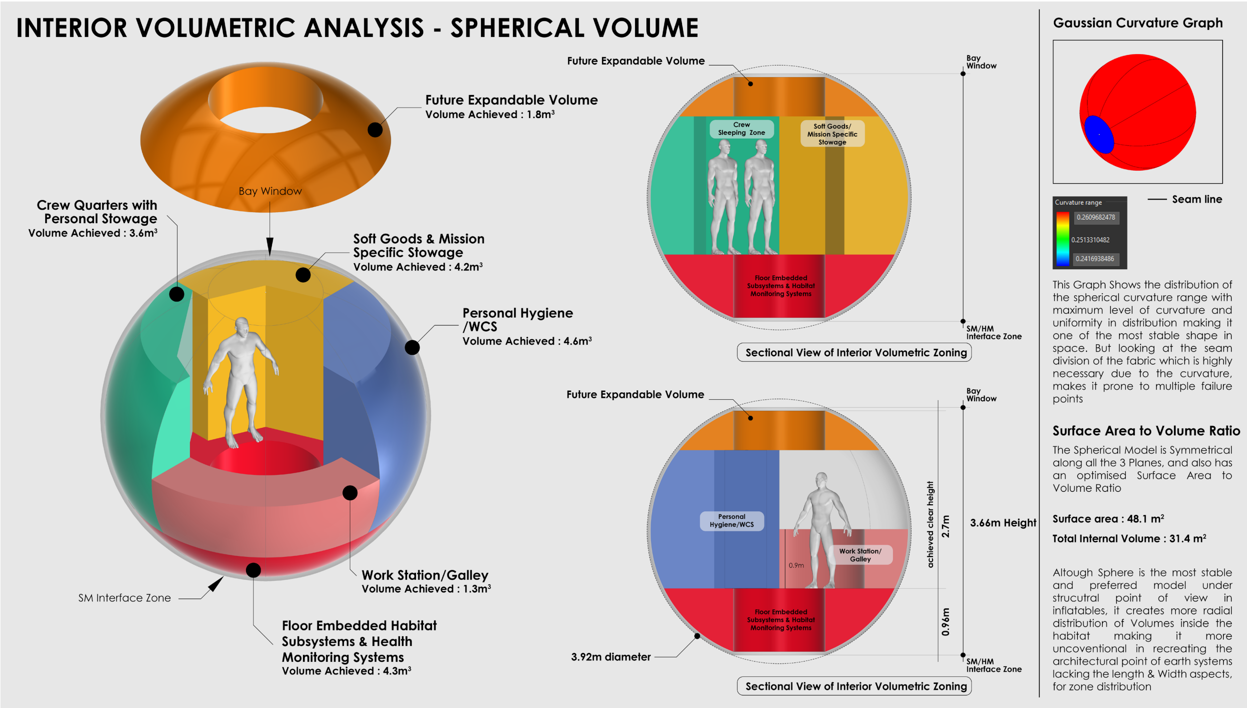

Figure 31. Interior Volumetric Arrangement Study 2 – Spherical model.

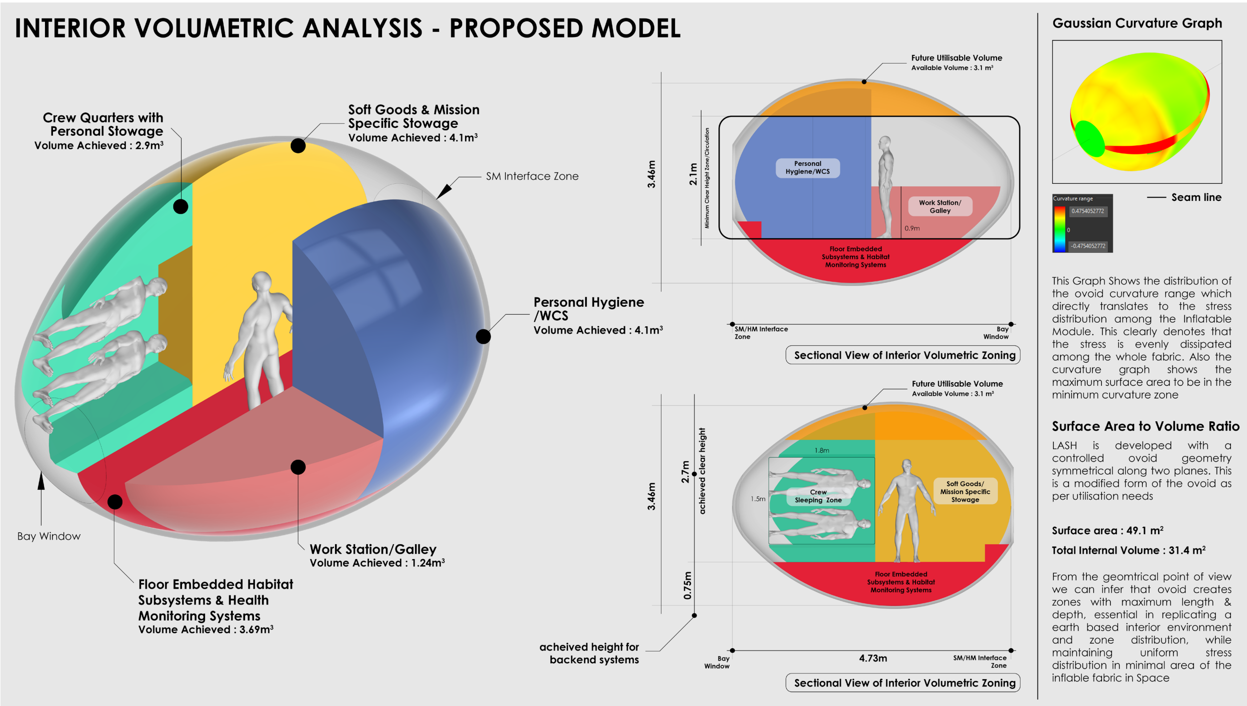

Figure 32. Interior Volumetric Arrangement Study 3 – Hugelschaffer Ovoid model.

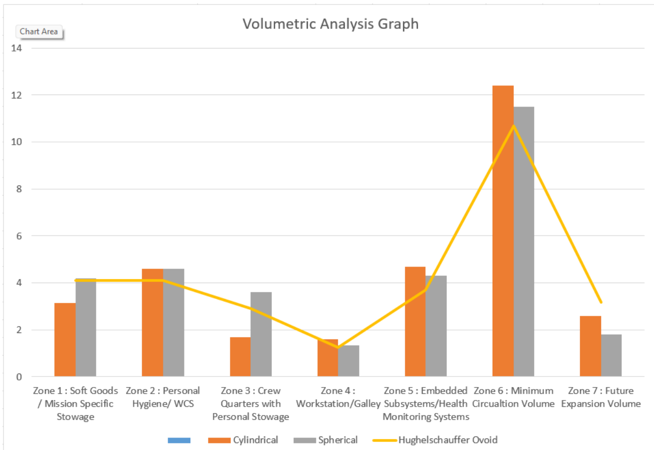

Figure 33. Performance Chart Hugelschaffer Ovoid to the Spherical & Cylindrical Study Models.

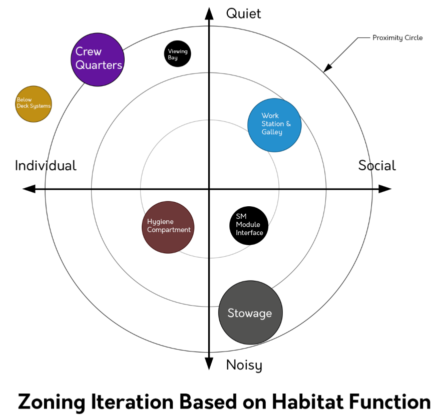

Figure 34. LASH Interior Zoning.

O. Inference

The forms are not directly compared to the existing inflatable systems as it will produce inaccurate results. Analyzing the Possible and Existing Geometries of Inflatables to the proposed & controlled Hugelschaffer form simulated for the same volume it is evident that the form has optimized Surface Area-to-Volume Ratio compared to the other geometries, which means it consumes less material in the development of the skin fabric when compared to the other two geometries while retaining the aspects essential for Architectural Replication. The form also displays, uniform stress distribution while minimizing the areas experiencing elevated levels of stress.

P. Proposed Architectural Layout

The Proposed Architectural Layout is developed based on the provided study model as shown in Figure 32. This Layout will be incorporated with four distinguishable zones with minimalistic finish, allowing for easier zone identification. The four zones as provided in the Figure 35, are identified as the crucial areas required for the development and study of a space-based Inflatable System. The zoning of the Habitat is developed based in the noisy-silent, Social-Private zoning model as provided in the Figure 34. Since this is an inflatable prototype that is developed to be deployed and tested after docking with the ISS, the model can be used as test bed for studying modular systems with Universal Connection nodes. The WCS Zone and the Soft Goods Stowage Zones are identified as fixed zones for the first iteration of the habitat as modularising those systems require high level of customisation & technical modifications, which is not a focus of this study. But the Workstation Galley and Crew Quarters can be utilised as a Modular Zone with complete adaptability, as they prove to be symmetrical in area and volume, allowing opportunities to develop various modular toolkits which can be integrated based on the mission nature. Moving from the modular capabilities of the Habitat towards the Interiors, the first architectural aspect that identifies a volume to be like earth are the floors, ceiling, Representation of Materials & Lighting. LASH geometry can achieve those architectural aspects length width and height ratio as per human anthropometry while equally performing against stress distribution. Since Utilisation of available space is a critical aspect to space systems this layout is proposed such that minimal future expansions can be seamlessly integrated to the structure, allowing for extra volume for stowage or other purposes for future long-haul missions. And the addition of Circadian lighting system and viewing bay adjacent to the crew quarters can enhance the sleep-wake cycle.

The Floor is also a possible are for modularisation as it can be useful in reducing EVAs for maintenance allowing for In-House Dismantling and maintenance adding to the crew's safety.

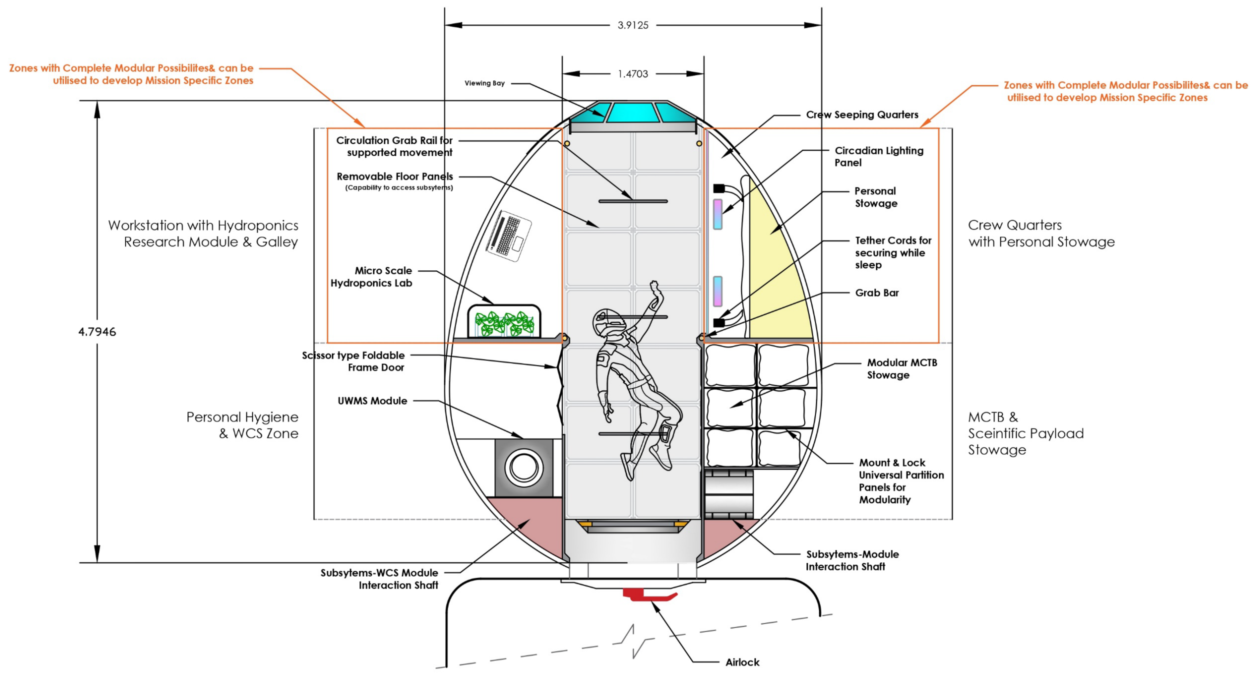

Figure 35. Proposed Interior Layout with Enhanced Features.

IX. Conclusion

In conclusion, this paper underscores the capabilities of LASH in wide range of platforms including the usage of novel and unconventional geometrical systems that can prove to be efficient in space. By incorporating human centric design principles and ideologies that add to the psychological & physiological wellbeing of the crew & the development of lighter deployment systems integrated with smart layers, *LASH* aims to be a modular infrastructure with its interiors using universal connection nodes and platforms that can be modified based on the mission needs as inspired from the TransHab allowing for wide range of Interior arrangement opportunities, thus justifying its modular nature. This whole paper presents the development of first stage of *LASH* which aims to be a deployable space habitat (first human test system) with facilities to accommodate two crew in Space, with all the integrated Zones. *LASH* is developed with aims to expand this micro level habitat to a Macro level habitat that can accommodate an increased crew capacity in future.

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