Design of a Microgravity Hybrid Inflatable Airlock

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Abstract—Spacewalks, or extra-vehicular activities (EVAs), are a critical component of human space exploration for science activities and habitat construction and maintenance. For NASA's proposed lunar Gateway system, an airlock module is required for vehicle maintenance, repair, and exploration. Traditional airlock structures are fully metallic, with two chambers, known as an equipment lock and a crew lock. The larger volume, called the equipment lock, serves as the storage, logistics and electronics area, while the smaller volume, called the crew lock, serves as the volume to transition from the vacuum of space to the pressurized cabin. A traditional metallic structure design offers mass efficiency for these elements, but cannot offer volume efficiency. The potential to use an inflatable fabric pressure shell supplemented by a metallic support structure allows for efficiency in both mass and volume. Inflatable structures are being used for human habitable space modules, starting with the Bigelow Expandable Activities Module on the International Space Station. They are high-strength fabric-based structures that are compactly stowed for launch and then, once in space, they are expanded and rigidized with internal pressure. They provide significant launch volume savings over metallic structures.

For Gateway, a hybrid airlock design is proposed with both metallic and inflatable structural elements, taking advantage of each material's capabilities. A metallic equipment lock serves as both a docking node and provides pressurized volume for pre-EVA activities including pre-breathe and suit donning/doffing. A rigid equipment lock offers stowage space during launch for integrated hardware and suits. Adding an integrated inflatable crew lock provides the volume required for EVAs with minimal use of launch volume. Using dual inflatable crew locks provides redundancy and the capability to move large pieces of equipment into and out of the vehicle for repair and maintenance. The inflatable crew lock is deflated and packaged in the launch shroud and expanded after installation on the Gateway. This packing capability allows additional volume to be added to the equipment lock and fully utilize the capability of the launch vehicle.

This report outlines the work completed to design, analyze, and test the systems of a microgravity airlock with inflatable crew locks. In detail, it includes launch vehicles, structural sizing of the metallic equipment lock, the fabric layers of the inflatable crew lock, the internal structure of the crew lock, the space suit interface elements, the crew restraint system, the hatches and pass-throughs, the material and thermal elements, and the crew operations for the usage of the system. This paper is meant to offer a reference design for a hybrid microgravity airlock design for deep space human exploration.

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1. INTRODUCTION

As the United States seeks to expand its human space exploration operations beyond low Earth orbit (LEO) and onto Mars, new spacecraft must be designed and developed that can withstand the harsh conditions of deep space, while minimizing mass and maximizing habitable volume. Designers should utilize the ever growing launch capabilities around the world and introduce novel materials and methods for optimized, lightweight structures. Designs based on inflatable structures, for example, provide a significant mass/volume ratio when compared to traditional metallic structures [1]. While a lot of work has been done in the past on large scale inflatable habitats, there has been only minimal development of inflatable airlocks [2]. The inflatable airlock design in this study, known as the Lightweight External Inflatable Airlock (LEIA), offers a combination of traditional metallic structures and softgoods structures. This unique design can maximize the final pressurized volume of an airlock element, while minimizing its launch mass, making it an optimal candidate for developing into a flight design.

Airlock History and Design

Airlocks have been used for space exploration since the first-ever extravehicular activity (EVA), conducted by the USSR in 1965 [3]. The primary function of an airlock is to provide an isolated volume that can transition crew from a pressurized vehicle to the vacuum of space. This transition is completed by isolating the crew members in a separate volume with an internal and external facing hatch. Space suits are donned to provide a breathing atmosphere for the crew. The pressurized gas is removed from the isolated volume, and the external hatch is opened, allowing the crew to go out into space. When the EVA is completed, the crew goes back into the airlock, closes the hatch, repressurizes the volume, opens the internal hatch, and removes their suits.

In the early days of US EVAs, there was no isolated compartment to conduct space walks and “capsule-based EVAs” were common, where the main crew cabin also doubled as an airlock. For the Gemini and Apollo programs, all crew members donned suits and the entire volume of the cabin was depressurized. This required that the components inside the cabin were vacuum compatible, including all electronics. In the Skylab Program, an isolated airlock volume was used to minimize gas loss in the orbiting module and simplify the required hardware [4]. The Space Shuttle Program also used an isolated volume, first in the crew cabin, then later moved to the payload bay, to conduct numerous EVAs [3]. Current US EVAs on the International Space Station (ISS) are conducted out of the Joint Quest Airlock module, which is a US-provided module on the radial port of the Unity node [5].

The ISS airlock uses a dual-chamber design as shown in Figure 1 that includes both an equipment lock (E/L) and a crew lock (C/L) that are isolated from each other with the intravehicular (IV) bulkhead and hatch. The E/L is the larger of the two volumes and is where the crew members don and doff their suits and prep for their EVAs. It houses the Servicing, Performance, and Checkout Equipment (SPCE), including batteries, chargers, suit don/doff stands, consumables, and spare parts. The C/L is a much smaller volume with only enough space for two suited crew members. It holds the Umbilical Interface Assembly (UIA) which is used to provide fluids and power to the suit before and after an EVA. The C/L also contains internal handrails, lights, suit umbilicals, tool bags, staging bags, and the extravehicular (EV) hatch, which is the primary passageway for the crew members to enter and exit open space.

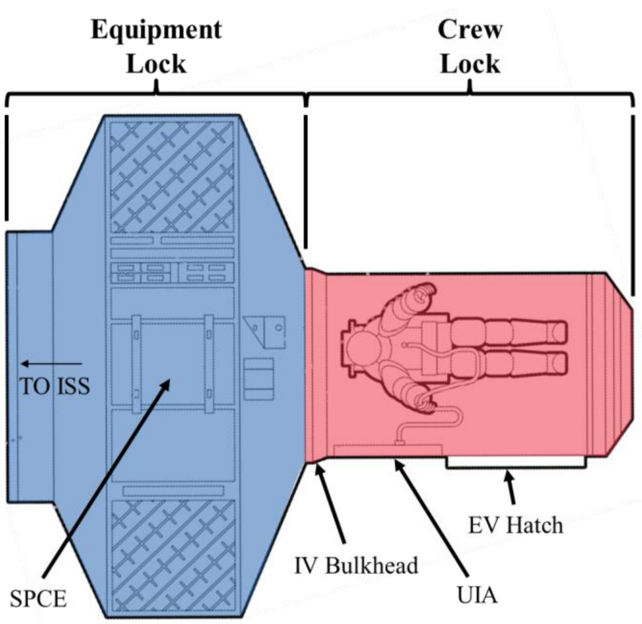

Figure 1. ISS Joint Quest Airlock module showing the dual-chamber E/L and C/L design

The dual-chamber design of the ISS airlock provides an alternate egress method in the event of a failure that prevents an EVA crew from reentering the vehicle using the nominal crew lock operation. A failure of the crew lock’s EV hatch, which prevents the crew lock from being repressurized, is an example of such a scenario. The ISS equipment lock would then function as a backup crew lock if needed. This means that the hardware inside the equipment lock can be taken down to vacuum and a secondary UIA can be installed in the equipment lock. The EVA crew members can translate into the E/L, close the IV hatch, and repressurize the E/L. This redundant capability is a significant safety improvement over the Gemini design and is a requirement for future airlock elements [6]. The dual-chamber concept of the ISS airlock formed the basis of the study for the LEIA design.

Gateway Overview

Gateway is a proposed lunar orbiting vehicle that will act as a home for astronaut expeditions on the Moon and be a proving ground for technologies and systems in preparation for a future trip to Mars. The Gateway is composed of a stack of elements, assembled in orbit, much like the construction of the ISS. The Gateway will be positioned in a near rectilinear halo orbit (NRHO) around the Moon. This location provides deep space thermal conditions, small orbit corrections, good communication, and access using the Orion Multi-Purpose Crew Vehicle (MPCV) [7]. At the time of this writing, the Gateway configuration and concept of operations is in flux, but the notional set of elements at the start of this study includes a Power and Propulsion Element (PPE), a US Utilization Module, a Habitation Module, a Robotic Arm, a Logistics Module, and an Airlock/Multi-purpose Module [8]. The Orion vehicle will carry an international crew of four to and from the Gateway, but the Gateway is not intended to be a long-term habitation station. It is planned to be used for short missions and could be dormant or robotically-operated for periods of time. Lunar landers could be docked to Gateway to provide access to the surface for future exploration and ground operations.

Ground Rules and Assumptions

The overall Gateway architecture continues to evolve, but the microgravity design and ground rules applied to LEIA are agnostic of the Gateway’s final configuration. Table 1 defines the driving requirements that are addressed in the various sections of this report. Along with these requirements, some assumptions were made to refine the scope of this work. The structural design and outfitting considerations are the primary focus of this study and mass estimates were made for required components that are not detailed in this report, such as an environmental control and life support system, power system, thermal control system, and command and data handling system.

Table 1. LEIA Top Level Requirements

Requirement	Description
Vehicle Lifetime	15 year operating lifetime
Operating Pressure	14.7 +/- 0.5 psia
Hatch Size	Provide a 1100 millimeter minimum opening for suited translation
Docking Ports	Include at least one axial forward (passive) and one axial aft (active) docking port
Space Suit Stowage	Provide volume for 3 suits stored on board (2 used during EVA)
Suit Don/Doff	Provide don/doff capability for two crew members with stand and allocated volume
Suit Interface	Provide umbilical interface assembly
Secondary Egress	Provide a secondary egress method in the event of a failed hatch during EVA
Launch Vehicle	Fit on a vehicle with capability of 15,600 kilograms and 4.6 meter diameter fairing

2. SYSTEM OVERVIEW

The LEIA module design includes a metallic equipment lock with dual inflatable crew locks (IC/L) on opposing ports, as shown in Figure 2. A cut-away view of the entire assembly is shown in Figure 3. The equipment lock includes volume for suit stowage and the SPCE, such as the don-doff stands, battery chargers, and maintenance items. The dual crew locks are identical volumes that include the UIA and EVA equipment such as tool and cargo bags. Besides the EVA specific hardware, the equipment lock offers additional volume for science experiments or extra stowage. The equipment lock acts as a node with two available docking ports, in addition to the pass-throughs and bulkheads for two crew locks.

Geometry and Mass

The primary geometry of the equipment and crew locks is cylindrical to maximize the ratio of useable net habitable volume (NHV) to system mass, while adhering to the geometric constraints of commercial launch vehicle shrouds. Protecting for a wide variety of launch vehicles drives a diametric constraint on the structure of 4.5 meters on the stowed configuration, to fit in a 4.6 meter fairing. The two radial docking ports on the E/L utilize the NASA Docking System (NDS), Block 2 design. The NDS extends beyond the outer mold line of the E/L by 0.5 meters [9]. In the launch configuration, the inflatable crew locks are stowed on the exterior of the equipment lock and are packed such that they extend no further than the NDS height of 0.5 meters. With these constraints, the diameter of the cylindrical equipment lock structure was maximized at 3.5 meters. Based on a first order approximation, the length of the equipment lock was set to maximize internal volume while adhering to Space Launch System (SLS) Block 1B size constraints with a co-manifested launch of LEIA and the MPCV [10]. These dimensions result in a pressurized volume of about 44 cubic meters, with approximately 27 cubic meters of NHV for the equipment lock.

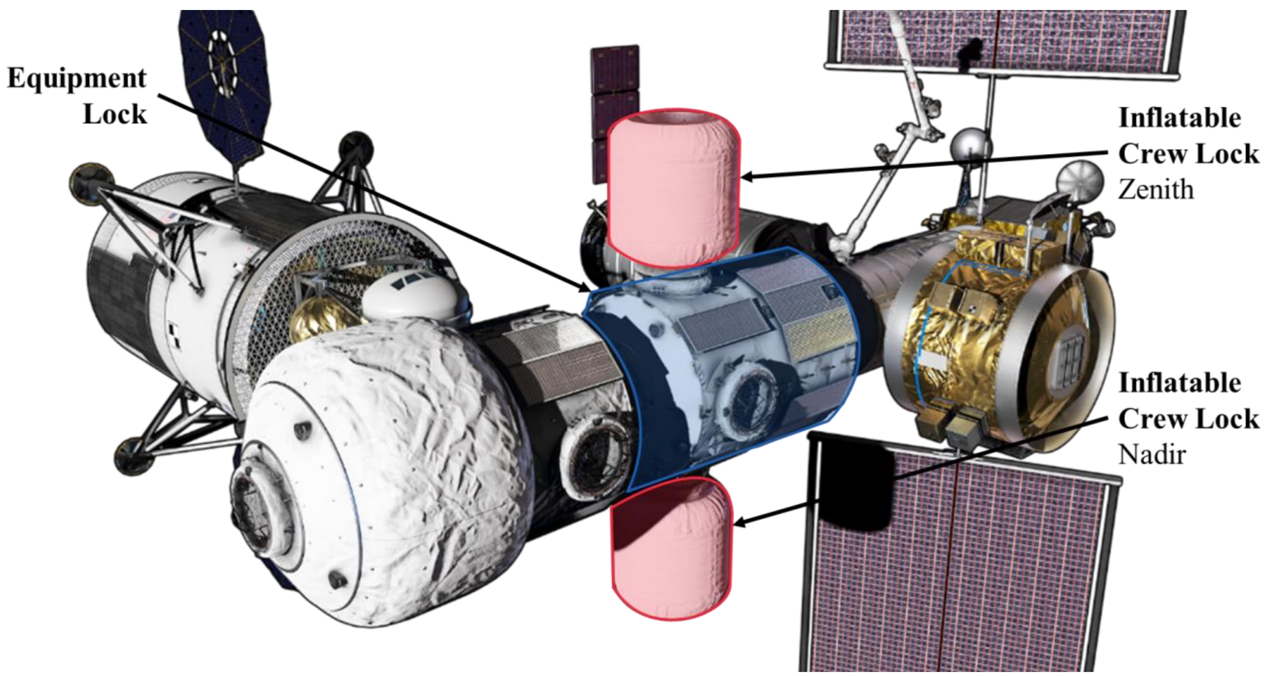

Figure 2. LEIA module design, highlighted, shown integrated into a notional Gateway stack

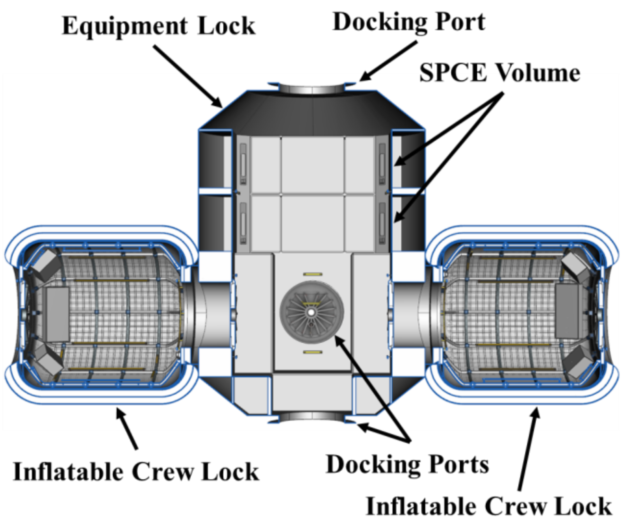

Figure 3. Cut-away view of the LEIA module, showing the equipment lock and dual inflatable crew locks

The inflatable crew lock was sized to maximize mobility of two suited crew members to operate the UIA and EV hatch during EVA operations. The ISS extravehicular mobility unit (EMU), or space suit, has visibility and mobility limitations that only allow operation of the ISS Joint Airlock EV hatch to be operated with the crew member facing the hatch plane [5]. Although the new suit to be used for Gateway, known as the xEMU will offer significantly greater mobility and visibility [10], the recommendation was made to use the constraints of the ISS EMU in this initial LEIA design.

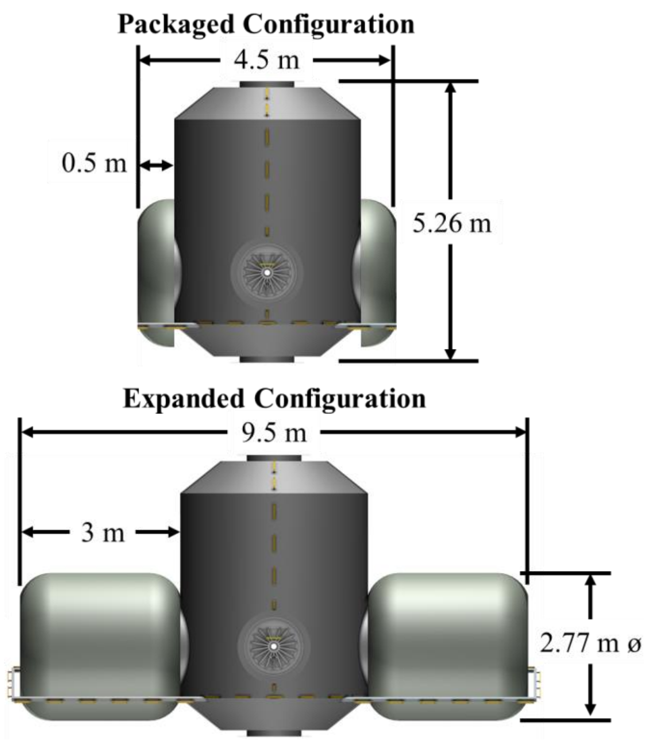

Figure 4. LEIA overall dimensions in both packaged and expanded configurations

Therefore, the inflatable crew lock accommodates a suited crew member in an upright position, to be facing the EV hatch. The length of the crew lock is sized for the EVA crew members to be back to back without interference. The internal length of the crew lock is 2.4 meters with an internal diameter of 2.3 meters. This results in a pressurized volume of 9.7 cubic meters, with approximately 9.4 cubic meters of NHV for each inflatable crew lock. The LEIA crew lock provides a 76.4% increase in pressurized volume as compared to the ISS airlock. Figure 4 shows the overall dimensions of LEIA in its packaged and expanded configurations, respectively.

When examining the overall system mass, allocations were derived from previous Gateway module design work with additional considerations made for the equipment required to perform pressure cycling of the crew locks for EVA. Due to the low maturity of these mass allocations, mass growth allowances (MGA) were applied to the subsystem totals to determine the current best estimate (CBE) of each subsystem mass. The MGA applied to the overall LEIA mass was a weighted average of the various subsystem MGAs, which resulted in a total LEIA CBE mass of 8.1 metric tons. The master equipment list in Table 2, provides an itemized list of MGA and CBE allocations.

Table 2. LEIA Module Master Equipment List

Subsystems	**Basic Mass (kg)**	**MGA (%)**	**MGA Mass (kg)**	**CBE Mass (kg)**
Primary Structure	1031	15	154.7	1185
Secondary Structure	226.5	18	40.77	267.3
NDS Block 2 (x4)	1104	5	55.2	1159.2
Meteoroid Protection	114	25	28.5	142.5
Power	560	30	168	728
Command Data Handling	135.8	30	40.7	176.5
Communications Tracking	17.5	30	5.25	22.8
Crew & Crew Systems	382.6	10	38.3	420.9
Thermal Control	810.6	21	170.2	980.8
Environmental Control	269.2	13	34.99	304.2
Equipment Lock Total	**4651.2**	**--**	**736.6**	**5387**
Inflatable Structure (x2)	1360	15	204	1564
EVA	849.2	5	42.46	891.7
Air Save Pumps	130	10	13	143
Crew Lock Equipment	80.9	0	0	80.9
Crew Lock Total (x2)	**2420.1**	**--**	**259.5**	**2679.6**
Airlock Module Total	**7071.3**	**--**	**996.1**	**8066.8**

Launch Vehicle and Interface

As mentioned above, LEIA was designed to fit within a variety of commercial and government launch vehicles. The two driving design constraints imposed by the various launch vehicles are the static envelope of the interior of the payload fairing and the payload adapter fitting interface diameter. The common, minimum size across all available vehicles is a 4.57 meter diameter fairing envelope and 1.575 meter diameter payload interface ring, which has a defined plane that cannot protruded by the payload.

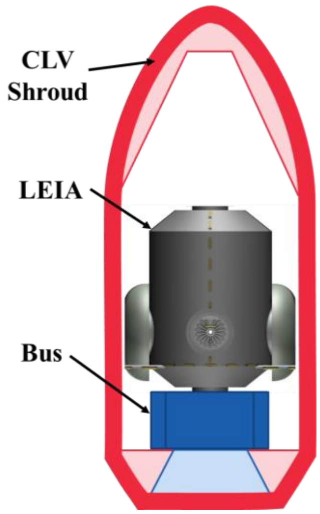

Figure 6. LEIA launch configuration with attached bus in a CLV shroud

With a total system mass of 8.1 metric tons, LEIA can be launched and delivered to the Gateway NRHO by the SLS Block 1, while co-manifested with Orion. If launched on a CLV, LEIA requires a co-manifested 'bus' to provide guidance, navigation, control, power, and propulsion to get LEIA to the Gateway orbit. The addition of the bus in the launch vehicle fairing imposes a height limitation on LEIA and cuts into the available payload launch mass. A number of commercially available busses with similar performance characteristics were reviewed and the bus with the largest mass and lowest height was chosen to envelope the options. Figure 6 depicts the launch configuration of LEIA with an attached bus in the most restrictive CLV shroud.

3. EQUIPMENT LOCK

Structural Sizing

Structural analysis was completed on the equipment lock design to maximize the available internal volume and minimize the overall structural mass. Three load cases were considered for this structural sizing effort including launch, ultimate pressure, and a predicted worst case on-orbit loading from a reboost event of the Gateway. The Gateway Program Structural Design Requirements defined the factors of safety and analysis approach used for this study as 1.1 for yield and 1.5 for ultimate [12]. Compared to the NASA Standard for Structural Design and Test Factors of Safety for Spaceflight Hardware, these leaner factors of safety in DSG ultimately resulted in the on-orbit load case sizing a majority of the equipment lock's primary structure [13].

The launch load case is defined as the maximum magnitudes found within the launch vehicle acceleration profile. The profile used is common for most launch vehicles and is considered the worst case [14]. The gage pressure between the equipment lock and the surrounding atmosphere during maximum acceleration was determined to be insignificant and was not considered for this load case.

The maximum design pressure (MDP) for LEIA is 15.2 psig, as defined by Gateway requirements, which protects for an ECLSS contingency scenario above the 14.7 psig operating pressure [14]. This MDP was used both for the ultimate pressure and on-orbit load cases. The predicted worst case on-orbit loads were a combination of MDP and the NDS docking loads [9], shown in Table 3. The factors of safety used in this analysis were defined by the Gateway structural requirements [12].

Table 3. LEIA On-orbit Worst Case Structural Loads

Load Case	Loads
Internal Pressure	15.2 psid
Compressive Axial	13,700 N (3,080 lbf)
Tensile Axial	13,700 N (3,080 lbf)
Shear	16,700 N (3,754 lbf)
Torsion	15,000 N-m (11,063 ft-lbf)
Bending	68,700 N-m (50,671 ft-lbf)

With the loads and assumptions established, a finite element model was created to perform the structural finite element analysis (FEA). The initial results of this analysis were then input into the optimization software HyperSizer (version 7.3.57), licensed by Collier Research Corporation. Within HyperSizer, different design concepts for panel and stiffener construction can be explored and optimized for a given set of model and analysis results. An iterative cycle of design and analysis is completed within the software until an optimized design is achieved. HyperSizer's objectives throughout this iterative process is to minimize mass and margins of safety while adhering to a set of over 20 failure criteria for each individual panel and beam component.

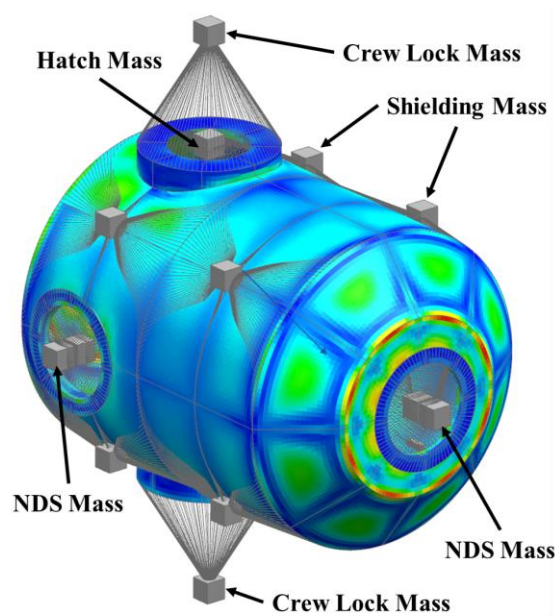

Figure 5. Finite element analysis results showing mass constraints and principal stress contours

For LEIA, the structural sizing was completed with five iterations of the optimization cycle. The finite element analysis results for the principal stress is shown in Figure 5. The final design of the LEIA equipment lock primary structure is an orthogonal, grid stiffened panel construction with a combination of I-beam and rectangular beam stiffeners. An example of this type of structural design is shown in Figure 7.

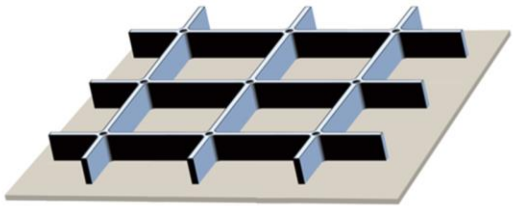

Figure 7. Orthogonal, grid stiffened structure example

Since the LEIA system mass is about 2 metric tons under the launch vehicle capability, further structural optimization can be completed to fully maximize the capability of the launch vehicle. Future work should be focused on narrowing down launch vehicle scope, so that increases to net habitable volume (achieved by increasing E/L barrel length) can be made until a system mass or launch vehicle shroud dimensional limit is reached.

Bulkheads and Hatches

Since an airlock is required to provide an alternate egress method in the event of a failure of the crew lock, the LEIA design uses dual crew locks to meet this requirement and offers redundancy and duplication in the crew lock systems. However, a single crew lock design was traded during development that looked more like the ISS dual-chamber design. Figure 8 shows a comparison of both LEIA designs. In the single crew lock design, a bulkhead and hatch were added inside the equipment lock that divided the volume into two sections. The node section can be used as the emergency egress volume in the event of a failure of the crew lock and the crew can move into the node and repressurize. This requires that the node section be vacuum capable and that all hatches are closed. However, with the hatches closed, the access to the Orion vehicle, and any other attached visiting vehicle, is cut off during the EVA operation. The dual crew lock design, on the other hand, does not restrict access to the ports and still provides an emergency egress method. It also reduces the complexity of the equipment lock design by eliminating the internal bulkhead and hatch. Although this dual crew lock design comes at an approximately 400 kilogram mass increase compared to the single crew lock option, its operational benefits should outweigh the mass cost.

The bulkheads and hatches on the equipment lock use an NDS clearance opening of 800 millimeters, except for those interfacing with the crew locks. The Gateway Program will use a common hatch design among all of the elements in the stack, which has yet to be determined, so the NDS size was used as a baseline. The radial bulkheads that support the two crew locks are 1500 millimeters in diameter, using the ISS D-hatch with a 1000 millimeter opening. The EV bulkheads on the crew locks also uses this D-hatch design. The decision was made to use the D-hatch as a reference for this study because of its historical precedence. However, the xEMU and Gateway requirements, shown above, require an 1100 millimeter opening. Future work will be conducted to finalize the design of a Gateway airlock hatch to accommodate this larger opening, but significant changes to the LEIA bulkhead interface are not expected.

Internal Layout

With the primary structure defined, volume allocations were made for required EVA components inside the equipment lock. The equipment lock has a total net habitable volume (NHV) of 27.3 cubic meters, which can be considered in two major sections, as shown in Figure 9. In the stowage section, 6.3 cubic meters of volume is allocated for recharge tank assemblies (RTAs), three xEMU assemblies, two suit donning and doffing stands, and the remaining SPCE [6]. The node section is similar to an ISS node, but contains two IC/L hatches, two visiting vehicle docking ports, and the forward docking port. This section is kept clear for translation paths into the various ports, but also offers an 4.7 cubic meters of additional stowage volume. Future work will be completed to define the secondary structure required for the internal components of the equipment lock and further refine the overall mass estimate.

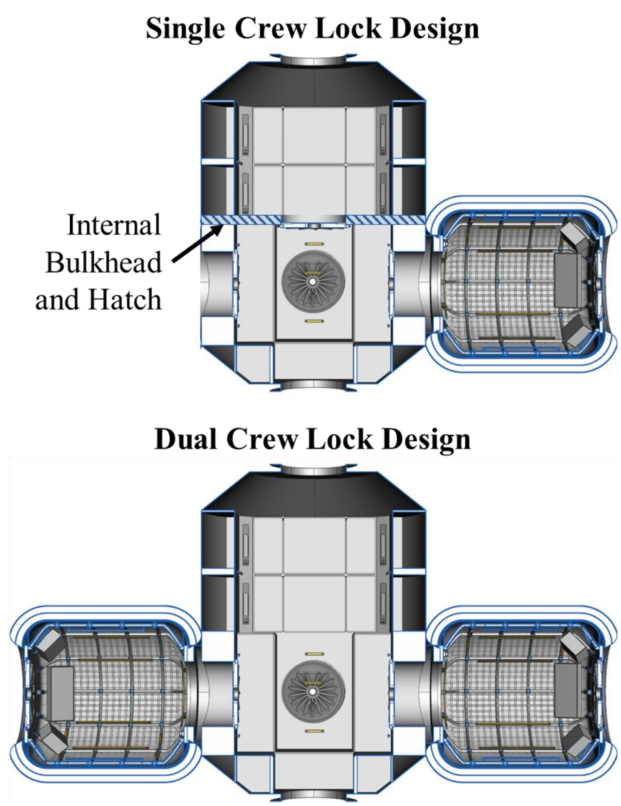

Figure 8. Comparison of single vs. dual crew lock design

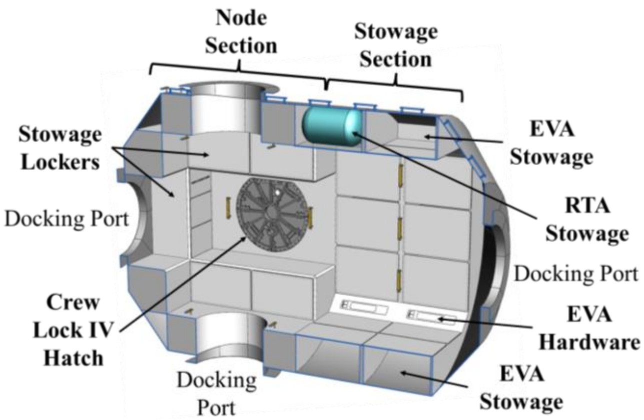

Figure 9. Equipment lock cut-away view, showing node and stowage sections with allocated volume

Module Interfaces and Docking Ports

The LEIA module accommodates axial installation on the Gateway stack, as proposed in early Gateway concepts, but can be installed off a radial node if required. Notionally, the module would be attached to Gateway through its aft docking port, while the forward port is used for docking of the Orion MPCV. One of the key features of the LEIA design is that it not only provides EVA capability, but also provides an additional two docking ports for visiting vehicles to Gateway. The two ports will enable acceleration of lunar surface exploration and operations, as more human lander systems and logistics vehicles will be allowed to dock to Gateway at the same time. Figure 10 shows a notional orientation of the ports on the LEIA module. The two crew locks are placed on

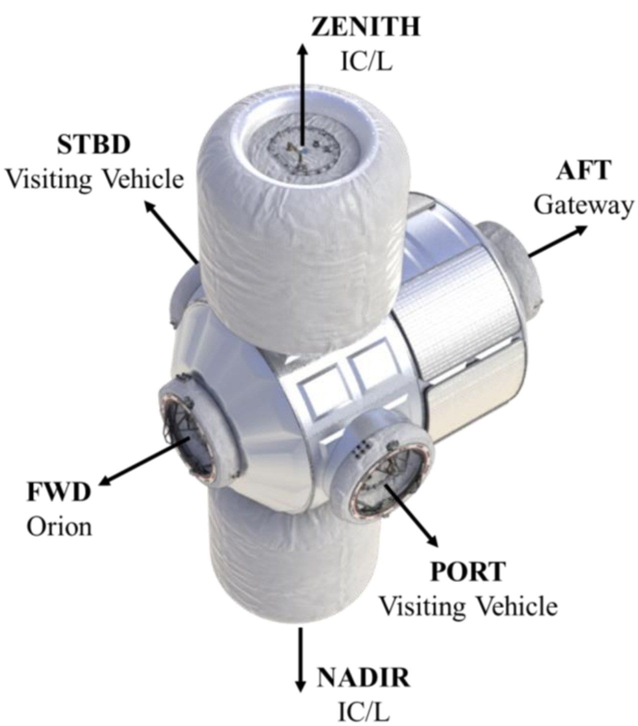

Figure 10. Notional orientation of LEIA docking ports

opposite sides of the equipment lock from each other to reduce loading going into the equipment lock during acceleration events and to provide common clearances for visiting vehicles on the two radial ports. The zenith and nadir positioning of the dual crew locks was to ensure equivalent thermal environments for both crew locks, so that a common design could be utilized and cost savings could be realized. This also allows visiting vehicles to approach Gateway from both the port and starboard directions. The 'inline' design of the airlock module, as shown in Figure 2, along with dual crew locks, ensures that IV crew members are never cut off from the Orion MPCV, if they require access during EVA operations.

4. CREW LOCK

Shell Layers

The inflatable crew lock uses a softgoods pressure shell that is structurally connected by two parallel metallic bulkheads. This allows it to be packaged for launch and expanded to full volume once at Gateway, saving coveted launch volume. The shell is made up of a number of fabric layers that provide atomic oxygen protection, thermal insulation, micrometeoroid and orbital debris (MMOD) protection, a structural pressure shell, and a gas barrier. The shell layup is based on the inflatable designs of the TransHab project [11] but is tailored towards an airlock application for microgravity. The baseline layup for LEIA is shown graphically in Figure 11 and includes an outer ortho-fabric layer, outer multi-layer insulation (MLI) thermal layer, MMOD shield layer, structural restraint layer, gas bladder layer, and inner protective liner.

The outer ortho-fabric cloth protects the vehicle from atomic oxygen, which is prevalent in LEO and low Martian orbits. The MLI layer provides passive thermal protection for the vehicle. The MMOD shield protects the vehicle from impacts from micrometeoroids and orbital debris. Orbital debris strikes pose greater risk in LEO where there is greater density of orbital debris, but micrometeoroids are the driving threat in the Gateway NRHO. The restraint layer is the load bearing structural layer that bears the pressure load from the inside of the inflatable. The bladder layer is a gas barrier to prevent air leakage from the vehicle while the crew lock is pressurized. The inner most layer is a flame resistant, abrasion and cut resistant liner that protects the bladder layers from damage from inside the vehicle.

MMOD Layers

The MMOD protection layer is shown in Figure 11 and is composed of four Nextel bumper layers and a rear wall of stacked Kevlar broadcloth layers. The bumper layers are separated by open-cell foam that is used as a lightweight spacer. During launch when the inflatable is packaged, the foam is compressed, but once in space the foam expands to provide the proper spacing.

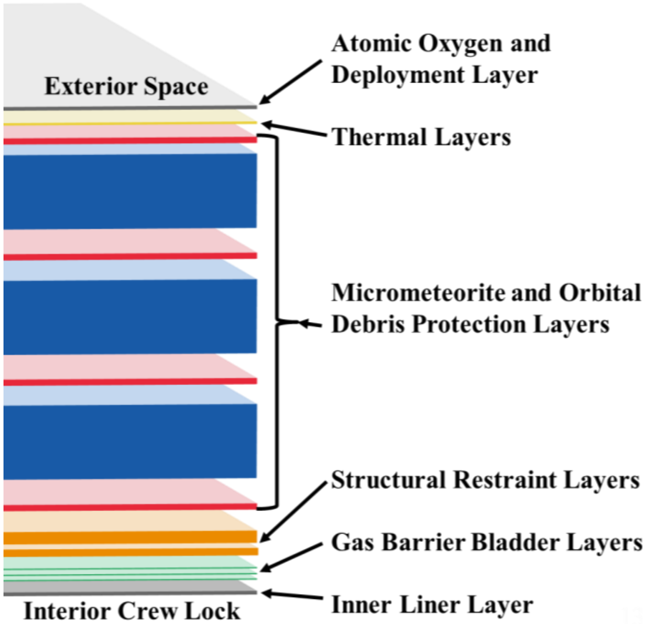

Figure 11. LEIA softgoods shell layer stack-up

A typical MMOD shield for a spacecraft is sized for its operating environment and the potential risk of orbital debris and micrometeoroids. This sizing is completed with hypervelocity impact testing and analysis from the NASA JSC software package known as Bumper, which has been used by NASA and contractors to perform meteoroid/debris risk assessments since 1990 [16]. For the LEIA assessment, the micrometeoroid environment model MEM-R2 in Bumper v3 was used. The total shield surface area and a variety of areal densities were used to calculate the micrometeoroid penetration risk per year for each shield configuration option. Comparing these results to the Gateway MMOD shield requirements drove the LEIA design to a four bumper layer configuration with a total 10 centimeter standoff from the outer layer to the rear wall. This configuration provides a 50% margin to allow for potential changes to the requirement environment. The results of the sizing analysis is shown in Figure 12 with the Gateway limiting requirement. This analysis will be continually updated as new environment models are released.

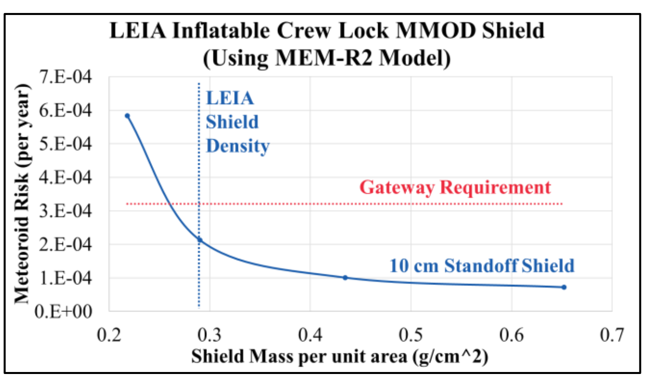

Figure 12. MMOD shield sizing results showing the meteoroid risk per year versus the shield mass unit area

Restraint Layer

The restraint layer is the primary structural layer of the LEIA softgoods shell. The internal, pressurized gas that inflates the module imparts pressure loads on the shell that are fully carried by the restraint layer. The restraint layer is made of high-strength Vectran materials in two sublayers. The outer sublayer is 25.4 millimeters (1 inch) wide Vectran webbing straps that are woven in a basket weave configuration. The webbing layer is composed of straps with 55,602 newtons (12,500 pounds) capability in the hoop direction and 26,689 newtons (6,000 pounds) capability in the longitudinal direction. The inner layer is a 200 denier Vectran broadcloth with a balanced weave of 70 newtons/millimeter (400 lbs/in).

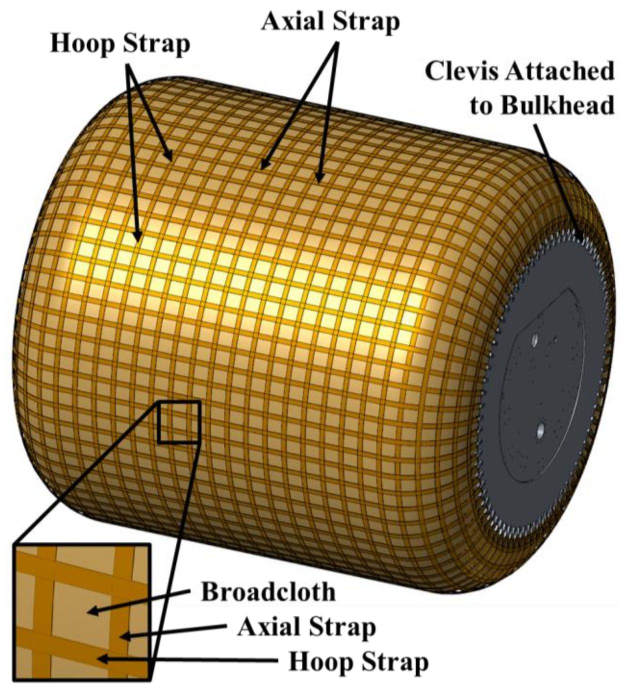

Figure 13. Restraint layer showing webbing layer, broadcloth layer, and clevises attached to bulkheads

The stress in the cylindrical section of the restraint layer can be found by using the stress equations for a thin walled pressure shell [17], the MDP, and the crew lock dimensions. Unlike the TransHab restraint layer [11], which was a tightly woven basket weave design, the LEIA design is a loose weave that includes gaps between the straps. The broadcloth layer is used to carry load between the gaps and prevent the bladder layer from being stressed. The webbing layer is sized by examining the hoop and longitudinal stresses separately and determining the optimal number of hoop and longitudinal straps in the design to provide positive margins of safety and redundancy. These calculations include a number of factors such as the NASA required factors of safety, the strength of the webbing straps, the efficiency of the looping seams, the creep life of the materials, the damage tolerance of the system, and the assembly knock downs that are imposed during weaving and final assembly.

The sizing of the LEIA restraint layer resulted in a design with 18 hoop straps and 73 longitudinal straps with a gap region of approximately 80 x 80 millimeters in the cylindrical region, as shown in Figure 13. Restraint layer showing webbing layer, broadcloth layer, and clevises attached to bulkheads. The longitudinal straps are looped at either end and are attached to each bulkhead through a rolling clevis that allows the strap to rotate during inflation. The clevis is structurally attached to the bulkhead and helps transfer any loads from the bulkhead to the restraint layer. The hoop straps are used around the circumference of the restraint layer and are overlapped on each other to form a single loop. Both the longitudinal and hoop straps use a TransHab developed high-efficiency overlap stitch.

The broadcloth layer, as shown in Figure 13, is used to carry load in the gaps between the webbing straps. It will only carry a small amount of load in the regions between the straps that will pillow out. The open weave design of the LEIA webbing layer results in a 40% weight savings compared to the tight weave TransHab design, even with the addition of the broadcloth layer.

To validate the sizing analysis, a 1/3rd scale test article is under construction that includes a representative restraint and bladder layer, including both the webbing and broadcloth layers. The restraint layer uses the same webbing materials as the full size design, but with fewer number of straps in order to get flight like stresses into the materials. This test article will undergo pressure testing to evaluate the overall design and better understand the knock down factors involved with a stitched assembly.

Bladder Layer

The bladder layer is the gas barrier of the softgoods shell and holds all the air inside the crew lock. Although the bladder layer is inside of the restraint layer, it is oversized in relation to the restraint and does not carry any loads. The bladder is sealed to the bulkhead using the TransHab O-ring interface [11]. Because of its oversizing, the bladder presses firmly against the fabric and the restraint layer takes the entire load. Due to the lack of loading, the bladder does not require a high tensile strength, but because of its primary gas barrier function, it does require low permeability.

In the TransHab design, the bladder was one of the inner most layers and could be kept warm by the internal gas and the outer MLI layer. In an inflatable crew lock however, the internal gas will be evacuated and the inner layers will be exposed to cold temperatures. Common polymeric bladder materials are sensitive to extreme cold temperatures and the bladder layer should be kept above the material's low temperature limit to prevent it from becoming brittle and failing prematurely. During a full EVA cycle, the crew lock internal layers will be exposed to deep space temperatures and mitigation may be required to protect the bladder. During EVA operations, while the EV hatch is open, a thermal blanket cover will be used as a closeout to reduce the thermal loss of the airlock interior.

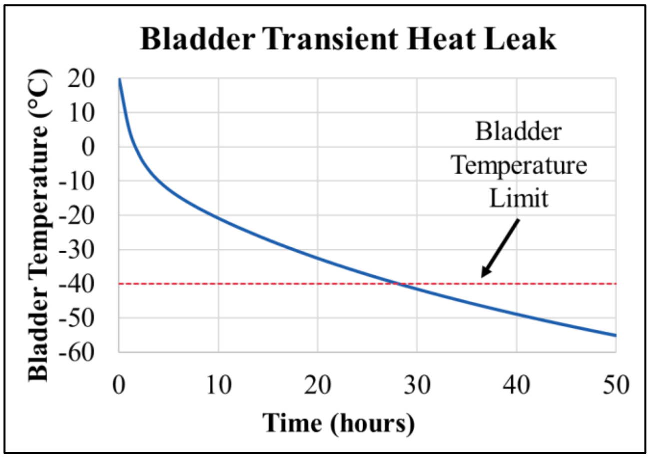

Figure 14. Results of the analysis model showing transient heat leak at the bladder layer over time

In order to analyze and predict the thermal performance of the shell layers in deep space, a thermal model was created based on the TransHab shell layer stack up. The initial model used Transhab materials for each of the shell layer except for the bladder material which was changed from TransHab's Combitherm to a commercially available CEPAC HD-200.

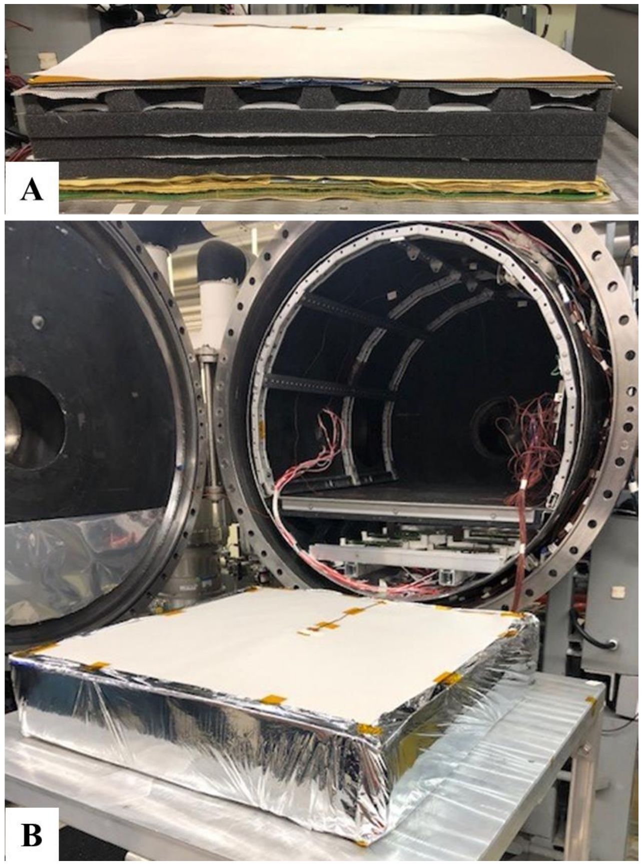

Figure 15. Thermal vacuum test article layup (A) and instrumented test article and JSC Chamber N (B)

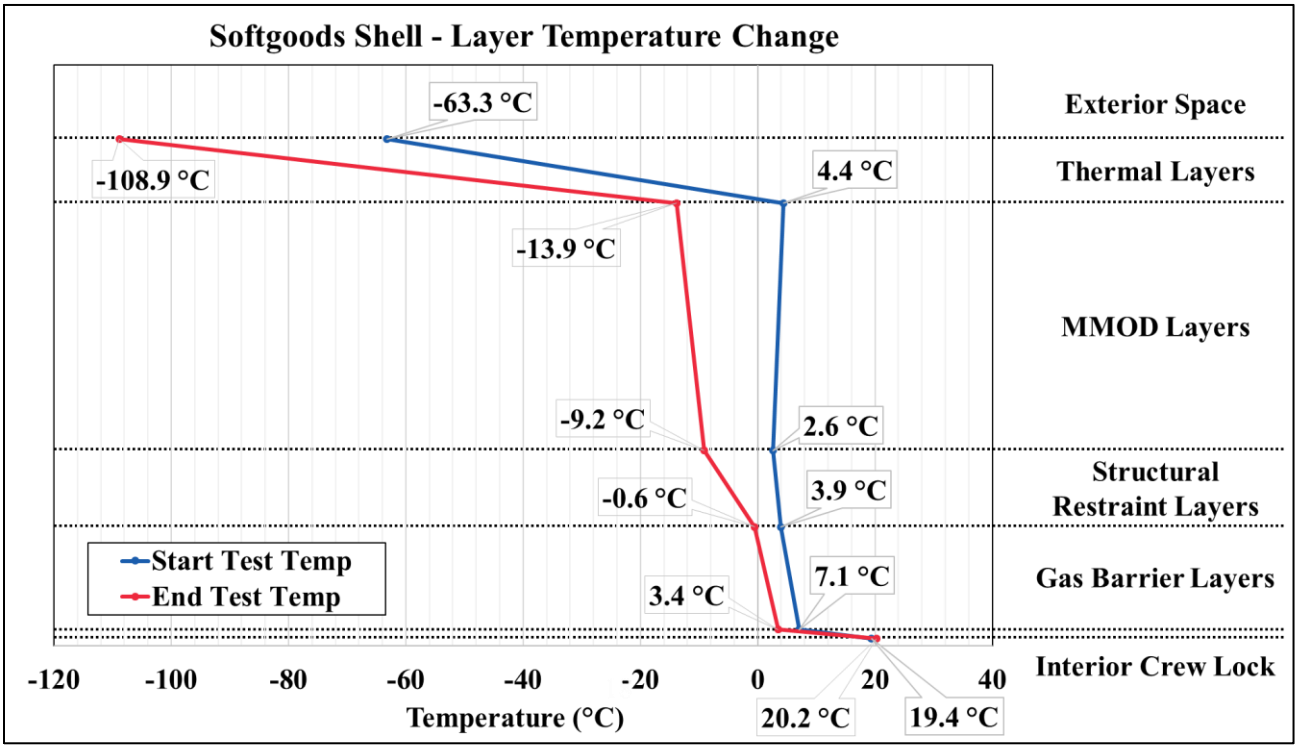

Figure 16. Results from the thermal vacuum test showing temperature change of the softgoods shell layers at the start and end of the test

The CEPAC material was listed as the preferred embodiment in a 2005 Bigelow Aerospace patent [13], and was used as a baseline for LEIA. The thermal model was used to understand the temperature change of the bladder layer during a full EVA cycle, from a warm, pressurized, shirt sleeve environment operation (20°C), to a cold, depressurized, suited environment with exposure to deep space (-271°C). Initially, a steady state one-dimensional model was created to predict the average thermal conductivity of the stack up. These results were then fed into a three-dimensional cylindrical model to predict material temperatures during an EVA cycle and assess the need for heater power to keep the bladder temperature above its material limit. The assumed lower temperature limit for the bladder material was -40°C. The transient analysis of the three-dimensional model set the starting temperature of the bladder layer to the crew environment of 20°C, then allowed for thermal transfer over time to determine when the bladder layer would hit the low temperature limit, simulating the cooling that will occur during an EVA of indeterminate length. The model predicted that the stack up would remain above that temperature for 29 hours with no heaters, as shown in Figure 14.

A thermal vacuum test was conducted to correlate the thermal model predictions. The test article was made up of a flat layer stack up as shown in Figure 15 with thermocouples between various layers to measure the temperature change during an 8 hour EVA cycle. The test started with the test chamber being pulled down to deep vacuum, which cooled the top side of the test article (to -63 °C), while a heater was used to maintain the temperature of the underside (to 20 °C) to represent the outside and inside respectively of the crew lock before opening. The test results are shown in Figure 16 and highlight the material layers' temperature change over time. The two data curves represent the temperature through the layers at both the beginning and end of the 8 hour test. The outermost layers cooled by 40 °C during the test, ending at -109 °C. The bladder layer changed by only 4 °C, from 7 °C to 3°C after 8 hours. The temperature differences show that the thermal layers of the shell stack-up very effectively insulated the interior layers. The data collected from this test characterizes each layers' thermal properties, which will allow the one-dimensional thermal model to be correlated to test data. From that correlated model, the three-dimensional model will be iterated to accurately predict the bladder temperature change during an EVA cycle and guide a potential design for internal thermal insulation or heaters, if required.

Internal Structure

The crew lock requires an internal rigidizing structure to support the fabric layers of the pressure wall during depressurization and EVA operations. This structure also provides mounting locations for equipment, tools, foot restraints, hand rails, etc. The design team traded four primary concepts for the internal structure as illustrated in Figure 18: a constructible truss, a deployable mechanism, an inflatable beam truss, and an inner inflatable wall.

The 'constructible truss' is a composite or metallic framework composed of longerons and hoop members connected by single action connector nodes. Crew members or robotic systems would assemble the truss in-situ with some assembly completed prior to launch by ground technicians. All components not preassembled on the ground would launch in a stowed construction kit for later use by the crew. Each section of the truss would connect to a node at either end, as shown in Figure 17, using a simplified version of the NASA Langley Research Center developed constructible truss connector mechanism [14]. This design was used as the baseline internal structure due to its apparent simplicity and relatively high technology readiness level (TRL).The 'deployable mechanism' concept consists of three independent three bar linkages, as shown in Figure 18. It could be stowed folded, and would unfold with the expanding EV bulkhead during inflation. Following initial inflation, the crew would then push the linkages over center and secure the joints with pins to remove all degrees of freedom and stabilize the structure. One benefit of this concept is that the designer could spring the joints in such a way to either assist or restrain the crew lock initial inflation depending on system needs.

The 'inflatable beam' concept and the 'inflatable wall' concept are very similar to one another. In both concepts, the secondary structure of the crew lock consists of fabric or graphite composite stiffened air beams inflated to a low gage pressure. The air beams would be pre-integrated into the softgoods layers of the crew lock. The inflation of the secondary air beams could occur at the initial inflation of the primary volume and remain pressurized throughout the life of the crew lock. Conversely, secondary inflation could occur just prior to each EVA, using the air from the primary volume as a means of air conservation. The primary difference between these concepts is the number, size, and location of the composite stiffened air beams within the crew lock. Both of these concepts would allow for more flexible packaging of the crew lock for launch, and minimize crew time after inflation.

To down select one of the four concepts, the team compared each concept against the following criteria, listed in order of importance: mass, stiffness, maintainability, TRL, operability, and internal volume intrusion. After going through the comparison process, the constructible truss was

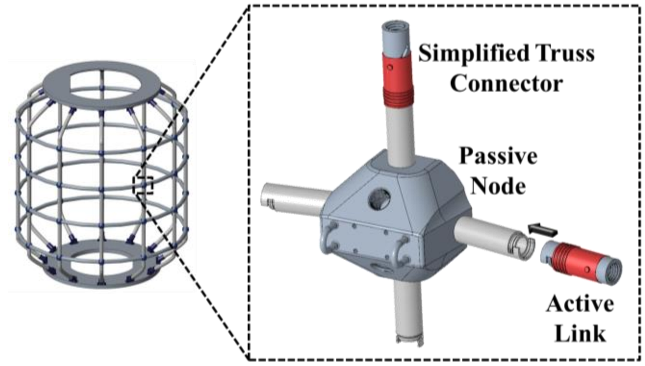

Figure 17. Constructible truss system uses a simplified truss connector with passive nodes and active links

awarded the highest rating, while the remaining concepts ranked from best to worst: constructible, inflatable, and deployable. Feedback from crew members indicated that the time required to build the constructible truss would not be significant compared to the maintenance time required for the more complex, inflatable truss design. Moving forward, the constructible truss will be the focus of development for the internal structure of the crew lock.

The other concepts will continue to receive some development attention at a lower level to advance their TRL to be more attractive options in future spacecraft. The deployable concept model and kinematics will be refined to arrive at a more mature and optimized design and scale prototypes will be 3D printed using plastics. The inflatable air beam concept will undergo some unit level testing on the air beams to get a better understanding of the stiffness versus internal pressure relationship. In addition, the team will investigate stitching methods for the air beams to determine a method that retains the maximum possible strength in the parent material.

As stated, the constructible truss will receive the majority of the future development effort. A tolerance analysis will be conducted to ensure the truss will fit in a pressurized airlock. A design effort for the simplified connector mechanism is underway, which should yield a connector better suited to IV requirements. This connector will be bonded to both

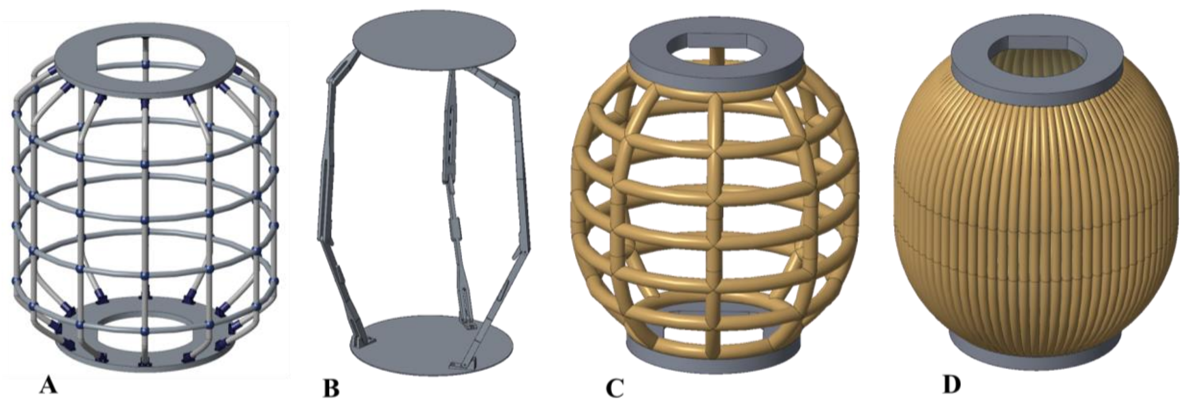

Figure 18. Internal structure concepts including the constructible truss (A), deployable mechanism (B), inflatable beam truss (C), and inner inflatable wall (D)

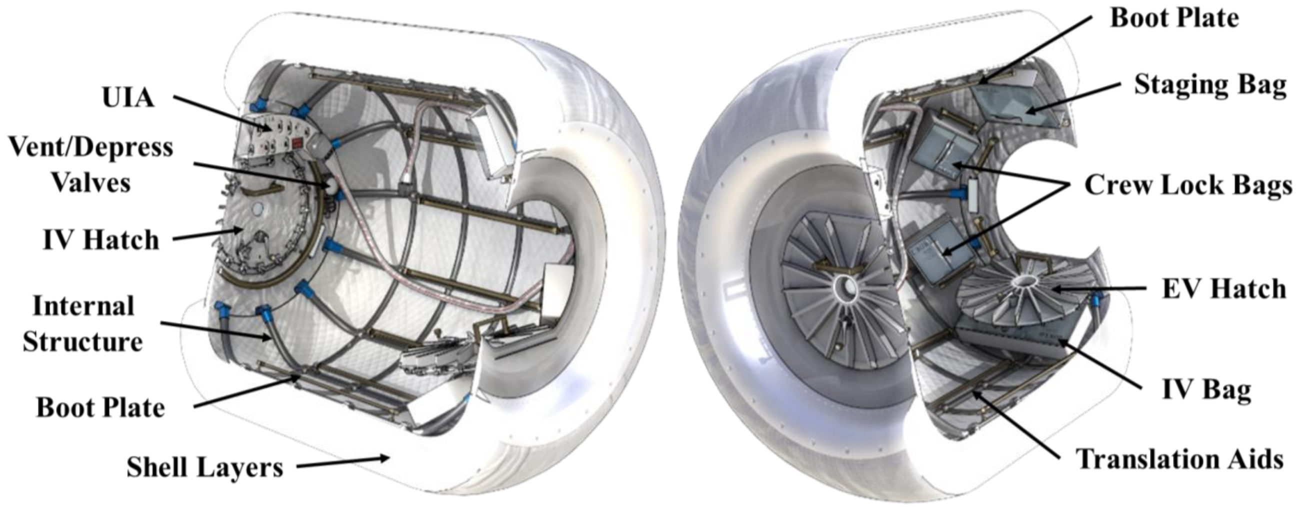

Figure 19. Cut-away view of crew lock with critical components identified

composite and metallic tubes to form the individual truss members. In parallel, design of the connecting nodes is also underway. When these efforts are complete, the metallic truss members will be used to construct a scale model of the internal structure for a mass estimate and load testing. The composite truss members will be used to construct an octant of the full scale structure for human in the loop usability testing.

Internal Layout

The crew lock provides interface equipment and mounting locations for all of the components necessary to support EVA operations. Because of the softgoods outer structure, most of the rigid components are mounted at the bulkhead ends of the crew lock and all other equipment is mounted on the internal structure, so nothing is attached directly to the softgoods layers. Critical components for a crew lock include the UIA, pressure relief valve, inter-module ventilation valve, and depress air valve. Additional components are attached to the internal structure including EVA bags, handrails, foot restraints, lights, cameras, as shown in Figure 19.

Figure 20 offers a view of the IV bulkhead, which shows the UIA, pressure relief valve, inter-module ventilation valve, depress air valve, two D-ring tether points, and bulkhead translation aids, all of which are mounted directly to the bulkhead. The crew lock pressure relief valve maintains the operating pressure of the crew lock within a nominal range. If the pressure in the crew lock exceeds safe levels, the relief valve will open and begin dumping air into the equipment lock. The inter-module ventilation valve performs the

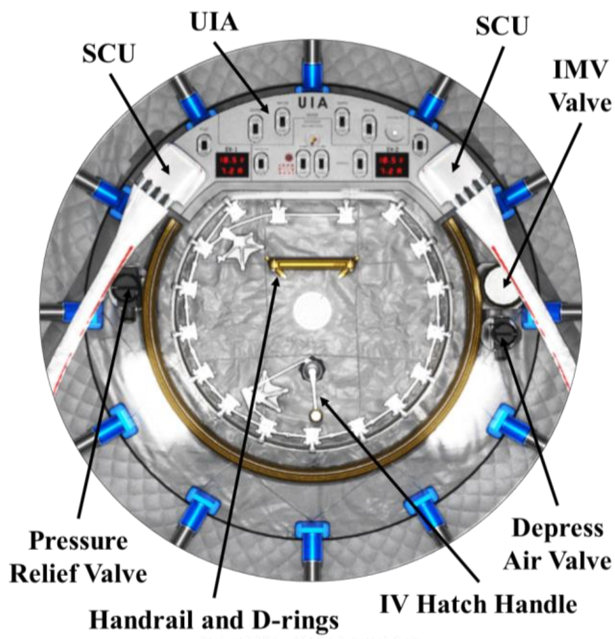

Figure 20. View facing the crew lock IV bulkhead with critical components identified

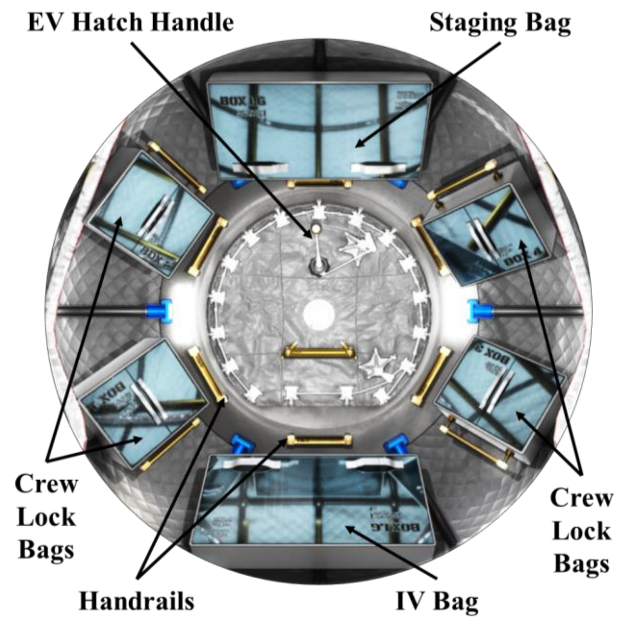

Figure 21. View facing the crew lock EV bulkhead with critical components identified

function of exchanging air between the equipment lock and crew lock. The function serves multiple purposes including maintaining a conditioned atmospheric composition, pressure equalization between the two volumes, transportation of heat/contaminates, and smoke detection. The depress air valve, when opened, allows a path for the crew lock air to reach the depress pump during depress operations. When the pump is activated, the crew lock air is pumped into the secondary crew lock, as described on pg. 14. Handrails are attached to the bulkhead and the internal structure to provide a translation aid for crew egress and ingress. Lastly, two D-ring tether points are located on each side of the IV bulkhead for the crew member operating the UIA.

The UIA is the interface between LEIA and the suits through the connection of service and cooling umbilicals (SCU). Power, data, communication, suit cooling water, oxygen, high pressure oxygen, a vacuum port, and drinking water pass through the umbilicals to their respective suits. The UIA provides mechanical switches which enable the crew to control the transfer of consumables to each suit during servicing and egress/ingress activities. Power (voltage/amperage) levels are read on two displays, and oxygen pressure is shown on a single O2 supply gauge. The UIA is installed on the zenith position of the IV bulkhead to provide direct access to pass-through connectors from the equipment lock. Mounting the UIA on the IV bulkhead stabilizes the UIA on a rigid structure and keeps it out of the way of crew activities. The biocide filters, which filter and iodinate feedwater and wastewater to and from the xEMUs, are accessible from the equipment lock for simplified maintenance.

The opposite end of crew lock, known as the EV bulkhead, is shown in Figure 21. This bulkhead provides mounting locations for translation aids, two D-ring tether points, the staging bag, four crew lock bags at the center and the IV bag. Mounted on the long axis struts of the internal structure are handrails spanning the length of the crew lock, according to the Human Integration Design Handbook [20] and the EVA Design Considerations report [21]. Also mounted on the internal structure are two boot plates that are 180 degrees from each other, one to support facing the UIA and one to support facing the EV hatch. Lastly, the SCUs are spooled and strapped along the internal structure of the crew lock when not in use.

Packaging and Deployment

The inflatable crew lock is packaged during launch and restrained in a compressed state until the initial inflation once fully attached to Gateway. The packaged crew lock will have internal structure hoop brace members and all structural nodes pre-integrated to the softgoods shell prior to launch. All hoop sections will be bunched together at the IV bulkhead, with the primary structure shell folded outward such that maximum axial compression is achieved, as shown in Figure 22. The entire packaged crew lock should fit within

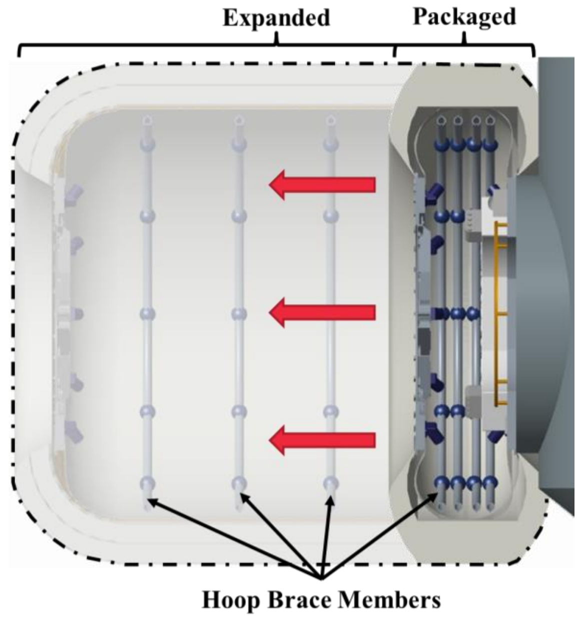

Figure 22. Crew lock in packaged and expanded configurations with structural hoop brace members pre-integrated into softgoods shell

a 0.5 meter distance from the outer face of the IV bulkhead. In regard to internal components, only the components rigidly connected to the IV bulkhead will be pre-installed on the ground, including the UIA, air save valves, and bulkhead handrails.

The inflatable crew lock will be initially deployed using internal pressure from its own inflation tanks, mounted in the equipment lock, and guided by unspooling cables attached to each bulkhead. These cables allow positive control of the structure during inflation via selective braking of the spools, which will enable a steady, even deployment. When the crew

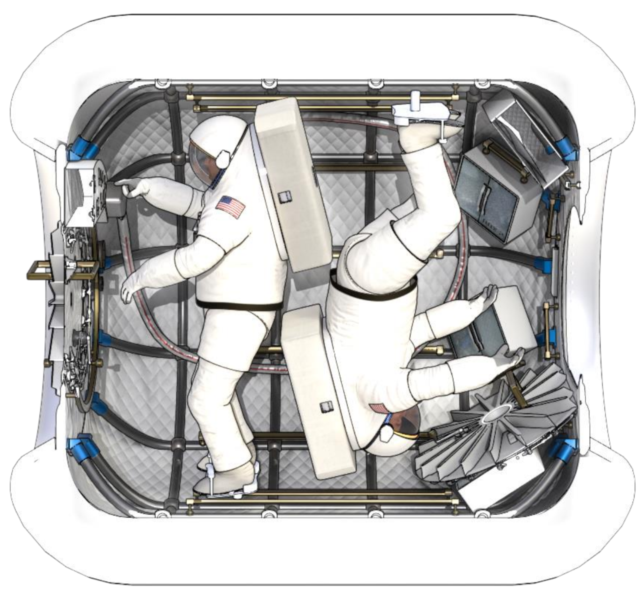

Figure 23. Cut-away view of fully outfitted crew lock with two suited crew members at the start of an EVA

lock is fully inflated, and leak and atmosphere checks are complete, the crew will move into the crew lock to finalize the hardware integration. In twelve locations around the circumference, the crew will install internal structure longerons, connecting the hoops and bulkheads at each node. Following this assembly, the crew will install support equipment to the internal structure, including handrails and foot restraints to the longerons, the SCUs to the UIA, lights/cameras to the hoops, and EVA bags to the EV bulkhead. The final, outfitted crew lock with suited crew members is shown in Figure 23.

Pressurization and Air Save

Initial inflation and post-EVA repressurization of the LEIA crew lock will be conducted using RTAs that are mounted inside the equipment lock, shown in Figure 9. The E/L will support a single O_2 and N_2 tank. The RTA is a ground filled composite overwrap pressure vessel currently used on the ISS for commercial resupply of the airlock module tanks [15]. Air save calculations were performed to determine how many EVAs can be supported with LEIA using a single set of RTAs. A nominal EVA, for these calculations, utilizes only one crew lock with a two person crew. The nominal operation is where the primary crew lock is depressurized, and the fill gas is transferred into the secondary crew lock, acting as an air save tank, saving 97% of the gas [16]. The remaining gas is vented, but could be transferred to the Gateway stack for additional savings.

In a two Crew Lock configuration, the nominal depress operations are completed in three stages, as described below and illustrated in Figure 24.

1. *14.7 psi to ~ 7 psi:* Crew Lock IMV valves are opened and Active Crew Lock air is transferred to the Secondary Crew Lock until pressure equalizes.
2. *~7 psi to 2 psi:* Depress Pump is activated to reduce Active Crew Lock air to 2 psi
3. *2 psi to Vacuum:* Depress Pump is turned off and remaining air is dumped to vacuum via the Vacuum Access Port.

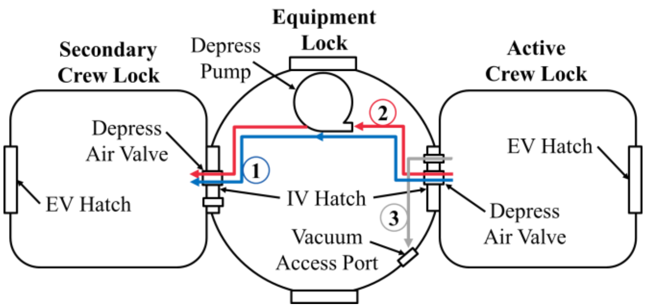

Figure 24. Graphical representation of active crew lock depressurization in three stages

The air save analysis was completed using the assumptions in Table 4 below. The analysis results show that the initial set of RTAs can support up to 6 EVAs, as seen in Figure 25. Additional RTAs can be delivered as needed on resupply flights to extend the EVA capability for the life of Gateway. Future refinement is still needed to validate the assumptions on air save analysis, but these results provide a baseline summary on the potential capabilities.

Table 4. LEIA Air Save Analysis Assumptions

Assumption	Value
Crew Lock Volume	9.7 m^3
Nominal Pressure	14.7 +/- 0.5 psia
Air Save % With 2nd Crew Lock as Inflation Tank	97%
Gateway Stack Volume	>316 m^3
EVA Pre-Breathe Mass	10 lbm O_2
RTA Initial Gas Mass	84 lbm O_2 , 63 lbm N_2

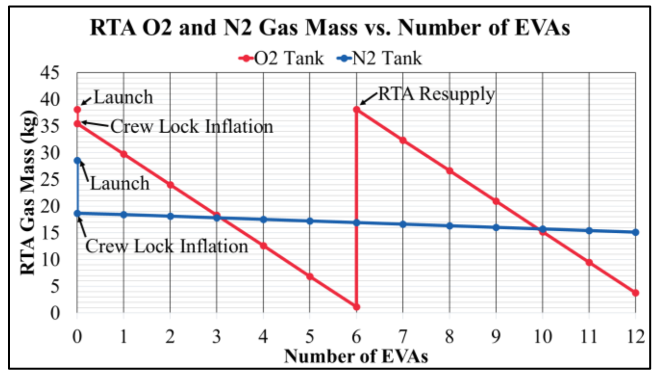

Figure 25. Remaining RTA gas mass for both the O2 and N2 tanks after initial inflation and 12 EVA cycles

External Layout

External handrails are required along the outer surface of the inflatable crew lock to provide a translation path from the EV hatch and across the crew lock to the Gateway stack. External handrails and tether points will be located on the EV bulkhead adjacent to the hatch. To mount handrails along the crew lock softgoods, other factors need to be considered. Several options have been evaluated as a possible solution, including fabric hand straps stitched to the outer shell layer, and fabric gap spanner straps that connect the EV bulkhead and the E/L structure. These solutions, however, do not provide tether capability or torque loads from a crew member. A potential design for external handrails is shown in Figure 26 and is composed of a rigid beam that is connected from the EV bulkhead to the E/L structure. The concept is based on the Crew Equipment Translation Aid (CETA) spur that is currently in use on the ISS. The beam structure will have handrails fastened along the length of the beam allowing for translation and safety tethering. This structure would be installed by the crew during the first EVA. Future work needs to be done on this translation beam design to ensure it works both structurally and with suited operations.

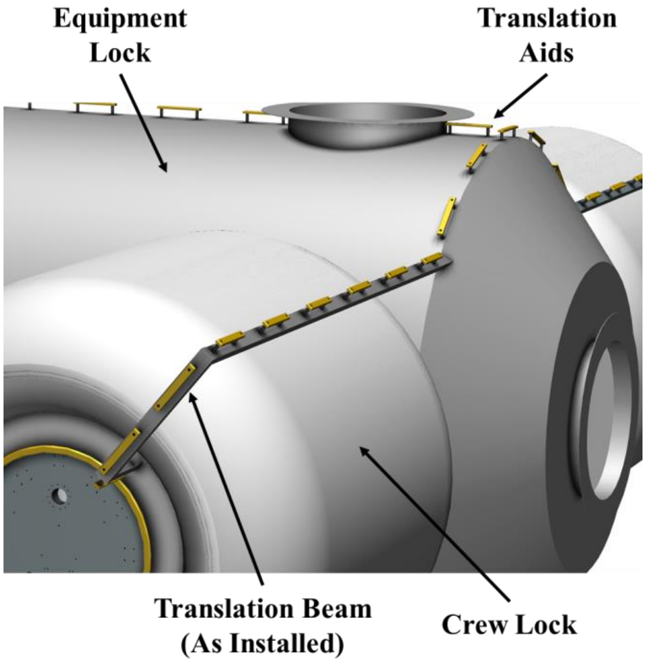

Figure 26. Concept for crew lock external translation beam with installed handrails

5. Conclusions and Future Work

The LEIA design presented in this study provides a hybrid microgravity airlock solution for Gateway. The combination of a rigid equipment lock with dual softgoods crew locks maximizes the launch mass/volume ratio of the airlock structure. The E/L provides not only volume for integrated hardware and suit stowage, but also acts as a node for docking of visiting vehicles. This capability will enable lunar surface exploration and accelerate the buildup of Gateway. Each C/L provides an enhanced volume for two suited crew members to perform EVAs, compared to the ISS crew lock. The dual C/L design provides an alternate egress method in the event of an emergency without blocking the Orion MPCV during an EVA. The second crew lock also offers redundancy and enhanced EVA capability, if both C/Ls are used at the same time.

The design work discussed in this study has developed a preliminary design for the LEIA, but additional work is needed to optimize the design and finalize a flight-capable system. When a launch vehicle and bus (if needed) are selected to deliver LEIA to the NRHO, then the structural sizing of the equipment lock can be finalized. This sizing will maximize the available capability of the launch vehicle by increasing the length and volume of the E/L. A refined set of loads for Gateway elements would also be used to optimize the equipment lock structure. The IV and EV hatches need to be defined for this airlock module to work with the xEMU suits planned for Gateway. The secondary structure in the equipment lock must be designed in conjunction with a detailed cargo plan that can help refine the overall mass table. Similarly, the subsystems not described in this study need to be designed including the power system, command and data handling system, and environmental control and life support system.

For the crew locks, the shell layers described in this study require some additional refinement including small scale pressure testing of the restraint layer that will help validate analysis models and understand manufacturing knock down factors. The thermal protection system was evaluated with analysis and testing, but optimization is still outstanding for the LEIA thermal model. This work will finalize the layup of the shell layers and determine if heaters are needed on the inside of the crew locks. The internal structure in the crew locks need to be developed and tested with refinement of the constructible node concept. A small-scale structure must be built to evaluate the structural capability of the design, while a full-scale mockup can be used to test the usability of the system. The air save system for the crew locks needs to be defined and tested to ensure maximize air is recycled, which is critical for deep space operations. The external handrail system needs to be designed to work with xEMU suits and planned Gateway EVA tools and equipment.

The LEIA design offers a hybrid element for Gateway that combines a docking node and an airlock by utilizing both metallic and inflatable structures. This solution can accelerate exploration plans and the Gateway buildup by offering an EVA capability earlier than planned. This design proves feasibility of an inflatable airlock and is extensible to future exploration systems for missions to the Moon and Mars.

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BIOGRAPHY

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Damien Calderon is an early career mechanical engineer in the Structural Engineering branch of the Structures Division at NASA Johnson Space Center. He received his B.S. in Mechanical Engineering, with Highest Honors, from the University of Texas at Austin. Damien has experience in structural optimization, sizing, mechanical design and analysis, and structural testing. He has worked on projects supporting the International Space Station, Orion, Gateway, and Lunar Surface Mobility. Before joining NASA, Damien served as a Non-Commissioned Officer in the 2nd Battalion, 75th Ranger Regiment for 6 years.

Carlos Gaytan Jr. started his NASA career as a Pathways Intern in 2015 while pursuing a B.S. in Mechanical Engineering at Texas A&M University at Corpus Christi. After graduation in 2018, he accepted a full-time position in the structures branch at the Johnson Space Center. He has provided structural design and analysis support for Gateway and Human Landing Systems. He has over 10 years of federal service as a United States Marine, helicopter mechanic at the Corpus Christi Army Depot, and NASA engineer.

Michael O'Donnell received a B.S. in Mechanical Engineering and a Minor in Electrical Engineering from the University of Pittsburgh in 2018. He started as a Structural Engineer with NASA's Johnson Space Center shortly afterwards, where he has focused on optimization of metallic structures. He has worked on several different conceptual, fully integrated, human rated spacecraft designs such as Gateway modules, Human Landing System cabins, and Artificial Gravity structures.

Khadijah Shariff is a structural engineer at the NASA Johnson Space Center. During her six year career at NASA, Khadijah has worked on design, analysis, and testing of inflatable structures technology for human spaceflight. She designed and analyzed the restraint layer primary structure for LEIA; designed internal and external fabric crew interface hardware for the Bigelow Expandable Activities Module (BEAM); tested candidate bladder materials for repeated folding and unfolding; and performed strength characterization of restraint layer and bladder materials. She has performed stress analysis on numerous space flight hardware, and tested spacecraft windows and composite materials. She earned a Bachelor of Science Degree in Aerospace Engineering with a specialization in Astronautics from Embry-Riddle Aeronautical University in 2013 at Dayton Beach, Florida.

Mallory Sico is a Materials Engineer at NASA Johnson Space Center. She graduated from the University of Texas at Austin with a B.S. in Mechanical Engineering in 2018. In addition to the LEIA project, she supports the Orion MPCV Program through mechanical testing of composite materials as well as other materials development and characterization projects.