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Successful Testing of Advanced Space Habitat

Matthew L. Morgan[1] and Elizabeth A. Schaepe[2]
ILC Dover, Frederica, DE, 19958, United States
Sierra Space, Louisville, CO, 80027, United States

John K. Lin[3] and Gerard D. Valle[4]
ILC Dover, Frederica, DE, 19958, United States
Sierra Space, Louisville, CO, 80027, United States

and

Shawn Buckley[5] and James A. Kirwan[6]
ILC Dover, Frederica, DE, 19958, United States
Sierra Space, Louisville, CO, 80027, United States

Commercial Space is an ecosystem which is rapidly evolving with advanced space habitats and broad interest in habitation development opportunities. Addressing this growing space economy requires the on-orbit presence of multi-use environments, similar to the International Space Station. One of these advancements is maximizing the livable volume of the space habitat without the burden of multiple launches or heavy lift capabilities, which is addressed by use of advanced fabric structures commonly known as softgoods. Softgoods provide the benefit of an expandable volume once on orbit but minimal packed-size while launched, creating a significantly better volume-to-weight ratio. This enables support functions for diverse payload, governmental and civilian human visitors, on orbit in various scenarios including robotic, human tended, and autonomous/remote operations. In order to support a variety of user case functions in the manner in which customer bases are accustomed, the ecosystem of services should be scalable. The ability to scale and evolve on orbit habitation is a key discriminator in the advancement of space exploration. ILC Dover and Sierra Space have successfully tested multiple Ultimate Burst Pressure (UBP) subscale softgoods space habitats, a significant milestone towards manned flight qualification. The UBP tests verify the structural integrity of the system at or above a 4.0 factor of safety requirement at maximum operating pressure (15.2 psi) and demonstrates repeatability in the design across test units with both units exceeding the required 182.4 psig (operating pressure x 4 = 60.8 x 3 = 182.4 taking into account the 1:3 sub-scale factor), averaging 198 psig internal pressure before failure. This paper discusses the system architecture, concept of operations, rationale for testing approach, and test results gathered.

Nomenclature

CLD = Commercial LEO Destinations
DIC = Digital Image Correlation
ECLSS = Environmental Control and Life Support Systems
ISS = International Space Station
JSC = NASA Johnson Space Center

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[1] Sr. Engineer, Space Systems, One Moonwalker Rd, Frederica DE 19946.
[2] Softgoods Certification Lead Engineer, Destinations, 500 Interlocken Blvd, Broomfield CO 80021.
[3] Principle Engineer, Space Systems, One Moonwalker Rd, Frederica DE 19946.
[4] Structures, Softgoods, & Mechanisms IPT Technical Lead, Destinations, 11551 Arapahoe Rd, Centennial CO 80112.
[5] Sr. Director Engineering, Chief Engineer, Destinations, 11551 Arapahoe Rd, Centennial CO 80112.
[6] Program Manager, Space Systems, One Moonwalker Rd, Frederica DE 19946.

LEO = Low Earth Orbit
LIFE = Large Integrated Flexible Environment
MSFC = NASA Marshall Space Flight Center
MDP = Mean Design Pressure
MMOD = Micrometeroid and Orbital Debris
UBP = Ultimate Burst Pressure

I. Introduction

ILC Dover develops and manufactures a variety of inflatable habitats, airlocks, shelters, and airbag landing systems for use in earth orbit and lunar/planetary exploration, leveraging over 50 years of experience designing, certifying, and fabricating space suits for NASA dating back to the Apollo Program. Sierra Space has over 30 years of proven spaceflight heritage, providing more than 4,000 systems, subsystems, and components to customers worldwide, and participating in more than 500 missions to space, including 14 missions to Mars and four to the moon. Sierra Space is a unique, vertically integrated space-tech company which operates through three complementary verticals: Space Transportation, Space Destinations and Space Applications. The Transportation business is developing and manufacturing the first highly reusable commercial space plane franchise capable of commercial runway landing from space. The company is currently executing a contract with NASA for seven cargo resupply missions to the International Space Station (ISS), and is also designing and developing the next spaceplane variants to carry astronauts. The Destinations business is creating the commercial space station product line of the future, which will replace the ISS upon its retirement. Sierra Space's LIFE (Large Integrated Flexible Environment) habitat product once deployed, can inflate to the size of a three-story building on-orbit. This technology provides a cost-effective way to meet mass to volume challenges by providing a stowed or packed system at launch that can deploy to a much larger volume upon pressurization. The Space Applications business has highly differentiated technologies across power generation, propulsion, environmental control and life support systems and motion control mechanisms. These technologies provide the key underlying technologies for Dream Chaser and LIFE product lines. Through a mutually beneficial partnership, Sierra Space and ILC Dover have agreed to cooperate on the development of inflatable space station modules and spacesuits.

The first serious look at inflatable spacecraft structures was by the Goodyear Corporation, in coordination with NASA, in the 1960's. Goodyear built multiple modules including an airlock, lunar surface habitats, and a toroidal space station concept[1]. Unfortunately, Goodyear was limited in its choice of materials. The materials required to support the high strength capability required by large diameter habitats were not available at the time. In 1965, the Russians launched Voskhod-2 and performed the world's first spacewalk out of an inflatable airlock. In the late 1990's NASA developed a large diameter inflatable originally designed as a MARS Transit Habitat (TransHab) and subsequently proposed as the U.S. Habitat for the International Space Station (ISS). After TransHab was canceled in 2000, a private company obtained the exclusive license to key NASA inflatable structure patents. That company, Bigelow Aerospace, advanced the technology and in 2006 and 2007 launched the Genesis I and II modules, respectively, on a Russian Dnepr rocket. In 2016, Bigelow Aerospace in partnership with NASA, designed and launched BEAM in the trunk of a Falcon 9 rocket (CRS-8). BEAM was berthed to ISS, deployed on May 28, 2016, and today is utilized as a stowage module. Originally certified for two years, BEAM has since had its certified life extended to 2028. To date, no full-scale stand-alone inflatable habitats have been deployed and utilized in space.

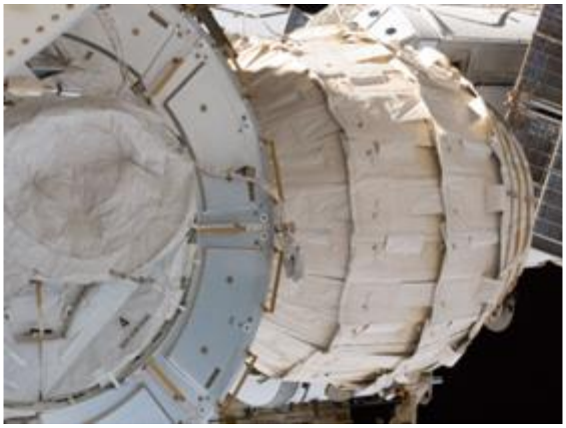

Figure 1. BEAM Module on ISS

The desired benefits for utilizing deployable habitat for space and terrestrial applications are large usable deployed volume, compact launch and transit size, and lower mass to volume ratio in comparison to state-of-the-art aluminum vessels.

The first two benefits are clearly demonstrated in the development of this class of habitats. For example, an eight to nine meters diameter deployable habitat can be packed and launched in a four meters class fairing. The benefit of small-packed size is reducing launch cost. The benefit of large usable volume is also evident in many architectural and human studies related to long duration flight habitation. Larger usable volume provides better living conditions enabling health and comfort of astronauts.

As already mentioned, two key benefits that translate to lower launch cost are smaller launch volume and lower launch mass. To date, due to strength factor of safety requirements differences (Inflatable-deployable 4X and Aluminum shell 2X), there is no clear mass benefit when comparing this class of deployable habitat to the aluminum shell vessels. However, with recent developments through certification testing, it is evident that the strength factor of safety could potentially be reduced to be closer to aluminum shell design. If realized, the potential added benefits are further reduction in launch and transit cost and/or larger diameter/volume habitats can be designed and implemented.

II. Background

The LIFE, in combination with the Node element, are the core product line elements for Sierra Space's Space Destinations. These elements provide a platform in space that can be utilized for a host of operations such as human or non-human tended payload operations, bio pharma, in space manufacturing, science research and tourism. Launched in a packed state, the LIFE habitat will be deployed, pressurized and reach its as-designed geometry upon reaching its designated operational orbit. Once pressurized, the LIFE habitat along with Node, will have over 300 cubic meters of volume, or about one-third the size of the ISS. This single launch provides significant mass-to-volume cost reduction savings in comparison to conventional aluminum or metallic habitats.

The LIFE and Node elements support programs such as the Orbital Reef Commercial LEO Destinations (CLD) (NASA sponsored program in conjunction with our partner Blue Origin). In the use case for Orbital Reef, the LIFE element provides primary astronaut support and habitation for the Orbital Reef station. LIFE will have crew quarters, a galley, commodes, support for human health and hygiene, exercise equipment, plant growth hardware for human sustainability, pressurized and non-pressurized payload hosting, and ECLSS systems (environmental support). The LIFE element is launched together with the Node and robotically berthed with the Core during assembly. The Node element is a metallic structure that supports visiting vehicles and provides the capability to maneuver itself and the joined LIFE element to mate with the Orbital Reef. The Node is a habitable volume element that is capable of hosting payloads and crew. Additionally, the Node provides an airlock to support the EVA capability for the integrated space station.

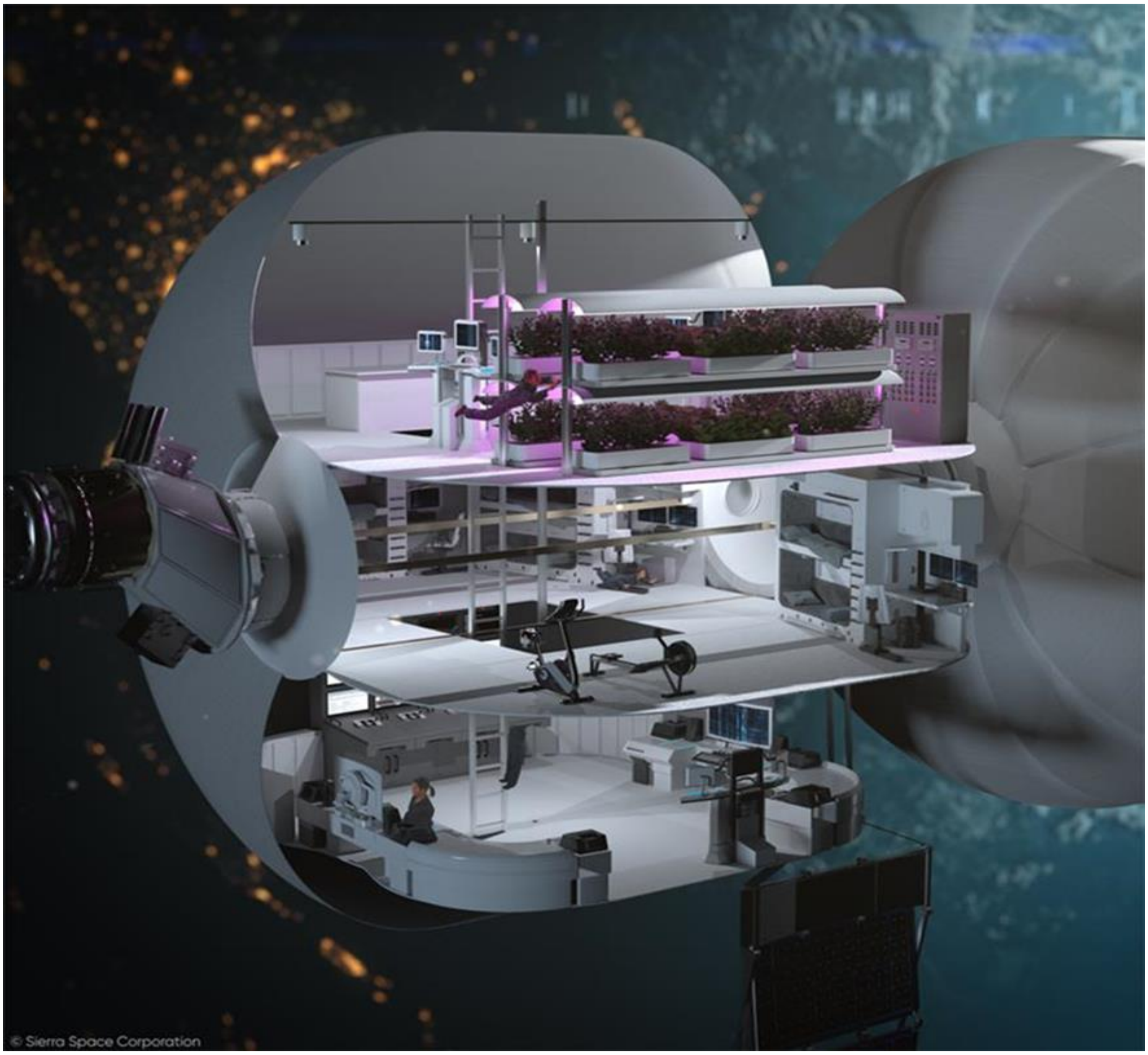

Figure 2. LIFE interior concept.

LIFE is currently undergoing certification for use in Low Earth Orbit (LEO), but future use cases exist for this technology. This technology, with minimal change, can be directly applicable for cis-lunar stations, Lunar and MARS surface, and deep space transit. Applications of this nature would likely require far longer stays for crewmembers, where having the additional livable volume would be invaluable for extra cargo space and comfort. The current LIFE architecture is designed for the microgravity environment, but modifications to the architecture would allow for planetary use as well.

The LIFE Habitat contains a total volume of roughly 10,000 ft^3 (280 m^3) through a 20 ft (6.0 meter) length and 27 ft (8.2 meter) outer diameter equating to an internal volume roughly one third of the International Space Station's livable volume today. This area is split into three floors, consisting of crew quarters, kitchen, laboratories, sick bay, storage, and a galley. LIFE is capable of supporting nominal atmospheric conditions and is actively undergoing certification for an operational life of 15 years in LEO. During that time, this space can comfortably house 4-12 crewmembers depending on the mission with closed-loop life support systems and Sierra Space's Astro Garden to provide fresh fruit and vegetables. LIFE is comprised of several layers of flexible materials all serving purposes such as providing protection from crew-induced damage, air retention, structural performance and structural health monitoring, and protection from exterior damage sources such as micrometeoroids, orbital debris, drastic temperature swings, and radiation.

Figure 3. Test article used in UBP.

Sierra Space is working towards and closely following the NASA JSC-67721[3] *Certification Guidelines for Crewed Inflatable Softgoods Structures*. The document was released by NASA in the Summer of 2022 with the intent to help guide both NASA and commercial industry partners in the development and certification of crewed softgoods Structures, such as LIFE. The primary focus of the document is on the restraint layer, or pressure shell, of the softgoods structures. JSC-67721 contains requirements, tests, and other guidance on critical metrics that must be met in order to achieve NASA Softgoods Certification. Sierra Space is working towards achieving certification from NASA, though there is a parallel, internal, effort for Sierra Space to self-certify the softgoods structures for human-rating.

In a manner similar to how softgoods materials are tested at the component level to an ultimate failure point, the same methodology and intent is captured through Ultimate Burst Pressure (UBP) testing of structural softgoods articles. UBP tests are performed on structural softgoods test articles by continuously pressurizing the test article until the softgoods fail and a burst event occurs. In Sierra Space's certification test campaign, these tests have been performed on subscale article architectures. The use of subscale test articles has allowed Sierra Space and ILC Dover to produce articles for lower cost and at a more rapid cadence while still maintaining direct scalability to the full-scale architecture (LIFE). Utilizing flight-like materials for the restraint layer of the subscale test articles further allows for scalability and direct applicability of the test results gleaned at subscale to certification for a full-scale article. Full-scale testing should be performed of the locked in design.

To support NASA's certification of Sierra Space's structural softgoods, at the date of this writing, Sierra Space has performed two (2) UBP tests on subscale test articles. Both test articles burst (failure of the structural restraint layer) at pressures which exceeded Sierra Space's structural softgoods architecture's required factor of safety. NASA JSC Structural Design Requirements and Factors of Safety for Spacecraft Hardware (JSC-65828)[2] specifies a 4.0 qualification test factor for safety critical softgood structures. Parachute systems, which are also considered safety critical, have alternate design and test factors, 2.0. Parachute systems undergo extensive testing prior to certification. Multiple UBP tests are performed on the same design architecture as specified in the NASA JSC Certification Guidelines for Crewed Inflatable Softgoods Structures (JSC-67721)[3], multiple ultimate burst tests should be performed to demonstrate consistency of the design and fabrication processes. The JSC Certification Guidelines recommends performing at least two subscale and two full-scale ultimate burst tests.

The test article is a roughly 7-foot (2.1 meter) long, 9-foot (2.7 meter) outer diameter cylindrical and toroidal shape, an exact one-third scaled version of the planned flight habitat. Given that these tests are pursuing structural data, all materials used in the test article that impact structural performance are that of flight fidelity. The test article is supported by a test stand allowing for ground clearance, handling and appropriate interface points for data acquisition equipment. In order to acquire digital image correlation data, the outermost layer of the test article is painted with a white base coat, then painted with a black speckle-pattern.

The hoop diameter of the test article is one-third of the full-scale unit. However, individual webbing components and hardware are in full-scale. In theory, because the stress in the inflatable shell is proportional to the internal pressure and radius of the vessel; by inflating the test article to three times the pressure of a full-scale unit, one can reproduce the same in-plane stress of the full-scale unit in a one-third scale unit. This approach, therefore, certifies the components of the full-scale design in a subscale test article. Testing at the subscale level is desirable in order to reduce cost and shorten schedule while still receiving relevant data.

III. Test Method, Approach, Instrumentation

Every one-third scale test article experiences a low-pressure leakage test followed by a proof test in preparation for a UBP or systematic creep test. The low-pressure leakage test is designed to verify the air-retention layer is free of leakage sources and produces an acceptable leakage rate. This test is performed at the ILC Dover plant where an article is pressurized to 2.0 psi, then isolated from the air supply for 2 hours while internal pressure is recorded to obtain a pressure decay curve. This data is then used to calculate an estimated leakage rate. The proof test is designed to confirm the integrity and geometry of the structural restraint layer by exposing an article to 1.5x max design pressure (MDP) (68.4 psi one-third scale). The leakage rate is again monitored to verify it remains within acceptable values at elevated pressure. A laser scan of the article is performed during proof testing at MDP to measure the as-built geometry and inform the design team of how closely the article matches the intended shape. This test is performed at Aberdeen Proving Grounds and is the last test before shipment to a NASA facility for a UBP or systematic creep test. For the current Sierra Space LIFE architecture, one-third scale articles have been tested by NASA at Marshall Spaceflight Center (MSFC) with exception of the first UBP test, which was performed at Johnson Space Center (JSC) in July of 2022.

UBP testing is performed by increasing the pressure of an article until the restraint layer fails. This test characterizes the strength of the restraint layer and is performed on multiple articles to inform repeatability of the design. The rate of pressure increase must be chosen such that enough time is given for the straps of the restraint layer to shift and settle as they elongate, but not too slow such that article exhibits significant creep strain which may reduce the burst value. Pressure holds are included in the test plan to allow the restraint to settle at various pressure values deemed low enough to not induce significant creep strain. For the second successful UBP test, a pressurization rate of 8 psi/min. was targeted, and pressure holds at 45 psi and 120 psi for 15 minutes each were executed.

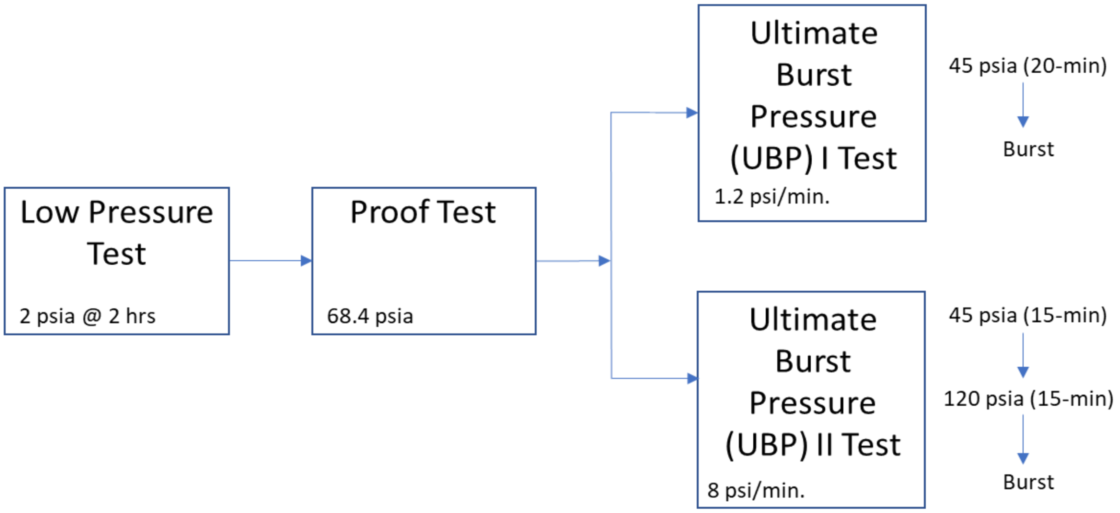

Figure 4. Test flow chart

Systematic creep testing involves pressurizing an article to a specified percentage of the UBP then holding that pressure until the restraint layer fails. The primary data to be captured is the duration that an article lasts for a given percentage of UBP. Creep testing is performed on multiple articles at varying pressure levels to form a trendline and estimate duration at much lower load levels, such as operational pressure. Duration exponentially increases as load decreases, so it is not feasible to directly test operational pressure as duration is estimated to last millions of years. The chosen pressure level for a given test is an informed decision based on specimen-level creep testing and performance of past articles with similar architecture. Since creep testing can potentially take weeks to complete, creep articles are placed in custom sheds with temperature and humidity control to keep the unit dry and maintain consistent test conditions.

All testing includes instrumentation to record essential information such as internal and external temperature, pressure, and humidity. Two high speed cameras are included, one placed on each side of an article to capture the failure event and identify the location of failure initiation. Digital Image Correlation (DIC) is utilized to understand the distribution of strain among the straps as the restraint elongates. This is a process where a speckle pattern is painted on the surface of the restraint which deforms with the restraint, and the deformation is tracked with a system of eight cameras evenly spaced around the article. The speckle pattern consists of a white based coat with black painted dots randomly distributed on top. Since the hoop straps of the cylindrical section are the highest loaded and dictate restraint failure, high speed footage and DIC processing is only enacted on the cylindrical section. The last significant instrumentation component includes strain gauges placed in various locations on the core structure. Strain gauges are included in a few locations on each bulkhead and clevises which terminate the restraint straps. This provides information about the stresses in the hardware core and how evenly the pressure loads were imparted on the core by the restraint.

Figure 5. Test article used in creep testing

IV. Results

Sierra Space and ILC Dover, in conjunction with test support from NASA, have successfully completed two UBP tests, one systematic creep test, and countless component-level (webbing) tests. Both UBP tests provided data in support of Sierra Space's Certification of Crewed Inflatable Softgoods Structures.

The first test, performed in July 2022 at JSC, was the first test of Sierra Space's run-for-record test campaign. This test, of a one-third scale of LIFE burst at 192 psi.[5] This result exceeded the 4.0 safety requirement (182.4 psi one-third scale) and overall threshold which Sierra Space is looking to surpass in order to validate and prove the structural softgoods architecture is fit for a long life in space. This threshold is calculated based on Roark's Formulas for Stress and Strain of cylindrical thin-walled pressure vessels. From this, the stress in the inflatable shell is proportional to the internal pressure and radius of the vessel; by inflating the test article to three times the pressure of a full-scale unit, one can reproduce the same in-plane stress of the full-scale unit in a one-third scale unit.[6]

The Sierra Space and ILC Dover teams then headed to MSFC for the next UBP test of a one-third scale LIFE. Taking into account some lessons learned from the first UBP test done at JSC, the MSFC team supported the second run-for-record UBP test which resulted in even better results. This was proven and validated when the second test article burst at 204 psi.[7] This result further exceeded the safety requirement Sierra Space is seeking to achieve. In addition to simply providing a great burst test pressure, the second UBP test also proved the repeatability of the design and fabrication of the test articles by ILC Dover.

With two UBP tests performed and with results that exceeded the threshold for certification, the Sierra Space and ILC Dover teams then dove into the next element of NASA's structural softgoods certification campaign and performed a systematic creep test of a one-third scale LIFE at NASA MSFC. Having an average ultimate burst pressure value is key to performing a systematic creep test, as there is an element of prediction involved with selecting the pressure value which the article will endure. Creep testing "is a destructive material testing method by which test engineers load the test unit – a subscale version of the inflatable habitat – with a sustained amount of pressure over time until it fails".[8] The selected pressure for this test was informed based on the UBP average value (198 psi) and numerous component-level ultimate tensile strength and creep tests. With the pressure selected, it was estimated that the test article would not reach a burst failure for 100 hours. The test article surpassed that mark and survived for over 150 hours before finally succumbing to the pressure and bursting.

V. Discussion

For a large inflatable habitat in Low Earth Orbit (LEO), the load bearing structural restraint layer mass is a relatively small percentage of the overall structural mass. This is primarily due to the large structural mass required for the micrometeoroid orbital debris protection layers. The micrometeoroid and orbital debris (MMOD) protection system mass is proportionally based on debris environment (more severe for LEO due to orbital debris), total surface area (obviously large for a large habitat), time on orbit, shadowing, among other factors.

Mass fractions (ratio of mass, primarily fuel, required to place each pound of payload in space) are lower for LEO than for the Lunar surface, Mars transit, and Mars surface. As Government and private entities pursue space destinations with much higher mass fractions, the need to reduce mass will greatly increase and therefore the need to push back on the 4.0 test factor will increase.

To push back on the 4.0 ultimate qualification test factor specified in JSC-65828[2], there will need to be a greater understanding of the ultimate burst capability of specific design constructs and demonstration of consistent performance of numerous test articles. In addition, there will need to be a thorough understanding of the creep life at the component and assembled level. Since the creep life chart for inflatable structures, component and assembled articles, has been plotted with percent ultimate load on the vertical versus time on a log10 scale on the horizontal axis[4], by lowering the test factor (example from 4.0 to 2.0) and thus doubling the operational load percentage relative to ultimate burst capability, the creep life is greatly reduced. Based on this type of component and assembly testing, according to JSC-65828[2], creep life will have to be shown to a 4.0 life factor at operational load. Sierra Space has conducted extensive creep life testing at the component level with additional tests at the assembly level[5]. Results from that testing are subject for a future publication.

To date, there has been limited ultimate burst testing and since LEO is the near-term objective, there has been less need, and required data, to push back on the 4.0 requirement. LEO will be the proving ground paving the way for future space destinations.

Figure 6. Orbital Reef Artist Depiction

VI. Conclusion

The successful burst and creep tests of the one-third scale units demonstrated the robustness of this class of deployable space habitat. The potential for even larger habitat or lower mass systems could be realized due to this advancement. From this success, additional features such as windows and/or equipment passthrough hardware are in development for upcoming one-third scale and full-scale test units. Full scale certification units are now in production implementing lessons learned from the one-third scale units. At the current pace of product certification, the first flight test of the LIFE module is to be expected in 2026.

Acknowledgments

Sierra Space and ILC Dover owe much of the success of our great testing performed in 2022 to the NASA teams that we worked with. Their expertise in testing combined with a bit of an unknown related to testing articles of this nature made this UBP test campaign one that all entities were excited to work on and get right. NASA JSC has been a longtime collaborator and test facility for Sierra Space and ILC Dover, so it was great to be able to utilize their facilities yet again to kick-off our certification test campaign with a UBP test there in July 2022. The NASA MSFC team has only expanded upon the great capabilities that NASA JSC offered to Sierra Space and ILC Dover for testing, setting up the facilities for both UBP and systematic creep testing.

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