ABSTRACT

Inflatable Structures: Test Results and Development Progress since TransHab

JSC's TransHab project was the first successful development program to prove the viability of inflatable habitats for space applications [1][2][3]. Although TransHab was cancelled in 2000, significant progress has been made this past year by JSC engineers.

Since February 2005, the following test articles have been manufactured and tested:

- An 88-in diameter restraint layer was pressure-tested to failure and reached an ultimate pressure of 197psi. This test article demonstrated the ability to build a 35-foot diameter inflatable with a factor of safety of 4.0 at 10.2 psi.

- An 88-in diameter restraint layer with a window frame incorporated into the restraint layer was tested to failure and reached an ultimate pressure of 197 psi. This test article demonstrated the ability to incorporate windows and other structural penetrations in the woven restraint layer without reducing its strength.

- An 88-inch diameter folding demonstrator that includes a bladder, restraint layer, and all of the MMOD shell layers was manufactured and assembled. This test article demonstrated an improved and simplified shell assembly and folding technique which installs pre-folded shell sections in a controlled manner.

- Fifth-scale MMOD hypervelocity test articles have demonstrated fiberglass as a viable material for a MMOD bumper shield which is cheaper and more readily available than previously used materials.

In addition, four different full-scale advanced shape inflatable mockups have been manufactured and evaluated for applications such as lunar habitats, airlocks, and transfer tunnels.

1. United States Patent, Inflatable Vessel and Method, 6,547,189, April 2003
2. TransHab: NASA's Large-scale Inflatable Spacecraft, American Institute of Aeronautics and Astronautics, Inc. 2000-1822, 3/06/2000.
3. Gossamer Spacecraft: Membrane and Inflatable Structures Technology for Space Applications, Chapter 21, American Institute of Aeronautics and Astronautics, Inc., 2001, Progress In Astronautics and Aeronautics - Volume 191.

Inflatable Structures

JSC Test Results and Development Progress since TransHab

Chris Johnson
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Overview

JSC's TransHab project was the first successful development program to prove the viability of inflatable habitats for space applications.

It demonstrated the manufacturing, structural loading, micrometeoroid / orbital debris (MMOD) protection, folding, and deployment capabilities for an inflatable habitat.

Although TransHab was cancelled in 2000, significant progress has been made this past year by JSC engineers

Overview

- Since February 2005, the following demonstration test articles have been manufactured and tested
  - 88” Diameter Restraint Layer (R/L) Test Article
  - 88” Diameter R/L with Integrated Window Frame Test Article
  - 88” Diameter Shell Folding Demonstrator
  - Fifth Scale MMOD Hypervelocity Test Articles
  - Advanced Inflatable Structure Shape Mockups

- Designed by JSC Engineers
  - 88” diameter test articles and advanced shape mockups manufactured and tested at Bigelow Aerospace facilities
  - MMOD hypervelocity test articles manufactured and tested at JSC and White Sands facilities

Contents

- These demonstration test articles increased the development of the following:
  - Restraint Layer
  - Window / Restraint Layer Integration
  - Shell Assembly, Folding, & Installation
  - Shell MMOD Materials
  - Advanced Inflatable Shapes

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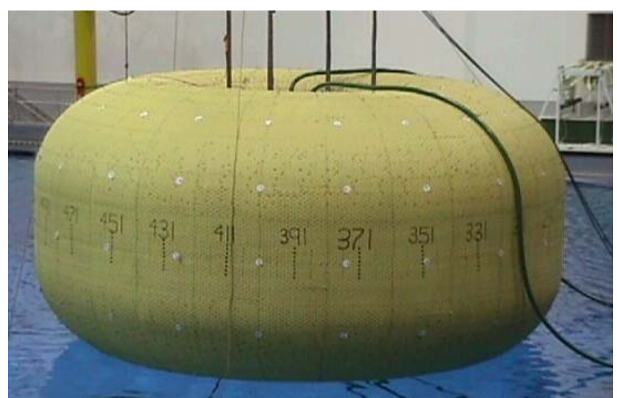
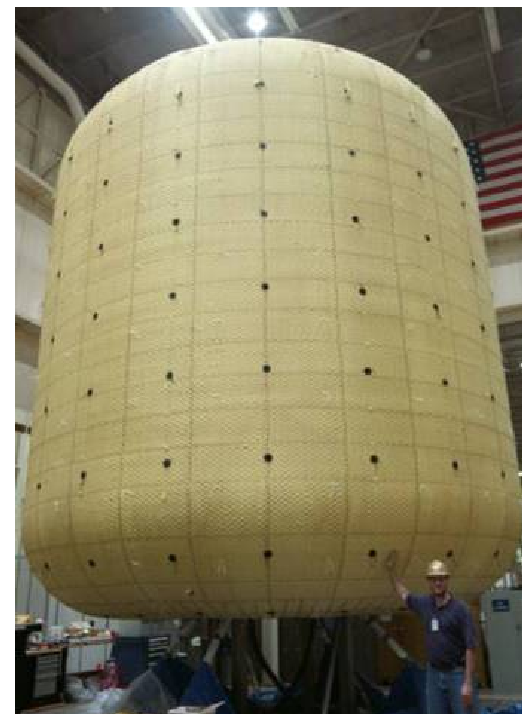
Restraint Layer

- **TransHab (1997 – 2000)**
  - CHALLENGES:
    - Fabric tensile load increases as a function of diameter.
    - Factor of Safety (FOS) of 4.0 used (per FAA Airship Requirements)
  - Built three 23-foot diameter restraint layers in 8-month period
    - 2 for hydrostatic testing
      - Woven restraint layer tested up to FOS=4.0
      - ** Highest loaded inflatable in history **
    - 1 for folding and deployment in thermal vacuum

FOS = 2.0 on Ultimate
(verified by test May 1998)



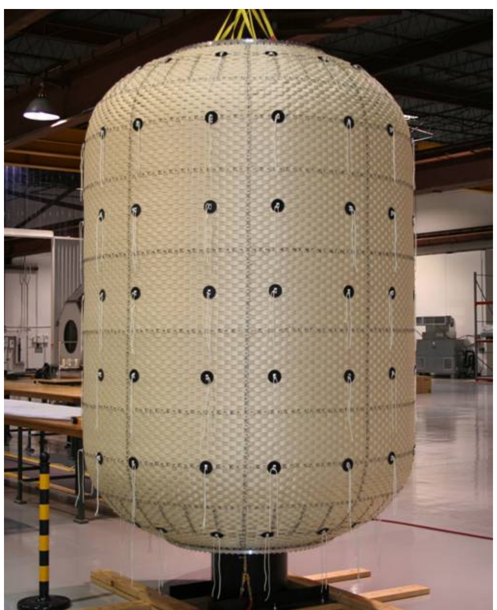
FOS = 4.0 on Ultimate
(verified by test Sept 1998)

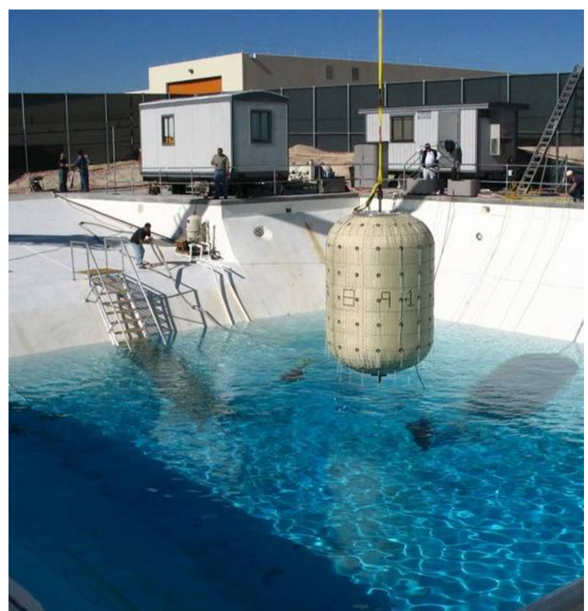


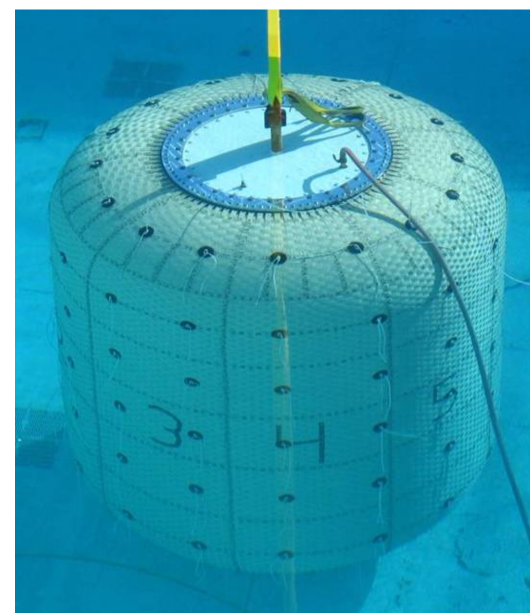
Full-scale Thermal-Vac Test Article
(1999)

Restraint Layer

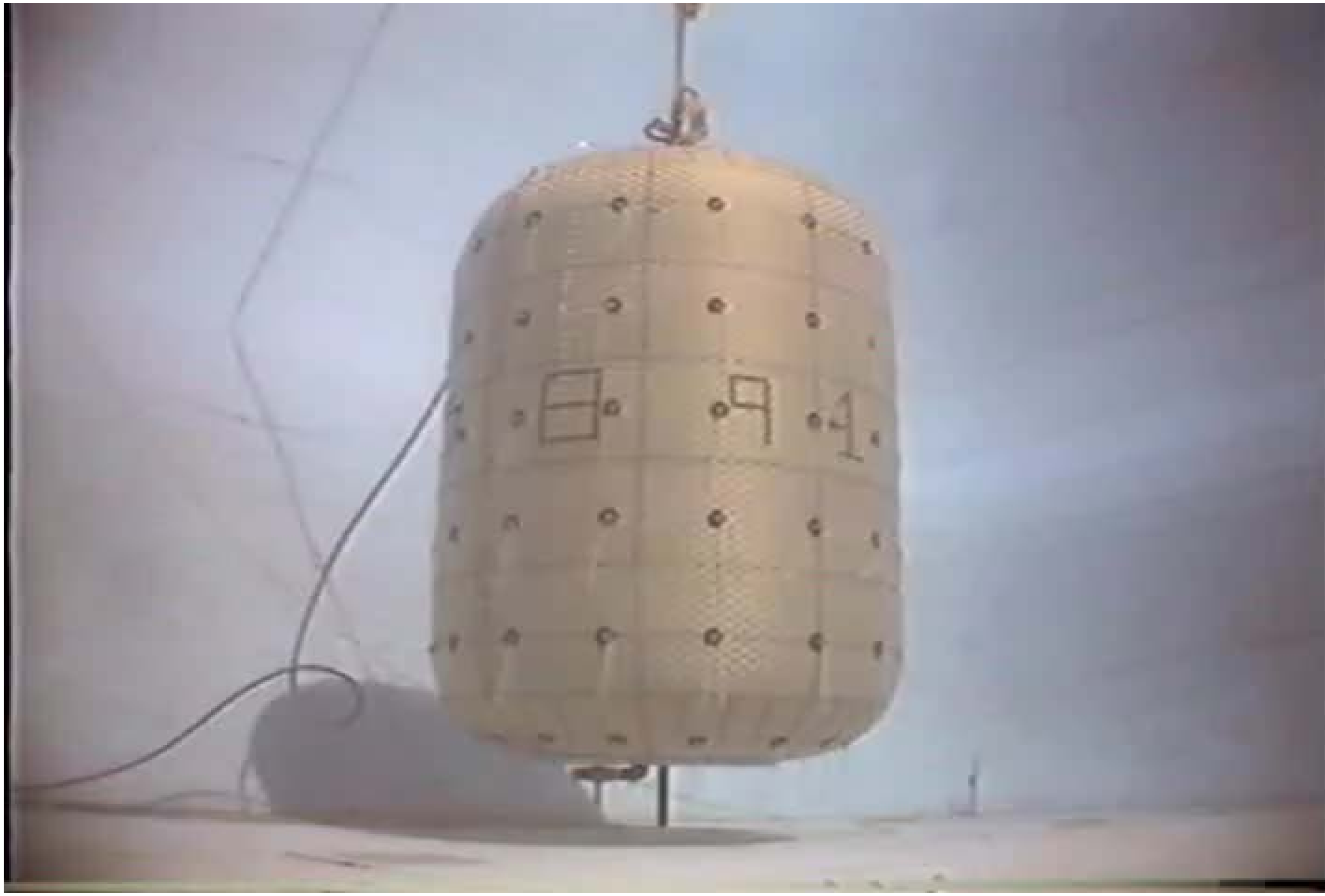
- **JSC Development (2004 – Present)**
  – GOAL: Pressurize a woven restraint layer to failure to understand the failure modes, safety margins, and other aspects of design
  – Designed and built an 88” diameter Restraint Layer test article
  – Hydrostatic Test, November 2005
    - Failed at 197 psi (exceeds FOS=4.0 for 30-ft dia module at 10.7 psi)
  – Improved Design Tools and Manufacturing Processes







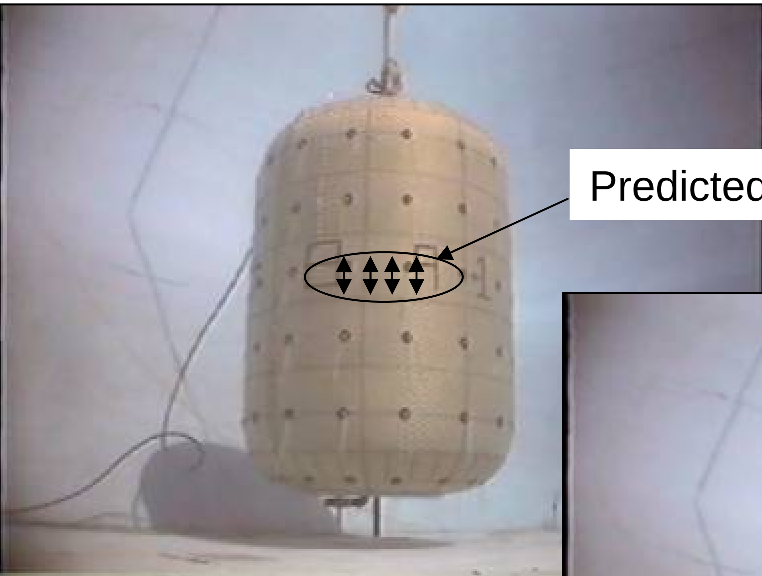
Restraint Layer



Restraint Layer

Pressure = 197 psi

Predicted failure mode and location.



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Restraint Layer

- RESULTS
  - Demonstrated Restraint Layer Capability
    - Exceeds FOS=4.0 for 30-ft dia module at 10.7 psi
    - Enabled correlation to analysis
    - Enabled understanding of knockdown factors
    - Demonstrated repeatability of manufacturing
    - Demonstrated first predicted failure mode
  - Bigelow Aerospace plans to use this design on Galaxy class vehicles
    - Planned launch mid to late 2007

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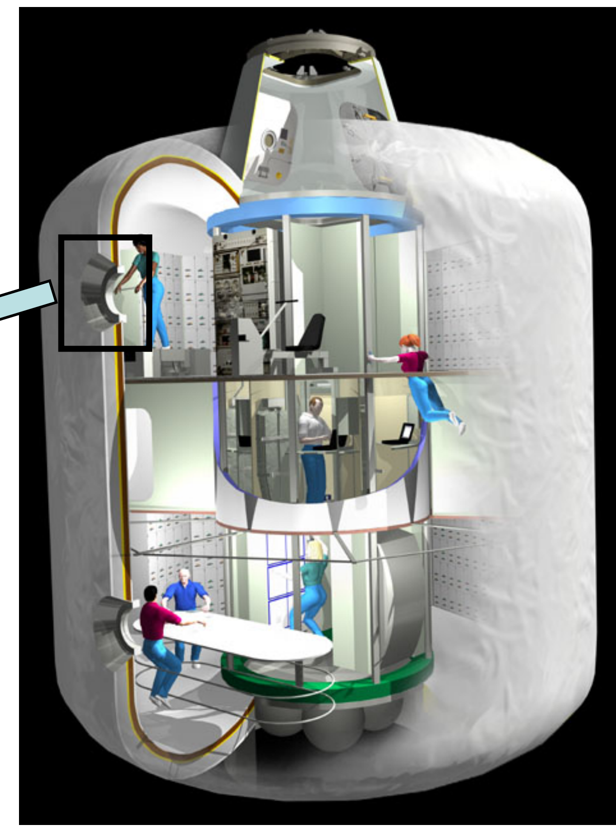
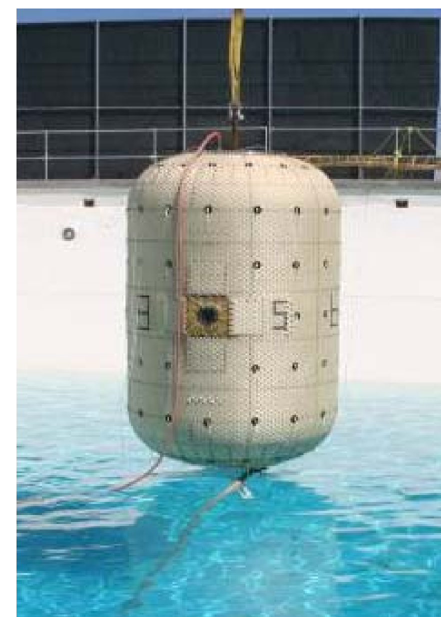
Window Frame / Restraint Integration

- **TransHab (1997 – 2000)**
  - CHALLENGES:
    - Install a window frame or “pass-through” in an inflatable structure.
    - Minimize Impact to Bladder / Restraint Layer
  - Designed Conceptual Window
    - Never Manufactured, Never Tested



Window Frame / Restraint Integration

- **JSC Development (2005 – Present)**
  - GOAL: Pressurize a woven restraint layer *with a window* to failure
    - Determine window effects on bladder and restraint layer.
  - Designed and built an 88” diameter R/L with integrated window frame test article
    - Demonstrate integration of window frame into restraint layer & capability
  - Improved window frame design
  - Developed restraint layer modification
  - Developed manufacturing & installation processes
  - Hydrostatic Test, March 2006
    - Failed at 197 psi (*same as without window*)
    - No loss in performance due to discontinuity



Window Frame / Restraint Integration

- RESULTS
  - Demonstrated window frame / restraint capability
    - Reached same ultimate capability of restraint ***without window***
    - Enabled characterization of load distribution around window frame
    - Demonstrated first predicted failure mode
  - Bigelow Aerospace plans to use this design on full scale class vehicles
    - Planned launch TBD

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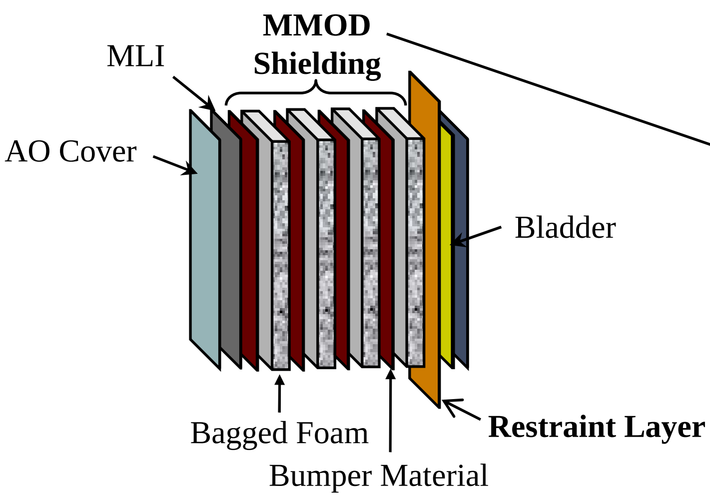
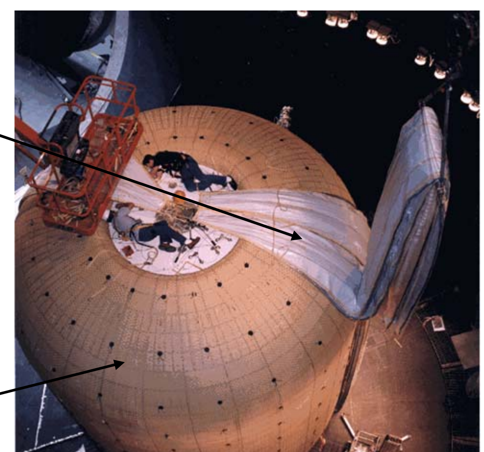
Shell Assy, Folding, Vehicle Installation

- **TransHab (1997 – 2000)**
  - CHALLENGE:
    - Fold 12,000 lbs of multi-layer fabric
    - Compound curved shape must be folded into a cylinder shape to fit into launch vehicle
  - Shell installed on vehicle in deployed configuration
  - Vehicle deflated, shell/restraint folded using Ground Support Equipment (GSE)
    - Fold Lines determined from scaled model
  - Problems
    - Cumbersome technique due to heavy material
    - Inadequate GSE / vertical configuration
    - Difficult to fold in compound curved region

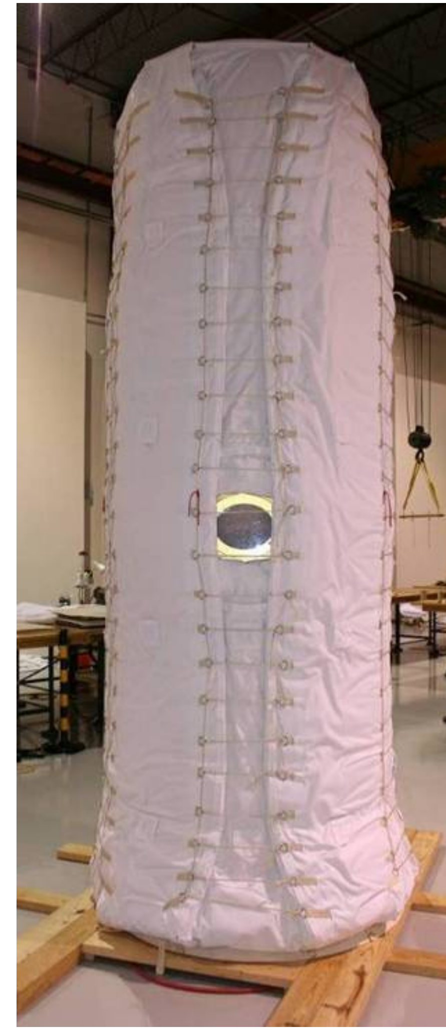




1998
TransHab
JSC Engineering Unit

Shell Assy, Folding, Vehicle Installation

- **JSC Development (2005 – Present)**
  - GOAL:
    - Demonstrate simplified design, assembly, and installation of shell – regardless of size and/or mass.
  - Designed and built an 88" diameter Shell Folding Demonstrator
  - Developed new fold configuration
    - Gore patterns and fold lines mathematically defined
    - Simplified the design
    - Simplified the assembly & installation (minimal GSE)
  - Developed design software tool
  - Developed design of shell with integrated window
  - Folding and deployment demonstration, Feb. 2006



Shell Assy, Folding, Vehicle Installation

- RESULTS
  - Demonstrated new fold configuration
    - Proved the simplified design concept
    - Design is scalable to larger size inflatables
    - Enabled correlation to stowed thickness prediction
  - Bigelow Aerospace plans to use this design on Galaxy class vehicles
    - Planned launch mid to late 2007

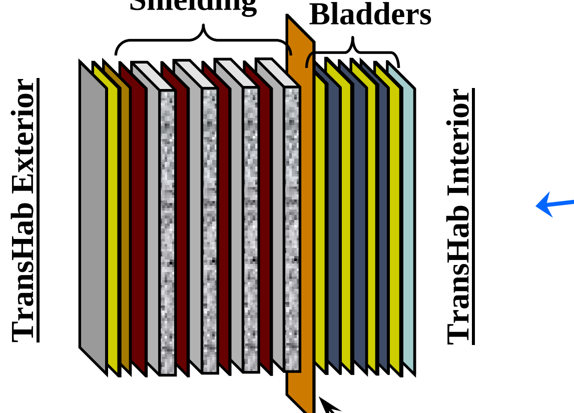
Contents

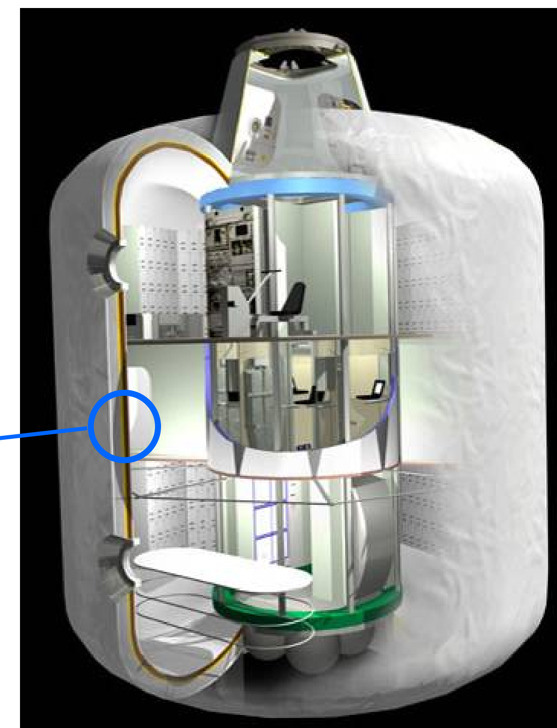
- Accomplishments over past 12 months
  - Restraint Layer
  - Window / Restraint Layer Integration
  - Shell Folding Demonstration
  - Shell MMOD Testing
  - Advanced Shapes

Shell MMOD Testing

- **TransHab (1997 – 2000)**
  - CHALLENGE:
    - Design a flexible micro-meteoroid / orbital debris shield that can be folded.
  - 0.985 PNP verified with over 100 test shots (1997-2005)
    - Met NASA-ISS requirement
  - Can stop 2 cm AL particle at 7 km/sec
  - Nextel / Kevlar selected as MMOD shield lay-up

Full-Scale Hypervelocity Test Article





Shell MMOD Testing

- **JSC Development (2005 – Present)**
  - GOAL: Determine a low-cost alternate to Nextel as a MMOD bumper material
  - Low cost material candidates tested
    - Testing performed by Eric Christianson (KX)
    - Fiberglass / Kevlar combination selected
      - Performed as well as Nextel / Kevlar
      - Out-performed carbon fabric
  - Additional testing in development (full-scale correlation, ballistic limit curve determination)
  - Bigelow Aerospace plans to use this design on Galaxy class vehicles
    - Planned launch mid to late 2007

- Accomplishments over past 12 months
  - Bigelow Houston Facility Build-up
  - Restraint Layer
  - Window / Restraint Layer Integration
  - Shell Folding Demonstration
  - Shell MMOD Testing
  - Advanced Shapes

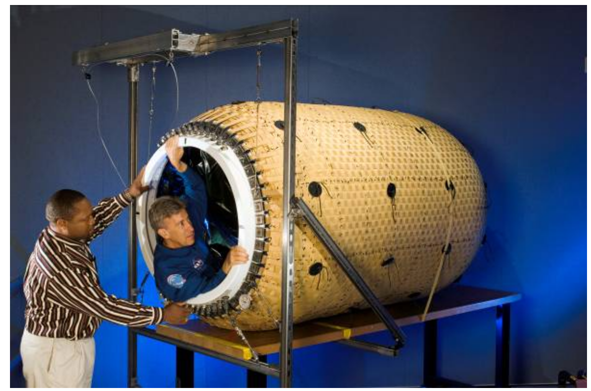
Advanced Shapes

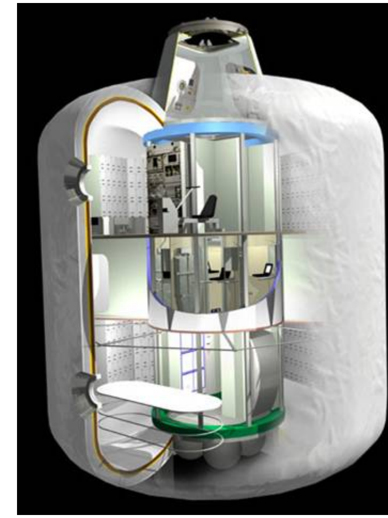
- New Inflatable Shape Development
  - Large Diameter, Short Height Inflatable Structures
    - Efficient in pressure loading
    - Desirable for gravitational environment architecture
      - Lunar and/or planetary habitat
  - “Coreless” Inflatable Structures
    - No internal rigid core structure
    - Desirable for small stowed packing volume
      - Habitation/Stowage
      - Deployable Airlock
  - Inflatable Transfer Tunnels
    - No internal rigid core structure
    - Not a body of revolution

BACKUP

JSC Past Inflatable Development Projects

- TransHab
  - Transit Habitation Module
  - ISS Habitation Module
- Hyperbaric Chamber
- Airlock
  - Honeywell design under NASA contract
- Bigelow Development Aerospace Partnership





Applications