Habitat Architecture Concept Definition for "Integrated Strategies for the Human Exploration of the Moon and Mars" (A NASA-funded Study): Interim Status Report

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In early 2009, a team led by the Department of Space Studies at the University of North Dakota was awarded a 3-year NASA grant to study advanced inflatable habitat architecture concepts that could be adapted for use on the surfaces of the Moon and Mars. This paper will present a progress report as the project passes its initial six-month milestone. The study involves a hybrid inflatable design concept that is intended to maximize the commonality of technologies used in several different pressurized subsystems, including the habitat, airlocks and connecting structures, space suits, and pressurized rover interfaces. The hybrid approach involves an inflatable fabric structure that is constrained by an internal rigid frame which is constructed from elements contained in a palleted kit of parts. Once the pallet is emplaced on the surface, the inflatable bladder is expanded partially whereupon astronauts enter the interior to erect the spaceframe. The purpose of the frame is to structurally support the habitat during times of depressurization. The frame also operates to support the attachment of concentrated loads such as floor and wall panels, life support equipment, storage racks, and importantly, to provide a means by which the habitat can be rigidly connected to other base elements. A unique node connector is being devised to marry the pneumatic bladder to the frame, thereby allowing substantial structural loads to pass through the bladder without penetration. By avoiding a domed upper surface and keeping the floor of the habitat near the surface, this configuration is structurally and morphologically capable of supporting an overburden of heavy regolith for radiation shielding.

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Nomenclature

CFRP	=	Carbon-Fiber Reinforced Plastic
EVA/IVA	=	Extravehicular Activity / Intravehicular Activity
Hybrid	=	A combination of inflatable and rigid structure types used to form a habitat enclosure
Inflatable	=	A structure composed primarily of engineered fabric and supported by pneumatic pressure
ISRU	=	*In Situ* Resource Utilization
MFHE	=	Minimum Functionality Habitat Element
SPE	=	Solar Proton Event

I. Introduction

This paper provides an early progress report on a design study presently being led by the Department of Space Studies at the University of North Dakota. This 3-year NASA-funded study, entitled "Integrated Strategies for the Human Exploration of the Moon and Mars," is directed at advanced inflatable architectural concepts. The study is aimed at concurrently studying the habitat as well as other pressurized elements, including airlocks, pressurized connectors, pressurized rovers, and space suits, all of which must be tightly integrated. The focus of this paper is to report on the progress being made in the study of the habitat element.

In this study, the main element of a planetary outpost, the habitat, is based on a hybrid inflatable design concept in which it may be possible to maximize the commonality of technologies used in several different pressurized subsystems (namely the habitat, airlocks and connecting structures, spacesuits, and pressurized rover interfaces). The technology concept for the habitat involves an inflatable structure that is stiffened and constrained by an internal rigid frame. A feature of the internal frame is that it is a spaceframe composed of a kit of parts that are palleted within the inflatable bladder package for transport to the planetary surface. It is believed that this approach allows the structurally robust parts to be most effectively transported to the planetary surface.

Once in place on the surface, the bladder is inflated to partial pressure whereupon astronauts enter the interior pressurized volume. Working within this pressurized volume they are able to erect the frame without the encumbrance of spacesuits.

It is an essential objective of this study to develop an inflatable structure that can support itself intact during periods of depressurization – a problem made all the more difficult if the structure is supporting the load of heavy regolith shielding.

It is a further objective of this study to maximize radiation protection measures. For this reason, the design is intended to include a means by which heavy regolith shielding may be incorporated into the architecture. The use of regolith shielding has been considered by many authors over the years, and we are working to develop a system which will be conducive to its use – namely by making the physical form of the habitat, and the structure, capable of supporting the loose soil and weight of this material. Doing so in the context of an inflatable structure is especially difficult as the doubly-curved morphology of such structures tends to shed loose regolith coverings. Additionally, the use of aluminum and other structural metals is deliberately avoided to reduce secondary radiation.

At this juncture, the specific geometry of the internal spaceframe is the subject of continuing study, however, we are illustrating here a common square-pyramid type space truss which we have determined will meet the structural loading, low mass, and ease-of-erection requirements. This internal spaceframe, which is composed of interlocking hub and strut elements, is constructed within the bladder by the astronauts. Once erected the frame provides support for mounting interior architectural elements, such as floor and wall panels, life support equipment, and storage racks. A unique node connector is used to marry the pneumatic bladder to the frame, thereby allowing substantial structural loads to pass through the pneumatic bladder *without penetration*. We have also deliberately avoided mixing rigid monocoque shells with intermediate inflatable bladder sections in order to reduce long seal lines and differential skin behavior under varying temperature and dynamic conditions.

Importantly, the proposed configuration accomplishes many of the objectives as described by Adams and Petrov in their discussion of a biomimetic endoskeletal structure, but allows the habitat morphology to expand beyond the constraints imposed by using a shroud-conforming monocoque end caps, and avoids long seal lines.[1] As in this reference work (as well as others) we are further exploring the biomimetic paradigm of an endoskeletal approach to hybrid structures.

II. Background

The requirements for lunar or Martian habitat architecture necessarily involve the collaboration of many professional disciplines. The unique challenges that habitat architecture present pose unprecedented difficulty and the various efforts to understand and respond to these challenges will invariably stimulate designers to invent systematic solutions. Over the past few years, since the inception of NASA's Constellation program and the promulgation of a well-studied lunar surface architecture, we have seen the intensity of these efforts coalesce in a number of new studies that have been required to work within an overarching set of realistic mission requirements and constraints.

The purpose of this paper is to report on the progress of one such study. Our work is being conducted in North Dakota and by researchers located in Pennsylvania, Florida, and in Spain, with disciplinary expertise in space architecture, space suit design, vehicle design, space life sciences, radiation protection, and structural, systems, and aerospace engineering. We begin with an extensive understanding of the history of space architecture, a working knowledge of many Earth-based habitat analogs, the technology of orbital space missions including the International Space Station, and working knowledge of engineered fabric structures.

While it is not the purpose of this paper to review the prior literature, we would like to acknowledge several important works which are guiding the study. One of the earliest studies, the 1959 Project Horizon Study illustrates one of the first designs to tackle the problem of emplacing rigid structures while using lunar geomorphology to protect inhabitants from SPE radiation.[2] Numerous studies involving the use of inflatable habitat structures are reported by Benaroya,[3] Mendell,[4,5] Johnson and Wetzel,[6,7,8] Cohen,[9] and others. Studies of inflatable structures, including work by ILC Dover has been considered as well.[10,11,12] And more recent studies describe highly innovative approaches to hybrid inflatable habitats, namely Adams and Petrov,[13,14] and Kennedy.[15] This is not an exhaustive list by any means, but it should be noted that it is the intent of the authors to expand on this prior work.

A recent 2009 NASA study conducted externally by Boeing represents a robust effort to study habitat architecture at the level of a pre-Phase A technology feasibility analysis and design study with the concurrent advice of NASA mission planners and subsystem managers as well industry experts.[16] This work, entitled the *Minimum Functionality Habitation Element* study, was focused on defining the habitat architecture with very tight constraints on mass and logistical operations, and was tied directly to NASA's surface system architecture and a preliminary manifest schedule. While this study was focused on a "minimum functionality" scenario, the effort was instructive because it underscored how a few simply defined design drivers could redound with long term implications for long-term habitability.

The present study is intended to build on this work and has been designed to present an extension of this study as it might evolve if the emphasis were changed from "minimum functionality" to "long-duration habitation." One of the lessons learned from the Boeing study was that there was a need for a versatile habitat technology that could be adapted easily for future growth. Knowing how the habitat interfaced with other elements, and how it could be transformed and extended to meet changing mission objectives over time, was a recurring issue among the study contributors.

At the time that this paper was written (April 2010), NASA's Constellation program had progressed further in the establishment of rigorous mission programming and surface architecture standards, and these have been used as the basis for guiding the present design study.

III. Lessons Learned from the NASA MFHE Study

The Boeing MFHE Study concentrated on a single habitat module that could be rapidly emplaced on the lunar surface with minimal site preparation, ground manipulation, or post-emplacement configuration; it was intended to be pre-configured to receive astronauts on arrival. The crew size was specified at 4 people for a minimum stay time of 30 days, with a contingency for an additional 30 days, and a maximum crew compliment of eight during change-out. All essential life support technology and crew support technologies were to be included in a single payload package, with the exception of modular airlocks with suitlock capability which would be landed separately. Importantly, a provision for radiation protection was mandatory, and in the final design report from Boeing (and that of two other concurrent studies), the provision of a minimally-sized storm shelter proved to be a difficult challenge in terms of payload mass and functional correspondence with other subsystems.

In order to determine the best-fit solution for the program, the study team weighed the advantages and disadvantages of inflatable, rigid shell, and hybrid structures. In the final analysis, a rigid shell structure was determined to be best, since it could most reliably be preconfigured prior to launch, placed on the surface and tested prior to crew arrival. Importantly, this was the deciding factor for the team to arrive at a consensus.

However, if the objective was changed from immediate habitability to long-duration supportability, it is the authors' view that this decision would have favored a hybrid (rigid-inflatable mix) solution.

One common problem with both pure inflatable and pure monocoque rigid shells is that neither is well adapted to supporting concentrated gravity loads without significant reinforcement. This makes the attachment of internal and external devices and loads difficult (e.g., life support equipment, storage systems, etc). Pure inflatable structures, which have the advantage of providing a large internal volume, will collapse upon loss of internal pressure.[17] Pure rigid structures have the advantage of being pre-configurable prior to launch, but they are constrained to the dimensional form of the launch vehicle shroud, and are necessarily limited in the amount of internal volume they can provide. If a thin-walled rigid shell structure is formed of aluminum, it suffers additionally by producing secondary radiation, rather than contributing to its mitigation.[18] Fig. 1 illustrates the final design as proposed by the Boeing study team.

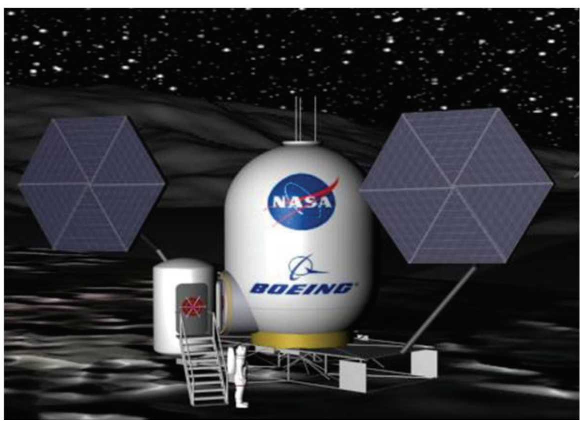

Figure 1 *Final Design for MFHE habitat. Note that in order to fit within the shroud and remain within bounds of other requirements of the study, a vertical pill-shaped form was found to be more effective than a horizontal structure. This architecture was not intended for long-duration stays. Courtesy Sasakawa International Center for Space Architecture (SICSA).*

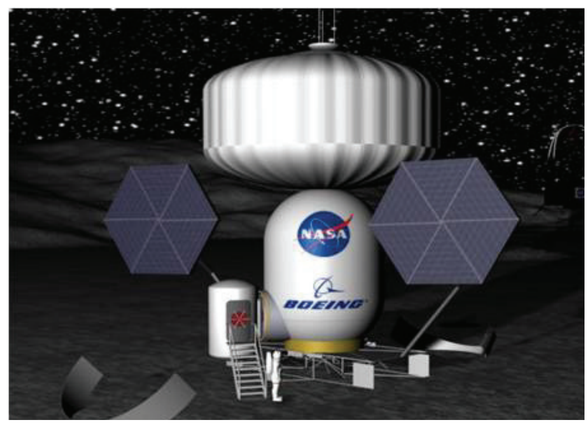

Figure 2 *In order to expand from the basic pill form to create more internal volume, an inflatable structure was proposed to be attached to the rigid shell. In effect, this is a hybrid structure. Courtesy Sasakawa International Center for Space Architecture (SICSA).*

IV. Problem Statement

The Boeing MFHE Study concentrated With the experience of the Boeing study, we began to focus more sharply on the specific problems of maximizing volume for long-duration missions. Having a concurrent study grant and extensive experience in the area of space suit design, we posited that the habitat and the space suits were in fact genetically related concepts that could be viewed as hybrid rigid-inflatable structures; and further, that other interfacing structures such as airlocks, connecting passages, emergency shelters, and pressurized rovers shared many of the same requirements and could benefit from concurrent design.

In principle, each of these elements can be approached as a pure inflatable, or as a pure rigid structure. But as the MFHE study brought out (Fig. 2), the tendency is to move toward a mixing of the two. Space suit design provides the best practical example of this.

In order to meet the needs of a robust long-duration (> 6 month stay time) habitat, our study team identified the following specific requirements:

1) The internal space must contain sufficient buffering volume for the mitigation of CO_2 and other toxic and noxious gases. Buffering volume is well understood within the life science community as a means of effectively maintaining safe atmospheric conditions; inadequate buffer volume reduces the time crews can react to a failure of toxic gas scrubbers and increases the intensity at which these systems must operate to maintain safe concentrations.

2) The structure must be able to support the application of concentrated gravity loads. The experience of orbital spacecraft, which utilize monocoque shells as the primary structure and the atmosphere-containing hull, demonstrates that such shells can support the attachment of hardware. However, this experience is not transferable to the planetary habitat where gravity loading will locally overstress the attachment points unless substantial reinforcement is installed. The following are examples of the concentrated load supports that must be included in a planetary base:

    a. External equipment attachments such as antennas and thermal radiators.
    b. Externally-applied radiation shielding developed from regolith.
    c. Internal equipment mounts.
    d. Internally-mounted architectural surfaces and supports, such as floors, walls, ceilings, and fixtures.
    e. Internally-applied stowage for water, food, waste, and other consumables.
    f. Airlock and passageway mounting interfaces; hatch mountings.
    g. Rigid connections to other habitat structures.
    h. Support legs and wheel structures which must transmit the habitat's mass to the planetary surface.
    i. Lifting points.

3) The structure itself must contribute to radiation shielding:

    a. Materials that produce excessive secondary radiation should be minimized. The use of thin sheets and parts of metals such as aluminum should be avoided because they yield high doses of secondary radiation (particle showers).
    b. The use of high density hydrogen content structural materials are preferred because they show improved behavior over other candidate structural materials when considering the problem of secondary radiation. Because hydrogen has only one proton and no neutrons, when an incoming high energy neutron strikes a hydrogen nucleus, it will undergo a head on nuclear collision with the proton; since both are nearly the same mass, the result will be a moderated neutron, namely a neutron with much lower energy than the incoming neutron and thus yielding reduction in the radiation dose for the occupants.
    c. *In situ* radiation shielding should be included in the design. Regolith installed in sufficient thickness to give adequate areal density has been shown to moderate secondary radiation (18).
    d. The ability to store intervening mass between the living environment and the sources of radiation, including reflected spallation products, should include shielding the floor, wall, and ceiling planes.

4) Preference for an architectural form that maximizes useful volume (which is sometimes difficult with curved and doubly-curved forms).

5) Only minimal site preparation should be required.

6) Must fit within a standard shroud volume for launch and flight operations. While there are a number of existing and proposed shroud designs, for our purposes – where the dimensions of a future vehicle are

unknown – it is a goal to decouple the ultimate habitat shape and volume from the constraints of any particular fixed shroud size (in terms of cross-section and length). This is one of the primary advantages of an inflatable structure. Therefore whatever the shroud is, while the habitat package must fit within it for launch and flight, the ultimate habitat should not necessarily be constrained by these dimensions when fully deployed. This allows for the maximization of interior habitat volume while allowing designers more flexibility during what will certainly be an extended period of uncertainty regarding the size and shape of launch vehicle shroud. (Assumptions about maximum launch mass are more easily estimated.)

7) Preference for modularity of components.
8) Should use interchangeable parts within habitat and between habitat and other related structures.
9) Should have the ability for interior equipment and space-defining objects to be relocated and reconfigured to meet changing human needs and mission objectives.
10) Access to structure must be provided for inspection and repair.

V. Concept for a Hybrid Structure

There are two basic approaches to building a hybrid rigid/inflatable structure in the context of lunar and Mars base design. The first is by composing discrete sections that are each either predominantly rigid or inflatable, as is shown in Fig 3. This is problematic because it tends to require long seal lines at the joining interfaces of each component. Within each component, one tends to suffer the same limitations that attend to each – namely the inability to support concentrated loads, as well as the tendency for the inflatable section to collapse when deflated.

The approach we are following involves placing one type of structure *within* the other in order to gain the maximum benefit of each. In our proposal, we take advantage of the large volumetric capacity of an inflatable as well as its capacity to self-deploy under pneumatic pressure, and augment this soft structure with an internal rigid frame. Unlike a monocoque rigid shell, a frame can be palleted for shipment and then erected from a kit of parts, so it is possible to create a frame that is dimensionally commensurate with the inflated section.

In the development of this approach, we place the rigid frame within the bladder so as to allow the bladder to unfold and deploy first, and then, in sequence, to use astronaut labor to erect the frame within the partially pressurized bladder. In this way, we believe it is feasible for the astronauts to enter the low-pressure bladder structure initially and to work within it without the encumbrance of full space suits.

In order to create a very strong and low-mass frame, we utilize a modular three-dimensional spaceframe. This type of structure is composed of two basic parts, namely a plurality of tubular struts and connecting hubs (Fig. 4).

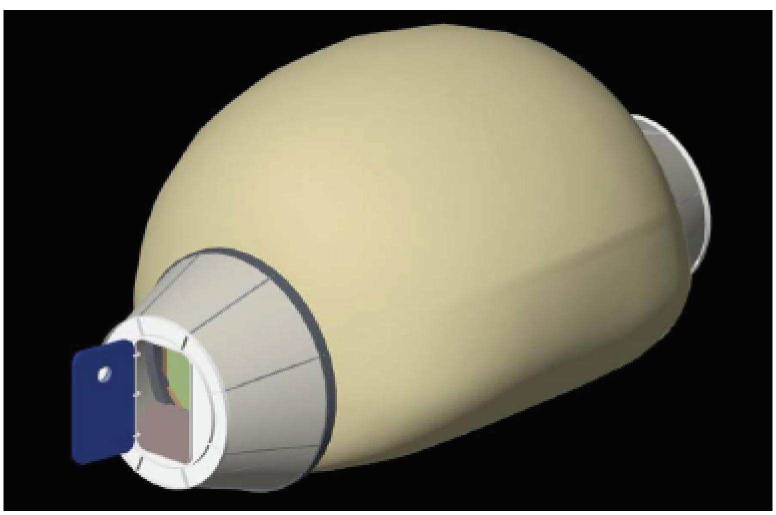

Figure 3 *A hybrid rigid/inflatable structure involving discrete sections of rigid and inflatable structure. The rigid end cones are internally tied together by endoskeletal longerons in order to resist outward-acting pneumatic pressure. However, the fabric bladder is discontinuous where it joins the cylindrical end caps and also at the bottom rigid panel (not visible here). At each of these intersections, a seal is needed, and while the longerons work to tie the caps together, they do not function to hold the bladder from ripping away along the seal lines, a factor which necessarily complicates the rigid shell design. From Adams and Petrov, 2005.*

This is a system that provides a very strong structure with low mass and one that has been well studied in terrestrial practice in terms of structural performance and constructability. The prefabricated parts can be assembled without tools very rapidly, and the hubs and struts can be packaged for shipment very efficiently on a pallet. In order to meet the requirement for high strength and low mass, and that the structure be non-metallic, we are studying the use of CFRP for this part of the structure. The actual geometry of the spaceframe remains under study.

To connect the inflatable fabric structure to the rigid frame, the team is developing a connector that attaches to the outboard hubs in the manner of a strut. The connector provides a slotted capture mechanism that slides over and holds a projecting T-stud that is embedded into reinforced panels of the inflatable fabric membrane. By this device, we avoid the need for penetrations at the connections, and provide a simple means by which the two structures can be made to cooperate, allowing both tensile and compressive forces to be passed through the membrane (Fig. 5).

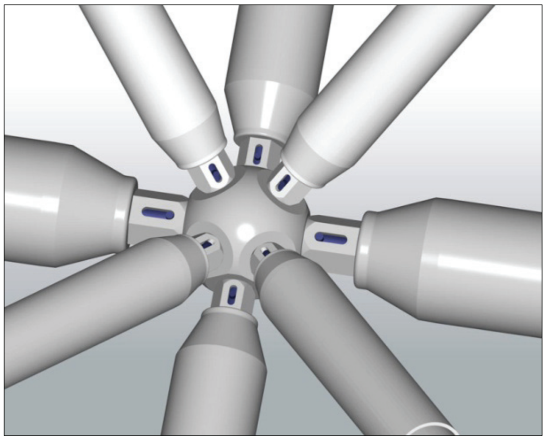

Figure *4* *A spaceframe is a three-dimensional truss that is composed of tubular struts and connecting hubs. This arrangement provides great strength and rigidity with very low structural mass. In the proposed design, the frame serves to support the inflatable membrane. The hubs provide attachment points for equipment and other concentrated loads, both internal and external.*

Illustrated in Fig. 5 below, the T-Stud and welded reinforced fabric section are currently being prototyped by the study team. The device is intended to allow both compressive and tensile forces to be transmitted through the fabric membrane without the need for a penetration of the fabric. The T-Stud thereby allows the fabric to be structurally connected to the spaceframe, and for load applied on one side of the habitat to be transmitted to the other side – for example, where the structural support legs are connected to the underside of the frame.

Using this approach, the only location where a seal is required is at the interface of the vestibule airlock and the fabric structure, and even here, the team is looking at ways to minimize the length of the seal. Penetrations through the fabric for utility conduits will also be required.

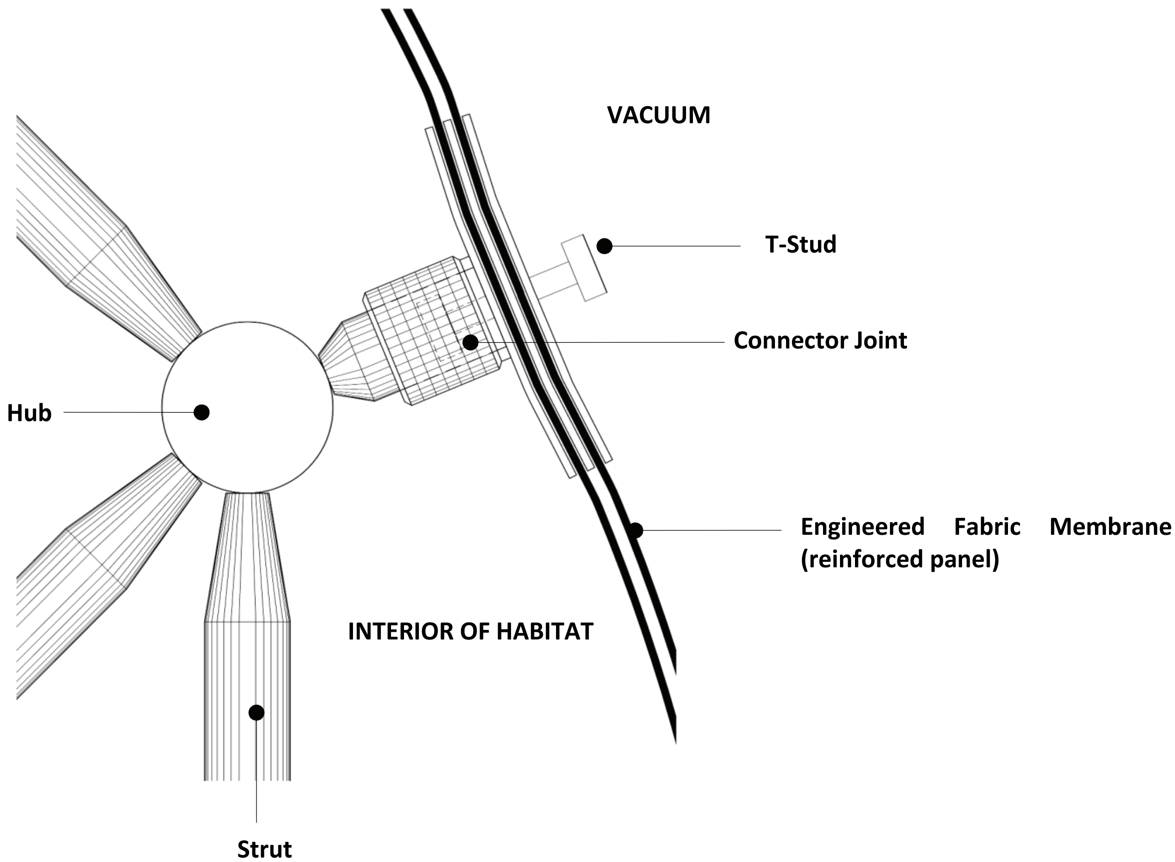

Figure 5 *The rigid spaceframe is connected to the inflatable fabric structure using a modified stub strut that connect to "T-studs" that are fabricated to welded reinforced sections of the fabric. The T-Stud is continuous and formed with an internal plate that is welded within two mutually-welded restraining layers of fabric. It should be understood that all surfaces of this interface are fused chemically and there is no penetration of the fabric.*

The purpose of the internal frame is to provide support for each of the requirements listed above, namely to provide connection points along the interior and exterior of the habitat for equipment and fixtures, to support these gravity loads and the weight of external radiation shielding (Fig. 6), and to do so in a such a way as to support the loads and the integrity of the habitat during periods of deflation.

The frame is located on the interior of the bladder to allow for inspection of the structure, potential future repairs, and to prevent degradation due to exposure to ultraviolet radiation and dust abrasion. Additionally, the tubular struts themselves may be given additional purpose by utilizing their internal voids.

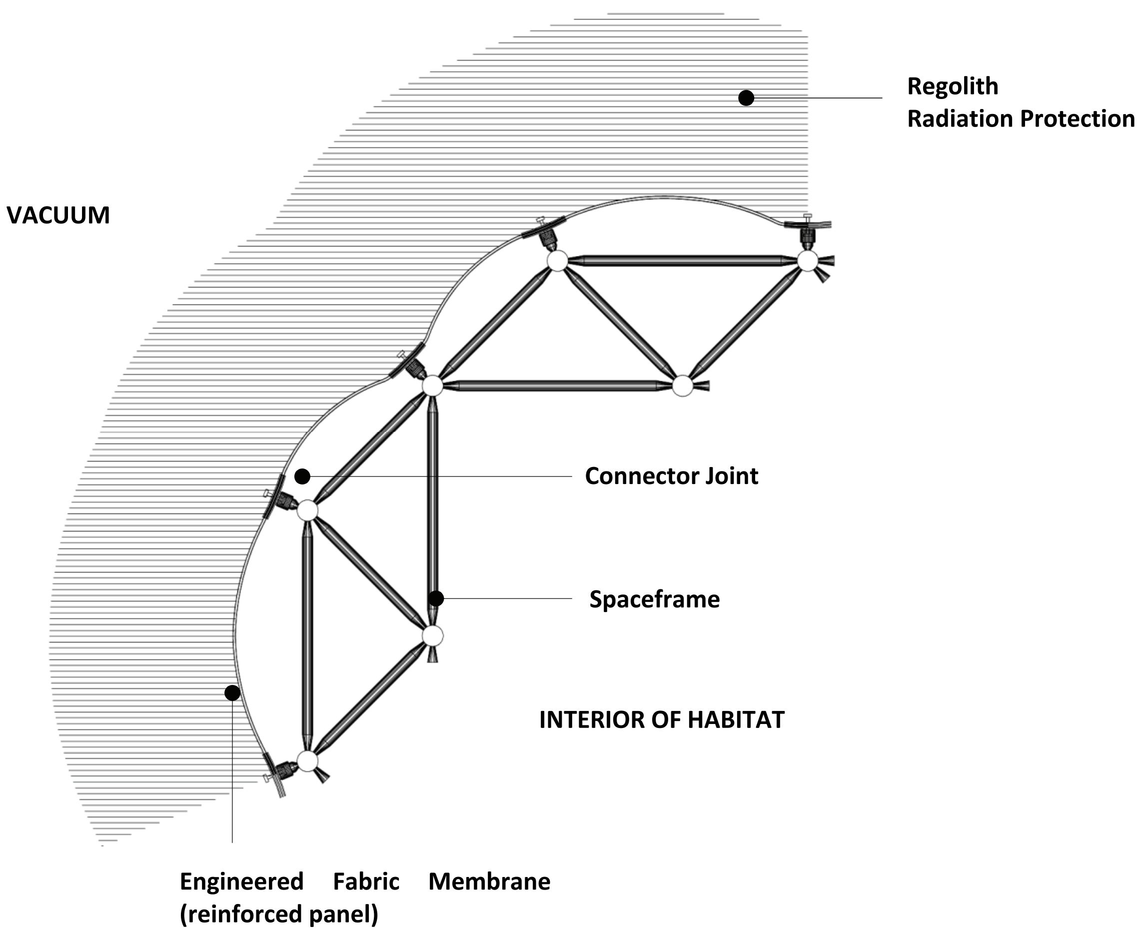

Figure 6 *This view shows a section through the combined hybrid structure. In this illustration, regolith shielding is piled loosely around the exterior of the inflated fabric membrane.*

To erect this system, we presume that an early operational capability (EOC) would have been previously established with a shelter and airlock architecture approximating the scale of a single MFHE-type base camp. From this base, with minimal additional equipment, a descent stage can deliver a container which includes the deflated and folder fabric structure with the kit-of-parts for the spaceframe palleted within. The container itself is to be designed in such a manner as to provide an airlock interface which may be connected to the existing previously deployed minimum habitat. Once emplaced and connected, the inflatable structure may be deployed by inflation using minimal pressure to prevent excessive rigidity in the fabric. At this point, entry to the partially-pressurized habitat can be made by crew members. Pre-located within the interior will be a kit of struts, hubs, and connectors, as well as other internal equipment, thereby avoiding the difficulty of complex EVA and IVA operations.

In order to prevent the fabric from expanding to a spheroid, temporary tension straps will be connected to the T-studs that are formed into the fabric; these hold the structure in approximately orthogonal box-form. Working in a pre-determined sequence, the crew will erect the frame in such a manner as to replace the tension straps with the spaceframe elements, connecting the fabric membrane to the frame, and thereby permanently constraining the shape of the inflated bladder. The outward-acting pneumatic force is resisted by the frame.

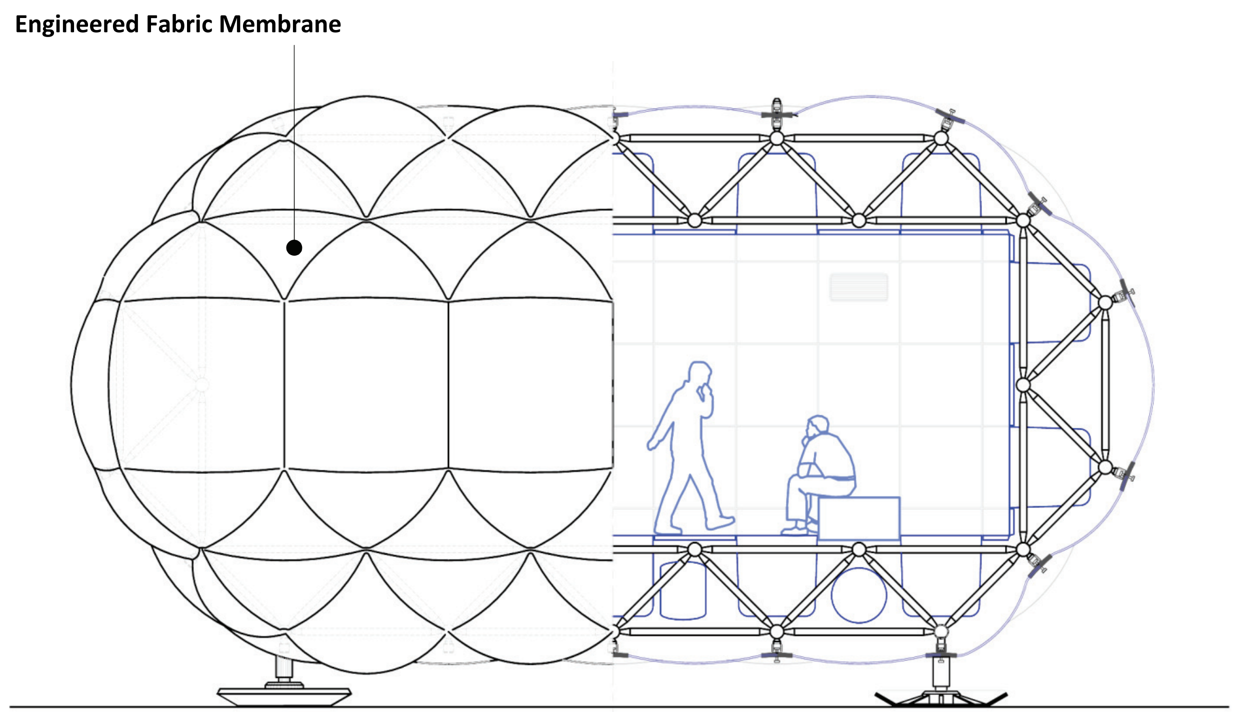

Figure 7 *Partial cross-section view through the habitat.*

Figure 7 shows a cross-sectional view through the habitat illustrating the relationship of the rigid spaceframe and the inflatable membrane. The living and working volume is defined internally by panels that attach to the frame to form floor, walls, and ceiling. The interstitial volume within the frame is used for storage of supplies and life support equipment, which can be accessed through the panels, and the interstitial volume itself contributes to atmospheric buffering. Conduits and loosely-placed ducts can be installed within the interstitial volume where they can be easily accessed.

The panels themselves contribute to the radiation protection by being produced of polyethylene or other hydrogenous materials. The panels and interior fixtures, equipment, and fittings can be reconfigured over time. Note that water and other hydrogenous materials can be stored behind the floors, walls, and ceilings in order to contribute to radiation shielding.

Figure 8 shows a three-dimensional image of the spaceframe as it is currently conceived. In this image, the module dimension has been developed at 1.5 m by 1.5 m with a module depth of 0.5 m. One module is omitted to provide clearance for the airlock connection. Storage racks are designed to fit into the interstitial space formed by the angular struts. Many possible storage rack geometries are possible, only one is shown here; the team is studying other combinations of spaceframe geometry and storage rack designs.

The box-form of the frame is deliberate; it provides a highly functional anthropometric environment for the crew and, by constraining the bladder from expanding to a spheroid, it allows the habitat to be located close to the surface. This is advantageous in that it avoids excessively long support structures that would be required to support the living environment at a higher level, as well as other attached structures, such as airlocks, which would need to be designed to allow for accessibility of crew and equipment.

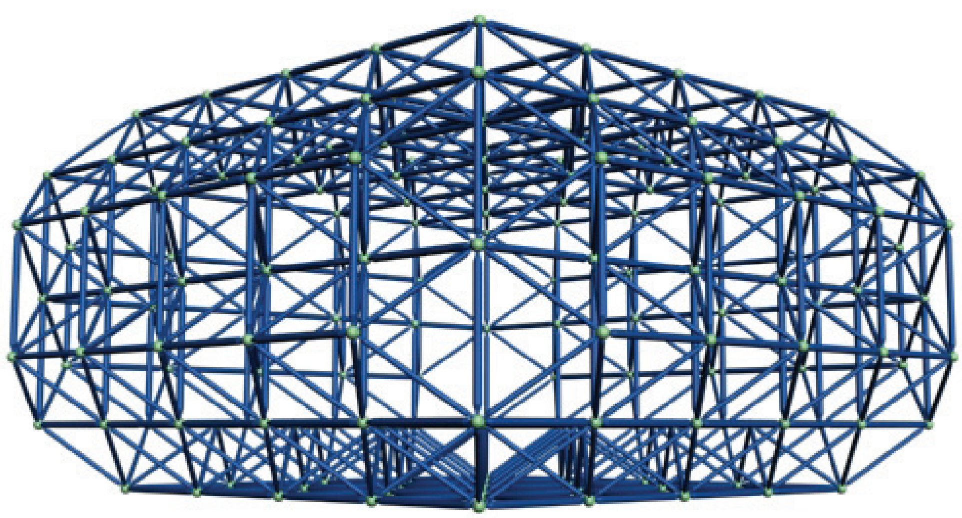

Figure 8 *Perspective view of the spaceframe.*

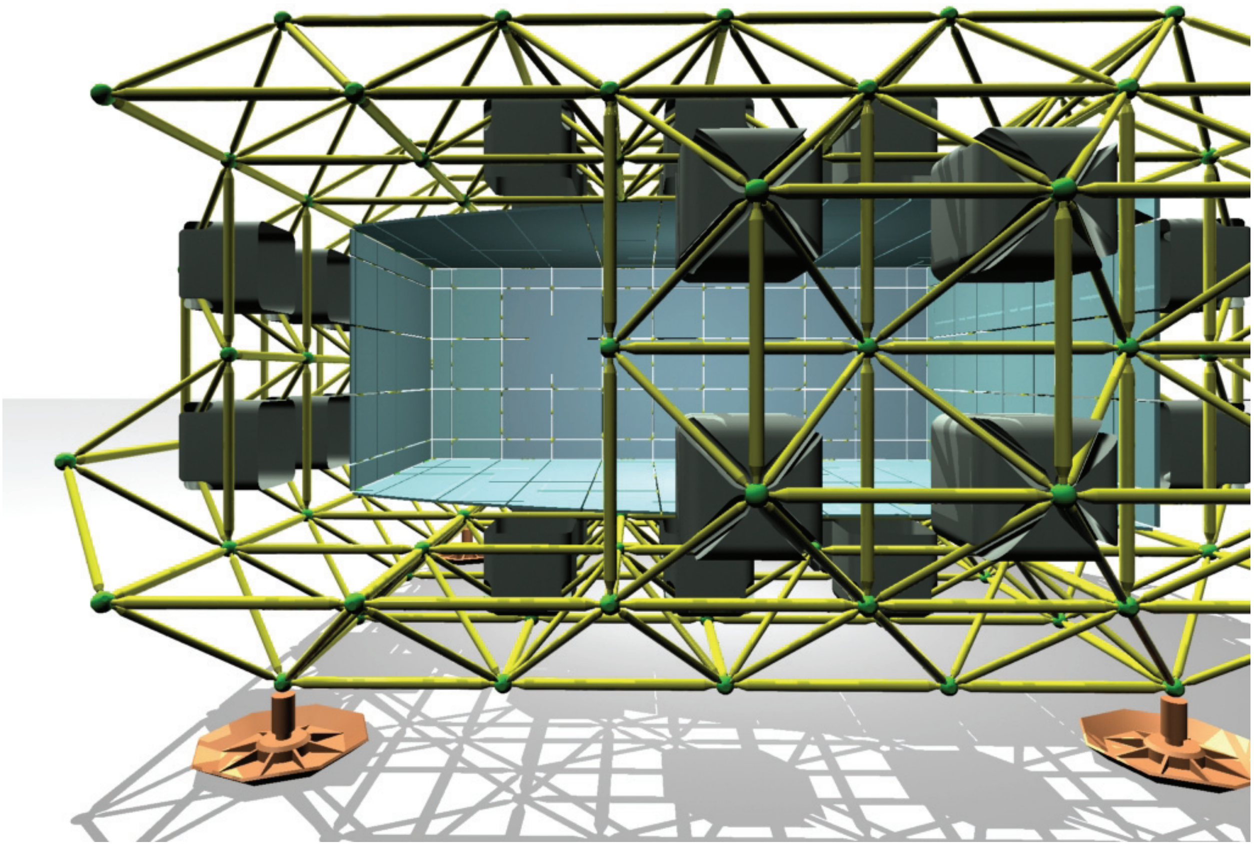

Figure 9 *Relationship of the panels and interstitial storage racks to the frame: side view.*

Figure 9 shows the relationship of the panels and the interstitial storage racks to the frame. Note that this structure can be located very close to the surface to improve access and mobility. Support legs attach to the rigid frame by way of the hub connectors, allowing the weight of the habitat to pass through the membrane without a penetration. The floor of the habitat is approximately 1.4 m above the surface.

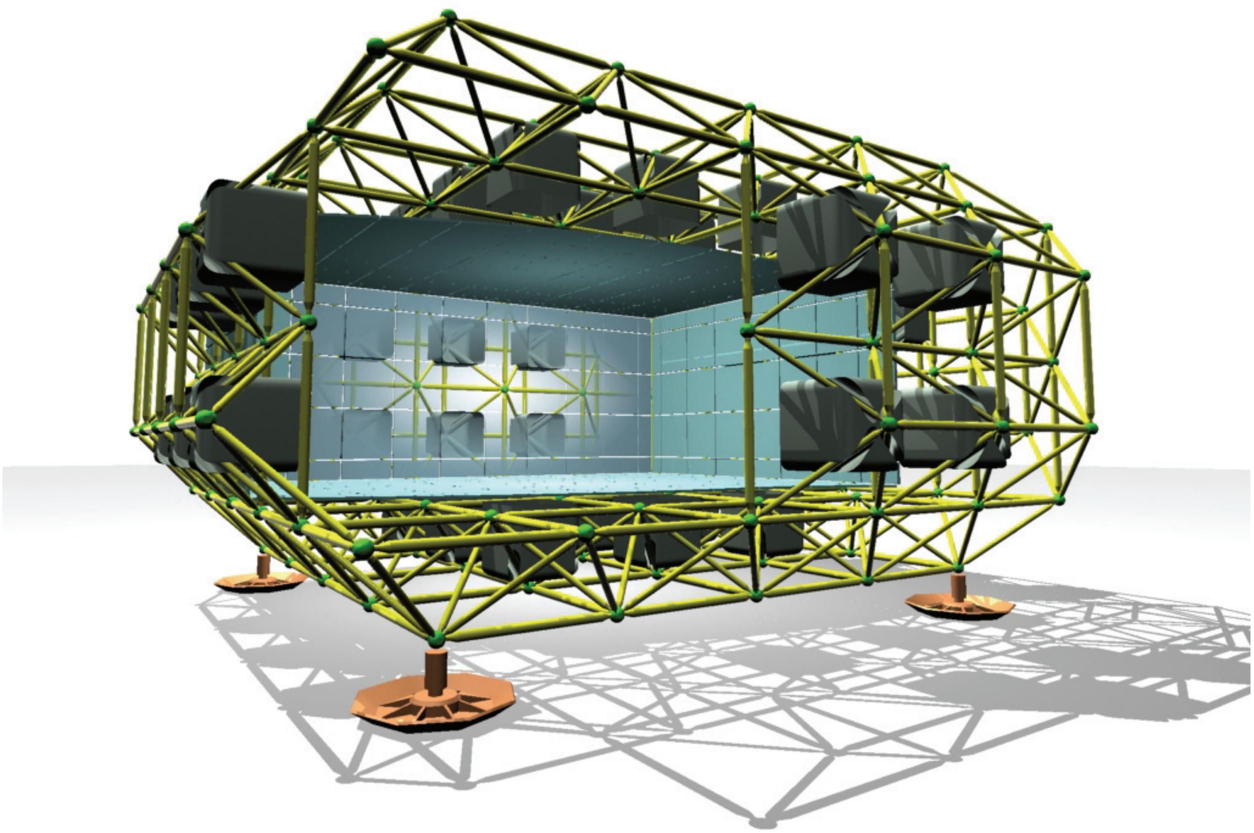

Figure 10 *Relationship of the panels and interstitial storage racks to the frame: corner view.*

Figure 10 provides a better perspective of the system views as a cut-away from the corner. Internal living/working volume for this baseline concept is 82 m^3. This illustration shows one possible geometry for the interstitial storage racks, which is intended to allow roof for running conduits and ductwork through the truss space. However, larger racks are possible and the team is investigating how the racks can be combined with other storage systems and with fold-away fixtures and other architectural features.

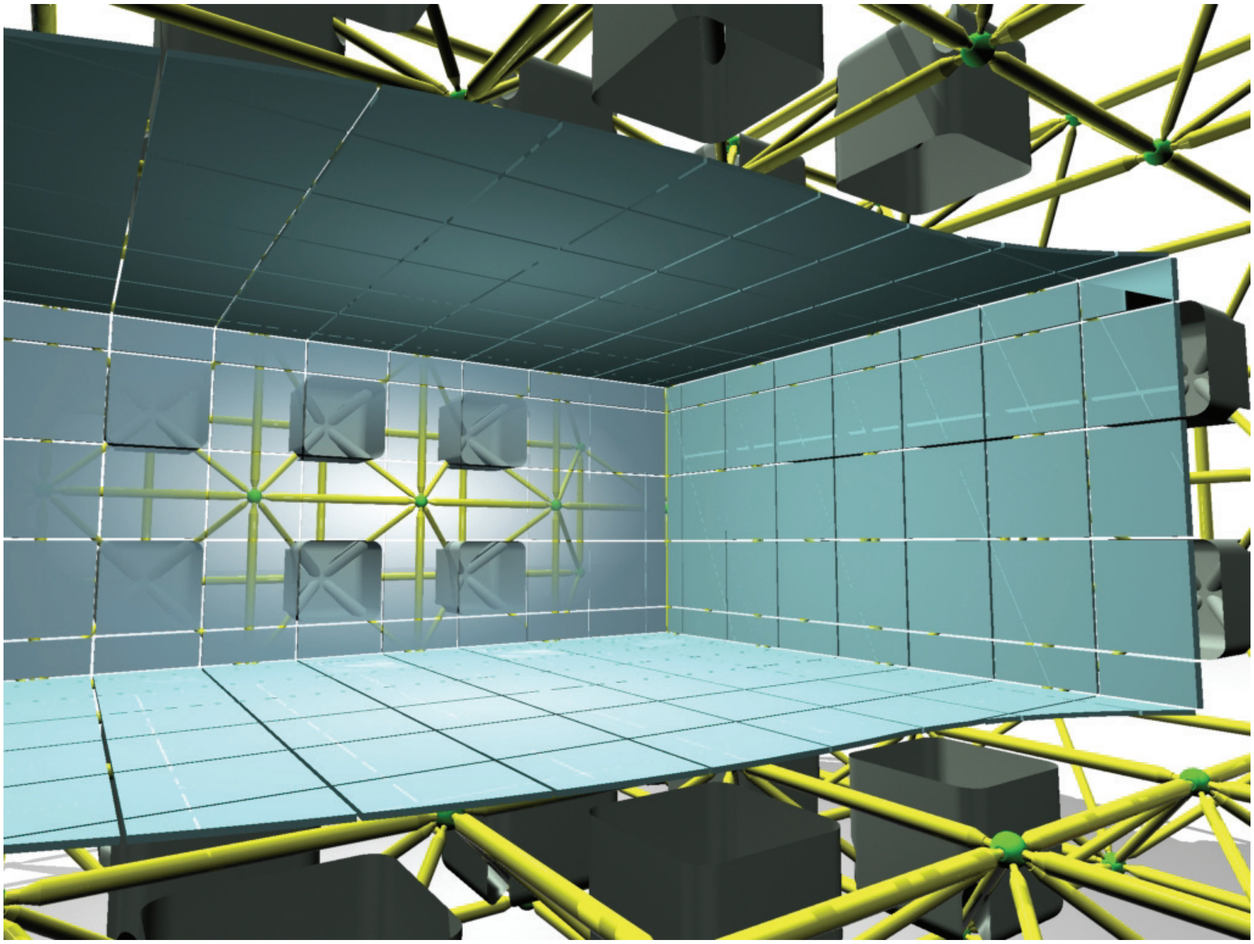

Figure 11 *Relationship of the panels and interstitial storage racks to the frame: detail view.*

Figure 11 is a preliminary concept and a starting point for interior architectural design. It is intended to give a sense for the interior of the habitat. In this system, a panel can be removed to gain access to the interstitial space for inspection and maintenance. Equipment designed for "plug-and-play" operation can be reinstalled and replaced and service conduits can be rerouted easily behind the panels. Lunar dust introduced into the environment will tend to collect below the floor in the lower interstitial volume. The panels themselves may be designed to accommodate special functions, for example they can be made into lights, display screens, air vents, and fold-away fixtures and work stations.

VI. Preliminary Structural Analysis and Modeling

We have performed a finite element analysis of the spaceframe using STAAD. The specific method used was space frame utilizing truss construction. All of the members were modeled as pinned connections. We assumed an internal pneumatic pressure of 14.7 psi (101 kPa), which is twice the anticipated pneumatic pressure of 8.3 psi used in the MFHE study (17). We further assumed a spaceframe strut of 3" diameter with a wall thickness of 1/4" composed of CFRP with a tensile modulus of 150,000 psi (1,030,000 kPa) and a compression modulus of 100,000 psi (689,000 kPa).

Additionally, we assumed that the outward-acting pneumatic pressure is assumed to be acting on the bladder as a flat plate attached through a series of nodes to the spaceframe. The nominal size of the basic spaceframe module measured on centers was 1.5 meters by 1.5 meters with a depth of 0.50 meters.

In the worst case loading condition, the midpoint of the truss frame would be subjected to a bending moment of 500 kip ft (678 kN▪m). This loading resulted in 44 kips (196 kN) applied axially through the hubs.
Lateral action on the frame caused by the containment of the bladder would apply a superposed axial tension force on the tie struts of 315 kips (1400 kN). We found that the structure was capable of supporting these outward-acting loads, but these results suggest that the design of the spaceframe connectors will likely require a composite involving some use of high strength metals.

We also examined the lateral forces exerted on the frame. The condition of the geometry of the frame causes the outward-acting pressures to be in balance, and in the worst case, a tensile load of 200 kips (890 kN) would be superposed on certain struts.

To a first order approximation, the combined effects of all loads in the worst case scenario would be well within the load-bearing capacity of the frame as indicated in the illustrations.

VII. Status Report

Our team has defined a technology concept that appears to meet the requirements that we have defined. Our current efforts are directed as follows:

1) Optimize the volume of the habitat relative to the mass and to the number of required structural components.
2) More detailed structural analysis and modeling of the frame and the inflatable engineered fabric.
3) Evaluating the use of fewer fabric-to-frame connections in order to reduce loading on the spaceframe in cases where regolith overcover is not required.
4) Integration of radiation shielding concepts that avoid loose over-covering.
5) Extension of this concept to other interfacing subcomponents, including airlocks, habitat connectors, and pressurized rover designs that may involve an emergency shelter.
6) Detailed design and prototyping of the connector and the T-stud.
7) Planning for a full-scale mockup to test the erection concept.

In the next stages of the study, we will be producing more detailed analysis including computer models that allow rapid what-if analysis to provide the team with a way of seeing the effects of changes in geometry. This will be conducted in conjunction with computer-based radiation analysis,[19] and parallel spacesuit technology engineering to better understand common technology systems and EVA and IVA activities.
We are working toward an eventual full-scale mockup test of the structural system in North Dakota at the conclusion of the three-year study.

VIII. Conclusion

A mixed discipline team based at the University of North Dakota has been studying a novel approach to a hybrid inflatable habitat structure. This paper reports on the preliminary results of the project as it passes the six month mark of what will be a three-year study.

The approach to the habitat design involves a hybrid inflatable structure that bears many similarities to prior work conducted by Adams and Petrov, particularly in its development of an endoskeletal rigid frame. However, our approach is to construct a more robust internal frame that is capable of supporting substantial gravitational loads and holding the habitat intact during periods of decompression. In a manner similar to TransHab, we allow the rigid frame to be fully encapsulated within the fabric structure. This approach allows the flexible fabric to be constrained to form by non-penetrating nodal attachment points. The advantage of this approach is that the fabric and the rigid systems are allowed to cooperate with minimal interference and the volume of the habitat can be maximized relative to the launch shroud.

We have evaluated the basic concept and structural loading and are now moving to refine and optimize the concept through additional iterations.

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