Composite Structure Enabling an Efficient Lunar Surface Habitat

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***Abstract*— The establishment of sustainable habitats on the lunar surface is paramount for advancing human exploration and scientific endeavors beyond Earth and enables NASA's Sustained Lunar Evolution in the Moon to Mars Architecture. Such habitats require structural solutions that minimize delivered mass while maximizing volumetric efficiency, long term integrity, and mission operability. This paper delves into the innovative design of an all composite Lunar Surface Habitat (LSH), replicating Boeing's proven composite design, analysis, and build capability but extending it into a novel system level application: a continuous, joint minimized carbon fiber reinforced polymer (CFRP) pressure shell layup that constitutes the primary structure for a crewed habitat. The innovation is both material and architectural — an integrated, all composite habitat concept that has not previously been implemented for habitable space modules.**

The study was conducted under NASA's NextSTEP-2 Appendix A. One of the key focuses of this study was the composite primary structure of the LSH, which constitutes only 17% of the total mission mass compared to typical module's structure comprising 25%-50% of the total mass. This remarkable weight reduction is achieved using carbon fiber reinforced polymer laminate, which offer a high strength-to-weight ratio essential for space applications. The lightweight nature of the composite structure not only facilitates the launch, landing, and transportation of the habitat but also enhances the module's overall performance by redeploying structural mass allocation to other functions, thereby increasing mission capability or reducing risks.

A significant advantage of utilizing composite structures is the expanded design space it affords. The reduced mass and flexible manufacturing of the composite primary structure enables the development of an innovative two-story module. This design not only maximizes the use of internal volume but also strategically locates hatches low to the lunar surface, facilitating easier ingress and egress for crew members during extravehicular activities (EVAs) and the mating of pressurized vehicles to its port. The two-story layout allows for a clear separation of functional areas, enhancing operational efficiency and crew comfort.

The paper details how all the defined Ground Rules and Assumptions (GRAs) were met or exceeded for a four crew, 30 day mission. Chief among the Ground Rules was the mass target, which was met by implementing very efficient structure and by a deferred items approach where equipment is brought up and installed on the first mission via a pressured logistics carrier.

The findings underscore the potential of composite technology to revolutionize habitat construction for deep space applications. The successful implementation of a lightweight composite primary structure not only enhances the feasibility of lunar habitation but also sets a precedent for future missions to Mars and beyond. The study demonstrates that the strategic use of composite materials in the LSH design significantly contributes to the mission's success by optimizing mass, enhancing structural performance, and enabling innovative configurations that improve crew operations.

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1. INTRODUCTION

This study advances a first of its kind all composite Lunar Surface Habitat (LSH), replicating Boeing's proven composite design, analysis, and build capability but extending it into a novel system level application. The study was conducted under NASA's NextSTEP-2 Appendix A. Boeing has made extensive use of advanced composite structures across its commercial and military product lines to reduce weight, improve fuel efficiency, increase corrosion and fatigue resistance, and enable more aerodynamically efficient shapes. On commercial programs, the 787 Dreamliner is a landmark example, with the wings and fuselage structure made predominately from carbon-fiber-reinforced polymer, and the 777X also incorporates large carbon-composite wings. In military applications Boeing integrates composites into airframes, control surfaces, and radomes of fighter jets and commercial derivatives aircraft in addition to rotorcraft components, unmanned systems, space and launch structures (payload fairings, satellites and spacecraft panels), and non-aerospace applications where high stiffness-to-weight and corrosion resistance are valuable.

Background

The great appeal of the composite LSH is the mass efficiency of the structure while maintaining a rigid structure that can accommodate extensive outfitting and subsystem testing and checkout on the ground prior to launch. The primary structure is traditionally the largest mass subsystem, so any reductions are significant.

Table 1 compares the primary structure percentage and mass to volume ratio of several modules. A range of International Space Station (ISS) modules were selected since there is no other recent habitats, crewed laboratories, or airlocks flown. The ISS modules were designed for a different mission and a different environment, so there isn't a direct comparison to a lunar surface habitat. But the comparison acts as a gauge to evaluate the efficiency of the conceptual LSH against actual built and flown space modules. The total vehicle mass does not include logistics or consumables and the mass to volume ratio is based on the total vehicle mass.

Table 1 Mass Comparison of Multiple Modules

Module	Primary Structure Mass (kg)	Launch (kg)	Deferred (kg)	Total Vehicle Mass (kg)	% Primary Structure	Vol (m^3)	Mass/Vol
ISS Node 1	6048	11256		11256	54%	75	150
ISS Lab	3447	14515	10819	25334	14%	106	239
ISS Airlock	3645	9680		9680	38%	16	605
Composite LSH	3495	13981	6791	20772	17%	126	165

ISS Node 1 has a very high percent primary structure (54%) because of the multiple docking ports and their associated beefy port bulkheads and hatches, but the mass to volume is very favorable. The ISS Lab has relatively few functions and simplistic structure with high volume to accommodate payload and science racks. It was launched not fully outfitted and nearly 40% of the total vehicle mass was brought up separate as deferred mass. Since the mass increased significantly post-launch, the percentage of primary structure mass to total vehicle mass is very low (only 14%), however the mass to volume ratio is unfavorable, indicating the overall vehicle is not very mass efficient relative to what would be needed for a lunar surface application. The ISS Airlock is similar in primary structure weight to the ISS Lab and Composite LSH, but the volume is significantly less resulting in a very poor mass to volume ratio of over 600 kg/m^3. The Airlock primary structure percentage is high at 38% and its primary structure, which is designed to facility just the EVA function, is more than the total Composite LSH structure which includes an airlock function along with all crew habitation and vehicle docking functions, to name a few. The Composite LSH demonstrates a very promising 17% primary structure to total vehicle mass while also demonstrating a mass to volume ratio of 165 kg/m^3. This structural and volume efficiency for a complete self-sufficient habitat sets itself apart from other heritage space modules.

Certification experience:

The composite LSH innovation is both material and architectural — an integrated, all composite human rated spacecraft has not previously been implemented and must go through a certification process. In general, composite human rated spacecraft have the same high-level requirements as typical terrestrial human rated composite structures, however the certification process lacks the maturity of the aviation industry. Over the past half century, the aviation industry has developed and demonstrated the ability to safely certify composite aircraft structure as evidence by the safe usage of the Boeing 787 Dreamliner for 14 years. The overall philosophy for certifying a deep space habitat structure does not differ from the philosophy behind Title 14 Code of Federal Regulations (14 CFR) Chapter 10 or the supporting advisory circulars, or CMH-17 [1]. Those documents are useful references and the methodology for defining damage threats and demonstrating durability and damage tolerance also applies to a composite surface habitat structure, provided the differences in threats, environments, and failure modes are accounted for.

Mission Overview:

The high-level Concept of Operations (ConOps) begins with the LSH launching on a heavy lift commercial launch vehicle, interfacing with a human-class delivery lander (HDL), and transits to the Moon atop the lander. The lander will deliver the LSH to the lunar surface near the south pole and near an available Mobility System during a sunlit period. The LSH will be offloaded onto the Mobility System for relocation to the final emplacement location. Figure 1 shows the overall LSH ConOps.

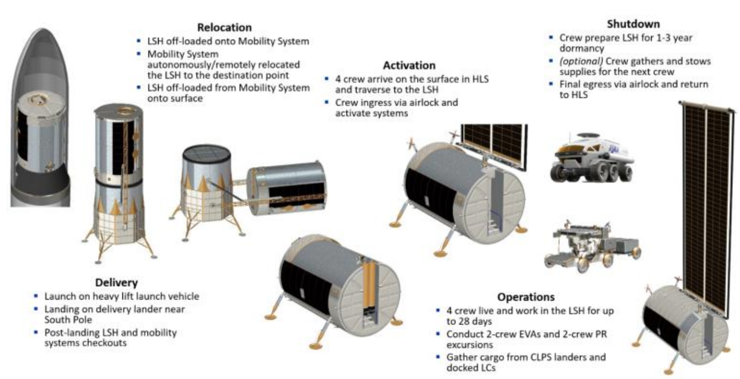

Figure 1 LSH ConOps Overview

The LSH enables habitation, EVAs, scientific and payload activities, and excursions with other lunar elements for 4 crew members for up to 28 days. Figure 2 shows the deployed and activated LSH on the lunar surface.

Figure 2 LSH Activated on Lunar Surface

2. APPLICATION OF COMPOSITE STRUCTURE

Composite Design

The introduction of composite primary structure impacted other subsystems such as secondary structure, Micrometeoroid Orbital Debris (MMOD), Power, and Thermal Control System (TCS). One characteristic of composite laminates is the very low thermal and electrical conductivity. This results in unique design considerations such as a Current Return Network to control shock hazards since a common ground cannot be established by grounding equipment to the shell. Additionally, thermal shell conditioning to preclude condensation cannot be accomplished with traditional patch heaters due to the material's poor conductivity, so a ventilation solution was implemented.

To avoid material incompatibility or dissimilar coefficient of thermal expansion (CTE), the amount a material expands or contracts at a difference in temperature, all of the primary structure is CFRP, including the hatch bulkheads.

Material Selection

Selecting the optimal material for a deep space habitat involves quantifying benefits and risks. Metal has been used successfully in similar applications and therefore offers a low-risk solution. However, Boeing conducted a trade study directly comparing optimized metallic, inflatable, and composite structure Mars Transit Habitat design under the same design reference mission and evaluation criteria. The results [2] showed significant mass savings by implementing composite structure.

The baseline composite material that Boeing has selected for the current lunar surface habitat study is Toray's T1100G/3960 slit tape prepreg. This is an aerospace grade carbon/epoxy prepreg with the highest strength, yet still high strain-to-failure, commercially available carbon fiber and well controlled material manufacturing processes. A publicly available database of material properties and specifications is currently in development by NCAMP. This public availability of data and specifications provides the benefit that the information can be shared with NASA and industry partners without complicated non-disclosure and proprietary usage agreements. Boeing has demonstrated that the material works well with the automated fiber placement (AFP) layup process. AFP is an efficient layup process which minimizes the potential for operator error and maximizes repeatability.

One potential concern with composite pressure shell is the leaking through the wall of the pressure shell (permeation) if there is no liner on the IML to act as leak barrier. Because the permeation is caused by microcrack networks developed in the resin if the resin is excessively strained under loads, the wall of the pressure shell is sized so that the wall strain is kept below the strain levels that cause microcracks in the resin. Additionally, a carbon fiber and epoxy system was selected that minimizes the risk of permeation. The material system was tested while under representative habitat pressure wall strain and showed no microcracking.

Material Allowables

Allowables for the material were derived from a series of testing performed on laminate coupons. The test based open hole tension (OHT) allowable was selected for sizing the structure because the pressure shell is a tension driven structure. The habitat design is using 0.25-inch open hole strength allowables given that test data and allowables are more readily available for this standard size hole. Subsequent testing has shown that the tension allowable of a hypervelocity impacted coupon is greater than the OHT allowable used for sizing. This demonstrates that the OHT allowable is a conservative value to use for the sizing of the module.

Damage Tolerance Approach

Since the primary acreage loads are tensile, the structural thickness is driven by the open hole tension (OHT) strength allowable. For reference, the OHT strength allowable is less than 60% of the pristine un-notched tension allowable. Eventually, in acreage areas where there are no fastener holes, the OHT strength allowable will be replaced by a "damage tolerant" strength allowable defined based on the residual strength of the structure with the worst-case flaw that could realistically occur. To quantify and bound this worst-case flaw, a preliminary damage threat assessment was conducted which considered a wide range of threats and the potential of each threat to damage the composite structure

Ground rules and assumptions for this assessment included:

1) All external composite structure is protected by MMOD shielding and/or insulation

2) Vehicle is protected inside of a fairing during launch
3) Rotating components of high energy equipment are self-contained within the unit's housing

The following are examples of the types of threats that were considered:

1) Manufacturing discrepancies found during inspection that are below the defect acceptance threshold
2) Ground handling damage during acceptance/ qualification
3) Inadvertent bump/kick during ground operations or in the lunar surface environment
4) Crew induced equipment impact
5) Robotic arm impact
6) MMOD impact, including surface ejecta
7) Degradation due to radiation (ultraviolet and/or ionizing)
8) Handling of habitat including offloading from launch vehicle and positioning on surface

The list is not exhaustive and is intended to cover multiple different threat environments ranging from deep space transit habitats, surface habitats, and logistics carriers.

A Damage Threat Assessment was performed and the residual threats that cannot be fully mitigated were brought forward and incorporated into a planned test matrix. These include both hypervelocity impacts and lower energy impacts. A coupon representing the pressure structure will be impacted at varying energy levels and then undergo permeation testing while under bi-axial loading. It is believed that permeation will be the more limiting failure mode, happening before a structural failure occurs.

3. CONFIGURATION DESIGN OPTIMIZATION

A significant advantage of utilizing composite structures is the expanded design space it affords. The reduced mass and manufacturing flexibility of the composite primary structure enabled the development of an innovative two-story module configuration for the LSH. This design not only maximizes the use of internal volume but also strategically locates hatches low to the lunar surface, facilitating easier ingress and egress for crew members during extravehicular activities (EVAs) and the mating of pressurized vehicles to its port. The two-story layout allows for a clear separation of functional areas, enhancing operational efficiency and crew comfort. This configuration is particularly advantageous for supporting simultaneous activities thereby optimizing the habitat's functionality.

An additional benefit of the composite pressure shell construction is the ability to embed an airlock within the pressure shell. Various alternate configurations were traded, but the capability to maximize the length of the module and utilize the volume above the airlock proved the most advantageous. The ability to form an airlock of this configuration and integrate it into the structure is uniquely due to the composite Automated Fiber Placement fabrication ability. A metallic module of this same configuration would not have been feasible due to panel forming and welding constraints. The primary structure, shown in Figure 3, features shallow end domes that also maximize the usable internal volume. Longerons internal and external are utilized to mount equipment and further stabilize the structure.

Figure 3 LSH Pressure Structure

The fully outfitted module, shown in Figure 4, sits in a horizontal configuration. A trade between horizontal and vertical configuration was also conducted, but the additional floor space of the horizontal two-story configuration resulted in greater crew habitability and was the more strategic orientation.

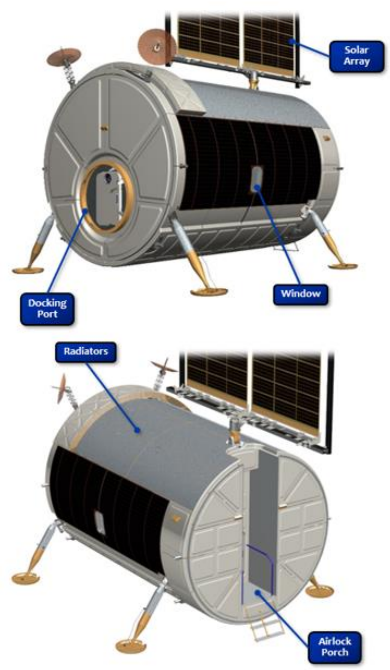

Figure 4 Fully Outfitted LSH

The separation of floors allows for functional groupings of equipment and also the purposeful separation of functions, such as the waste compartment, hygiene compartment, and exercise on the first floor while the crew quarters, galley, and social gather/common area is on the second floor. The voluminous layout for a 4 crew, self-sufficient habitat is how below in Figure 5 - Figure 7.

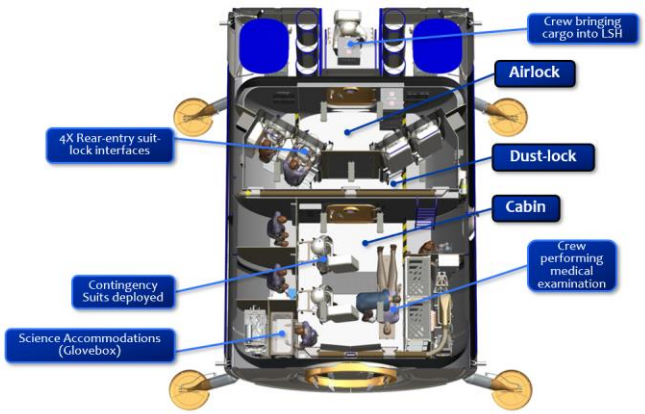

Figure 5 LSH First Floor Layout

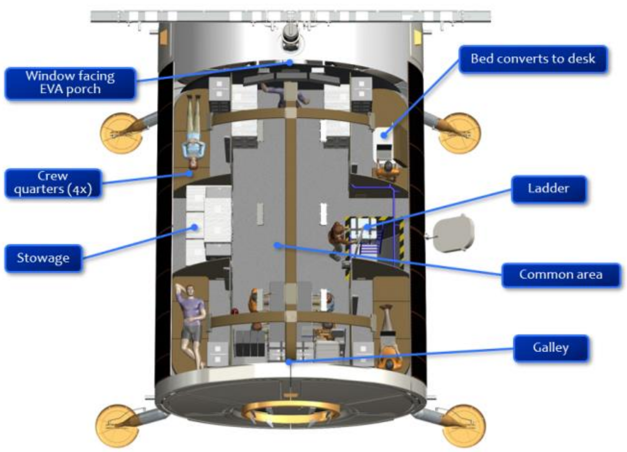

Figure 6 LSH Second Floor Layout

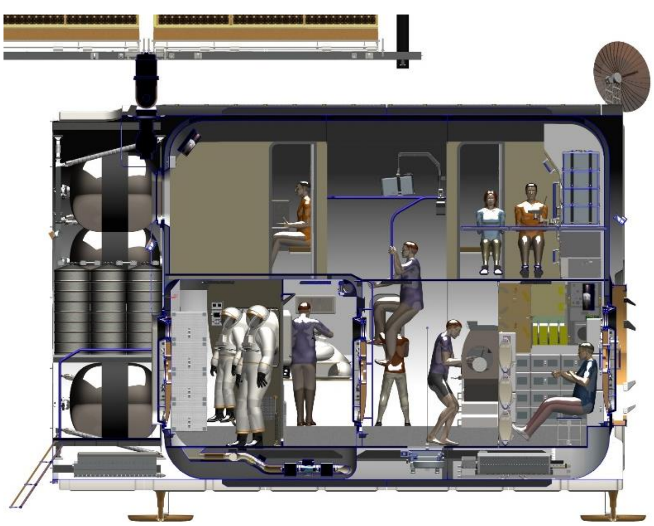

Figure 7 LSH Cross-Section Layout

4. COMPOSITE MANUFACTURING

The Boeing Company has extensive experience in the manufacturing of large-scale composite structure. The knowledge of how to design for manufacturing a large, pressurized structure was brought to bear in this study. Beyond the experience base built up through developing and producing the first composite wing and fuselage of a commercial aircraft, Boeing has the development and production facilities and equipment, such as robotic AFP systems and large-scale autoclaves, to produce the LSH. Facilities, equipment or autoclave size were not a constraint or limiting factor in the development of the LSH design and manufacturing plan.

The flexibility in shape and size of what can be produced using composite materials opened up the trade space for the study. The design process incorporates automated fiber placement manufacturing techniques, which ensure precision and consistency in the construction of complex geometries. This method allows for the optimization of structural performance while minimizing mass.

Composite Tank Manufacturing Experience

In addition to the 787 Dreamliner fuselage barrels that are similar in diameter and utilize breakdown layup mandrels in the same way as the proposed LSH, the Boeing team has experience fabricating launch vehicle fuel tanks. The Composite Cryotank Technologies and Demonstration (CCTD) project with NASA matured the technology readiness level (TRL) of composite cryogenic propellant tanks at diameters similar that proposed for the LSH. The full-scale composite tank completed a demanding series of tests including structural loads to replicate launch loads and filling with liquid hydrogen (chilled to -423°F) and cycling pressure. Extensive experience was gained in the design, manufacturing, and testing of the large-scale composite pressure shell. Solutions for permeation concerns were realized.

Figure 8 CCTD 5.5m Tanking in Fabrication (Left) and being shipped for testing (Right) [3]

Additionally, Boeing designed, built, and tested the cryogenic propellant tank for the Experimental Space Plan (XSP) program funded by DARPA and tested at NASA's Marshall Space Flight Center. The 4.3 m diameter composite tank built upon the experience of the CCTD and was designed for the rapid reusable space plane concept [4]. The tank was fabricated and certified as a flight unit.

Figure 9 XSP Composite Tank During Testing [4]

LSH Composite Fabrication

The manufacturing approach involves utilizing AFP for laying composite tape, breakdown tooling to enable integration of multiple parts, co-bonded composite assemblies, and mechanically fastened and sealed opening for hatch bulkheads and windows (enable by padups and inserts in the composites). Because composite manufacturing allows for unique or complex structure, the novel embedded airlock design was adopted and evaluated in the study.

The overall approach (Figure 10) is to produce the endcaps via a Gantry AFP system and pre-cure, then load the airlock end caps onto the airlock tooling and fiber place the airlock shell. Following its autoclave cure and Non-Destructive Evaluation (NDE), the airlock is assembled into the habitat layup mandrel, the habitat end caps and longerons are loaded and the habitat shell is fiber placed, cured and completes NDE.

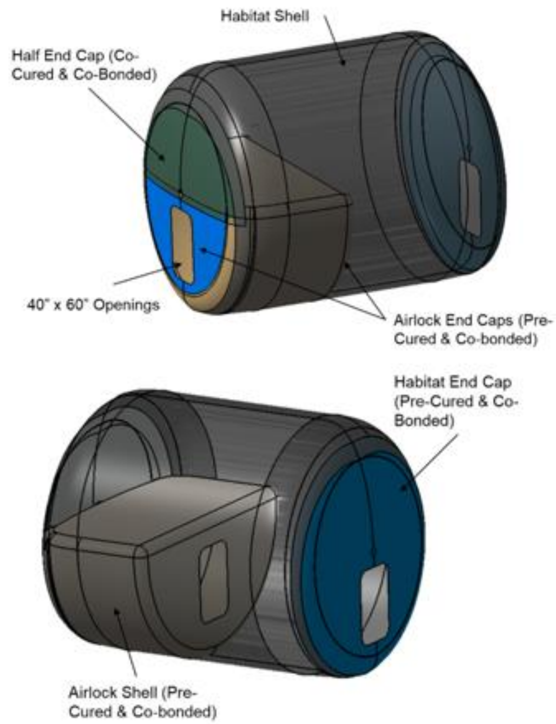

Figure 10 Composite LSH Manufacturing Approach

The tooling approach is a key consideration in the fabrication of the complex module. Composite breakdown Layup Mandrels enable low rate fabrication of large structure with limited extraction space. Segmenting the tools also enables integration of internal longerons so the shell can be laid up over pre-formed longerons embedded in the tooling. Integrating pre-cured component parts have previously been demonstrated on similar structure designs The horizontal module allows for spindle integration via the hatch bulkheads opening and the docking port bulkhead opening. Figure 11 shows the two distinct pieces (airlock below, habitat cabin above) on the left with the spindle (pink cylinder) fitting through the openings and on the righthand side of the image the laid-up airlock integrated to the Layup Mandrel of the cabin. Indentions, or cavities, are shown on the cylinder where the pre-cured longerons are placed.

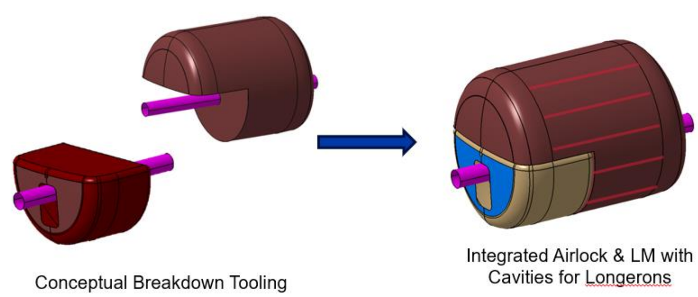

Figure 11 LSH Breakdown Tooling Approach

Figure 12 shows the Gantry AFP cell producing an endcap and Figure 13 shows the integrated airlock and cabin on the Robotic Electroimpact AFP Cell. The AFP robotic head holds multiple spools of the composite tape and lays it, layer by layer, over the mandrel and the airlock structure.

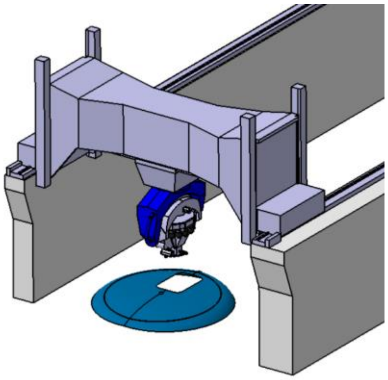

Figure 12 Gantry Electroimpact AFP Cell

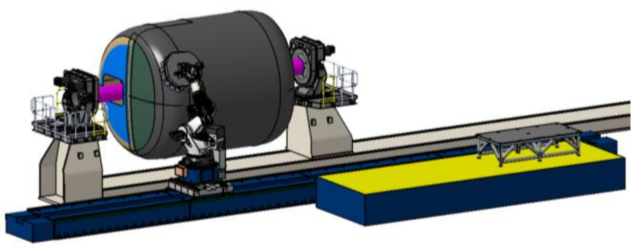

Figure 13 Robotic Electroimpact AFP Cell

The AFP process and multi-cure approach enables efficient structural design and configuration. Such a configuration would not be attempted with a metallic design. Through an innovative design and manufacturing flow, an internal airlock was accomplished by embedding it inside the LSH module on the first floor.

5. STUDY RESULTS

Through the course of the study, all subsystems were evaluated and their key performance metrics were reported. Habitability assessments were performed for the given volume and layout and the results were favorable for a four crew 30 day mission due to the spacious outfitting. The NASA provided Ground Rules and Assumptions (GRAs) were evaluated for the design. All were met and some were exceeded such as accommodating four crew for 30 days instead of the specified 2 crew and accommodating logistical storage amounts above the minimum of 7 days and up to the maximum of 33 days. Chief among the Ground Rules was the mass target of 14mT (including Mass Growth Allowance and 15% Mass Margin) to fit within the landed payload mass of the HDL providers. Figure 14 shows the mass summary table and the Mass Breakdown bar chart. The mass target was met by implementing the very efficient structure and through the use of a deferred items approach where equipment not immediately required is brought up and installed on the first mission via a pressured logistics carrier. The crucial aspect of staying within the mass target while also exceeding the Ground Rule for number of crew was the mass and volume efficiency of the primary structure. The total Primary Structure was only 17% of the overall mission mass.

Basic Mass (kg)	MGA (kg)	15% Mass Margin (kg)	Total Launch Mass (kg)
10554	1844	1583	13981

Lunar Surface Habitat Composite Mass

Sub-System	Sub-System Basic Mass (kg)	MGA (kg)	MGA (%)	Sub-System Predicted Mass (kg) w/ MGA	% of Total Launched Predicted Mass (%)	% of Total Mission Predicted Mass (%)	Sub-System Predicted Mass (kg), Mass Margin
Body Structures (total)	4106	732	18%	4838	39%	**26%**	5454
Primary Structure	2659	438	16%	3096	25%	**17%**	3495
Secondary Structure	1448	294	20%	1742	14%	**9%**	1959
Radiation	13	3	20%	16	0%	0%	18
MMOD	451	68	15%	519	4%	3%	586
Power System	2776	477	17%	3253	26%	18%	3670
C&DH	150	65	43%	215	2%	1%	238
C&T	110	23	21%	133	1%	1%	150
Crew Displays and Controls	35	6	16%	41	0%	0%	46
TCS	1067	226	21%	1294	10%	7%	1454
ECLSS	841	107	13%	948	8%	5%	1074
Crew/Habitation Systems	353	47	13%	400	3%	2%	453
EVA	397	89	22%	486	4%	3%	546
Manipulation and Maintenance	3	1	25%	4	0%	0%	4
Payload Provsions	249	2	1%	251	2%	1%	289
Payloads and Research	0	0	0%	0	0%	0%	0
Launch Total	**10554**	**1844**	17%	**12398**	**100%**	*N/A*	**13981**
Deferred In-Space Installation	*5572*	*383*	*7%*	*5955*	*N/A*	*32%*	*6791*
Total Mission Mass	**16125**	**2228**	14%	**18353**	*N/A*	**100%**	**20772**

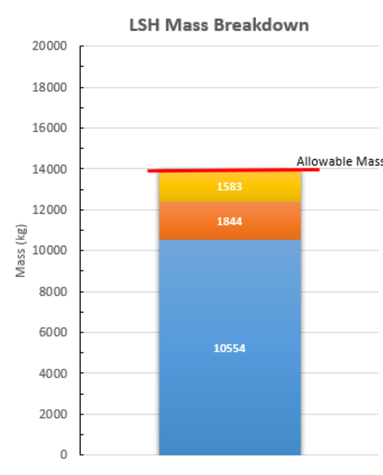

Figure 14 Composite LSH Mass Summary

6. TECHNOLOGY DEVELOPMENT

The use of composite structure does introduce unique design challenges and maturation efforts have been identified. Precluding condensation on the shell using air ventilation is a new development effort since traditional patch heater shell conditioning is insufficient due to the laminate's poor conductivity. Implementation of the solution is still be studied and advanced through follow-on efforts.

A damage tolerance approach is another development area since impacts or damage to the shell can cause permeation, a failure criterion that develops prior to structural failures. A damage threat assessment has been completed which identified external hypervelocity impacts from micrometeoroids and orbital debris (MMOD) and internal low velocity impacts during production or while in operation on the lunar surface. Both conditions are being tested on representative composite panels that will be impacted at varying impact energies, then biaxially strained and screened for leaks to determine the impact energy required to cause permeation.

Manufacturing Readiness Levels have also been defined for the various features of the LSH. The joints between the airlock and the habitat cabin are of particular interest and will be further studied and subsystem level testing conducted. Additionally, fracture properties of the laminate are being acquired via Double Cantilever Beam (DCB) and End-Notched Flexure (ENF) testing to produce the GIIc material property (resistance to interlaminar fracture from shear loading with crack propagating parallel to fibers). This will assist with further refining the design and analysis of the critical joints.

7. CONCLUSION

By demonstrating an all composite LSH, this work introduces an innovative capability for deep space habitats. The benefits include reduction in mass per habitable volume, elimination of multi material interface failure modes, and enabling of architectural configurations that are infeasible or impractical with conventional metallic or softgoods designs.

The findings underscore the potential of composite technology to disrupt habitat design and configurations for deep space applications. The composite structure, being rigid, retains all the benefits of pre-launch outfitting and ground install, checkout, and testing of equipment like traditional metallic modules but at a lower mass for the structure. The successful implementation of a lightweight composite primary structure not only enhances the feasibility of lunar habitation but also sets a precedent for future missions to Mars and beyond. The study demonstrates that the strategic use of composite materials in the LSH design significantly contributes to the mission's success by optimizing mass, enhancing structural performance, and enabling innovative configurations that improve crew operations. Composite habitats open new opportunities for higher mission performance by reducing total mass or allowing for reallocation of the mass saved to other subsystems that further the mission objectives and open up new possibilities.

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REFERENCES

[1] J. Eichinger, M. Ziglar, M. Bland, B. Gingras, Certification of a Composite Habitat for Deep Space, 2024 AIAA ASCEND, July 30-August 1, 2024, Las Vegas, NV. AIAA-2024-4895

[2] M. Ziglar, M. Elsperman, Deep Space Habitat Primary Structure - A Comparison between Metallic, Inflatable, and Composite Materials, 2024 AIAA ASCEND, July 30-August 1, 2024, Las Vegas, NV. AIAA-2024-4846

[3] "Composite Cryotank Technologies & Demonstration," NASA Technical Reports Server [online], URL: https://ntrs.nasa.gov/api/citations/20140016807/downloads/20140016807.pdf

[4] "Boeing Breakthrough in All-Composite Cryogenic Propellant Tank Advances Technology Readiness", URL: https://boeing.mediaroom.com/news-releases-statements?item=130996#assets_all

BIOGRAPHY

Matthew Ziglar *received his B.S. and M.S. in Mechanical Engineering from Mercer University. He is currently the habitation technical integrator within Boeing Exploration Systems working on a variety of space exploration projects from new development of future exploration habitats and surface transportation to leading technology development testing efforts. Additionally, Matthew works as a Structures Engineer working to develop lightweight, efficient structures and to infuse new technology into projects. Prior to this he helped sustain and upgrade the ISS structure.*