Inflatable Habitats Technology Development

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ABSTRACT

For many years inflatable structures have been theorized for use as satellite dishes, deployable arrays and human habitats. They fall into human-rated and non-human rated structures. As such the structural design requirements and safety redundancy are much different. This paper will discuss the Habitat and Surface Construction Technology that would support the development of Mars greenhouses and well as habitats. This paper will briefly describe the ISS TransHab architectural design and structural testing for the proposed as a habitation module for the International Space Station. It will also discuss inflatable greenhouse design considerations and examples.

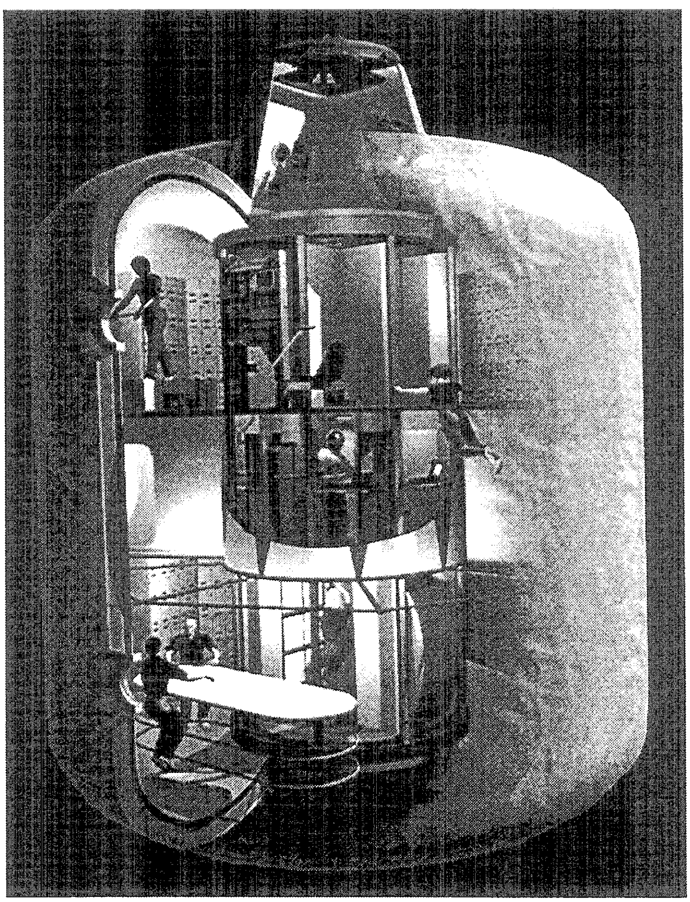

Figure 1. ISS TransHab Internal View, NASA JSC S99-05363

INTRODUCTION

Space habitats are a re-creation of the earth environment for the purpose of sustaining human life. The space environment is characterized by vacuum, orbital debris, micro gravity for orbital space stations and transfer missions, partial gravity for planetary exploration missions, radiation, and planetary dust. Habitats are complex, heavy, expensive elements around which support systems are functionally arrayed, both in transportation systems and permanent facilities like space stations and future planetary bases.

NASA has considered tensile fabric structures in the past. In the late 1960's several inflatable structures were designed and tested for space applications. The Langley Research Center leads efforts to develop and test a 24' diameter torus space station, a Lunar Stay Time Extension Module prototype and a large space station module nick-named Moby Dick. All of these were successfully tested, but were moth balled when the Moon program was halted in favor of a new space vehicle. During the 60s, 70s, and 80s NASA relied on metal (mostly aluminum) structures for all their habitat efforts. It was known, safe and proved reliable. So when the Lunar Base System Study team started proposing an inflatable as a primary structure; they drew a great deal of criticism. It took many years of persistence, and a few failures, before the textile industry turned the technological corner with fibers like Kevlar, Vectran and Polybenzoxazole (PBO).

Over the years the idea of inflatable structures for space habitats slowly began to make sense. Several important NASA reports such as the Synthesis Group Report identified inflatable structures as an enabling technology that would allow NASA to accomplish lighter weight structures at a lower cost. Inflatable structures have caught on and are one of the promising new technologies for NASA. They will change how we think about designing habitats and laboratories, hotels, resorts for space and greenhouses. They will also revolutionize the space architecture world by opening up the possibilities of shapes and sizes to create human settlement of the solar system.

With the emergence of TransHab, NASA is at a crossroads of not being limited to cylindrical hard modules. Many wonderful and architecturally pleasing shapes will emerge bringing in a new space era and new century. Perhaps this is fitting that NASA step into the new century with inflatable structures leading the way.

TransHab pushed the technological envelope beyond previous design work. The innovative engineers at JSC soon shaped a revolutionary concept from the hard aluminum shell alternative. Since that early inception in early 1997 it has been through numerous design iterations. The current design is proposed as the habitat module for the International Space Station. A team of architects and engineers at the Johnson Space Center has been working, designing and testing this concept to mitigate the risky technical challenges that the critiques continue to throw at them. So far the TransHab Project team has surpassed every challenge with vigor and determination.

Habitats & Surface Construction

NASA has long been a leader in research and development of new technologies for space activities. Many of which have spun off to benefit human kind and Earth. Prime examples are computers, medicine, recycling and there are many, many more. Numerous technology thrusts were identified for NASA technology development need. One of these technology thrust areas is Advanced Habitats and Surface Construction Technology as part of the Exploration Office technology strategy. Habitats are categorized into three classifications. Class I is a pre-integrated habitat in that it is entirely manufactured, integrated and ready to operate when delivered to space. Class II is a pre-fabricated habitat and space or surface deployed. Class III is an in-situ derived habitat that it's structure is manufactured using local resource available on the Moon or Mars. For example, mining Martian gypsum and making a concrete material used to form habitats.

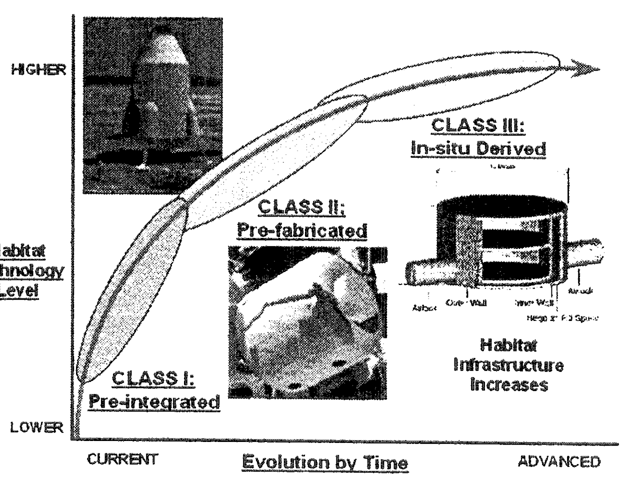

Figure 2. Habitat Classifications

A Class I technology road map for inflatable structures was laid out that includes the development of different technical solutions and different manufacturing approaches types of inflatable habitat structures, figure 3. Whereas inflatable structures are in the fore front of the technology roadmap, there are other important areas such as robotic construction, self deploying structures, smart structures and self-healing structures to mention a few.

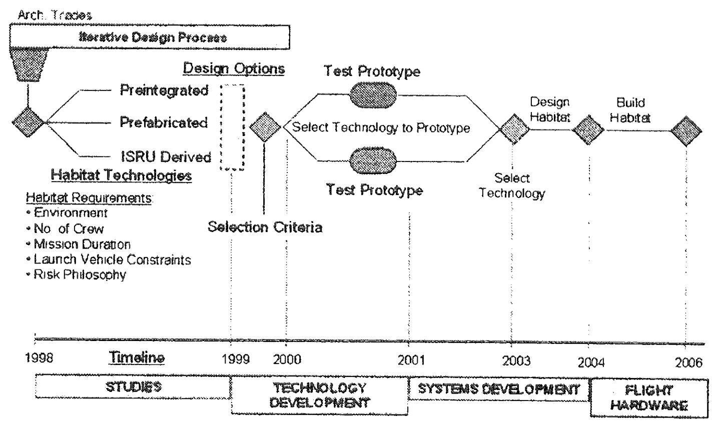

Figure 3. Inflatable Habitat Technology Development Strategy

The Advanced Habitation and Construction Technology vision is to begin working on innovative technologies required to enable the Human Exploration and Development of Space Enterprise to meet the demanding environment of better, faster, cheaper. Space and planetary habitation, pressure structures and unpressurized shelters are being sought out for innovative structural solutions that combine high strength and light weight materials, along with the reliability, durability, repairability, radiation protection, packaging efficiency and life-cycle cost effectiveness. Advances in material developments and manufacturing techniques that enable the structure to "self-heal," and the emplacement, erection, deployment or manufacturing of habitats in space or on the Moon and Mars are considered enabling technologies for the evolution of humans into space and the eventual settlement on Mars. Integration of sensors, circuitry and automated components to enable self-deployment and "smart" structures are considered necessary to allow a habitat to operate autonomously.

The objective is to create an advanced habitat that becomes a "living" structure that not only runs autonomously, but also has self-healing capability. A number of technologies and techniques have been proposed that allow the delivery of deployable habitats to space and planet surfaces or the manufacturing and construction of habitats on planet surfaces. Many new and exciting break-throughs in biotechnology have opened up exciting possibilities. The use of biotechnology combined with a fabric or matrix structure could someday produce a self-healing property analogous to our human skin.

NASA will be researching methods and techniques for fully integrated inflatable "skin" and sensors/circuitry that enables "smart" structures that autonomously detect, analyze, and correct (repair) structural failure. Manufacturing methods of integrating miniaturization technology into the habitat skins, thus reducing weight and increasing self-autonomy are being considered. Technologies of this nature will be required to develop large planetary bases and support infrastructure such as inflatable greenhouses.

Methods for designing, manufacturing and testing of inflatable structures that meet human space flight requirements are being developed for TransHab. History has taught us that architects and engineers have shaped our built environment; and they will continue to do so on Earth and in space. Ground breaking technology work by architects and engineers at JSC are laying the technology foundation by which many will follow for years to come. Whereas the TransHab team has made incredible strides there still remains a great deal of work on the ground and in space to get humans living in fabric structures. Many companies are very interested in this technology for many different space applications.

TransHab Architecture

TransHab is a unique hybrid structure that combines a hard central core with an inflatable exterior shell. An integrated pressurized tunnel is located at one end to provide access to the space station. An unpressurized tunnel is located at the opposite end and houses the TransHab inflation system. Figure 4 shows an overview of the ISS TransHab architecture.

The ISS TransHab is divided into four functional levels within its pressurized volume. Levels one through three are for living space and the fourth is the connecting tunnel. Level one is the galley / wardroom and soft stowage area. Level two is the crew quarters and mechanical room area. The crew quarters are inside the central core and radiation shield water tanks. Level Three is the crew health care and soft stowage area.

The architecture of TransHab provides an integrated habitable environment that creates private and social spaces. A functional and physical separation of the crew health care area, crew quarters, and galley/wardroom area creates a home-like design for the crew while they are in space. With a larger volume than a station hard module TransHab provides more storage volume, two means of unobstructed egress, and permanently deployed equipment, such as a treadmill and ergometer. Some of the important design objectives of TransHab are to maintain a local vertical configuration, separate the exercise area from the dining area and to provide larger crew quarters.

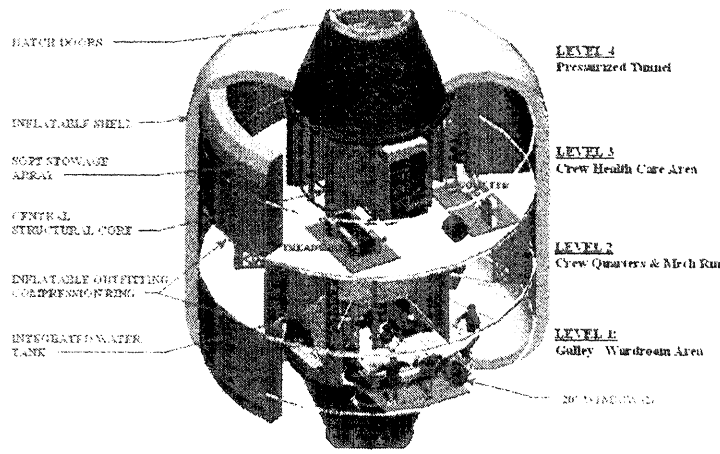

Figure 4. TransHab Overview

The TransHab module currently being proposed for the ISS is approximately 40 feet (12.19 m) long overall by 25 feet (7.28 m) internal diameter providing 12,077-ft3 (342 m^3) of pressurized volume. Levels 1 and 3 are 8-ft tall at the Central Core and Level 2 is 7-ft tall at the Core. TransHab is 23 feet from inside bulkhead to inside bulkhead (not including the 7-ft long Level 4 pressurized tunnel). This module is packaged and launched in the Space Shuttle for delivery to the space station. After the Orbiter docks with station the TransHab is removed from the Orbiter payload bay and berthed with station. Once captured on station the TransHab is deployed and inflated to its internal operating pressure of 14.7 psia. Following inflation of the module, systems are activated for conditioning the environment for crew entry and outfitting.

Because TransHab is a prefabricated, packaged and deployed habitat, it requires the crew to perform setup and outfitting activities in order to make it operational.

<u>Level One</u>

Level one incorporates the galley, wardroom and soft stowage area. This level has three ISS galley racks, a large wardroom table, an Earth-viewing window and a soft stowage array that incorporates ISS standard collapsible transfer bags (CTB), figure 5 and 6.

A unique aspect about this area is that it includes a clerestory above the wardroom area. The clerestory (two story opening) was created in response to the psychological and visual creation of open space. This is very important for crew moral and productivity during long duration isolation and confinement in space.

Mechanical Room is external of the core structure and uses only half the floor space. The other half of this area is the clerestory above the wardroom area, figure 7 and 8.

The crew quarters are surrounded by a 2.5 – 3" thick water jacket for radiation protection during solar flares. Access to this area is from Level 1 (below) or Level 3 (above), via the 42" central passageway. The shown configuration will be assembled and outfitted after TransHab's inflation. Launch shelves are used as crew quarters partitions and the crew quarter door panel and door are installed on-orbit. Rack based crew quarters equipment from the Node 2 will be moved into the TransHab crew quarters.

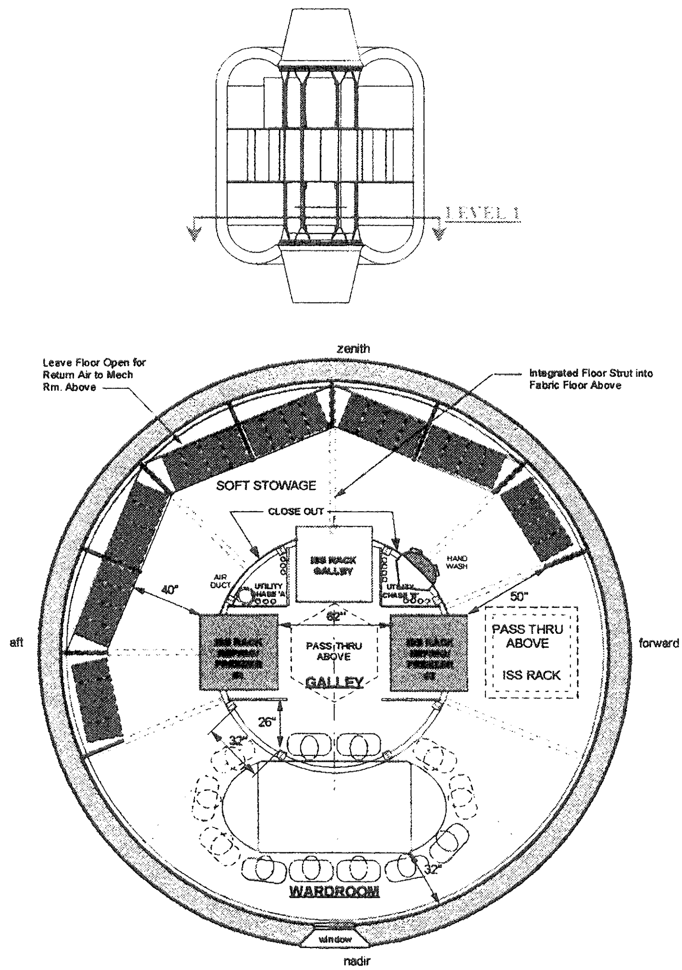

Figure 5. TransHab Level 1 Top View

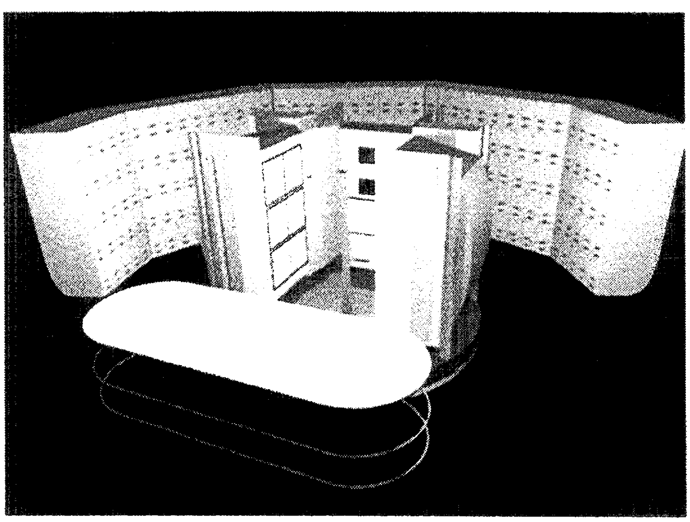

Figure 6. TransHab Level 1 Galley/Wardroom Area CAD image

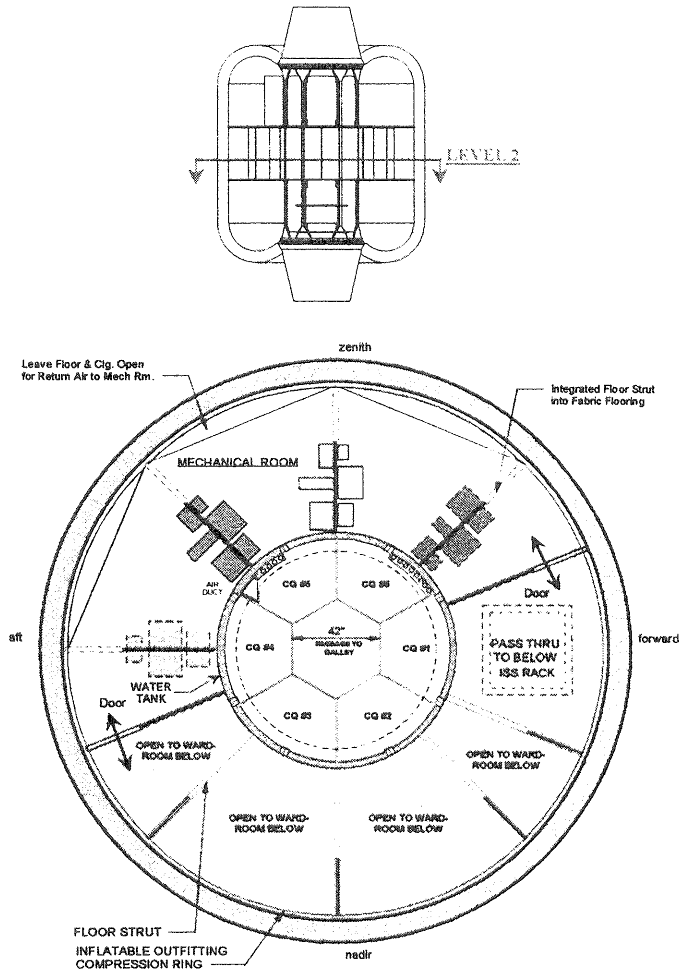

Figure 7. TransHab Level 2 Top View

Each of the crew quarters is ≈ 81.25-ft3 of volume (C.Q. 5 & 6 are less) and has a full height of 84". This is ≈ 27% larger than the ISS Rack-based CQ (flush face) which is ≈ 64 c.f.

Each C.Q. will have personal stowage, a personal workstation, sleep restraint, and integrated air, light, data and power, figure 8. An integrated soffit at the top of the crew quarters contains the ductwork, and power and data cables that feed the work station area. The acoustic wall panels will be designed for cleanability and change out.

Level Two

Level Two is composed of the mechanical room and the crew quarters (C.Q.). The crew quarters area has six crew quarters and a central passageway located within the second level central core structure and water tanks. The

This change out capability could allow new crew members to bring "personalized" panels to decorate their crew quarter according to personal taste. Studies and research on long duration isolation and confinement have shown this concept and larger private crew quarters to have a very positive impact on crew moral and productivity.

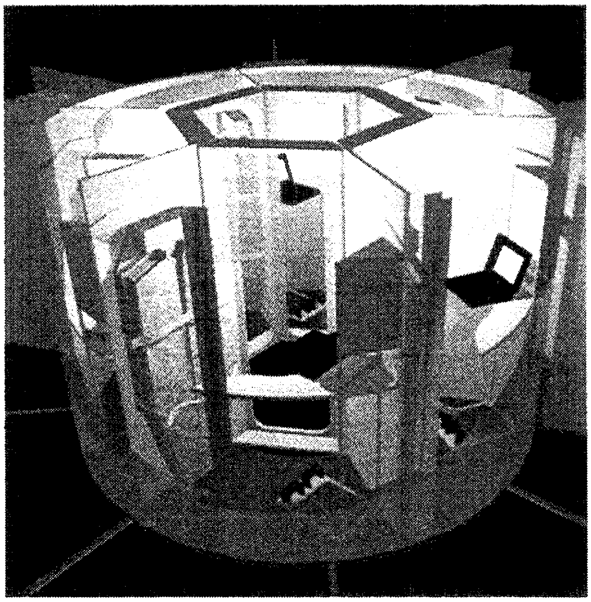

Figure 8. TransHab Crew Quarters CAD Image, JSC S99-05359

Level Three

Level Three is the crew health care and soft stowage area. The crew health care area incorporates two ISS Crew Health Care System (CHeCS) racks, a Full Body Cleansing Compartment (FBBC), changing area, exercise equipment (treadmill and ergometer), a partitionable area for private medical exams and conferencing, and an Earth-viewing window, figure 9. Also included on this level is a soft stowage area identical to level one.

The exercise equipment are permanently mounted in their deployed position, figure 9. This will save crew time in the deployment and stowage of exercise equipment on a daily basis. Placement of the exercise equipment is synthesized with the window location to allow the crew Earth viewing during exercise. Two launch shelves are placed on the floor struts as exercise equipment mounting platforms and structural integration.

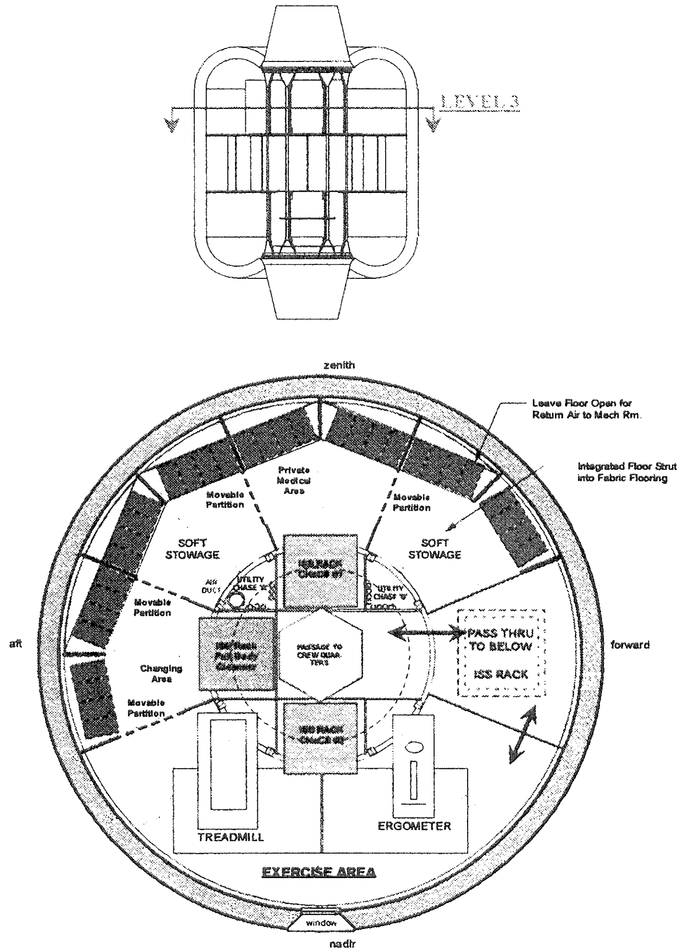

Figure 9. TransHab Level 3 Top View

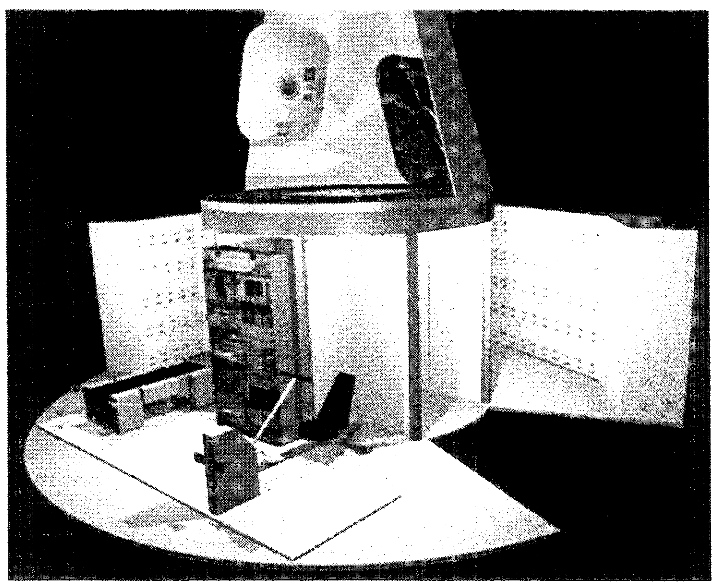

Figure 10. TransHab Level 3 CAD Image

Level Four

Level Four is the pressurized tunnel area. It has two station standard hatches, avionics and power equipment. Its function is to 1) provide a "transition" between Node 3 and TransHab, 2) house critical equipment required during inflation, and 3) provide structural connection to space station. It is the only pressurized volume in TransHab during launch. The packaged central core will vent during launch to a vacuum state until TransHab is inflated. Once TransHab is berthed and bolted to Node 3, Level 4 provides immediate access to the vestibule area between Node 3 and TransHab. This will allow the critical power and data vestibule connections to enable initiation of the deployment and inflation operations.

TRANSHAB STRUCTURE

TransHab has a unique hybrid structure that incorporates an inflatable shell and a central hard structural core, figure 11. This unique hybrid structure combines the packaging and mass efficiencies of an inflatable structure and the advantages of a load carrying hard structure.

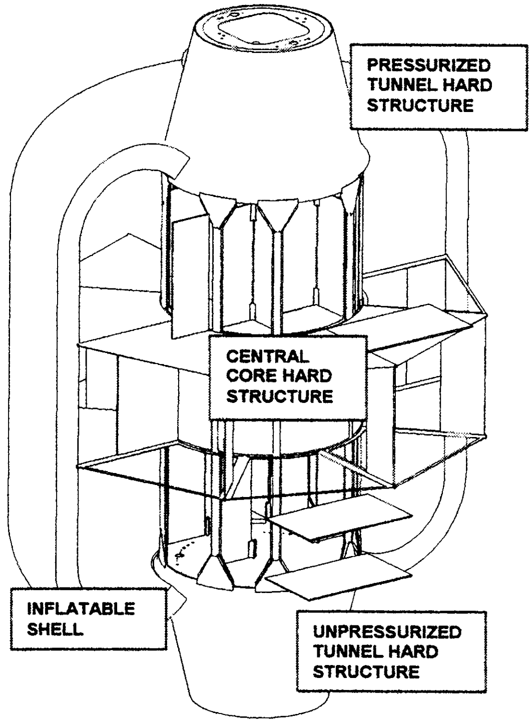

Figure 11. TransHab Structure

Central Core Structure

The central core structure is the hard structure that is comprised of the longerons, repositionable launch shelves, bulkheads, radiation shield water tanks, utility chases (2), and integrated ductwork. The inflation system and tanks are incorporated into Level 0, the unpressurized tunnel.

The launch shelves are placed into the central core for launch. There are 36 shelves in two different sizes: a) 30" x 84" and b) 50" x 84". About half of the shelves are repositioned once on-orbit and the others remain in place, figure 12.

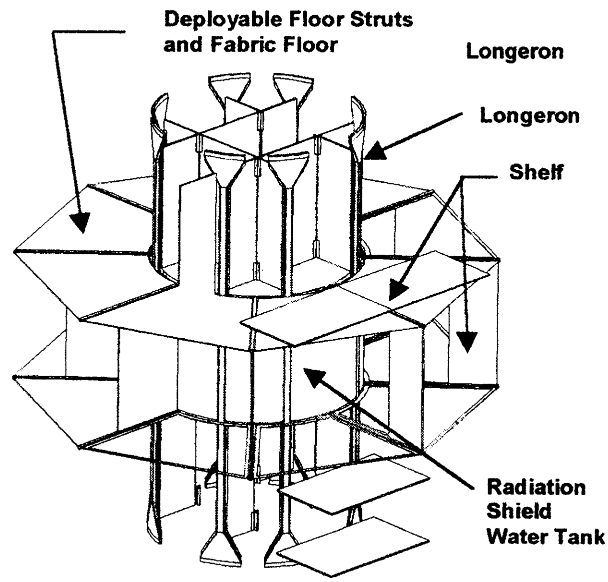

Figure 12. TransHab Deployed Core Structure

Inflatable Shell Structure

The inflatable shell is composed of four functional layers: the internal scuff barrier and pressure bladder, the structural restraint layer, the Micrometeoroid/orbital debris shield, and the external thermal protection blanket, figure 13.

Key Structural Features

- Composite Longerons:

The longerons provide the primary load path through the core reacting to both pressure loads and launch loads. They are 23 feet long with flares at each end to attach to the bulkheads.

- Radiation Storm Shelter and Crew Quarters for Six

The crew quarters are located within Level 2 central core annular water tanks. The water tanks provide a safe haven in the event of a solar flare. The water tanks are sandwiched between inner and outer shear panels that are structurally connected to the longerons.

- Light Weight Launch Shelves

For ground operations and launch, these shelves provide structural support and lightweight equipment mounting for pre-integration. For launch they are locked into position in the central core for TransHab launch loads. Once TransHab is deployed, approximately one half of the shelves are relocated into the habitat volume to support floor beams and equipment. The shelves are designed with dual use in mind—primary and secondary structure.

- Multi-Layer Shell

The inflatable shell is the TransHab's primary structure. Folded and compressed around the core at launch, it is deployed on orbit. The shell contains the crew's living space, provides orbital debris protection and thermal insulation.

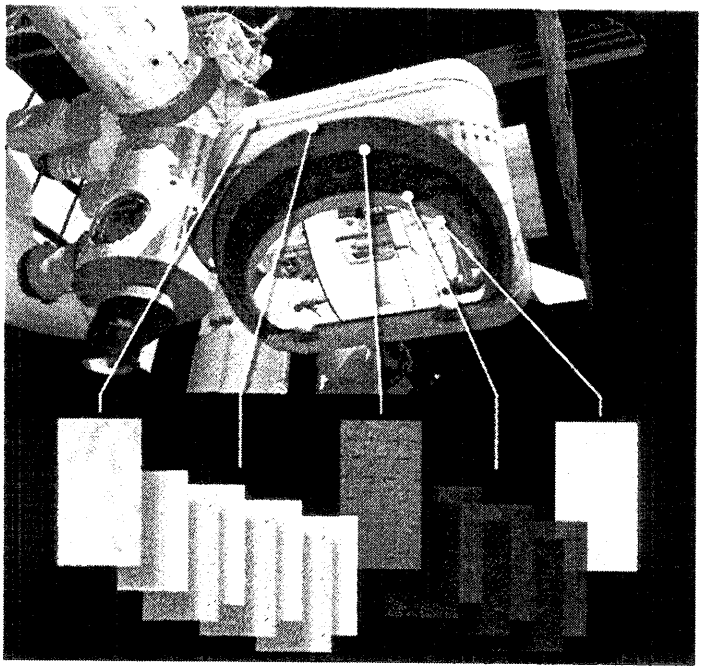

Figure 13. TransHab Shell Multi-Layers NASA JSC S99-05362

- Micro-Meteoroid Orbital Debris Protection (MMOD):

Particles hitting at hyper velocity impact expend energy and disintegrate on successive Nextel layers, spaced by open cell foam. Backing layers of Kevlar add an additional degree of protection. Still undergoing further development and testing, the configuration above (figure 14) has withstood impacts of up to a 1.7-cm diameter aluminum projectile fired at 7 km/s (15,600mph).

- Restraint Layer:

Woven from 1" wide Kevlar straps, the restraint layer is designed to contain four atmospheres of air pressure. Each shell restraint area is structurally optimized for that area's load. In order to accomplish this, strap seams were developed achieving over 90% seam efficiency.

- Bladder/Inner Liner Assembly:

An inner liner of Nomex provides fire retardance and abrasion protection. Three Combitherm bladders form redundant air seals. Four layers of felt provide evacuation between bladder layers (necessary for launch packaging).

Demonstration of Inflatable Shell

TransHab's design concept is based on a relatively unproven space inflatable structural technology. The team had to prove this technology would work and is safe. There were three important goals set to prove to skeptics that inflatable structures will work in space:

1. How to protect an inflatable structure from being ruptured by micrometeoroid and orbital debris impacts.
2. Prove a large diameter fabric inflatable structure can hold one atmosphere pressure in the vacuum of space with a Safety Factor of four.
3. Prove TransHab can be folded, packaged and then deployed in the vacuum of space.

Goal One

The first goal was achieved by building a typical shell lay up and performing Hyper Velocity Impact testing at JSC and the White Sands Test Facility. The one-foot thick orbital debris shield took shot after shot and kept passing—exceeding all expectations. Whereas testing continues, TransHab's shell has survived a 1.7-cm Aluminum sphere at hypervelocity of 7 km/second.

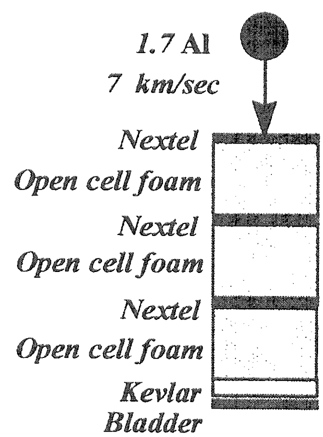

Figure 14. TransHab Orbital Debris Shield

Goal Two

Two shell development test units were built and tested at JSC to prove the second and third goals. The first test unit was to prove the inflatable restraint design would hold the 14.7 psia operating environment for the crew to live in. This unit was 23 feet in diameter by 10 feet tall. Since the hoop stress was being tested, it did not have to be full height. Figure 15 shows the test article being lowered into the large Neutral Buoyancy Lab pool.

A Safety Factor of four was used for this test; thus the restraint layer had to withstand the equivalent stress of four atmospheres. A hydrostatic test of four-atmosphere delta pressure was successfully performed in the Neutral Buoyancy Lab at JSC in September 1998.

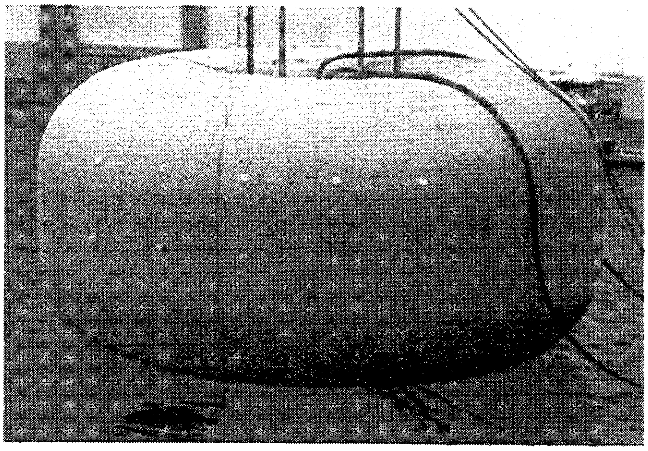

Figure 15. TransHab Hydrostatic Test

Goal Three

The second test unit was to prove the inflatable shell design could be folded and deployed in a vacuum environment. This test unit reused the hydrostatic test article bulkheads and rebuilt a full height restraint layer. Also included in this test was the orbital debris shield that was proven in the first goal. The one-foot thick debris shield is vacuum packed to reduce its thickness for folding to enable the module to fit into the Orbiter payload bay. Once on orbit, TransHab is deployed and the debris shield is released to its desired thickness. Figure 16 shows two technicians performing a final inspection of the test unit before folding the unit. TransHab was successfully folded and deployed in the vacuum environment of Chamber A in December 1998, proving the third goal.

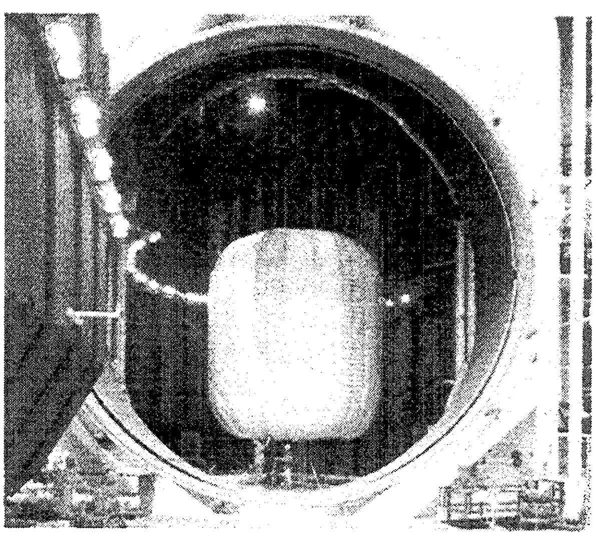

Figure 16. TransHab Vacuum Chamber Test

With the successful completion of the Hyper Velocity Impact testing and inflatable shell development tests, TransHab has proven that the inflatable structure technology is ready for the space age.

TransHab has made great strides to prove inflatable structures technology is ready to be applied as habitats for space applications. ISS TransHab's design meets or exceeds habitation requirements for space station and it has put the "Living" into "living and working in space." TransHab is proposed as a replacement of the hard aluminum can habitat for the International Space Station. It would be launched as the last station element in late 2004, figure 17.

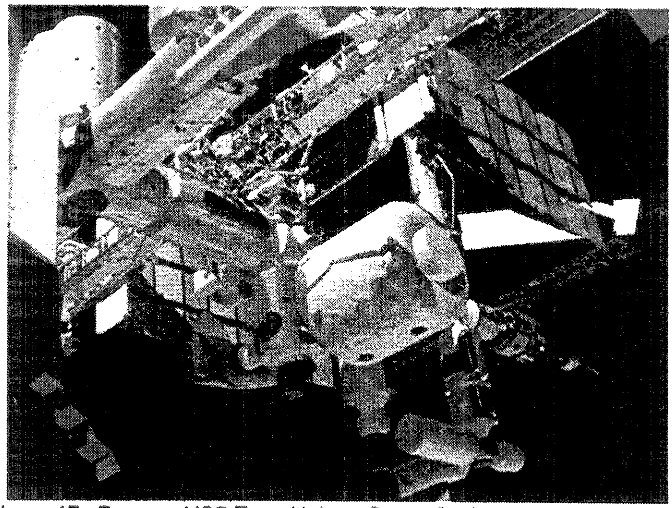

Figure 17. Proposed ISS TransHab on Space Station

When deployed on the International Space Station the TransHab will provide a habitable volume nearly three times larger than a standard ISS module; and yet it is launched on the Space Shuttle. TransHab provides facilities for sleeping, eating, cooking, personal hygiene, exercise, entertainment, storage, and a radiation storm shelter. TransHab also helps to develop, test and prove technologies necessary for long duration interplanetary missions.

This basic design and technology are appropriate for space and planetary surface habitats. Technologies developed for TransHab have multiple applications for both Earth and space. Technological advancement on material, manufacturing and deployment will continue to be developed, which will enable the design and manufacture of deployable greenhouse for use on other planetary bodies.

Mars Inflatable Greenhouses

When one thinks of growing plants for food we think about maximizing the crop yield per given growth area. This intuitively makes sense, produce the most edible mass per growth area. The scientists have studied and researched plant types and their growth environments that will yield the highest return. However, these are under optimum 'controlled' conditions, with abundant power, an amble supply of nutrients, and human interaction to ensure success. These optimum conditions are being performed in "growth chambers."

A greenhouse and a growth chamber are two different systems; each performing the function of growing plants. A growth chamber is relatively small, self-contained and tends to be dedicated to a specific crop at one time. It provides the plants necessary nutrients, air, water, and light. Examples of a growth chamber range from a small desktop chamber growing a couple of plants to larger human-tended pod the size of a 55-gallon drum. Growth chambers, due to it very use and size, do not have to be a human-rated pressure vessel/system. As such it should not have to meet the verification, reliability or failure redundancy as it would if it is human-rated.

A greenhouse on the other hand is a larger facility that a human would walk into to tend a larger variety of crops on a larger production scale. A greenhouse also has to provide the plants' necessary nutrients, air, water, and light. An example of a greenhouse ranges from the one used by Nigel Packham in the 90-day CELSS test at JSC to large covered facilities such as those used at the South Pole. The biggest impact to a greenhouse design is that it is a pressurized space system that will have to meet the human-rated requirements and subsequent testing. This will impact the greenhouse design, mass and costs. An underlying assumption about a Mars Greenhouse is that it will be an inflatable structure in order for it to have a low mass and yet provide a large pressurized volume(s) on the surface. As such it needs to have a high packaging ratio when stowed and be easily deployable.

Inflatable structures are in fact tensile fabric membrane pneumatic structures. As such they are inflated by air or a fill material to stress the membrane in tension. There are three basic pneumatic structure types:

1) Air Inflated: a multi-layer composite membrane that is inflated by internal pressure (fig. 18), i.e. TransHab.

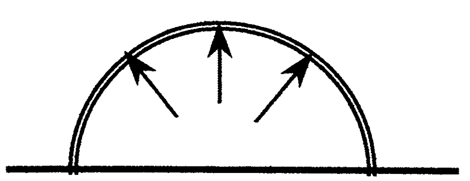

Figure 18. Air Inflated Pneumatic Structure

2) Air Supported: a multi-layer dual membrane cavity or air beams that rely on air pressure in the cavity wall to maintain the volume (fig. 19) with a resulting volume that can be pressurized at a lower pressure or not at all.

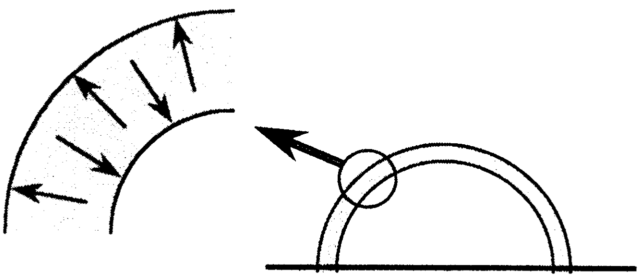

Figure 19. Air Supported Pneumatic Structure

3) Rigidized: a multi-layer single or dual membrane that relies on change-of-state in materials to rigidize the shell or beams upon deployment (fig. 20) with a resulting volume that can be pressurized at a lower pressure or not at all.

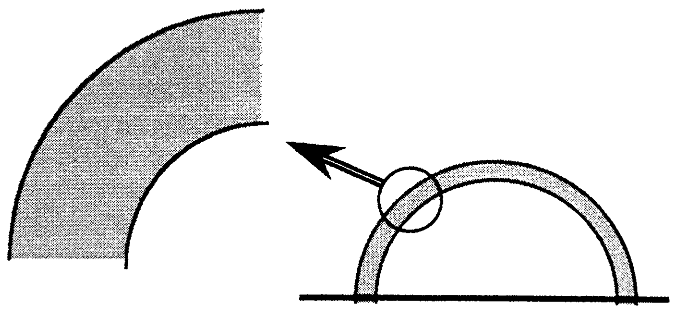

Figure 20. Rigidized Pneumatic Structure

Greenhouse Requirements

The functions of an inflatable greenhouse are to provide an environment to grow plants and interface with equipment, provide life support, robotics and human interfacing. From this a strawman list of requirements can be derived as a starting point. Whereas these requirements are not all inclusive, they do provide a beginning point for Mars Greenhouse design.

- Provide low internal pressure: 3 –5 psia (to be verified).
- Provide tbd c.f. (c.m.) growth area per crewmember per tbd% food supplement.
- Provide pressure vessel enclosure
- Provide secondary structure to support equipment and plant growth systems.
- Provide Environmental Control and Life Support: air distribution and collection, water and thermal conditioning.
- Provide communications: human to human, human to machine/system.
- Provide command and data handling.
- Provide a transition space (airlock) for crew and equipment into greenhouse.
- Provide lighting: natural and artificial, tbd fc.

- Provide external structural interfaces to other pressurized vessels (modules).
- Provide external power interface to power supply and/or other pressurized vessels (modules).
- Provide external data interface to data supply and/or other pressurized vessels (modules).
- Provide external thermal interface to thermal supply and/or other pressurized vessels (modules).
- Provide external water interface to water supply and/or other pressurized vessels (modules).
- Provide external gaseous oxygen and nitrogen interface to oxygen and nitrogen supply and/or other pressurized vessels (modules).
- Provide external wastewater interface to waste water return and/or other pressurized vessels (modules).
- Provide external communication (audio/video) interface to other pressurized vessels (modules).
- Provide tbd robotic system interfaces, i.e. grapple fixture, etc.
- It shall have integrated subsystems.
- It shall be easily deployed and assembled. Requiring less than tbd watts for deployment, has a mass less than tbd lbs. (kg), requires less than tbd EVA/IVA crew members hours to become operational.
- Provide tbd radiation protection.
- Provide tbd micrometeoroid and/or dust storm protection.
- Provide tbd % natural sunlight to enter through into the greenhouse interior.

Materials

Composite inflatable structures require three principal components or materials. The first component is for structural (load bearing) purposes, and is usually comprised of high tenacity fibers to react stresses associated with the structure. The second component is an impermeable gas barrier or liner needed to minimize air loss inside the module. The final component is a joining or matrix material whose function is to maintain alignment of the other components, particularly while folded and during deployment, and, while pressurized, to transfer loads between structural elements by inter-laminar shear.

Several joining techniques are employed for inflatable structures, including stitching at fiber intersections, adhesives, and use of braiding to restrain movement of adjacent fiber members. Choice of stabilization technique/material exerts a significant influence on the complexity of the subsequent fabrication task and on the performance of the final product.

The following set of material selection criteria should be considered to assist in selection of all materials for the an inflatable greenhouse:

- High strength-to-weight;
- Minimal Creep at working pressure for 10 - 15 year service life;
- No weakening when folded for extended periods (months);
- Negligible degradation in expected environment.

The tensile structure concept, the flexible matrix materials, and the full-scale manufacturing method must clearly be mutually compatible. The relationships between requirements and concept compatibility are diagrammed in figure 21 (Brown, Harris).

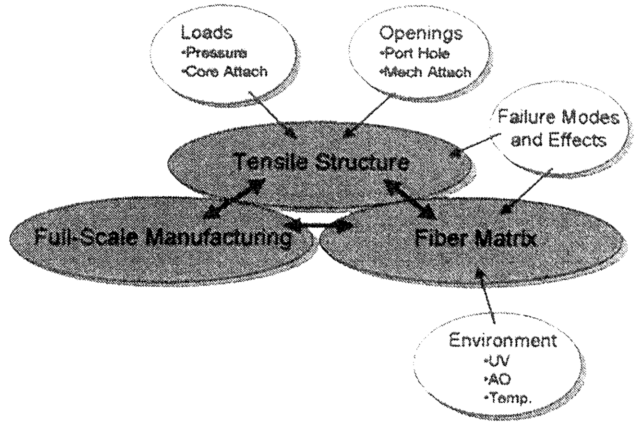

Figure 21. Inflatable Structure Relationship Diagram

Strength is not the only consideration, however. The lifetime anticipated for ISS is 10-15 years. Creep in the structural component over this lifetime must be minimal. When most textile fibers are subjected to load, they suffer three kinds of distortion:

- Elastic Deformation: closely proportional to load and fully and instantly recoverable upon load removal.
- Primary Creep: Increases at a decreasing rate with time and which is fully, but not instantaneously recoverable with time following load removal.
- Secondary Creep: varies in an obscure manner with time and load and is completely non-recoverable upon load removal.

Potential fiber choices that provide tenacity exceeding 22 gram/denier for flexible composite structures include most of the current generation high tenacity fibers, such as Kevlar™, Technora™, and Vectran™. The superior abrasion resistance demonstrated by Vectran™ during folding/unfolding cycles coupled with high tenacity combine to make Vectran™ the current leading candidate. This material has also exhibited excellent resistance to long term radiation damage.

Significant additional work remains to be accomplished before a determination of optimum materials can be made; however, the results to date appear exceptionally promising. Development of flexible composite structures from these materials will enable creation of large enclosed volumes for a variety of space missions with minimal mass and volume penalty incurred during the launch process

Interfaces

An important feature of any pressure vessel is the use of interfaces to connect to other pressurized vessels (modules) as well as utilities. There are both internal and external interfaces. These interfaces are critical to overall system's capability and performance. Not only are fluids, data, power, etc passed through the interfaces, but also are the internal connections to the plant growth systems. The more interfaces required the higher the risk of potential failure areas and/or leaks (fluid or gas). Use of known and approved space qualified hardware will reduce the risk of failures. However, these items are costly and tend to be heavy. Interface connections play an important role of an inflatable greenhouse and should be identified early and resources allocated accordingly. Pay attention to line length limits and bend radii.

Subsystems

Greenhouse subsystems include its structure, avionics, environmental control and life support (ECLSS), power management and distribution, crew accommodations, and plant growth system.

The greenhouse structural system will include the pressure vessel, connection ports, ground/anchoring interface, radiation protection, micrometeoroid/sand protection, and internal secondary support structure. The design of these items will depend on evaluation selection criteria of cost, schedule, performance and risk. Optimizing a system concept will take several trade studies with a clear set of assumptions, constraints and requirements.

The avionics subsystem includes the communications, and command & data handling. The communications has both the audio and video. Also included is the caution and warning system. If crew are going to be inside then every precaution will be taken to protect them and ensure their safety. The command & data handling can run off the habitat's main computer or provide a secondary tier for control of the greenhouse. In either case, software commands and data control, retrieval and storage will be a function of this subsystem.

A greenhouse's ECLSS system can either rely on the main habitat's ECLSS, provide it's own, or a combination thereof. The ECLSS subsystem includes the collection and distribution of air, water, waste, and thermal control. Based on the mission objectives, trade studies should be performed to optimize the ECLSS performance for the lightest mass and most efficiency power consumption.

Power generation and storage will be a part of the surface base infrastructure, so the greenhouse power system will include the management and distribution of power to the other subsystems and plant growth systems. This subsystem will include the power switching, relays, wiring harnesses and connectors. Control of the power allocation can be done in the computer or at the switching equipment by use of firmware controllers. The big unknown about the greenhouse power is the quantity of power required and subsequently the massive amount of cabling.

Since the greenhouse will have crew personnel interacting within the pressure vessel there will be the need for a crew accommodations subsystem. This ensures human factors design is considered, as well as restraints and mobility aids, lighting for crew and repair tasks, human to machine interfaces for maintainability and repair of equipment, and the interaction of crew and crops.

The plant growth subsystem will vary depending on the mission objectives and growth rate requirements. The basic system would include plant holding, plant nutrient distribution and collection, lighting, and air circulation.

Each subsystem can be optimized for its own performance, but as a whole they have to work together in harmony to produce the desired design at a reasonable cost, schedule, performance and risk.

Transition Spaces / Airlocks

When crew and/or equipment move from one pressurized environment to a different environment then a transition space is needed. These spaces are typically know as airlocks, but other types of spaces can serve a similar function. An airlock is the extreme example of a transition space since it is taking you from a 14.7 psia environment to a vacuum. The Apollo Lander did not use an airlock. It vented the entire cabin to vacuum. Where as this worked for a small environment and short mission; it is not recommended for long term surface habitats and greenhouses.

Examples of other transition spaces are vestibules and pressure chambers. A pressure chamber could also be considered an airlock depending on its purpose and function. A vestibule allows crew to lower or increase pressure between the spaces by manually opening a valve to equalize the pressure or by opening the door (hatch).

Concepts

There are numerous concepts of growth chambers and inflatable greenhouses; and there are many more to be invented and created. At this point in time, there is no one best solution. Numerous point designs should be embraced and then evaluated based on a prioritized set of selection criteria. Often the final design that gets built is a hybrid of many ideas and concepts.

The 'TorDome' is but one of many ideas by this author. It is an inflatable structure that combines both a high-pressure (8.3 – 10.2 psia) environment for the humans and a lower pressure (3 – 5 psia) environment for the plants. An 8'-10' (2.43 – 3.04 m) inner diameter torus circumscribes the larger low-pressure domed greenhouse at the ground level, figure 22. By splitting the functions of the human area and the greenhouse area the inflatable structure can be optimized and thus more efficient and lighter.

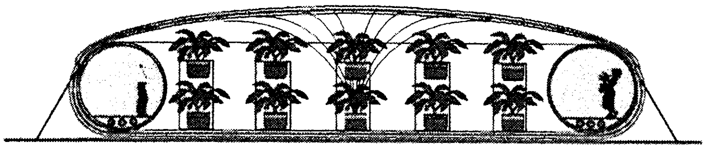

Figure 22. Inflatable Greenhouse Concept

The torus section incorporates the port interface to an airlock or habitat, utility interfaces and distribution, human viewing ports and workstations for monitoring and tending the crops. The dome section encapsulates the torus and provides the plant growing area. The optimum size and shape is to be determined. However, the basic shape of a Quonset style elongated cylinder may prove volume efficient for plant growth, fig. 23.

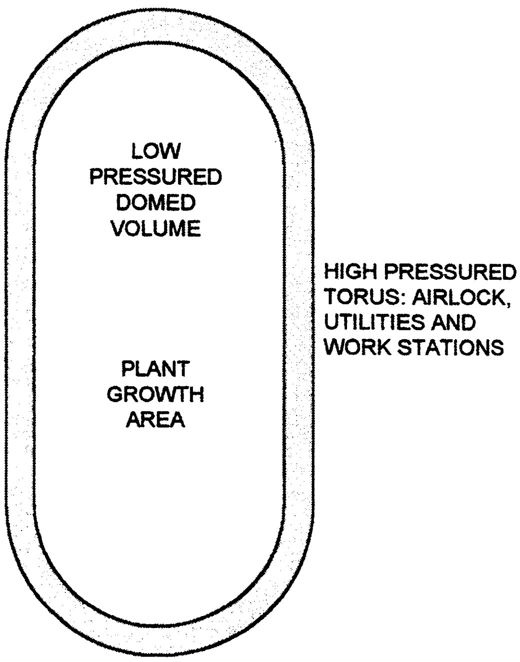

Figure 23. Inflatable Greenhouse Concept

A portion of the dome's roof could be designed to allow natural sunlight to enter into the greenhouse, fig. 24. The percent of roof opening and translucency will have to be determined based on material availability, structural integrity and plant growth rate. The technological challenge is to develop a 100% translucent bladder. The plants growth scientists would like 100% of the solar capability at the Mars surface, which is about half of what the Earth gets. The purpose of providing natural light is that this will reduce the lighting needed during the grow time. This will drop the power required and thus the overall mission mass due to reductions in power generation and storage. However, there are other concerns with a translucent bladder. One, it will not have the structural strength to with hold the 3-5 psia and thus will require some sort of restraint system. This will further reduce the amount of light getting through. Two, there is not a 100% translucent bladder materials available that are space qualified. Three, it will allow a large thermal loss to the Mars atmosphere, thus rendering the greenhouse interior cold.

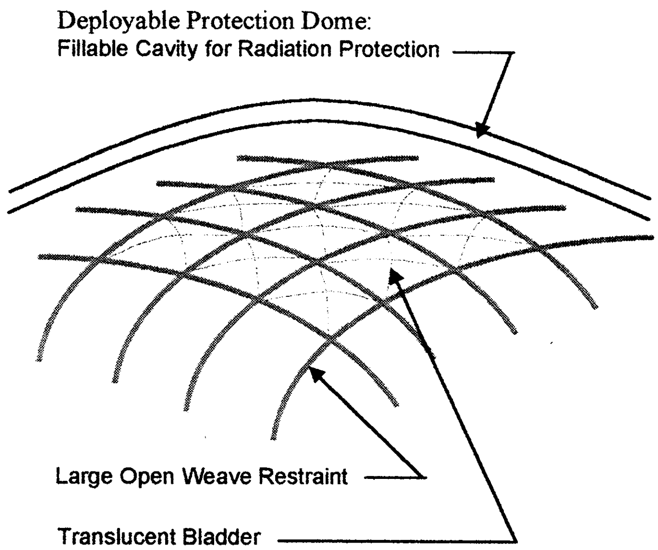

Figure 24. Inflatable Greenhouse Shell Concept

A deployable protection dome could achieve radiation and thermal protection. This concept is an external cavity shell (separate from the bladder/restraint shell) that can be filled or flooded with water when protection is desired during the night or intense solar activity, fig. 24. This protective shell would include the multi-layer insulation (MLI) and protective beta cloth. Section of it can be left open (no MLI/Beta) to allow the natural sunlight to enter through. This idea has some advantages and disadvantages. The advantages are 1) you can control or section the areas (flood) that you want protection; 2) You can vary the thickness of the protective layer; 3) you can use a variety of fluids/materials to fill the cavity; 4) It can be folded, packaged and deployed void of the fill; and 5) it can make use the in-situ water supply on Mars. Disadvantages include 1) it will reduce the translucency of the 'openings' for natural sunlight; 2) it will require ports, valves and fill lines; 3) it may have to be kept warm to keep the fluids from freezing; and 4) unknowns about maintenance and repair. This idea of a deployable protective dome and the 'TorDome' is very preliminary and requires a lot more design and analysis before it should be considered feasible.

SUMMARY

There are several points to summarize from this paper.

1. **Lower Mass**: The overall greenhouse mass should be designed to be light as possible. A shell mass metric of 1.5-3 kg/m3 volume deployed should be considered and an overall system mass of 10-20 kg/m3 should be strived for.

2. **Less Power**: Use of natural sunlight should be studied and traded against mass savings in reduced equipment and power systems. Every kg saved on the Mars surface has enormous savings in launch mass from Earth-to-Orbit. Other concepts such as fiber optic sunlight delivery systems should also be traded in mass savings.

3. **Efficient Lighting**: Development of higher output efficiency, robust and safe lighting is important to the success of greenhouse capability in food production. The emerging technology of Light Emitting Diodes (LED) integrated into solid state lighting systems is very promising for growth chambers and greenhouses.

4. **Genetically Engineered Plants**: The impact of this technology on greenhouse design and food production efficiency is tremendous. If plants can be engineered for maximum output at less than optimum conditions this will reduce the water, nutrients, light and growth area that is required. Thus reducing the system mass.

5. **Heat/Thermal Sharing**: Often we think about having to keep the greenhouse warm, when in fact we usually are trying to cool them off. There will be a delicate balancing act between the amount of heat given off by the internal lighting and systems, the amount lost through the inflatable membrane and the amount needed by the plants. One should consider a technologies that collects, distributes and exchanges the waste heat produced by the internal systems to keep the greenhouse environment in a optimum growing temperature.

In summary, there is much research to be done on the plant growing systems before optimally design greenhouses can be considered. Parametric trade studies should be performed, which will help flush out the driving requirements, issues and technologies that inflatable greenhouses will rely on in the future. However, it is premature to begin designing greenhouses when there are so many unknowns about the plant growth systems and environments needed to sustain a productive and healthy crop.

CONTACT

For more information about the ISS TransHab please contact NASA Johnson Space Center's Public Affairs Office.

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