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Development and Testing of an Inflatable Airlock Module for Gateway Station and Beyond

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With the support of the NASA Exploration Habitat (X-Hab) Academic Innovation Challenge, the University of Maryland is developing and testing a full-scale inflatable airlock capable of safe and reliable operation in a 1-g environment, with the intent of delivering it to NASA JSC to be used in support of Gateway development operations. The airlock is designed to accommodate two crew in microgravity operations, with an internal diameter of 1.5m and a length of 2m. Square hatches with a clear passage width of 0.95m are installed in rigid bulkheads at each end. The structure is deployed by vent pressure air, held below 0.5 psi to ensure the safety of humans in the area. The airlock also contains an internal structure which deploys with the pressure envelope and latches into place, maintaining the deployed shape even when the interior is depressurized, and allowing reliable crew mobility on the distal bulkhead. The airlock is outfitted with power, communications, lighting, air ventilation, and simulated suit support interfaces for simulation purposes. The airlock will be tested in both 1g and neutral buoyancy at the University of Maryland prior to delivery. Since NASA intended to only use the inflatable airlock module in a horizontal orientation in a 1g environment, a matching piece of ground support equipment will also be delivered which will allow crew operations internal to the airlock without placing a load on the inflatable envelope or deployed structure. The paper covers design history including trade studies, developmental testing, and operational testing in 1g, neutral buoyancy, and simulated lunar and Mars gravity. The airlock is planned for delivery to JSC in June, 2019.

I. Introduction

One of the critical operations for future human space flight is the capability to provide routine access to extravehicular activities (EVAs). Nothing has defined human spaceflight in the public mind more than EVA, from the images of Apollo astronauts exploring the lunar surface to shuttle astronauts repairing Hubble Space Telescope, or Bruce McCandless' canonical flight untethered in the Manned Maneuvering Unit. The creation of International Space Station was enabled by EVA, and there is no sign that the future will change in terms of the need for human extravehicular interventions.

However, with the end of the Space Shuttle program and the coming era of Orion, Dragon, and Starliner, none of the operational human spacecraft will have the capability to support routine EVA. While the Gemini and Apollo programs allowed full cabin depressurization for suited egress, modern avionics systems would require a completely new development cycle to allow operation in vacuum. What is needed is an airlock, whether for access in orbit, or for access from a human lunar lander to and from the lunar surface.

Airlocks come with significant costs in terms of both mass and volume requirements. One possibility to address the volumetric issue, and perhaps the mass to a lesser extent, is the concept of an inflatable airlock. Inflatable airlocks date back to the first EVA from Voshkod 2, which was modified to support EVA through the addition of the Volga inflatable airlock module. Also in the decade of the 1960's, Goodyear produced a prototype of the D21 single-person airlock and Whittaker Corporation developed its own inflatable airlock concept under NASA funding.[1] Several experimental or prototype units were sponsored by NASA around the year 2000[2,3] (Figures 1 and 2), but none of these have led to flight hardware development. Recently, through the NASA NextStep program, six aerospace contractors have been designing and fabricating ground prototypes of habitation modules for the Gateway Station, recently designated as NASA's next major milestone in human space flight. None of these NextStep contracts have included an airlock; indeed, there have been some attempts to encourage international partners to take on the airlock as a contribution to Gateway.

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Figure 1. Honeywell inflatable airlock prototype[3]

Figure 2. ILC-Dover inflatable airlock as part of inflatable habitat prototype

Over the last eight years, NASA has supported university involvement in human space flight through the Exploration Systems and Habitation (X-Hab) Academic Innovation Challenge. Each year a number of research topics of interest to NASA are proposed as topics for capstone design courses in engineering departments. While the funding in this program is far below that which would be expected for a sponsored research project, the X-Hab program at least provides some funding and motivation to keep students interested in human space flight. In February of 2018, the annual solicitation for proposals included the following topic statement:

> Inflatable/deployable structures are being researched at NASA and in industry to provide habitable modules for future space exploration missions. One of the proposed Gateway elements is an inflatable crew-lock, which allows crew to egress from a pressurized to an unpressurized environment. This project seeks the design, fabrication and delivery of a full-scale, low-pressure (0.1-0.5 psig) inflatable/deployable crew-lock structure that demonstrates the volume, operation and outfitting of a crew-lock for use in NASA Gateway ground test efforts.[4]

Airlock mockups developed under the X-Hab program are to be delivered to the NASA Johnson Space Center (JSC), and set up in the same facility as the Gateway module concepts from the NextStep contractors. While several orders of magnitude lower in cost than the NextStep modules, the X-Hab airlock modules will at least provide some representation of an inflatable airlock for these larger systems.

The University of Maryland Department of Aerospace Engineering, which has participated in the X-Hab program in almost every year of its existence, responded with a proposal to design, fabricate, test, and deliver an inflatable airlock module to NASA over the 2018-2019 academic year. This report summarizes the activities performed in support of this X-Hab grant. Readers interested in more detailed discussions on the background of inflatable structures[5] or small airlocks[6,7] can find excellent overview papers in the cited literature.

II. Results from Prior Inflatable Airlock Research at UMd

Three years previously, the University of Maryland had a prior grant from the X-Hab 2016 program to design and fabricate an inflatable airlock. In that case, the funds were much more limited ($15K), and the directive was to design and fabricate an airlock, which could be a scale version rather than full scale. Since much of the current project was informed by this prior experience, the results of that work will be summarized here.

One of the early investigations was in the required diameter of the airlock. The concept (then and now) was to develop a *crew lock*: a chamber to hold two suited crew for depressurization and repressurization, but without any requirement for suit donning/doffing or refurbishment. This minimally-sized airlock reduces demands for transition time and consumables, but requires other EVA preparatory operations to be done elsewhere in the habitat. A tube of bendable polycarbonate was created which could be varied in diameter from 1.22m (48in) to 1.68m (66in). The system was tested in the University of Maryland Neutral Buoyancy Research Facility (NBRF). Two test subjects wearing mockup backpacks replicating the EMU portable life support system (PLSS) tested their ability to ingress and egress the airlock volume, maneuver in proximity to each other, and perform motions representing those required for airlock operation (Figure 3) repeatedly as the cylinder was resized in diameter by 15cm (6in) increments. This testing led to the selection of a standard airlock internal diameter of 1.52m (60in), which provided adequate internal clearance while minimizing excess volume which would represent atmosphere lost in depressurization.[8]

Figure 3. Neutral buoyancy investigation of required airlock diameter using resizable test fixture

In parallel with the neutral buoyancy testing, an evolutionary series of scaled model developments were undertaken. Two teams were tasked with developing an innovative hatch design and a baseline fabric envelope design for larger scale airlock prototypes. The hatch was aimed at being held sealed by internal pressure, but still opening outwards to keep the internal volume of the airlock unburdened of any requirement for door clearance during its opening and closing. The final design was a D-shaped hatch with a fairly complex opening sequence, but which had an opening trajectory almost entirely external to the airlock. Both the hatch and airlock envelope were initially tested in 1/10 scale, and demonstrated under pressure in one of the spacesuit arm adapters of the UMd glove box at 29.5kPa (4.3psi).

One of the unique requirements of an inflatable airlock is that the force maintaining its shape (the internal pressure) is not present in operational use when it is depressurized. For that reason, some other means of maintaining the envelope shape must be part of the design. This focused on two approaches: an internal or external structure which is deployed and latched with the initial inflation, or a series of pressurized tubes around the periphery which maintains the cylindrical airlock shape without pressure in the larger internal volume. This latter approach was tested with a 1/5 scale prototype, which demonstrated the feasibility of using the bladder approach to keep the airlock expanded when depressurized.

The pressurized airlock was prototyped in 1/2 scale, resulting in a diameter of 0.76m (30in) and a length of 1m (40in). Two versions of this were manufactured and tested under pressure. The first consisted only of the pressure bladder and restraint layer, although a simulated thermal/micrometeoroid protective layer was installed on half of the cylinder to investigate its impact on folding patterns and minimum stowage volume. The second included a woven network of webbing representing the restraint system needed for an operational airlock at 101kPa (14.7psi) with a safety factor of 4. Both versions used blank bulkheads without hatches, and incorporated an internal bladder network for unpressurized shape maintenance. While these tests were successful in terms of airlock operation and shape maintenance, it was noted that the internal bladder had to be inflated to a significantly higher pressure than the nominal airlock pressure to provide sufficient stiffness, and that in its inflated state it took up a substantial amount of the internal volume of the airlock.

There were no resources to fabricate a full-scale pressurized airlock in this project, but there was a strong desire to test the functioning of the airlock hatch and to begin to investigate some features of the necessary internal outfitting for crew accommodations such as handrails. For this purpose, a full-scale mockup of the airlock was constructed for neutral buoyancy testing (Figure 4). The final hatch concept was fabricated and installed on one end of the mockup, which modeled the internal boundaries by using polycarbonate wrapped around a PVC tubing structure. This was tested in neutral buoyancy to verify hatch functionality, to assess handrail placement, and to develop and test hinge designs for the hatch.[8]

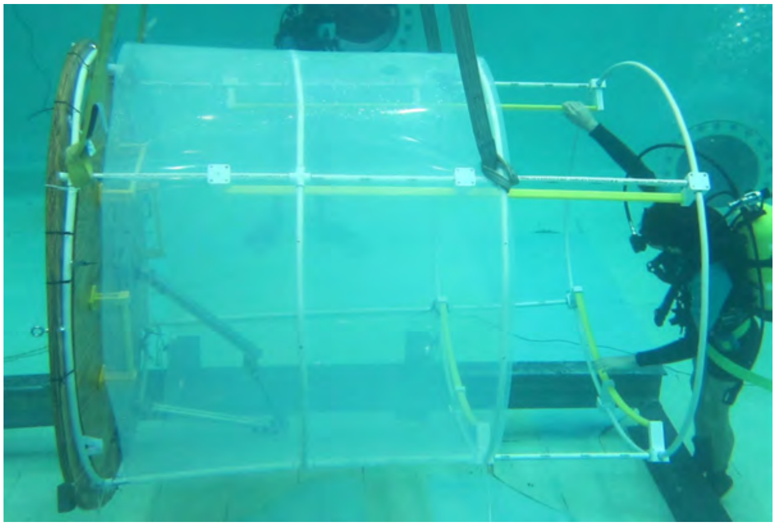

Figure 4. Final airlock test fixture configuration for neutral buoyancy evaluations

III. Requirements Development

At the start of the 2019 X-Hab Inflatable Airlock project, there was a minimal set of specifications from the solicitation document.[4] It specified that the goal was to design, fabricate, and deliver a full-size crew lock to JSC for use with the NextStep mockup hardware, and that it was constrained to operate only at vent pressure; that is, no more than 3.4kPa (0.5psid). At this pressure, there is no meaningful probability of a pulmonary embolism if the airlock has a catastrophic failure with a person inside the pressurized volume. Other than that, there were no other specifications from the solicitation.

At the project kickoff meeting, more specifications were developed by the team in discussions with the NASA technical monitors. There was to be no instance in which a person was inside the airlock when pressurized, so there was no need to design a crew-compatible ventilation system in conjunction with the pressurization system. The system was to be constrained to have no pressure above the previously discussed vent pressure to mitigate any concerns about pressure hazards to individuals in the vicinity of the airlock. Based on the prior UMd experience with inflatable structures to maintain airlock configuration, which required pressures in the inflatable support structures of 275kPa (40psi) to achieve required structural integrity, this meant that the required system to maintain airlock shape when unpressurized would have to be a deployable mechanical structure rather than an inflatable system, as 3.4kPa would be far too low a pressure to be able to support the airlock's weight against Earth gravity.

One of the biggest questions at the outset was whether this airlock was to be designed for Mars/lunar surface operations or for microgravity, such as on Gateway. An airlock for a surface habitat is best designed to allow walking transit through the airlock and its hatches, rather than requiring the crew to exit on hands and knees as in the Apollo Lunar Module. Assuming the airlock has a basic cylindrical shape for structural efficiency, this would require either a horizontal cylindrical orientation with a 2.5-3m diameter as in the NASA dual-chamber hybrid inflatable suitlock concept (DCIS),[9] or a smaller diameter vertical orientation with radial transport, as in Figure 2. This configuration allows the suited crew to walk in and out with a smaller overall airlock, but is much harder to design due to the interruption of the cylindrical structure of the pressure vessel to accommodate the hatches. A microgravity airlock is best designed with axial transport (Figure 1), which allows easy hand-over-hand egress and ingress, but would require crawling to transit the airlock in a surface application. The directive from NASA was to design for Gateway, despite the impact this will have on simulated operations in the analog environment of Earth.

In actual application an inflatable airlock for Gateway would have a permanent mount to the Gateway pressurized volume, mostly likely a common berthing mechanism (CBM) such as is used on ISS for connecting between modules. This would have a design impact on both the end interfaces and the fabric envelope shape itself. However, since none of the NextStep mockups are designed to interface to the airlock module being developed under the 2019 X-Hab program, NASA directed the University of Maryland team to make it "station agnostic", and to incorporate EVA hatches on each end rather than provide a notional intermodule connector. This discussion added the additional requirement for a "bridge" structure which would fit inside the deployed airlock to allow at least two individuals to move around and work inside under Earth gravity without standing/kneeling on the soft goods or the rigidizing structure. UMd proposed a D-shaped hatch based on the hatch studies from the 2016 airlock project, but NASA personnel responded that current airlock designs were focused on square airlock hatches with minimum clearance widths of 0.9-1m with corners rounded with a 15cm radius; this was taken as a design requirement by the UMd team. Since humans would not be allowed inside the airlock under pressure, or even with the hatches closed, the locking latches were optimized for external actuation, and have no ability to be opened from the inside. The NASA technical monitors also expressed an interest in having the mockup as delivered include lighting, air ventilation (for crewed operations with the hatches open), and the ability to simulate crew lock systems such as simulated suit umbilical panels.

IV. Detailed Design

A. Configuration Development

With the completion of the top-level requirements, teams were created at UMd to work on the project, connected to both the ENAE100 freshman introductory class and the ENAE484 senior capstone class in Spacecraft Design. The ENAE100 team worked throughout the Fall 2018 semester on outfitting issues with an inflatable airlock, particularly issues with handrail/handhold design and placement. The team developed handrails based on the classical oval cross-section, as well as fabric handholds which would be able to stow more easily in a folded airlock envelope.

Initial testing was performed on a rack structure in the NBRF. Rigid and flexible handholds were each mounted to rigid and flexible structures. Neutrally buoyant test subjects were directed to rotate their body position and to perform a rotary motion with one hand while maintaining body orientation only with the other hand using one of the test handholds. Data was collected based on task times, NASA task load index (TLX) surveys, and subjective crew evaluations.

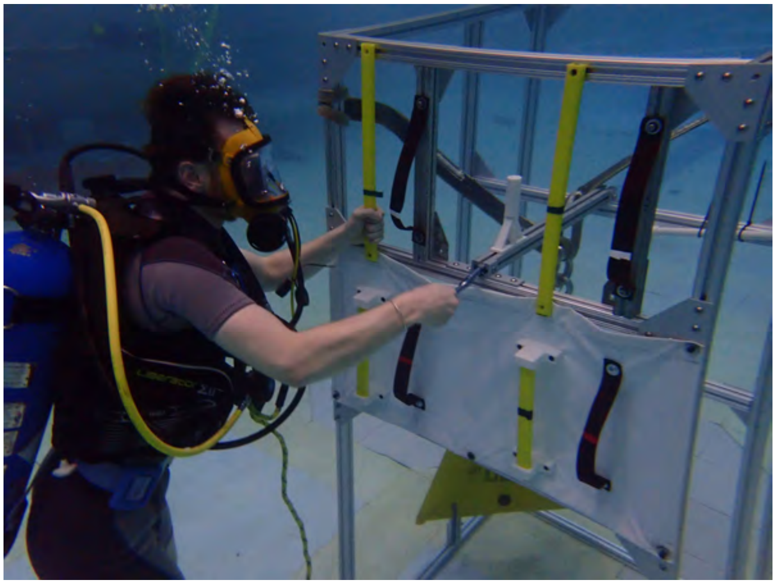

Figure 5. Test fixture with handrails and handholds on rigid and flexible mounts

Quantitative results of testing indicated that rigid handrails on rigid mounts provided more accurate restraints for the crew. However, it was also noted that all test subjects subjectively preferred the flexible handholds when attached to a flexible substrate. Since the results of the task board tests were unclear, a full-scale 1.52m diameter airlock mockup was fabricated with a low-fidelity hatch as the primary task for subjects to perform. This was a straight cylindrical structure made with rolled aluminum hoops, 80/20$^{\mathrm{TM}}$engineering extrusions for external structure, and polycarbonate sheeting as the boundary for the airlock interior. Both rigid handrails and flexible handholds were installed on opposite sides of the airlock mockup, and tested with two test subjects wearing simulated PLSS backpacks (Figure 6). A separate test series was conducted with a single subject wearing an MX-B suit simulator, developed previously at the University of Maryland (Figure 7). These tests confirmed that the 1.52m diameter was adequate for two users, and that all of the handrails and handholds were usable with suit gloves. Since the airlock has to stow as compactly as possible, it was originally decided to incorporate the flexible handholds for crew mobility aids throughout the airlock. With the refinement of the deployable internal digitizing structure, this decision was revised to provide NASA-standard handrails rigidly mounted to the internal airlock structure, along with attachment points for tethers and restraint reels.

Figure 6. Dual-subject testing – note rigid handrails on left side, flexible handhold on right

Figure 7. Airlock and hatch testing with suited subject

The overall concept developed as an axial flow airlock, with fabric layers for the cylindrical section and rigid endcaps incorporating hatches on each end. Since both ends were directed to be identical, the envelope is symmetrical around the center. As described below, the largest practical size for each bulkhead was a 1.52m outer diameter, fixing the airlock diameter at the ends. Three generic shapes were considered and analyzed for the envelope: a constant-diameter cylindrical section (Figure 8), a larger diameter cylindrical midsection with tapered sections mating to the bulkheads (Figure 9), and an ogive cross-section to provide maximum diameter at the centerpoint (Figure 10). Maximum diameter of the last two configurations ranged upwards to 2m, to allow full standing headroom in the center when the airlock is deployed horizontally on Earth.

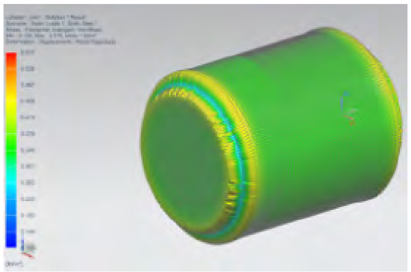

Figure 8. Cylindrical airlock configuration

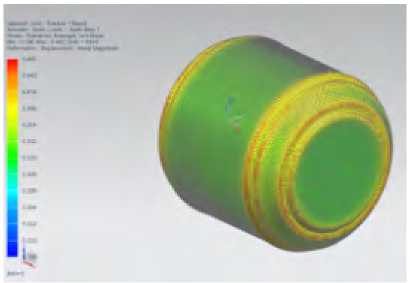

Figure 9. Tapered airlock configuration

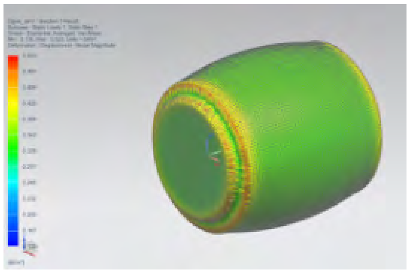

Figure 10. Ogive airlock configuration

Analysis showed that all three airlock configurations were feasible, on the basis of structural integrity (shown by the finite element analysis stress patterns shown in Figures 8-10) and manufacturability. The tapered and ogive configurations provided up to twice the internal volume as the straight cylindrical concept, but significantly complicated the stowage and deployment operations. While the standing head height in the center allowed comfortable usage in a horizontal orientation on Earth, the endcaps and hatches were still sized for microgravity axial transit and would require switching to hands and knees for entry and exit. Since the requirements from NASA were for a microgravity Gateway-compatible test article, and the two versions with larger center diameters would significantly impact the fidelity of stowage and deployment for an airlock designed for use on Gateway, it was decided to go with the cylindrical configuration and accept the discomfort of limited headroom in Earth testing.

B. Pressure Envelope

Based on prior experience, the soft goods of the airlock took the form of a series of fabrics selected to perform specialized functions, as listed in Table 1. The materials selected are specific to this ground-based analog application, and take into account the limited funding ($50K, including overhead costs) for this project. This configuration omits layers which would be present in a flight unit, including multi-layer insulation and micrometeoroid/orbital debris shielding, which are unnecessary for Earth testing of the basic deployment and utilization concepts.

Table 1. Fabric layers in airlock soft goods

Airlock layer (inner to outer)	Material
Inner mounting layer	Fire-resistant ripstop nylon
Pressure bladder	Heat-sealable urethane-coated nylon packcloth
Restraint layer	Uncoated nylon packcloth
Restraint webbing	Woven gridwork of polyester webbing
Outer scuff layer	Fire-resistant ripstop nylon

The pressure bladder is fabricated using manual heat-sealing, This is a time-consuming process, but has been used extensively in the past by the University of Maryland in the development of pressurizable suits and habitat elements. The remainder of the layers can be fabricated using an industrial sewing machine.

C. Bulkheads and Hatches

As described above, the X-Hab 2016 inflatable airlock project featured the design and testing of an innovative hatch design. One of the NASA directives for this year's project was that they have decided on square hatches, approximately 1 meter on a side, with rounded corners as the standard design. This simplified the design process, but also negated the possibility of using the hatch design to ameliorate any design issues with the bulkheads or sealing surfaces. The conceptual design for the current airlock bulkhead and hatch is shown in Figure 11.

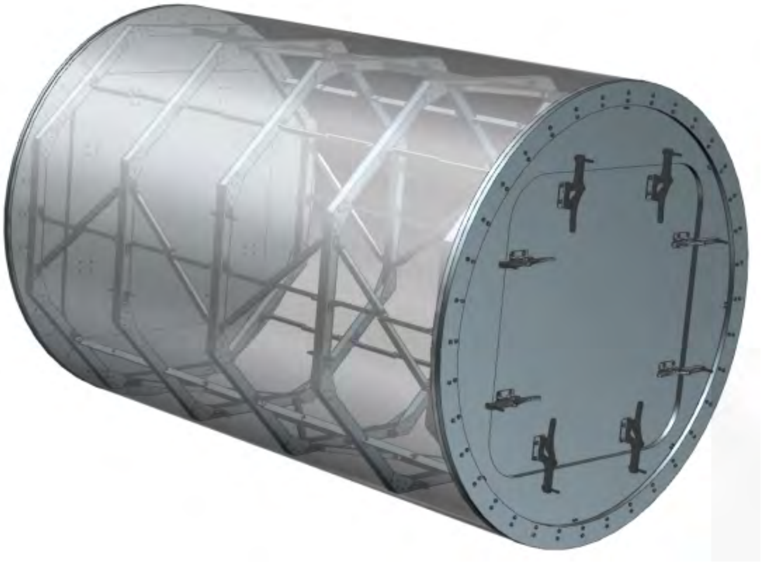

Figure 11. Conceptual design of airlock bulkheads, hatch, and latching mechanism

One of the major challenges of this project is the development of the bulkheads and hatches for the endcaps of the cylindrical airlock, due to the required diameter. In the 2016 X-Hab project, the endcap components were fabricated from indoor/outdoor plywood, which was then sealed with multiple layers of a marine-grade epoxy. Since the plywood panels were only available in 1.2m (48in) widths, multiple layers were glued together to reach the required width. The advantage of this approach was that the plywood could be shaped with traditional woodworking tools, including a computer-controlled router for complex cuts. However, the application of the epoxy was time-consuming, and proved to be inadequate for a useful waterproof seal when used for neutral buoyancy testing.

While flight airlock structures would be fabricated in aluminum, obtaining aluminum plate with a minimum 1.52m (60in) width was impossible within the budget and schedule limits of this project. Nor were there any milling machines available which could fabricate the bulkheads or hatches at that width. For this reason, the team started a search for alternative materials, taking advantage of the requirement that the airlock would never be pressurized to more than 3.4kPa (0.5psi).

The final material chosen for the endcap structure was Starboard^{TM}, a rigid polymer sheet marketed for use in place of wood on boats. The published material properties were found to be adequate for the loads, and the substance can be shaped with hand power tools such as a router. It is available in 1.5m (60in) widths up to 1.8cm (0.75in) thick. Bulkheads and hatches are fabricated from a single thickness of this material, made possible by the restriction to use no more than vent pressure (and incorporating a required factor of safety of 4 for an inflatable structure).

While the endcaps are not intended to be flight fidelity, it is important that the prototype airlock be capable of pressurization to demonstrate inflation. For that reason, it was necessary to incorporate a series of latches on the hatch to provide compression of the sealing surfaces prior to achieving a pressure differential. As mentioned above, the NASA operating restrictions prohibit crew internal to the airlock when sealed or pressurized, so early designs for a pawl-driven mechanism to seal the hatch from either side were dropped for the simplicity of eight lever-actuated over-center latches externally on each hatch. Once pressurization gets established, the pressure differential seats the hatch more securely against the seals, but the adjustable latching pressure helps to transfer pressure loads through the hatch and minimize deflections on the edges of the hatch opening in the endcap.

D. Support Structure

Inflatable airlocks require a separate system to ensure that it maintains its inflated shape when it is depressurized during use. A simple approach to this is a set of alternative pressurized chambers built into the wall structure which are maintain pressure throughout, and thereby keep the airlock shape even when the main interior volume is depressurized. This was developed and incorporated into the 2016 airlock, but was found to cause a significant impact to the available interior volume. Although a number of approaches were conceptualized to minimize this volumetric impact, the directive for the 2019 X-Hab project that all pressurized volumes were to be limited to no more than 3.4kPa (0.5psi) meant that no feasible solution was available which utilized separate pressurized structures, as the allowable pressure produced insufficient forces to maintain the airlock shape against Earth gravity. For this reason, the team focused instead on deployable structures for shape maintenance, as shown in Figure 12.

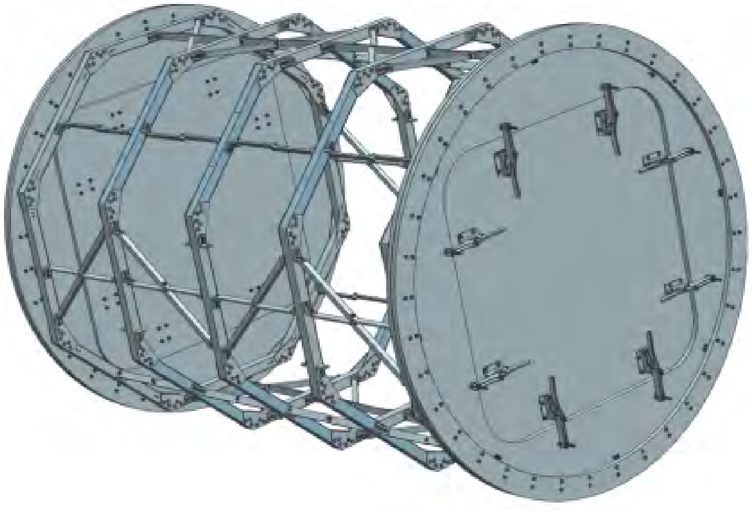

Figure 12. Conceptual design of airlock internal rigidizing structure

The first issue was to decide on interior or exterior support structure. In a flight application, the airlock would be inflated by pressurizing the main volume, and crew would be able to enter it while pressurized. This would allow the incorporation of manually-actuated elements in the structure, up to and including manual assembly following inflation. Similarly, crew operations could be utilized for releasing structural restraints prior to restowing the airlock if that should be required. An external deployed structure would be difficult to verify in terms of all latches engaged without an EVA, which would require the use of an unverified airlock (or external robotic cameras). For this reason, it made sense to define the structure as internal to the airlock volume.

However, this test article was specified as not having any crew internally while sealed and pressurized. With this constraint, it would be much simpler to design the support structure to be external to the airlock envelope, where it could be easily inspected and verified, and manually latched if necessary. However, since this seemed to be so suboptimal for the flight design, it was decided to maintain the internal structure configuration in this prototype airlock and deal as effectively as possible with the constraints against humans inside during inflation or other pressurized operations.

The internal structure is designed around five internal octagonal reinforcing rings built up of standard 6061-T6 aluminum extrusions joined by water jet-cut gusset plates and rivets. These support the fabric envelope in its deployed configuration at three equally spaced locations along the axis of the airlock, with 20in gaps between the rings. It was felt that the fabric envelope itself should do fairly well at maintaining its shape across these gaps, but deployable truss structural elements were designed to provide additional internal support for the envelope, and to provide a rigid connection between the two endcaps and all three intermediate reinforcing rings while the airlock is in use unpressurized.

Some effort went into the design and testing of latching mechanisms which would automatically latch into place during inflation, and thereby keep the airlock shape throughout unpressurized operations. However, these concepts proved to be complex to design, tedious to fabricate, and impossible to verify without direct visual inspection. In addition, there was no way to release these latches remotely to allow collapsing and restowage of the airlock. For all these reasons, it was ultimately decided to have the structure manually rigidized post-inflation by inserting ball-lock pins at each of the twenty folding structural fittings throughout the airlock. The same pins would be manually removed before stowing the airlock. Since NASA specifically did not require an automated stowage capability, returning the airlock to its stowed configuration will involve the use of support personnel pushing the endcaps together and “encouraging” the fabric envelope to fold in the design pattern during retraction.

E. Interior Outfitting

The NASA specifications for the airlock included the desire to have representations of systems which will be required for a flight airlock, including ventilation, lighting, communications, and spacesuit support equipment including life support umbilicals. Lighting is accomplished by LED flexible cables built into the inner scuff layer of the airlock envelope; the same routing paths as the lights are used for communications and data cables running to compact preintegrated interface boxes. Likewise, ventilation is accomplished with a flexible fabric conduit with several ventilation grids spaced along it. Both approaches allow the outfitted hardware to be stowed and deployed in place inside the airlock. Handrails for body positioning are integrated onto the deployable rigidizing structure, and will be able to be repositioned to meet crew preferred positions. Suit support hardware is supplied as inactive mockups, which can be attached to mounting points internal to the airlock by simulated crew.

One of the challenges is that none of the internally outfitted systems can be allowed to interfere with airlock inflation and pressurization. Power, lighting, and data/communications lines are routed via hermetically sealed electrical connectors mounted in the bulkhead structure. While it should be possible to have a sealable ventilation conduit running through the bulkhead, for simplicity the ventilation air is routed from the external blower to the internal distribution conduit via a flexible hose running through the open hatch.

F. Ground Support Equipment

The airlock will be used, among other things, to test and demonstrate the ability to perform inflation operations in the environment of the Gateway mockup facility. This means that the two endcaps have to move two meters relative to each other on a concrete floor. Similarly, it would be more operationally useful if the airlock unit could be easily moved around, whether deployed or stowed. For this reason, each endcap will be mounted to a ground support structure which will maintain the bulkhead and hatch vertical while providing a set of castering wheels to allow it to roll easily across the floor. The casters will have locking wheels to secure the airlock when it is in its operating configuration and in the desired location.

NASA has expressed an interest in using the prototype airlock for simulated activities in support of ground operations testing of the Gateway concepts. This will require having at least two people inside the airlock while unpressurized. Without further ground support equipment, the internal crew would be stepping on the unpressurized fabric envelope, or worse, stepping on the components of the deployable truss structure. To prevent this, the University of Maryland team has also designed a “GSE Bridge” structure. Following inflation, depressurization, and opening the hatches on each end, this lightweight structure will be manually inserted into the airlock through the hatches. It projects through the open hatch and is independently supported on the floor by the endcap support structure and casters. The bridge structure routes all of the loads induced by the crew weight and dynamic loading through the hatches and down to the floor, isolated from the airlock structure. This bridge structure has to manually removed prior to restowing the airlock.

V. Development, Fabrication, and Testing

A. Component and Scale Testing

Initial testing focused on developing and verifying techniques for design and fabrication of specific aspects of the inflatable airlock. Critical areas included envelope fabrication, sealing the pressure bladder to the endcaps, and development of a deployable rigidizing structure.

The pressure bladder for this airlock design is basically an open-ended fabric cylinder of heat-sealed urethane-coated nylon. The favored technique for hand heat-sealing the pressure bladder was developed after extensive experimentation during the 2016 X-Hab inflatable airlock project, and involves directly face-sealing seams and then reinforcing the seams with an additional strip of fabric across the joint, as shown in Figure 13. This was shown to ensure that any pressure loads taken by the bladder would be transmitted across the heat-sealed joints in pure shear, rather than a tension force between the two heat-sealed fabric sheets. Samples were tested to destruction to verify operating loads (Figure 14). This showed that the addition of the seam reinforcement increased the failure stress by more than a factor of two. While in nominal operations all pressure loads will be taken by the restraint layer and woven webbing layer, these tests showed that the pressure bladder is actually capable of supporting all pressure loads itself even without a restraint or webbing layers.

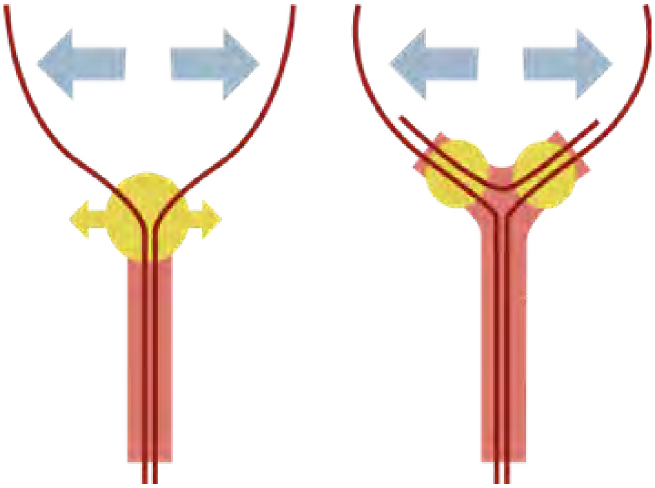

Figure 13. Detail of heat-sealing pressure bladder seams – left: face seal (pressure loads result in peeling of joint); right: overlap reinforcement (pressure loads taken in shear)

Figure 14. Pressure bladder sample post-failure in tensile testing machine

One of the largest challenges for this project was in establishing a robust, reliable seal between the fabric envelope and the rigid endcaps which can be easily fabricated by student labor. Initial approaches considered included sealing radially on the outer edge of the endcaps (similar to fabric/rigid interfaces on the A7L series of spacesuits), and face sealing to the rigid elements with rigid backing rings to provide seal compression and fabric retention (analogous to the interfaces used in shuttle extravehicular mobility units (EMUs) for assembling the modular soft goods). Considering that the final design requires 479cm of circumference sealed against an endcap thickness of only 1.8cm, the radial seal was rejected in favor of a face seal.

Extending the design analogy to the EMU design, the face seal would be established external to the airlock envelope on the side of the endcap proximal to the fabric. This offers the advantage that the through-bolts holding the bulkhead, envelope, and backing ring together are external to the sealed volume, and are therefore not a potential leakage source. Of greater concern for this application, the pressure bladder fabric has to be cut to open outwards, which requires the bonding of a separate sealing ring around the entire periphery, a task which has proven problematic in the SSL for much smaller components. For that reason, the airlock team devised the concept of bringing the envelope around and past the endcap and sealing to the external face of the endcap. This allows the use of formed darts in the material for a sealing surface, which will also increase the tensile strength of the assembly. This will require a separate sealing technique for the bolts, which is not a major problem considering the constraint to only operate at vent pressure.

The rigidizing structure was challenging mainly due to the large number of possible configurations. The structure needs to fold compactly to produce the smallest possible stowed envelope, but self-latch on inflation to hold the envelope in its deployed configuration without internal pressurization. Due to the choice of an internal structure, it is necessary to have the capability to manually release the latches prior to stowage while still maintaining sufficient airlock support to allow the internal person to complete the unlatching and exit the airlock without a chance of a collapse. A number of possible designs were created in CAD models, and several were taken to rapid prototyping using additive manufacturing for visualization and deployment/stowage testing. The final version, chosen largely for simplicity of both fabrication and operation, uses ball-lock pins to digitize hinge mechanisms interior to the airlock. This system provides both axial and torsional stiffness for the envelope, while allowing a simple procedure for installation and removal.

B. Operations Testing

The airlock will be assembled and tested at the University of Maryland before being packaged for shipping to JSC. The endcaps will be assembled with bulkhead structure, hatch, hinge, and latching mechanism and individually tested. Each endcap will be integrated to the external GSE support structure and castors to allow free motion on the laboratory floor. They will be connected with the internal support rings and the deployable support structure, and the deployment and retraction will be tested repeatedly without the complication (and visual obstruction) of the pressure envelope.

Once the structural elements are tested and determined to be satisfactory, the fabric envelope consisting of the inner scuff layer, pressure bladder, restraint layer, restraint woven webbing, and outer protective cover will be pulled over the assembly and attached to the endcaps. At this point the airlock will be pressurized to demonstrate automatic deployment, and the leakage rate measured. It is anticipated that some minor leakage is inevitable; the pressurizing air pump has been sized to ensure that the internal pressure can be maintained despite the expected nominal leakage rate. Following deployment, the airlock will be vented, the hatches opened on each end, and the GSE bridge inserted into the airlock. This hardware will not be structurally connected to the airlock itself, but will cantilever out each hatch and be supported by the airlock's ground support structure going down to the castors. This will ensure that crew loads from personnel inside the airlock will not be applied to the airlock itself, and that the airlock assembly can be easily repositioned on a flat floor regardless of whether stowed or deployed.

VI. Conclusions and Future Plans

The University of Maryland inflatable airlock will be delivered to the NASA Johnson Space Center and demonstrated in the early summer of 2019. It, as well as another inflatable airlock system under development by the Oklahoma State University, will remain at JSC and be available for evaluation or use with the NextStep habitat mockups throughout the life of the Gateway program. This represents a double win: NASA is obtaining inflatable airlock modules at a small fraction of the cost from an aerospace contractor, and groups of students will have the motivation that hardware they designed, fabricated, and tested is being used by NASA on a cutting-edge human spaceflight program. The 2019 inflatable airlock X-Hab project has been an excellent source of practical engineering experience to students at the University of Maryland from first-years through graduate students.

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