41st International Conference on Environmental Systems
17 - 21 July 2011, Portland, Oregon

AIAA 2011-5044

Design, Development, and Testing of an Inflatable Habitat Element for NASA Lunar Analogue Studies

Massimiliano Di Capua, * Dr. David L. Akin, †

Kevin Davis ‡

Space Systems Laboratory, Department of Aerospace Engineering, University of Maryland

College Park, MD, 20742, USA

The University of Maryland (UMd) was selected as a finalist in the 2010 NASA X-Hab Academic Innovation Challenge. Students in the Aerospace Engineering department of the A. James Clark School of Engineering designed, fabricated, and tested a full-scale inflatable upper-deck habitat for the NASA Habitat Demonstration Unit (HDU), for possible incorporation into future analogue field testing through the NASA Desert Research and Technology Studies (D-RATS) program. The vision for this effort is to facilitate human lunar exploration by exploring technologies which may provide long-term habitation with minimum mission impact.

The upper deck habitat, or "loft" has a circular 5m diameter footprint, an internal volume of 60m^2, and retains its shape when the envelope is not pressurized. The inflatable envelope also includes a simulated radiation protection layer and a thermal insulation layer, and is capable of sustaining 50mph winds. The element has a total mass of 372kg, and has been designed to accommodate a crew of 4.

A series of initial concepts were proposed and examined experimentally; subsequently, a final configuration was identified. Drawing on decades of UMd research experience in pressure suit development, the inflatable habitat was based on the same inflatable fabric technologies that are traditionally used in the development of space suits. The UMd team conducted a series of analytical trade studies and analysis as well as experimental tests to inform the design process, including fabric tensile strength testing, wind tunnel testing, hydrostatic testing of various structure prototypes and models, and finite element analysis of all critical sections of the loft.

A full scale element was built and tested, and the internal crew accommodations were designed and incorporated in the loft. The internal layout includes four individual sleeping quarters, a multi-functional recreation/medical area, storage space, windows, lighting, ventilation, emergency egress, and power outlets. The loft also includes a pressure monitoring system for the inflatable structure and a suite of environmental sensors.

In response to NASA's desire to maximize the meaningful involvement of students in the X-Hab project, the development activities described in this paper are the work of students in three undergraduate and one graduate class, mentored by faculty and graduate students in the Space Systems Laboratory; by the completion of this project in the summer of 2011, more than 50 students will have had substantial involvement in the design, fabrication, and testing activities. Results from the integration and testing of the UMD X-Hab full-scale prototype with the NASA HDU habitat are also included in this work.

*Ph.D. Candidate, maxdc@ssl.umd.edu, Student Member, AIAA.
†Laboratory Director and Associate Professor of Aerospace Engineering, dakin@ssl.umd.edu. Senior Member, AIAA.
‡Graduate Student, kpdavis@umd.edu, Student Member, AIAA.

D-RATS	Desert Research and Technology Studies
ECLIPSE	Extensible Concept for Live-In Pressurized Sortie Elements
ESMD	Exploration Systems Mission Directorate
EVA	Extravehicular Activity
FEA	Finite Element Analysis
HDU	Habitat Demonstration Unit
MMSE	MicroMeteorite/Secondary Ejecta
NASA	National Aeronautics and Space Administration
NSGF	National Space Grant Foundation
SSL	Space Systems Laboratory
UMd	University of Maryland
X-Hab	eXploration Habitat
HVAC	Heating, Ventilation, and Air Conditioning

I. Introduction

On June 23, 2010, the National Space Grant Foundation (NSGF) and the NASA Exploration Systems Mission Directorate (ESMD) released the 2010 X-Hab Academic Innovation Challenge solicitation. The Space Systems Laboratory at the University of Maryland responded with a proposal, and was selected along with two other schools (University of Wisconsin-Madison and Oklahoma State University) to participate in the competition. Beginning Fall 2010, more than 50 students ranging from freshman to graduate students, a faculty advisor and three student mentors (both graduate and undergraduate students) from the SSL have been involved in the design, fabrication and testing of the UMd X-Hab unit.

Figure 1. UMd X-Hab logo

The effort was divided into three main phases. The design phase initially delivered a preliminary concept, which evolved through several experimental and analytical processes. These allowed the team to better understand the challenges associated with inflatable space structures, as well as initiating innovative solutions to the various engineering problems that rapidly arose. The second phase encompassed the manufacturing of the final design of the habitat, as well as the detailed design and development of all the subsidiary systems and mechanisms. Lastly, the final phase included systems testing and performance evaluation, operational procedures development, and delivery of the unit and its documentation.

The following manuscript will expand in detail the above phases in a chronological fashion, and will include experimental and analytical procedures descriptions, results and lessons learned as well as a brief summary of the competition. Unfortunately the competition outcome will not be included in this work since the winner will be announced subsequent to the submission deadline of this manuscript.

A. X-Hab Competition Details and Requirements

The solicitation[3] for the X-Hab competition describes the general guidelines that drove the project. For completeness, the most relevant sections have been included verbatim below.

> The X-Hab Academic Innovation Competition is a university level competition designed to engage and retain students in Science, Technology, Engineering and Math (STEM) disciplines. NASA will directly benefit from the competition by sponsoring the development of innovative habitat inflatable loft concepts from universities which may result in innovative ideas and solutions that could be applied to exploration habitats. The challenge is for a senior and/or graduate level design course in which students will design, manufacture, assemble, and test an inflatable loft that will be integrated onto an existing NASA built operational hard shell prototype. In June of

2011 the NASA-HDU Project will conduct a head-to-head competition for successfully designing and demonstrating an attachable inflatable habitat "Loft" (2nd level attachable) concept given a list of requirements for the design. Universities may collaborate together on a Project Team. Up to three project teams will be selected for funding. The head-to-head competition will determine the winner that will be awarded additional funds to integrate their design with the HDU-Lab during the August-September 2011 HDU-Hab/Lab integrated field testing. The objectives of this challenge are to engage and inspire the next generation of innovative engineers and the successful design, manufacture, and demonstration of inflatable habitat loft. Concepts are to be self-deploying in a specified time, will install to a standard interface on NASA's hard shell Lab, and will meet total mass and volume constraints in both stowed and deployed configurations. Concept shapes and sizes will be determined by the proposer while meeting the constraints of the design requirements. The Foundation anticipates that up to three awards will be made under this solicitation for $48,000 each. Up to an additional $10,000 will be awarded to the team that wins the head-to head competition to offset their costs of participating in the HDU-Hab/Lab integrated field testing.

The first level requirements were provided and read as follows:

- Shall provide sleeping accommodations for a crew of 4 (propose private or shared, acoustic privacy, etc.)
- Shall provide power to sleeping areas (via HDU source)
- Shall provide integrated lighting (via HDU power source)
- Shall provide air circulation (HVAC via HDU source)
- Shall provide personal crew items stowage
- Shall provide group meeting function
- Shall provide crew stowage items translation into loft function
- Materials used shall function as an analog for the final materials that would be adapted to space qualification. Shall use nylon or similar fabrics that are of equivalent weight and construction that will simulate flight like materials such as Vectran.
- A structural analysis shall be done of the shell flight configuration designed to support 8.3psid with a SF = 4.0.
- The demonstration unit fabric structure shall be capable of being inflated to a minimum low pressure (approx. 0.125psid) that is capable of supporting the weight of the fabric, pre-integrated window, and wind loading of 50mph. A (2.0 x 0.125psid) proof test will be required prior to the HDU and loft integration.
- Interface with the HDU "Barrel Interface Ring," Develop an interface ring (it may be or may not be segmented) that is pre-integrated to the inflatable shell (fits in a folded package) such that when mated to the top surface of the HDU as a complete ring, meets a low leak rate requirement and structural loading requirements. There shall be no visible damage of the bladder at the sealing interface.
- Provide an inflation system to perform initial deployment and delta inflation as required.
- Single story.
- Minimum deployed volume shall be no less than $60m^3$.
- Shall include pre-integrated utilities (air circulation, power, and lighting).
- Shall include no less than one pre-integrated window. Window minimum size 0.5m diameter.
- Maximum weight including interface hardware is 500kg.

- Provide simulated micrometeoroid/secondary ejecta (MM/SE) and radiation protective layers, Assume a 2-layer Lunar MM/SE bumper shield with a mass of (CxAT Lunar Analysis MMSE = $1.52 kg/m^2$) $1.5 kg/m^2$
- Shall provide multi-layer thermal insulation equivalent to an R-value of no less than R=16.
- Expandable structure shall be self-supporting when crew is translating into or out of the HDU to Loft.
- Shall be capable of re-packaging from the deployed configuration to the package configuration.

A number of these requirements were modified by the NASA sponsors throughout the progress of the habitat development. For example, it was discovered that NASA safety regulations would not allow humans to be inside a sealed and pressurized habitat, even at the vent pressure level planned. For this reason, the requirement for pressurization was dropped in favor of an emphasis on rapid deployment of a free-standing lightweight structure which could employ inflatable structural elements. Additional requirements were also added, such as accommodations for D-RATS instrumentation modules and interface specifications for integration into the HDU avionics architecture.

B. Background: Habitat Demonstration Unit

Figure 2. NASA Habitat Demonstration Unit (HDU) at 2010 Desert RATS

The HDU was not part of the development documented in this paper. However, the details of the HDU drove the design process throughout the effort, so a brief description of HDU from the NASA Analog Testing website[1] is included here for completeness.

> The Habitat Demonstration Unit (HDU) Project is a unique project from a multi-center team of NASA architects, scientists and engineers, working together to develop sustainable living quarters, workspaces, and laboratories for next-generation space missions. The knowledge gained from low Earth orbit projects, such as the International Space Station, and Earth-based analog research from the Desert Research and Technologies Studies (Desert RATS) is being used in this project to find out what is required to expand human presence to more formidable environments, like an asteroid, Lagrange points, the moon or Mars. The HDU vision is to develop, integrate, test, and evaluate various habitat configurations that will advance NASA's understanding of alternative mission architectures, requirements, and operations concepts for Exploration Habitats.
>
> HDU is a non-flight rigid shell composed of eight composite fiberglass, resin-infused sections obtained from a single mold, and is supported by large, C-shaped steel ribs. HDU sits on top of a 13.8-foot square cradle that also functions as mount point for an airlock and a front porch. It is arranged as a cylindrical structure with vertically oriented axis 3.3m tall and 5m in diameter. It has a volume of 1,978 cubic feet (56 cubic meters) in one story, and has four access ports that are used to interface with rovers and an airlock.

The Habitat Demonstration Unit - Excursion Configuration for human exploration missions was rolled-out for remote testing in July 2010, and was used for day-long test simulations in the September, 2010 Desert RATS tests in Northern Arizona.

II. Phase 1: Preliminary Design and Technology Development

As part of the X-Hab competition, all university teams were required to complete the canonical set of NASA design milestones such as a Systems Design Review (SDR), a Preliminary Design Review (PDR) and a Critical Design Review (CDR). The first review (SDR) was completed on October 1st 2010; on that occasion the UMd team proposed several concepts to address the given top level requirements. The proposed system architecture is shown in figure 3.

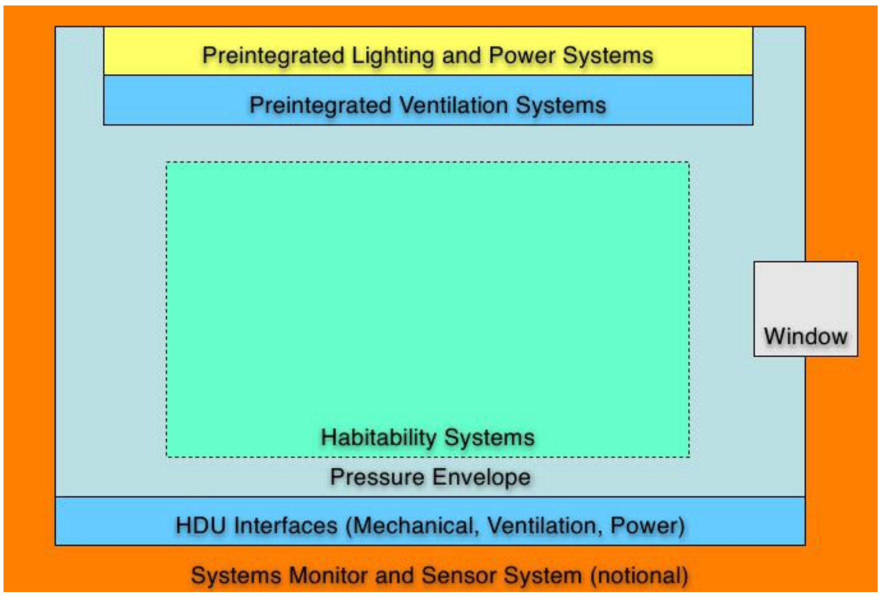


Figure 3. Preliminary System Architecture

The initial loft concept envisioned an inflatable structure composed of seven layer groups. Based on the traditional space suit layering, X-Hab was to include (from inside to the outside of the shell) an interior nylon fire-resistant layer that would also serve as the main mounting layer for interior accommodations; a urethane-coated nylon pressure bladder, used to contain the habitat internal atmosphere; a nylon restraint layer, used to distribute the pressure loads to the main structural element; the restraint lines layer, a nylon web-like woven layer that takes the primary pressurization loads; a simulated multi-layer polyethylene radiation shield; a fiberglass batting thermal insulation layer, configured for functionality on Earth rather than space; and a nylon simulated Micrometeorite/Secondary Ejecta (MMSE) protection layer.

The first question that arose in the conceptual phase was the geometrical configuration of the loft. Given the pressure vessel nature of the loft, the options were confined to cylinders and ellipsoids. The first trade study conducted expressed the relationship between loft peak height and loft cylinder section height.

The fixed parameter in the study was the internal volume, that was set to 60 m^3. The internal volume of the loft allows for 15m^3 per crew member, and as can be seen from figure II it allows for optimal crew performance for mission durations up to two months. For longer mission durations, the internal volume still remains above the performance limit threshold as stated in NASA STD 3000.[2]

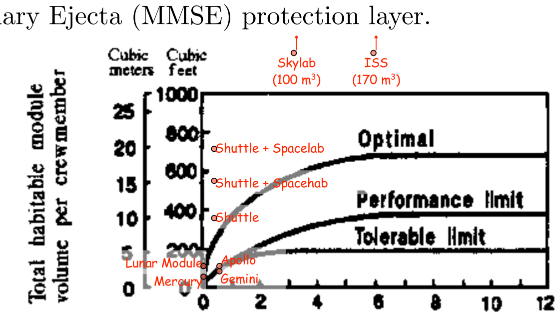


Figure 5. Volume per crew member with overlay of current and historical men rated spacecraft data points

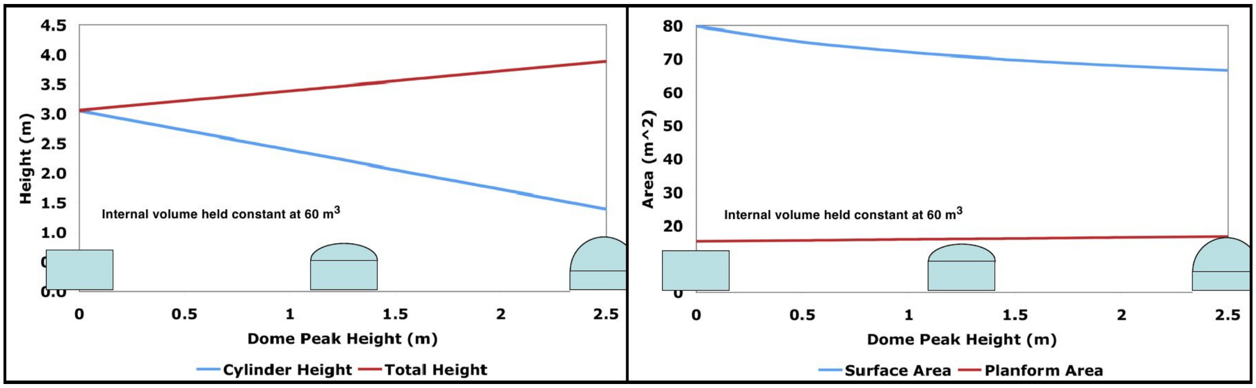


Figure 4. Initial trades

The plot on the left in figure II shows the geometrical relationship, which led to a more interesting trade focused on the available cylinder wall area.

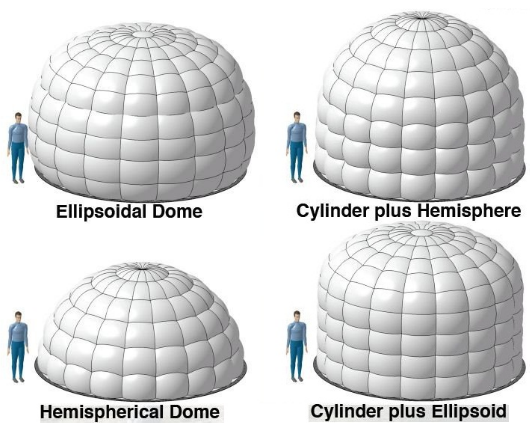


Figure 6. Proposed Shell Concepts

In habitable volumes, the flat cylinder wall area is the main interface for docking ports, equipment mounts, cable routing, etc., and is possibly the most valuable habitat surface. On the other side, having a high ceiling does not really add any practical functionality unless one is envisioning a multi-floor system or overhead stowage space. This last consideration applies exclusively if the habitat is deployed in an environment where gravity is present, such as the Moon or Mars.

Usually, as long as the envelope's height allows the inhabitant population to have an unobstructed workspace (which is a function of the strength of the gravitational forces that are present), there is no reason other than aesthetics to increase the loft's height (as a rule of thumb, the minimum ceiling height should allow for the users to stand and extend their arms upward without touching the ceiling and be able to "walk" without colliding with the envelope ceiling). The curve on the right in figure II shows that the relation between available cylinder wall area and the aspect ratio of the dome is quadratic; therefore, if we were to purely optimize for wall area, a bare cylindrical configuration would be ideal, but impractical for pressurized structures.

Four different shell layouts, shown in figure 6, were proposed with the goal of aiding the identification of a feasibly constructible inflatable loft. In addition to the above, a set of preliminary finite element analyses (FEAs) on preliminary CAD drawings were run to acquire an initial estimate of the mass of the load bearing layers and various hardware elements like window frames and the HDU interface mounting ring to better inform the initial mass estimate for the loft.

The initial mass estimate of 181kg included just the seven fabric layers, one window and the HDU interface mounting ring. During SDR another concept was introduced in order to satisfy another primary requirement: the inflatable support structure. In order to allow the

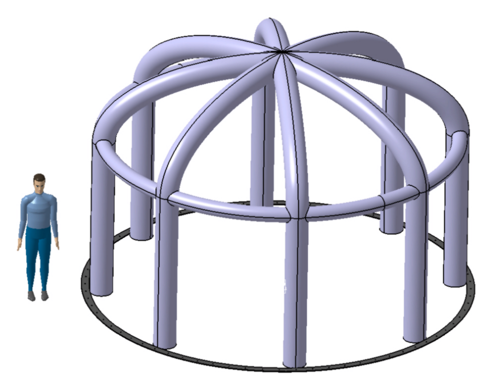


Figure 7. Initial truss concept

loft to retain its shape when the internal volume is not pressurized, the UMd team proposed an inflatable fabric truss-like structure shown in figure 7.

Also during SDR a preliminary interior layout, shown in figure 8, was proposed, along with a detailed work schedule and secondary objectives. As part of the secondary objectives, a series of experimental development tests were proposed and were aimed in increasing the student participation in the project. The UMd team was joined by the 2010 ENAE100 "Introduction to Aerospace"' freshman-level students.

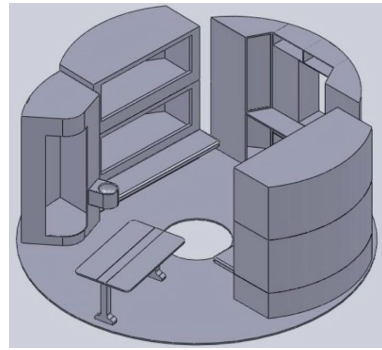


Figure 8. Preliminary interiors concept

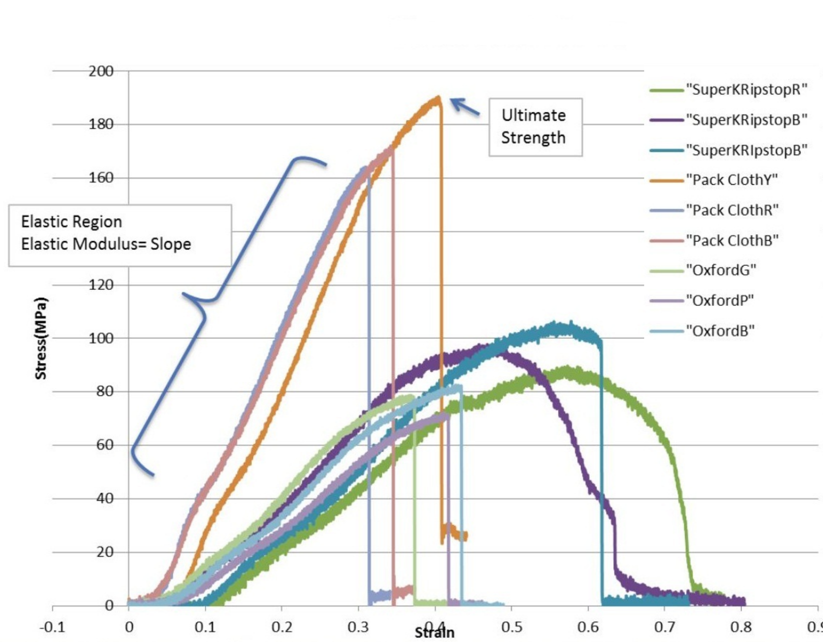
Twelve students guided by three SSL student mentors were involved in the X-Hab technology development process. The students were divided into three teams: Materials Testing Team, Wind Tunnel Testing Team, and the Habitat Shape Team. Each team was required to design and conduct a series of experimental protocols, analyze and reduce the resulting data, draw meaningful conclusions, produce a poster presentation, and present their work on the last day of classes of the Fall 2010 semester. The following subsections will describe their work in detail. The Preliminary Design Review was conducted on the 29th of October 2010. At that time, no fundamental changes in the design were made pending the results from the experimental tests above that were completed in December, 2010.

A. Materials Testing

Figure 9. Materials Testing

A wide array of materials were tested for both material properties and porosity. Materials testing included tensile testing to failure, and visual and microscopic inspection of the tested specimens. The results from this phase were used to build a detailed data matrix that has been used to identify the optimal materials for each layer. Specimens were built using a standard "dog-bone" shape, and the gripping ends were reinforced to mitigate deterioration due to the Materials Testing System (MTS) pneumatic grippers. The specimens were measured and inspected through a digital microscope for imperfections. Three samples for each material were produced; a single unaltered continuous sample, a single overlap sewn sample and a double stitched flat sewn sample. Three specimens were built and tested for each material and configuration. The results from this study are reported below in figure 10.

Materials testing was confined to several weaves and weights of coated and uncoated nylon fabric ranging from 200 Dernier Oxford to 1050 Dernier Cordura, as well as Spectra-reinforced fabric. All specimens were produced from fabric samples that were provided by our suppliers. The results showed that the pack cloth was the weave with the highest ultimate strength, while heat sealables were the ones with the lowest. Worthy of note is the difference in behavior between rip stop and non rip stop weaves. The first shows a gentle curve following the ultimate strength point while the non rip stop materials show an instantaneous drop typical of fragile materials. The rip stop behavior is very desirable since it reduces the likelihood of an instantaneous burst, but given the overall low strength of the available fabric weights, the option was deemed unfeasible. The results from this test were later used to refine the loft FEM analysis and a decision was made for the load bearing layers based on both material performance and cost.



	Ultimate Strength(Mpa)	Modulus of Elasticty(Mpa)
FEE	46	
FS	123	
CEE	25	
CS	66	
CO	77	
FO	69	
YEE	11	59
YO	30	103
YS1	10	79
YS2	29	185
YDO	26	118
Oxford Heat Sealable Red	84	
Oxford Heat Sealable Orange	77	
Oxford Heat Sealable Yellow	115	
Pack Cloth Blue	172	555
Pack Cloth Red	164	581
Pack Cloth Yellow	191	543
White Widow 1	108	
White Widow 2	134	
SuperKRipstop Black	106	219
SuperKRipstopBlue	98	242
SuperKRipstopRed	90	185
1050 D Balistic Black	112	
1050 D Balistic Brown	196	
1050 D Balistic Gray	117	
500 D Cordura Blue	144	
500 D Cordura Brown	121	
500 D Cordura Red	128	
200 Denier Coated Oxford Black	83	222
200 Denier Coated Oxford Pink	72	197
200 Denier Coated Oxford Gray	79	243

Figure 10. Materials Testing Results: Stress-Strain

B. Wind Tunnel Testing

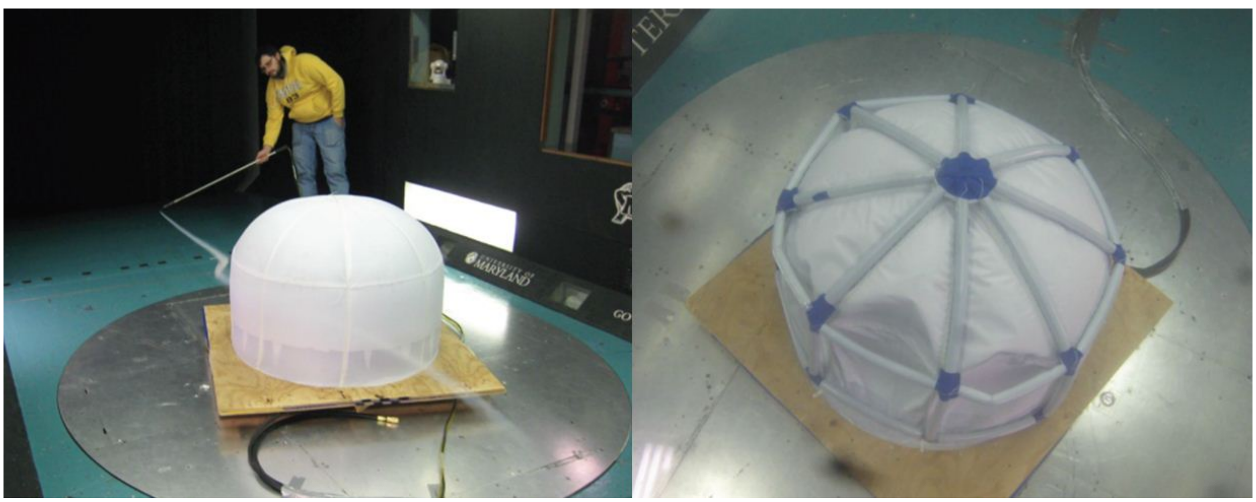
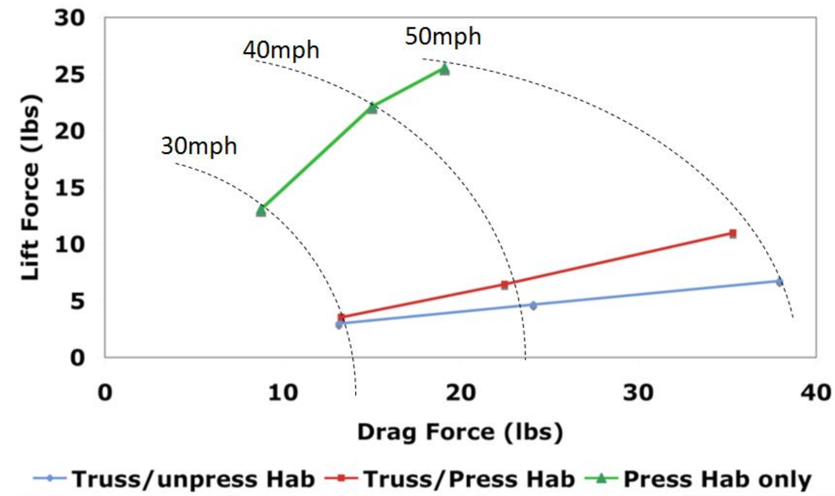


Figure 11. Wind Tunnel Testing

Wind tunnel testing on a high-fidelity 1/5 scale inflatable model was conducted to address the wind load capacity of the inflatable loft in several configurations. The high-fidelity model included all the significant layers of the final full-scale envelope, as well as the first iteration inflatable beam structure. This model was also used as the main tool to evaluate stowing configurations and procedures, and to foresee possible assembly challenges that could arise during the construction of the full-scale element. The model was tested in the Glenn L. Martin Wind Tunnel at the University of Maryland. Four data points were acquired during the tests. Initially the plain model mounting flange was connected to the wind tunnel balance, and tested at 30, 40 and 50 mph to estimate the impact of the mounting flange on our measurements. We then repeated the measurements with the model deflated, but with the inflatable structure pressurized at 20 psi, with both the inflatable structure and the habitat volume pressurized (habitat at 4 psi and inflatable structure at 20 psi), and finally with the habitat pressurized at 4 psi and the external inflatable structure removed. Figure

12 shows the calibrated data. We also had the opportunity to do a flow visualization test using a smoke wand shown in figure 11. This test allowed us to estimate the wind patterns around the structure, and highlighted the need of a streamlined external layer in order to reduce the wind induced drag.



Condition	Drag Coefficient	50 mph Full Scale Wind Force (lbs)
External Truss Unpressurized Hab	0.704	983
External Truss Pressurized Hab	0.675	942
No External Truss Pressurized Hab	0.421	587

Drag coefficients referenced to habitat base area

Condition	Lift Coefficient	50 mph Full Scale Wind Force (lbs)
External Truss Unpressurized Hab	0.140	278
External Truss Pressurized Hab	0.194	402
No External Truss Pressurized Hab	0.606	2001

Lift coefficients referenced to habitat base area

Figure 12. Wind Tunnel Testing Results

A streamlined exterior would also increase the aerodynamic lift, which would be beneficial in holding the habitat up and relieving the inflatable structure of some compression loads. The tests allowed us to estimate the aerodynamic coefficients of the loft, and to scale up the loads to estimate those expected in the full scale element.

C. Habitat Shape Studies

Figure 13. Habitat Shape Testing

Three 1/10 scale low-fidelity prototypes of various configurations were built and hydrostatically tested to measure burst pressure, leak rates, failure points, and discrepancies between the expected and actual inflated shapes. These models included just the pressure-bearing layers, specifically a pressure bladder and restraint layer, and were designed to replicate three of the candidate inflated shapes for the final habitat. The three candidates consisted of a cylindrical wall with a 2:1 ellipsoidal dome loft, a cylindrical wall with a hemispherical dome, and an elliptical wall section with a 2:1 ellipsoidal dome. A test rig was also designed, built, and tested, based on an analogue pressure sensor and a NI-6009 NI-DAQ module. The three models were initially designed in CAD, from which fabric patterns were produced. The models were built by cutting and sewing the restraint layer. A single 420 Denier nylon layer was stitched together through a double folded type stitch, while the internal bladder made of urethane-coated nylon was heat sealed. The three models shown in figure 13 were then tested hydrostatically. The test was executed in 1g conditions (models were not immersed in water for the test). Unfortunately leaks in the interface plate did not allow any of the models to reach burst pressure, therefore no substantial conclusions were obtained from this specific test. The recorded data is shown in figure 14. The models were subsequently inflated with air, which gave significant insight for the down-selection of the pattern type to be used in the final design. The three patterns used all showed a significant give when under pressure, therefore the ellipsoidal wall section was deemed unnecessary due to excessive bulging. The hemispherical dome model resulted in an elongated elliptical dome that was considered suboptimal in terms of interior space usage and aesthetics. In conclusion, the 2:1 ellipsoidal dome with the cylindrical wall was the favorite candidate, since it assumed an "under load" configuration that allowed for a stable wall section and a moderately curved dome. The test also pointed out that obtaining a reasonable seal on the walls and dome sections was not difficult, while sealing the interface ring and the dome apex was going to be a very challenging task, especially in the full scale element.

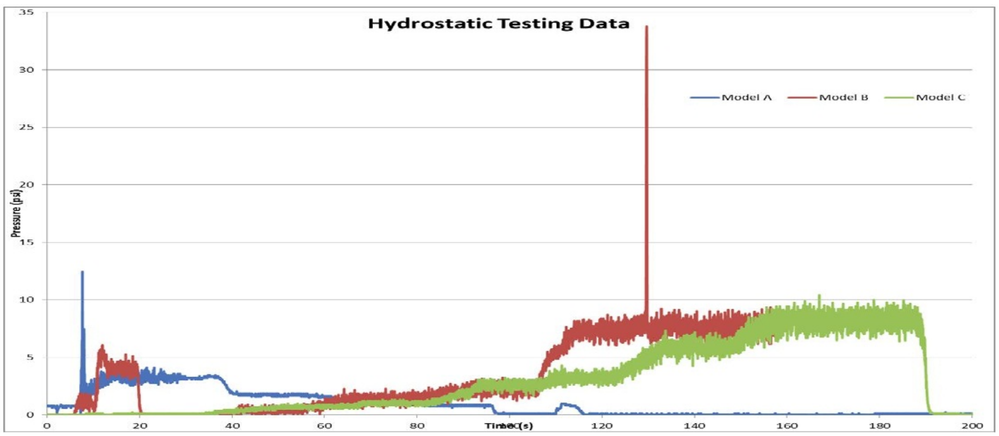


Figure 14. Habitat Shape Testing Results

III. Phase 2: Final Design and Loft Assembly

Figure 15. UMd X-Hab Final Design

On the 2nd of February, 2011, the University of Maryland held its X-Hab Critical Design Review. The UMd team discussed the experimental tests that were conducted, and the decisions that were made with the resulting knowledge. The proposed design was composed of a cylindrical section 2.2m tall and 5m in diameter with a 2:1 elliptical dome above it, resulting in an overall height of 3.6m. The loft estimated mass was 451kg, including five 18in windows, one safety exit, and a seven layer shell with an internal inflatable truss structure. The design process was enabled through the use of CAD models, FEM analysis and sub-scale prototypes.

A. Envelope Layers Configuration and FEM Analysis

The internal layers architecture was slightly modified from the initial design presented at SDR and PDR, by including the inflatable beam structure inside the shell between the pressure bearing layers and the simulated environmental protection layers.

Figure 16 shows a cross-sectional schematic of the X-Hab structure to illustrate the CDR-configuration envelope architecture. From the materials testing database, the following materials were chosen for the final element:

- Internal fire-retardant layer: 200 D fire retardant rip-stop nylon
- Bladder: 200 D urethane coated nylon
- Restraint layer: 420 D pack cloth nylon
- Restraint lines: 2in wide, 5500lbs rated nylon webbing
- Thermal insulation: 6in thick (R19) fiberglass batting
- Simulated Radiation Shield: 10, 6mil thick polyethylene sheets
- Micrometeoroid Layer: 1000 D abrasion resistant Cordura

The use of CAD models allowed us to design the patterns for the shell, based on the shell design and the available raw material dimensions (fabric rolls usually are supplied in lengths between 50 and 100 yards and widths of 60in). With this process we were able to achieve a 96 percent efficiency in the use of the fabric, reducing the overall cost of the loft.

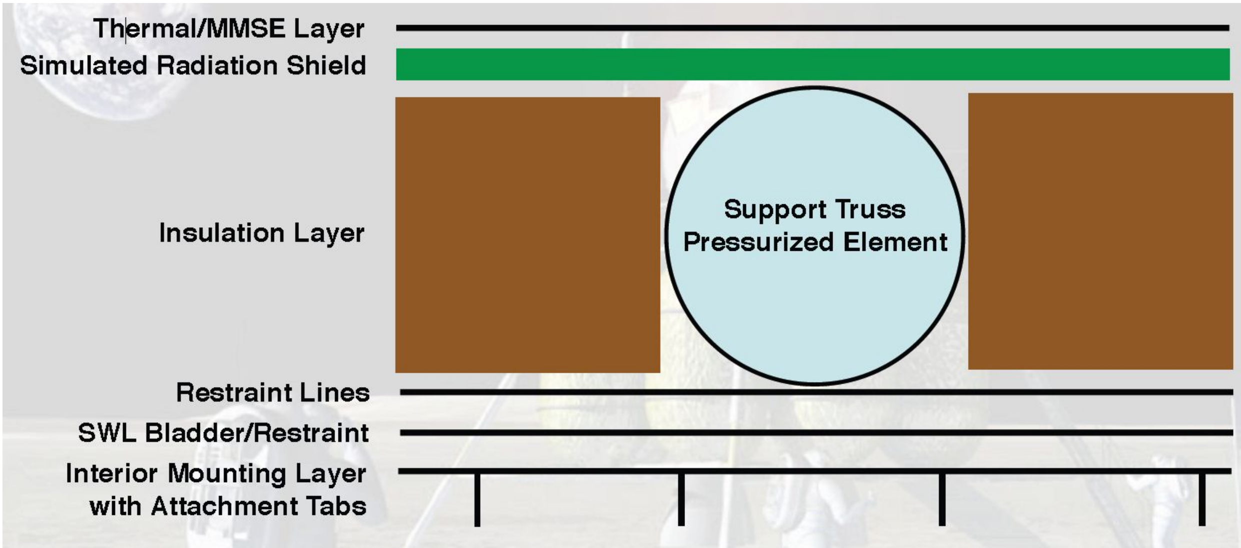


Figure 16. Final design layers cross-section

1. FEM Analysis

Several FEM analysis were run during the preliminary concept phase. In this section, though, we will refer only to the final set that was used to address the structure's response to wind and pressure loads.

Four cases were evaluated on a slice of the habitat: the first case considered exclusively pressure loads, the second added wind loads, the last two were notional cases used to address possible overpressure, and lastly the wind load case at vent pressure. The results are shown in the figures below. In the first two cases, we can see that the deflections due to wind loads are negligible when the habitat is pressurized, and that the current choice of materials and restraint lines configuration allows for safe pressurization. The last two cases show that a safety factor of 2 is plausible, and that even at vent pressure, the habitat shell does not experience compression loads (collapse of the shell on itself) when subject to wind loads and its own weight

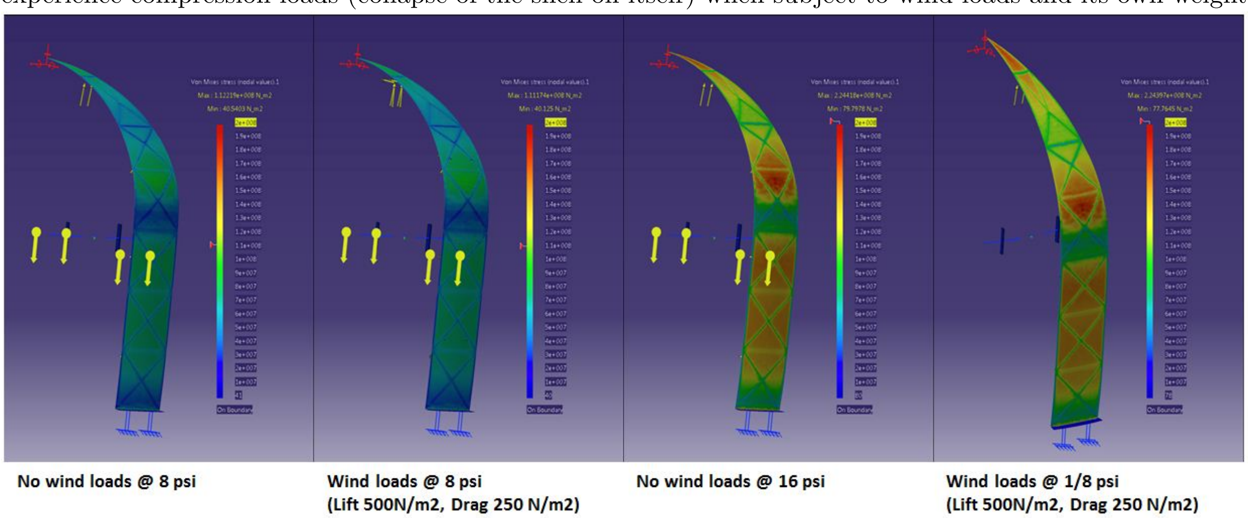


Figure 17. FEM Results (Deformation Scale Factor = 1)

B. Inflatable Support Structure

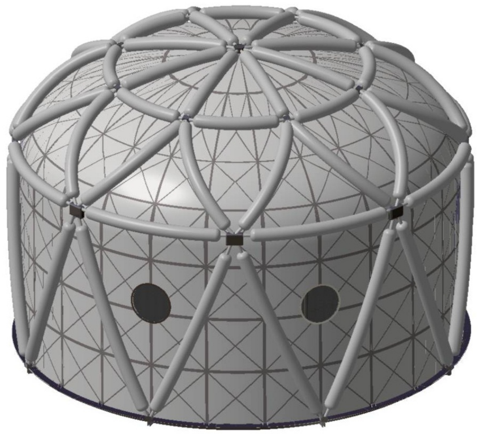


Figure 18. Inflatable Support Structure

The inflatable structure is perhaps the most complex element in this project, and also the most critical in terms of functionality. It is a collection of 56, six-inch diameter fabric beams interconnected through 25 manifolds. The beams are designed to create a triangular sequence cage. The triangular structure also ensures a higher resistance to side loads (wind loads) by allowing the lateral loads to be spread over several beams. All beams are curved when inflated to mitigate the inflation singularity problem that would occur if they were straight.

The beams are also connected to both the inner and outer walls of the loft reducing the likelihood of lateral instability. Particular attention was dedicate in the beams connection interface and manifolds. The beams are connected on each end to a manifold via a threaded NPT custom plug that was machined to include a rubber sealing flange and a clamping interface. The plug schematic is shown in figure 19.

C. Prototype Testing

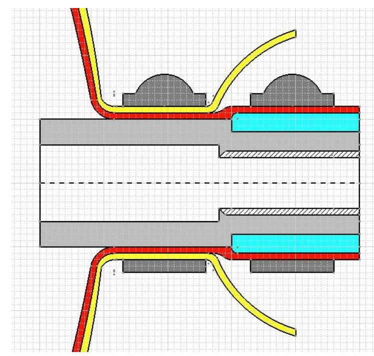


Figure 19. Plug Schematic

Three beam prototypes were produced and hydrostatically tested to ensure the validity and feasibility of the concept during the design phase. Initially a 12ft long beam was built along with a prototype plug. The plug was connected to the beam through two worm drive hose clamps; unfortunately during the first test, the clamps did not hold pressure at 23psi, causing a premature termination of the test. The failure of the worm drive clamps led to the use of low profile custom sized metal band clamps in the subsequent tests. The test beam was refurbished and tested once again.

We were able to burst the refurbished and modified beam at 45.44psi during the second test. Failure in this iteration was due to an imperfection in the bladder heat sealing process. The damage on the beam was such that a new section was necessary. The last series of tests were conducted on the spare sections of the final beam structure. We were not able to burst the subsequent prototypes due to insufficient pressure on our pressure source (80psi upstream pressure on the water faucet). The beams were able to sustain pressures in excess of 60 psi while being subjected to mechanical abuse. Pressure profiles of the second hydrostatic test are shown in figure 20.

Figure 20. First hydrostatic test of a prototype beam

D. Internal Layout

The proposed internal layout of the loft will include 4 individual crew quarters, a common area, power outlets, lighting, a safety exit and a ventilation system. The crew quarters are arranged in a radial fashion, and include a bed, a desk and personal storage (4 CTBs under the bed frame). Each bunk is enclosed in fabric walls and is accessible through a privacy curtain that is equipped with a zipper. Each crew compartment includes an 18in diameter window with a curtain, two power outlets, a reading light, and a main light.

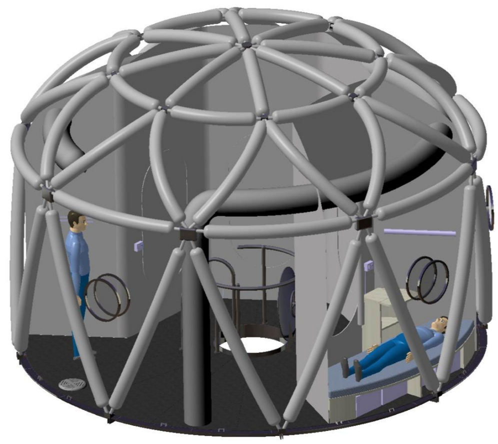


Figure 21. Interiors Layout

The common area will include 4 power outlets, three global lights, a table, and four chairs for social activities. The common area also includes a window and a safety exit.

One of the main issues experienced in current man rated spacecraft is storage space and equipment management. In order to address this point, the UMd team proposes to equip all vertical surfaces with pockets that could be used to store and organize equipment. The wall surface is also used as the main mounting point for the loft instrumentation. It is also conceivable to equip the crew quarters with overhead cargo nets that would provide additional storage space but those would have to be traded with overhead space. The final say would be left to the individual preference of the specific crew member. Most of the wall mounted equipment is designed to be easily relocated by using carabiners mounted on the wall itself.

The internal layout design was in part inspired by the proposed designs from the graduate level 2011 ENAE697 “Space Human Factors and Life Support” class. In this class, 32 graduate students have been involved in the X-Hab project, and produced eight different internal designs for X-Hab as their collaborative term project. Their designs are focused on the X-Hab flight unit; in addition to internal layouts, their designs include proposed life support systems and extended ancillary systems design. In this class, students were given freedom in the location of the loft access hatch. As it was shown by the authors in previous publications[4,5] a center hatch results in a suboptimal use of the interior space. Unfortunately for the X-Hab competition, the UMd team does not have a say in the location of the access port, which is dictated by the pre-existing HDU architecture. Unfortunately none of the proposed designs were usable ”as is”, but the authors believe that interesting solutions were proposed and could be used in future iterations of the loft or on any other future habitation module of comparable size to HDU or X-Hab. A sample layout is shown in figure 22.

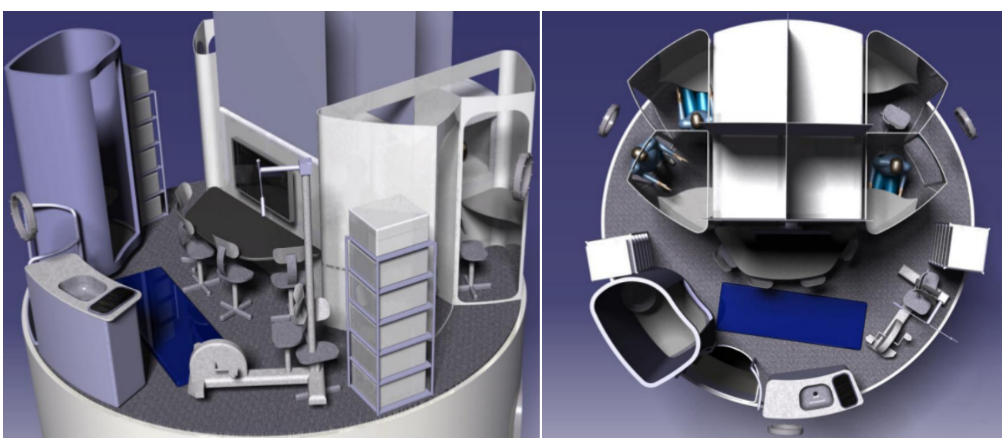


Figure 22. Alternative X-Hab interior design

E. Preliminary Stowage Procedures

Initially the 1/5 scale model was used for a preliminary evaluation of the folding strategy. A possible proposed strategy is shown in the picture sequence below.

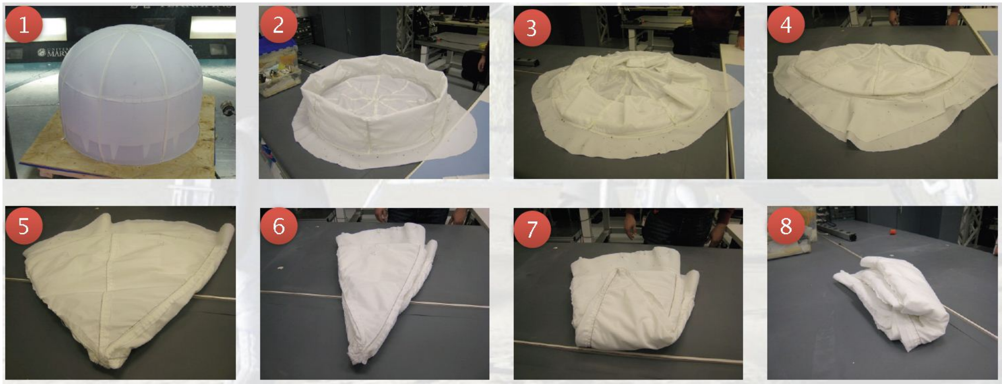


Figure 23. Folding Strategy

F. Ancillary systems

In this section we will discuss all the ancillary systems that were designed in order to ensure full functionality of the loft during the 2011 Desert RATS field trials, which is the ultimate design application for all three X-Hab competitors.

1. Pressurization System

The loft's pressurization system underwent several iterations during the design phases. The final version emphasized simplicity and reliability over complexity and redundancy.

For the specific purpose of the competition such a system is sufficient, but it is very likely that if the loft will be deployed in the field during the upcoming D-RATS trials, some modifications will be necessary (more pressure transducers should be added along with a pair of solenoid valves on each beam that would allow isolating a damaged beam from the rest of the structure, preventing this way a complete deflation of the system). In order to inflate the loft's structure, a compressed air source must be provided. Two sources have been used during both the initial loft tests and during integration with HDU. The first is a standard shop air outlet at a pressure of about 200psi, while the second is a small 20 gallons, 1.8Hp compressor. The shop air outlet has two main advantages over the compressor: the first is the reduced noise level, and the second is a semi-constant upstream pressure. The compressor, given the current leak rate of the structure, is able to maintain the upstream pressure between 100psi and 130psi once the habitat is at operational pressure, therefore allowing for some variation in the inflatable structure pressure. The compressor fill-discharge cycle has been measured to be 6minutes off and 7minutes on during nominal operations. The pressure regulator that is immediately downstream of the air source is set to an output pressure of 6.5psi-7psi when the compressor tank is full. In order to avoid overpressure in the structure, a high flow pressure relief valve was placed immediately downstream of the pressure regulator and set to 10psi. The valve is triggered at a higher pressure, since the initial inflation process requires a higher output pressure from the regulator to reduce inflation time. The pressurization system is also equipped with an analog pressure gauge and two digital pressure transducers to enable local and remote monitoring of the health status of the structure.

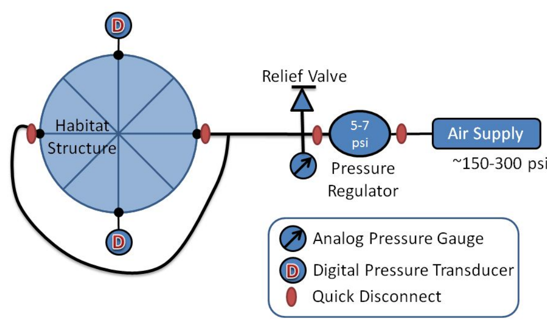


Figure 24. Pressurization Systems Diagram

2. *Power*

Power is provided by the HDU team through a series of outlets on the floor panels of the loft. HDU provides a single 15 Ampere 120V AC circuit to be used for crew quarters and common area outlets for laptops, lighting and inflation system. A separate 28V DC circuit is also provided for the embedded avionics. Power distribution will occur through a series of extension chords routed and restrained on the habitat walls. Each crew quarter is equipped with two outlets, a small LED reading light and a main florescent light. The common area will include four outlets and three main florescent lights.

3. *Ventilation*

The loft makes use of the existing HDU HVAC system by using an air in and an air return 12in diameter duct (which is closed in this application, since air return will be granted from the leaks on the interface ring and through the HDU hatch) provided under the loft flooring. The loft will distribute air flow in all crew cabins and common area through a 4in aluminum hose. Each bunk is equipped with an air outlet while the common area is served by a 6in outlet and an adapter that brings down the 12in HDU duct to the loft 4in duct.

4. *Avionics*

The avionics included in the loft monitor the inflatable structure via 2 pressure sensors (SSI Technology P51) located on two of the mounting flange manifolds while an Arduino-based custom board equipped with a WiFly module broadcasts the calibrated sensors readings on the HDU wireless network. This system will be used as the main control interface for the system. The avionics system will also be responsible of autonomously detecting and recognizing an anomaly and warning the loft inhabitants of the issue through acoustic and visual warnings. The avionics package was designed to allow readings from sensors located on each manifold and two solenoid valves on each beam that would be incorporated if additional funds would be available. In addition to the physical boards, a graphical user interface (GUI) was developed to ease the monitoring of the system. A color coded bar is displayed for each sensor. Each bar elongates as a function of the sensor detected pressure. When the pressure is below the 5psi threshold the bar is displayed in blue, while if the detected pressure is between 5psi and 7psi, the bar turns green indicating that the system is at operational pressure. In case the detected pressure is higher than 7 psi the bar will turn red and an acoustic warning is emitted. The GUI was developed in Python.

G. X-Hab Manufacturing

Once CDR was successfully completed, the manufacturing process began with the acquisition of all the required materials. Of the many students that participated in the project during the Fall 2010 semester, five volunteered to continue for the construction phase, working in coordination with graduate and undergraduate students of the Space Systems Laboratory.

The team began by producing detailed designs and engineering drawings of all the hardware that was later manufactured in the in-house machine shops. Students were involved in the operations of CNC and manual machine tools to produce the HDU mating flange sections and restraint lines attachment points, window frames, manifolds and beam plugs.

In parallel with the manufacturing of the hardware, the inflatable structure was built. Restraint layers and pressure bladders were sewn and heat sealed, and underwent a series of quality inspections. Once the inflatable structure soft goods were completed, it was integrated with the custom built manifolds and beam plugs. Each beam is connected to two beam plugs via two custom low profile band clamps. The first clamp seals the pressure bladder to the plug rubber insert, while the second clamp constrains the restraint layer. Upon completion of the inflatable structure, the team executed a series of test inflations to verify the reliability and construction quality of the system. During the preliminary inflations, several leaks were identified and repaired. Following the assembly of the inflatable structure, the interior walls section were designed, traced, cut and sewn together. This layer group includes the inner layer, a simulated pressure bladder, a restraint layer and 27 restraint lines (24 vertical lines and 3 horizontal) The assembly of the inner layers proceeded as planned with no mayor roadblocks. Lastly the outer layer was manufactured. The outer layer is the thickest and heaviest layer in the system and it includes a outer micrometeorite protection layer, a total of 10, 6mil layers of polyethylene and a 6in thick layer of fiberglass batting. This layer was the most

Figure 25. Students during the manufacturing of the inflatable structure

challenging to assemble. The overall thickness of the layer and its weight required an average of 5 people to sew the 16 sections together. We were only able to sew up to 8 sections together with the aid of our industrial sewing machine at a time; therefore, joining the two final halves of the loft was done by hand sewing. The final step of the process was integrating the three main elements and mounting the windows, inner walls and manufacturing the interiors. The pictures below show the loft manufacturing process during the several stages of construction.

Figure 26. Integration process of the UMd X-Hab loft

IV. X-Hab HDU Integration

On June 13th 2011 the UMd "Away Team" composed of two graduate students and two undergraduate students began the integration process of the X-Hab loft on HDU. The first day was passed unstowing the loft from the shipping crates on a test platform and performing an initial inflation.

On the second day the loft was hoisted on top of HDU and the connection ring bolted to the HDU mating flange. Once mounting operations were complete the loft was inflated once again, and a new set of inflation procedures was defined to comply with NASA's operational safety requirements. Unfortunately a minor leak was identified during the first inflation that prevented a the team from completing the inflation. The loft was depressurized, the leak inspected and promptly repaired. Following the repair, the loft was once again inflated and this time all want as planned. The loft was once again deflated for the night and was ready for the judges to arrive on the following day to time the inflation process.

Day three saw the loft ready for the timed inflation; unfortunately, once again a small leak prevented a complete inflation, but a quick fix was performed, and the loft achieved inflation and the test outfitting of the interiors followed.

The fourth day, the loft was once again inflated, this time with no complications, outfitted and the entire process was once again timed. Once the loft was completely set up, the judges and other visitors were given tours of the habitat and shared their insight with the students. The last day the loft was inflated one last time and then deflated, removed from HDU and stowed in the original shipping crates.

Figure 27. X-Hab integrated on HDU

V. Conclusions

The X-Hab Academic Innovation Challenge was established in the summer of 2010, with the intent of directly involving students at all levels in ongoing development activities related to NASA human space exploration. If the experience of the University of Maryland is any indication, it has already succeeded admirably at that. More than fifty UMd students at all levels have been involved in X-Hab, through academic coursework, laboratory experiments, volunteer and paid research positions. At the same time, NASA stands to gain three HDU loft elements representing the best that the three universities can offer. The goal of the UMd X-Hab team has been to deliver a professional-quality loft habitat capable of supporting extensive Desert RATS simulations for years to come.

Acknowledgments

This work was supported by NASA, and administered through the National Space Grant Foundation. Supplemental funding was contributed by the Maryland Space Grant Consortium. This support, along with the dedication and enthusiastic contributions of the entire NASA team, especially Larry Toups, A. Scott Howe, Terry Tri, Kriss Kennedy, and Tracy Gill, along with our NASA project mentor, John Dorsey, are all gratefully acknowledged.

The authors wish to thank all the students of the 2010 ENAE100 X-Hab teams, the students of 2010/11 ENAE 483/484 and 2011 ENAE697 for their great contributions to this project. A very special thanks goes to the Glenn L. Martin Wind Tunnel personnel for their support during our tests in their facility, and to Dr. Wereley and Ben Woods for their support during materials testing. Our most heartfelt thanks goes to Jonathan Franck, Christopher O'Hare, Jen King, Dennis Sanchez, Justin Brannan and Chris Carlsen for their admirable dedication and hard work; without them all this would not have been possible. Last but not least we wish to thank the entire SSL personnel for their help in times of need and all the personnel of building 220 at the Johnson Space Center in Houston.

References

[1]NASA HDU website `http://www.nasa.gov/exploration/analogs/hdu_project.html`

[2]NASA, Man System Integration Standards, Tech. Rep. NASA-STD-3000, NASA, 1987.

[3]eXploration Habitat (X-Hab) Academic Innovation Challenge 2011 Solicitation, National Space Grant Foundation, NASA `http://www.spacegrant.org/xhab/2011`.

[4]Di Capua, M., Mirvis, A., and Akin, D. L., Minimal Functional Habitat, NASA Lunar Surface Systems Concepts, February 2009

[5]Di Capua, M., Mirvis, A., and Akin, D. L., Minimum Functionality Lunar Habitat Element Design: Requirements and Definition of an Initial Human Establishment on the Moon, 39th International Conference on Environmental Systems, 2009-01-2369, July 2009, Savannah, Georgia.