Inflatable Softgoods Design of an Articulating Crew Transfer Tunnel

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Future NASA exploration plans call for lunar and Martian surface systems that form a base camp of multiple, pressurized elements. These discrete components, including habitats and pressurized rovers, require interoperability to meet the Artemis Accords and standard docking systems to physically connect elements together. A pressurized, articulating crew transfer tunnel can be used between a rover and habitat to enable shirt-sleeve transfer of crew and cargo, saving valuable crew time and resources. While transfer tunnels have been described in the past, this work details the design of a structural softgoods system that has compliant capability through a proposed docking range of motion. The inflatable softgoods design is based on a zero-hoop stress shape, known as a Taylor surface, that is stacked and truncated to form a unique and flexible configuration. Analytical, non-linear models have been developed to examine and predict the behavior of the structure, and material testing was used to determine the properties that were used in the model. Finally, a sub-scale test article was constructed using the baseline design and pressurized testing is in work. Additional full-scale testing is planned for future years to fully demonstrate the capability of the system.

I. Introduction

NASA's deep space exploration roadmap seeks to return humans to the Moon with long-term habitation capabilities in preparation for a crewed mission to Mars. For long-term exploration, an architecture with multiple pressurized elements, such as a lander, habitat, airlock, and pressurized rover will be needed [1]. To ensure interoperability of these elements, as required by the Artemis Accords [2], a surface docking system standard is being developed to physically connect elements. When direct docking cannot be achieved, an articulating Surface Attachment System (SAS) docking tunnel is needed to bridge unaligned elements. This pressurized transfer system enables shirt-sleeve transfer between elements and aids expedited movement between them for both crew and cargo. It simplifies operational timelines by reserving extravehicular activities (EVAs) for human led exploration of the surface terrain, instead of EVAs to simply translate from one element to another. Eliminating transfer EVAs will maximize surface science objectives and reserve the use of lunar surface spacesuits for exploration. For Mars missions especially, pressurized transfer is required for planetary protection [1]. A Martian surface transfer tunnel concept is shown in Fig. 1. Exercising the system in the lunar environment aligns with the Moon-to-Mars Architecture and will directly benefit Artemis exploration goals while demonstrating the necessary technologies for Mars missions.

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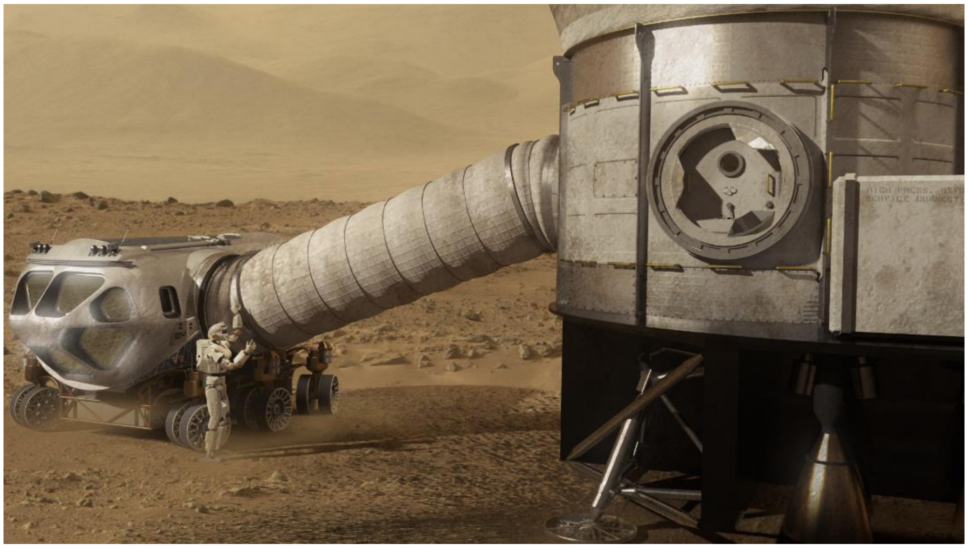


Fig. 1 Conceptual Rending of a Pressurized Transfer Tunnel Between a Habitat and Pressurized Rover on the Martian Surface [3]

II. Tunnel System Overview

A pressurized transfer tunnel between two surface elements requires a flexible tunnel system that can expand, contract, and move in multiple degrees of freedom to bridge the physical gap between mating interfaces. The maximum gap between elements is a function of each element's capabilities. For example, a pressurized rover could approach a habitat and directly dock, while two habitats will not likely be close enough for docking without a connecting tunnel. To meet multiple mission needs and objectives, a pressurized tunnel with standard mating interfaces is needed across the Artemis architecture. Numerous factors will need to be considered to make surface docking possible including element stiffness, habitat ground anchoring, and rover mobility, not to mention the extreme thermal and dust environment of the lunar surface where a tunnel would have to operate. Internal crew systems to aid in translation, as well as details on the mating surfaces including seals and latches to contain the internal gas should also be considered. The docking interface details should be standardized to promote interoperability, similarly to the International Docking System Standard (IDSS) that is used for docking between two elements in microgravity [4]. While details of an interface standard are being established, the SAS concept was developed to demonstrate pressurized transfer and define future requirements.

The SAS is a pressurized crew transfer tunnel design developed at NASA Johnson Space Center to be used as a testbed for surface docking, with a focus on the mechanical systems and structural softgoods. High level project requirements were defined to size the SAS structure. For surface exploration, a 10.2-psig operating pressure was chosen. To maximize transfer volumes, it was assumed that the crew would walk through the tunnel instead of crawl, so a rectangular hatch passageway with a clearance of 40-inches wide by 60-inches tall [5] was used. From that driving dimension, a circular bulkhead that encircles a rectangular mating frame was designed, and a six-degree-of-freedom Stewart platform was used as a notional articulating mechanism. The internal mechanism has a large articulating envelope for coarse alignment and a smaller docking envelope for mating of the interfacing surfaces. While the mechanism is used to physically connect the two docking frames, a seal and latching system must be used to fully connect them along with a softgoods enclosure that contains the internal gas and carries membrane loads from the internal pressure. Internal systems are also required for crew passage, such as a floor and handrails. A hatch or closeout panel is also used to prevent dust penetration and allow for low levels of internal pressurization when not docked. Fig. 2 shows the external view of a notional SAS prototype.

A. Tunnel System Operations

The operational concept for docking a rover with a habitat using the SAS is broken into two main stages:

1. Unpressurized Stage
    a. Rover moves into position near the habitat docking interface
    b. SAS extends and articulates to coarsely align with the docking interface
    c. SAS uses fine movements to align the mating interface and soft mate to mesh the two interfaces

    - d. SAS structural latch system engages and locks the interfaces to hard mate
2. Pressurized Stage
    - a. Tunnel is pressurized to rover pressure, softgoods take shape while fabric is tensioned
    - b. Leak check is performed on the tunnel, while rover and habitat hatches remain closed
    - c. Rover hatch is opened, tunnel protective cover is opened
    - d. Crew ingress into tunnel, close rover hatch
    - e. Tunnel is pressurized to habitat pressure, crew translates towards habitat
    - f. Tunnel protective cover is opened, habitat hatch is opened
    - g. Crew egress tunnel, translate into habitat
    - h. Tunnel remains pressurized while docked between the two elements

To remove the tunnel and undock the elements, the steps listed above are completed in reverse. Once both hatches are closed, the tunnel is depressurized, the mating system is unlatched, and the SAS retracts back to the stowed position.

B. Tunnel System Demonstration

During initial development of the SAS, a full-scale non-structural test was completed to evaluate the attachment system and internal mechanism. This test used non-structural softgoods on a mechanical test article that was attached to a Johnson Space Center designed pressurized rover, as shown in Fig. 2. A full-scale, unpressurized, demonstration was completed where the rover and attachment tunnel moved into a docking position next to a simulated habitat docking target, extended, aligned, and latched the two systems together. A crew member that was controlling the rover then opened a hatch and translated through the tunnel to the habitat. This demonstration showed viability of the overall system and technical readiness improvements of the mechanical systems.

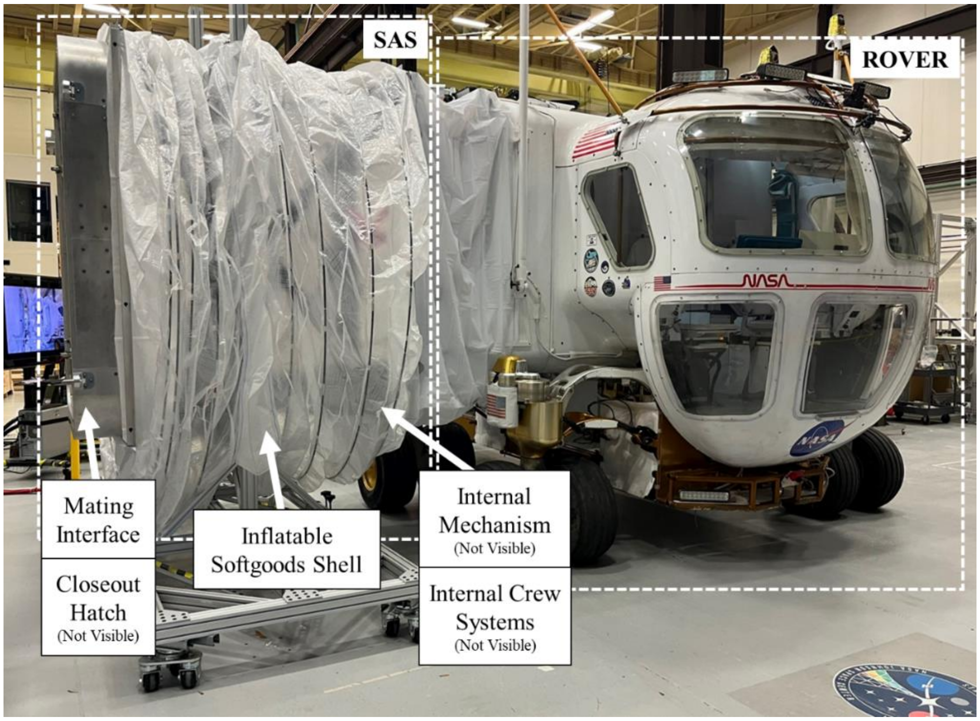


Fig. 2 Full-scale Demonstration Test of the Surface Attachment System on a Pressurized Rover at Johnson Space Center

III. Softgoods System Overview

Following the full-scale demonstration, detailed work on the inflatable softgoods shell was completed to develop a system capable of meeting the intended requirements under pressure. Since the focus of this report is the design of the structural softgoods element, the articulating mechanism, latching, sealing, crew systems, and closeout panel/hatch considerations for the SAS are not detailed further. While the softgoods solution described was developed for SAS, it is designed to be agnostic of the docking mechanism, mating interface, or hatch size. It is based on a circular cross-section pressure vessel that can be scaled for circular or rectangular passageways, such as in [6] and [7].

A. Softgoods Design Constraints

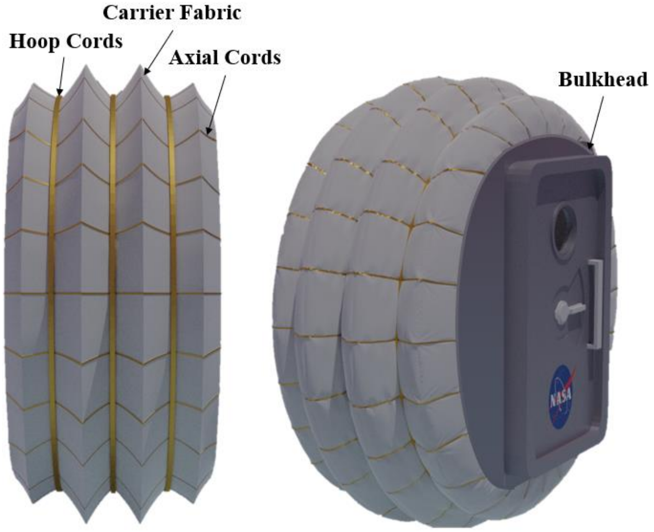
For development, softgoods specific design constraints were derived using the SAS mechanism as a baseline design, and are listed below:

1. Designed to Maximum Design Pressure (MDP) of 10.2 psig x 4.0 FOS (Factor of Safety).
2. Designed for 50 pressure cycles (0 psig to MDP to 0 psig) x 4.0 FOS.
3. Able to be pressurized to MDP with the tunnel in any position within the docking envelope.
4. Accommodates tunnel’s full articulation envelope when unpressurized.
5. Able to retract from its pressurized position back to its stowed position when unpressurized.

Note: The internal mechanism carries all axial loads generated by the internal pressure of the tunnel.

B. Softgoods Structural Design

Traditional crewed inflatable structures are designed to fixed dimensions that optimize the shape of each softgoods component to ensure predictable stress distributions. In these applications, traditionally habitats or airlocks, the fabric is designed to take on a specified shape when under pressure. A fabric transfer tunnel, however, must accommodate misalignment between the two connected elements. The softgoods section must therefore be able to be pressurized with the two hatches at any relative location and orientation within the system’s docking envelope. The size of the required internal passageway, the articulation envelopment from the internal mechanism, and the MDP of the tunnel are the primary drivers for the softgoods design. Since the system could be pressurized with significant variations in hatch orientation, the softgoods shell needs to accommodate many shapes while imparting minimal load on the tunnel’s internal mechanisms. This design complexity calls for a unique structural softgoods design that can move with the attachment system and still maintain structural rigidity under pressure. It also needs to be able to repeatedly pack down into a small, retracted volume.



A) Unpressurised “Flat” View

B) Pressurized View

Fig. 3 Softgoods Tunnel Design Overview

The proposed solution uses a “pumpkin” lobe concept, known as a “zero-hoop stress shape”, or “Taylor surface” [8] that has been used in practice on the Ultra High Performance Vessel (UHPV) architecture, pioneered by Thin Red Line Aerospace [9] as well as the Non-Axisymmetric Inflatable Pressure Structure (NAIPS) Concept designed by NASA [10]. The pumpkin design is a statically determinate structure under pressure that uses a combination of axial cords and a fabric carrier layer. This concept is well demonstrated on a parachute where the canopy fabric transfers the pressure load to the suspension lines. This dual-component restraint layer concept allows for a lightweight carrier fabric to be used along with a series of high strength cords that carry most of the load.

For the transfer tunnel design, four pumpkins are stacked along the central axis to allow for articulation of the tunnel while isolating the load within each lobe section. This stacking concept has been demonstrated for use as a Venus Altitude Cycling Balloon [11], but the stacked inflatables for that application were still isolated pressure vessels. When the inflatables are stacked for the tunnel application, they are also axially truncated, so they form a single inflated volume. This produces a highly flexible yet statically determinate restraint layer that can meet all the requirements of a softgoods tunnel with minimal mass. This design also simplifies manufacturing since each fabric carrier section is constructed as a flat annulus section which creates wrinkles when inflated. Like a common mylar balloon, these wrinkles are in areas of low hoop stress and are natural channels for the axial cords to be routed. Fig. 3 shows the representative “flat” cross-section of the tunnel and the same section when pressurized. The axial cords act as tendons that carry the load between the pumpkin sections while hoop cords, which are buried between the pumpkins, carry most of the hoop load. The interface to the bulkhead contains a sealing surface for the inner fabric/bladder and a series of clevises makes the structural connection to the axial cords.

C. Softgoods Material Selection

Due to the complex environmental requirements of the lunar surface, softgoods material selection is an ongoing process. Initial design of the restraint layer uses a Vectran broadcloth with a Urethane coating on the inside to act as a combined carrier layer and air barrier. The axial and hoop cords would be Vectran braided cords, commonly used in parachute applications. While not described in detail, the flight application will also include environmental protection layers on the outside of the structural layer. These layers will include dust protection, thermal insulation, and a minimal amount of micro-meteoroid protection – all intended to protect the softgoods layers and the crew during operation. Packaging considerations also need to be included to ensure the tunnel can properly retract after each use and keep all its critical systems protected.

IV.Sub-Scale Demonstration

To demonstrate the articulation and pressure capability of the softgoods pumpkin design, a sub-scale test article was developed at one-third scale of the baseline SAS. The test article includes an internal mechanism with the full six-degree-of-freedom articulation and a representative softgoods restraint layer. The restraint layer was constructed using similar techniques planned for a full-scale restraint layer, but with more readily available commercial materials. The interface between the softgoods and the metallic bulkheads was custom designed for this test article to ensure proper load transfer between the components and will be scaled for the full-scale design. Fig. 4 below shows the details of the sub-scale test article design.

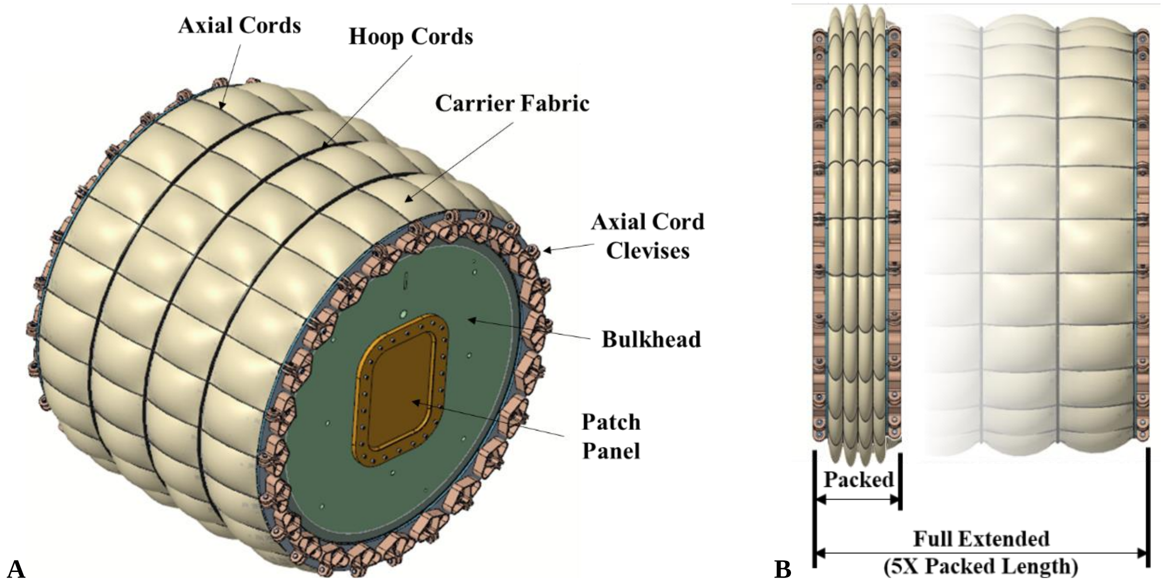


Fig. 4 Sub-scale Test Article A) Extended ISO View With Callouts and B) Packed vs. Extended Comparison of the Softgoods Restraint Layer Only

A. Materials Testing

Characterization testing was completed on the baseline structural materials to get representative material properties to drive the analytical model. Three materials were tested that were used in the restraint layer for the sub-scale test article.

The first material was the broadcloth, which serves as the carrier fabric. This was a 1500 denier, Kevlar 29 plain weave fabric. While Vectran was outlined for the full-scale tunnel, Kevlar was used for this sub-scale test article as a substitute because of material availability. The material was prepared in one-inch-wide raveled strips, as shown in Fig. 5, and tested per PIA-Test Standard-4108A. The specimens were speckled with black and white paint to measure fabric strain via photogrammetry. Split-capstan grips were used to secure the specimens, as shown in Fig. 7. Tensile properties were generated in both the axial and transverse directions and shear properties were estimated. Future biaxial tension testing and in-plane shear testing is planned for this material using a combined multi-axis and shear test fixture [12].

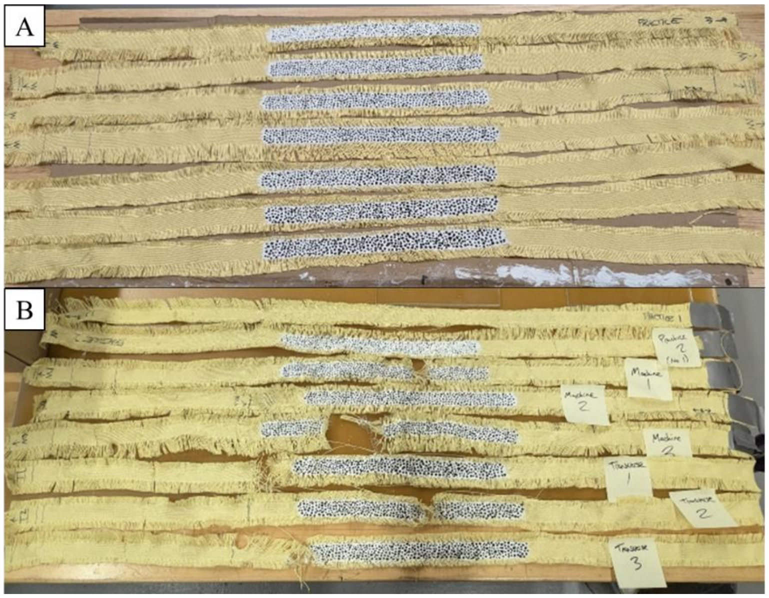


Fig. 5 Broadcloth Tensile Specimens A) Pre-Test with Speckle Pattern and B) Post-Test

The second and third materials were a 3/8” diameter and 3/16” diameter Vectran 12-strand braided cord, used as the hoop and axial cordage of the restraint layer respectively. The cords were initially prepared in the same fashion as the constructed cords used in the test article. The axial cords used Samson Class-II Eye-Splices as on both ends as shown in Fig. 6, while the hoop cords used Class-II End-for-End splices. The cordage was tested per a modified ASTM-D4268 method. The cordage samples used individual white-on-black (eclipse) targets carefully sewn into place to avoid any damage to individual fibers or yarns. The targets were tracked by the photogrammetry cameras to measure strain during the test. The strain data was combined with the collected load cell data to derive stress-strain curves for the analytical model and represent the materials as constructed. Since the 3/16” diameter cordage used eye splices on each end, they were tensioned by pin connections on the tensile test machine. The 3/8” diameter cords were disassembled and tested by wrapping them around two high-strength cordage capstan grips, due to the available load frames not having the required length or displacement capability for the as-built cords.

Fig. 6 Cordage Tensile Specimens A) Pre-Test With Marker Targets and B) Post-Test

The nominal setup for the testing consisted of loading the samples into an electromechanical load frame, where the visual markers or speckled gauge areas were centered vertically. Stereo photogrammetry cameras observed these gauge areas during tensioning. The samples were tested to failure, and high-speed video was used to capture failure modes when possible. The test setup can be seen in Fig. 7. Once installed on the load frame, all samples were pulled at a rate of 1-inch-per-minute until failure. The load frame recorded the specimen tension and time, while the photogrammetry system captured the movement of the speckled gauge area of the broadcloth samples and the motion of the installed markers on the cordage samples. The samples were monitored, and their failure modes were observed to determine any deficiencies in the material quality or the assembly of the samples.

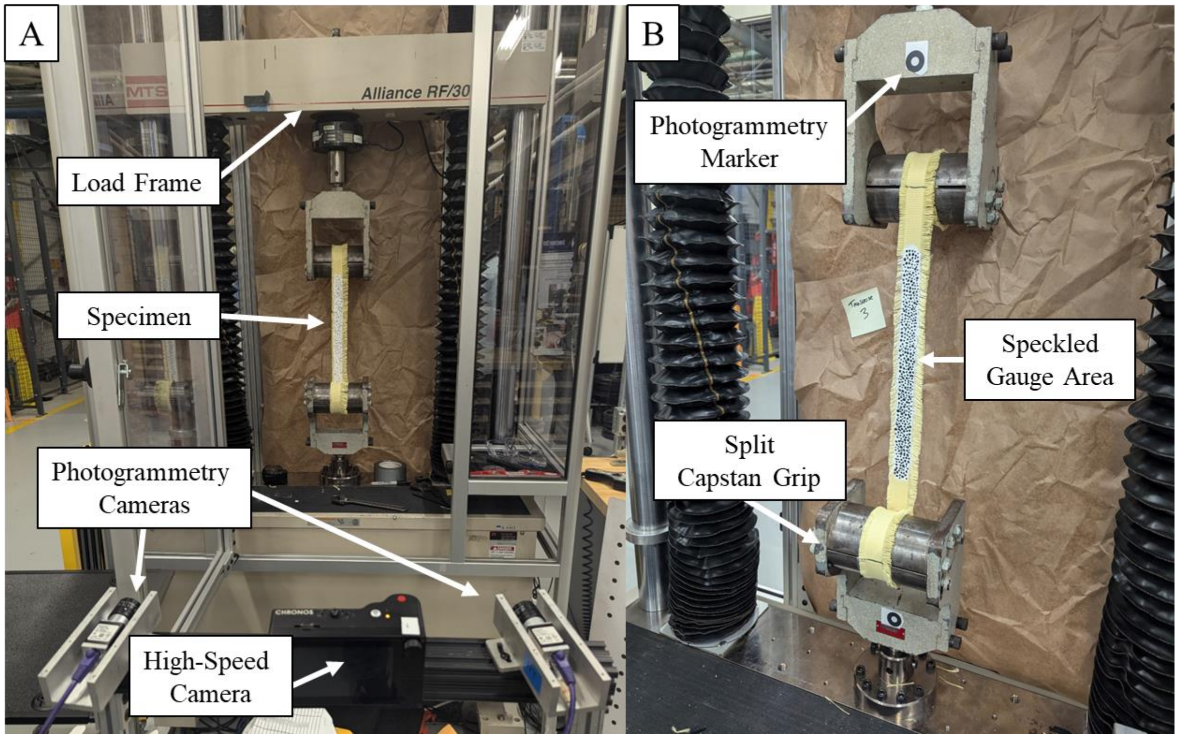


Fig. 7 Tensile Testing Setup Showing A) Camera View and B) Close-Up View

After the testing, each set of photogrammetry data was processed to determine the engineering stain experienced by the sample gauge areas under test, which was then exported and converted to true strain. The load recorded was then applied to the material cross-sectional area (based purely on the unloaded dimensions of the fabric and cord) and a stress was calculated before being plotted against true strain. The stress-strain curves for each material, along with the breaking strength, were exported for use in the analytical model and simulation of the article under pressure. The final curves and results are shown below in Fig. 8.

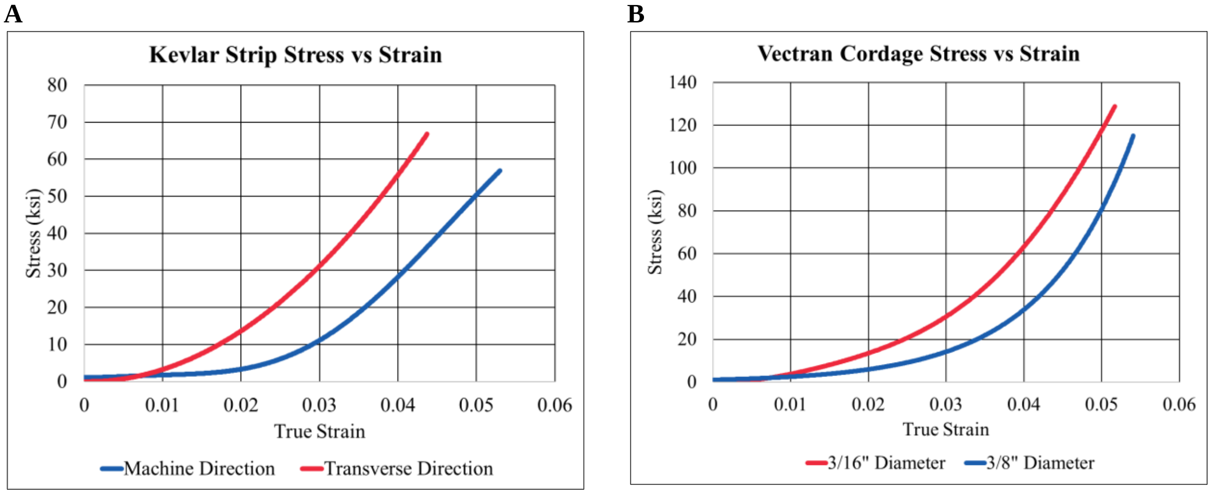


Fig. 8 Stress vs Strain Curves for A) Kevlar Broadcloth Strips and B) Vectran Cordage

V. Models and Simulation

To better evaluate the behavior of the softgoods tunnel under various configurations, multiple models and simulations were developed. First, a physics-based fabric model was developed in Blender to animate realistic fabric folding and pressurizing scenarios. Second, a non-linear finite element model was created using LS-DYNA to determine the stress state of the fabric elements under various pressures and positions. Both models were also used to evaluate alternate designs, number of lobes, and interfacing hatch frame shapes, resulting in the baseline design as presented.

A. Blender Model

The Blender model uses fabric draping tools within the software to create an accurate simulation of the three softgoods materials – the hoop cord, the axial cord, and the carrier fabric. The model is setup such that it produces real-life motion under pressure, and a physics simulation is employed to provide accurate inflation dynamics. A trial-and-error process was used with multiple iterations of the model to develop the correct armature Bezier curve and bone mesh links within the model elements. Once correct motion and inflation was achieved, final shading and lighting was used to create a realistic model as shown in Fig. 3 above.

B. Full-scale LS-DYNA Model

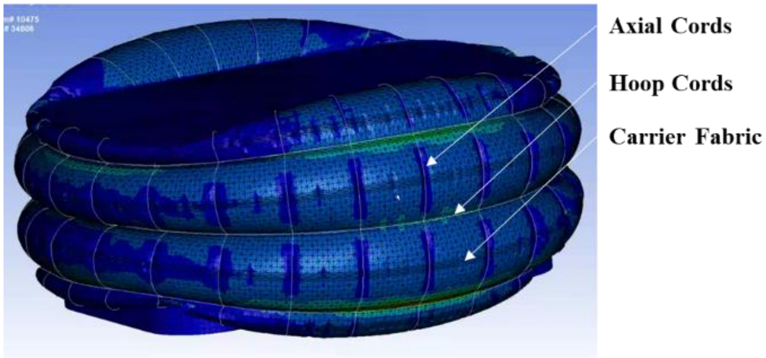


Fig. 9 LS-DYNA Model Screenshot of Full-Scale Tunnel

The LS-DYNA model, shown in Fig. 9, is an explicit non-linear model of the softgoods elements that includes three flexible parts – the hoop cords, the axial cords, and the carrier fabric, using material properties from component testing. It also includes two rigid bulkhead frames; the lower is fixed, while the upper is positioned with time varying motion constraints on all six degrees of freedom. The carrier fabric is a membrane shell tri-element mesh with non-linear material properties derived from the tensile testing described above and manufacturer data. The axial and hoop cords are cable (discrete beam) elements that are modeled with non-linear material properties from the cordage test data. Two-way contact forces are calculated between the cords and fabric, along with fabric self-contact. The model was used to evaluate the softgoods performance at extreme articulating positions and under various pressures, as shown in Fig. 10. The outputs were then used to measure the highest stress of each fabric element and calculate material margins in the design. Additionally, forces and moments on the frames were recovered to aid in mechanical actuator sizing calculations.

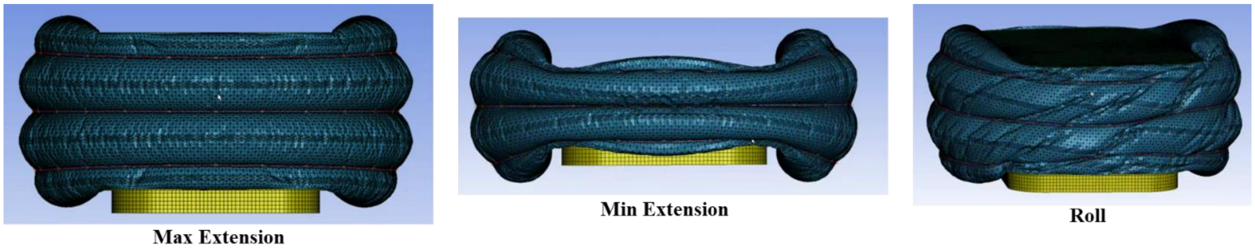
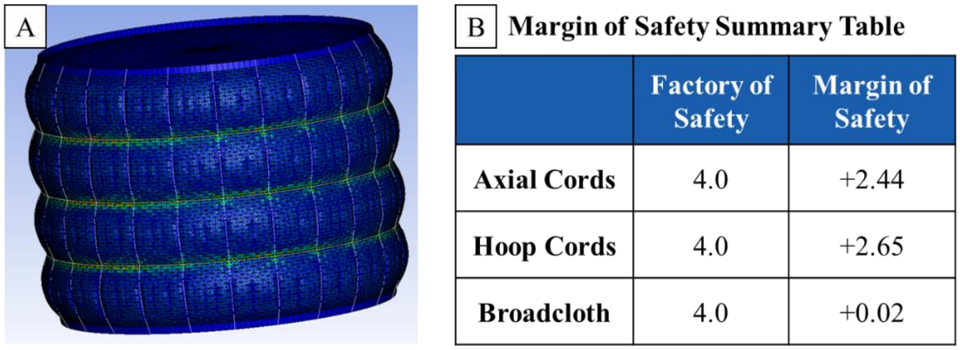

Max Extension
Min Extension
Roll

Fig. 10 LS-DYNA Model of Full-Scale Tunnel Showing Extreme Cases

C. Sub-scale LS-DYNA Model

While the initial LS-DYNA model was developed for the full-scale SAS, a more refined model was developed that matched the geometry and material properties of the sub-scale test article. This model was used to ensure positive margin in the softgoods design prior to pressure testing and helped to refine the test matrix. The analysis results shown in Fig. 11 represent the fully extended test position, which is the worst-case configuration for the softgoods. The structural margins at max extension were positive, providing confidence that the softgoods test article will perform well during pressure testing.



Margin of Safety Summary Table

	Factory of Safety	Margin of Safety
Axial Cords	4.0	+2.44
Hoop Cords	4.0	+2.65
Broadcloth	4.0	+0.02

Fig. 11 LS-DYNA Results For Sub-Scale Test A) Fully Extended Stress Results and B) Margin of Safety Summary Table

VI. Conclusions and Forward Work

The work completed to date on the softgoods pressurized transfer tunnel shows remarkable improvement in the state of the art for a crewed, articulating transfer tunnel system. While the described work is a high-level overview, there is detailed work ongoing to continue development of the softgoods tunnel. The sub-scale test article referenced in this document is under assembly at the time of this writing and will undergo a pressurization test in the coming months to fully demonstrate the softgoods' capabilities. The testing will include articulation of the tunnel through multiple positions to evaluate the softgoods movement while unpressurized, as well as pressurization tests to evaluate the inflation process in each of the extreme test positions and measure the axial loads on the internal mechanism. Photogrammetry cameras will be used to track the movement of the softgoods test article and measure the strain in the structural elements of the system. This data will help validate the LS-DYNA model of the softgoods tunnel and allow for building a full-scale analytical model, leading to a future full-scale pressure test to fully evaluate the tunnel technology.

All the data generated by these tests will help to better define any external loading that an attached element would have to endure to utilize a tunnel system and will inform an international surface docking standard definition. Leveraging this work on testing and modeling a full-scale concept, future lunar and Martian exploration can take advantage of pressurized transfer between elements and enable long term human exploration of planetary surfaces.

References

[1] Exploration Systems Development Mission Directorate, "Moon to Mars Architecture Definition Document," National Aeronautics and Space Administration, Washington, D.C., 2024.

[2] National Aeronautics and Space Administration, "The Artemis Accords," United Nations, 2022.

[3] M. Rucker, "Mars Ascent Vehicle Design Considerations," in *AIAA Space Conference*, Pasadena, CA, 2015.

[4] National Aeronautics and Space Administration, "International Docking System Standard (IDSS) Interface Definition Document (IDD)," 2022.

[5] National Aeronautics and Space Administration, "Exploration EVA System Concept of Operations," 2020.

[6] M. Rucker, S. Jefferies, S. Howe, R. Howard, N. Mary, J. Watson and R. Lewis, "Mars Surface Tunnel Element Concept," in *IEEE Aerospace Conference*, Big Sky, MT, 2016.

[7] S. Howe, "Pressurized Adapter for "Shirt-Sleeves" Transfer and Universal Base Expansion (PASSTUBE)," in *AIAA/AAS Astrodynamics Specialist Conference*, Long Beach, CA, 2016.

[8] G. I. Taylor, "On The Shapes Of Parachutes," in *The Scientific Papers of G. I. Taylor*, Cambridge, MA, Cambridge University Press, 1963.

[9] Thin Red Line Aerospace, "Thin Red Line Projects," [Online]. Available: http://www.thin-red-line.com/projects.html.

[10] W. Doggett, T. Jones, W. Kenner, D. Moore, J. Watson, J. Warren, A. Makino, B. Yount, M. Selig, K. Shariff, D. Litteken and M. Mikulas, "Non-Axisymmetric Inflatable Pressure Structure (NAIPS) Concept that Enables Mass Efficient Packageable Pressure Vessels with Sealable Openings," National Aeronautics and Space Administration, 2016.

[11] M. de Jong, "Venus Altitude Cycling Balloon," in *Venus Lab and Technology Workshop*, Hampton, VA, 2015.

[12] P. Cavallaro, A. Sadegh and C. Quigley, "Contributions of Strain Energy and PV-work on the Bending Behavior of Uncoated Plain-woven Fabric Air Beams," *Journal of Engineered Fibers and Fabrics,* vol. 2, no. 1, 2007.