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Baseline

CERTIFICATION GUIDELINES FOR CREWED INFLATABLE SOFTGOODS STRUCTURES

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National Aeronautics and
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Certification Guidelines for Crewed Inflatable Softgoods Structures

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1.0 INTRODUCTION

The design, testing, and certification of a human-rated, inflatable space structure requires a thorough knowledge of both the unique mechanical behavior and the fabrication processes required of the material system. The high-strength synthetic softgoods components used in these structures, which include fabric, webbing, and cordage, are influenced by a number of factors in manufacturing including tension and spinning processes, the oils and sizings used, fiber friction, yarn twist and ply number, weave type and crimp, and many other parameters that result in non-linear time- and load-dependent mechanical behavior that is specific to each softgoods component type. These components are joined together, via seams, splices, and stitches, to construct an inflatable article whose performance is strongly influenced by the precision and repeatability of the fabrication process. The multiple levels of structural hierarchy in softgoods inflatables, shown in Figure 1, add a high level of complexity to the mechanical behavior, analysis, and testing of the finished article versus a composite or metallic shell, where component-level or panel testing can typically be directly extrapolated to the behavior of the full-scale article, and for which a higher level of experience and heritage currently exists for human spaceflight applications.

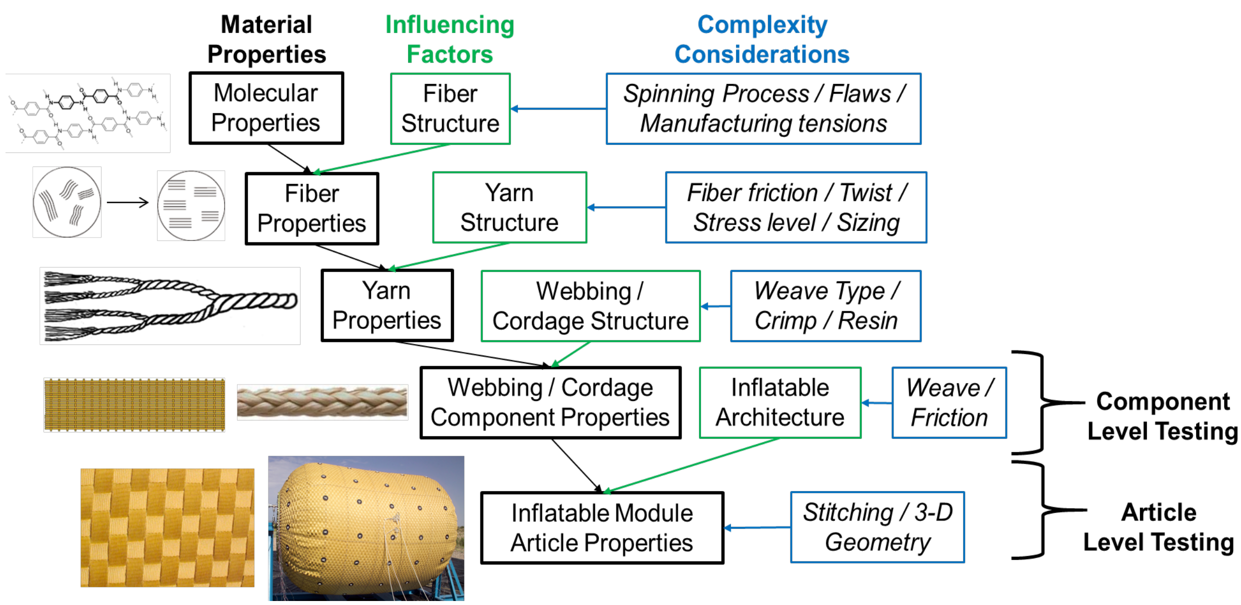

FIGURE 1 – STRUCTURAL HIERARCHY OF SOFTGOODS

The realization of a crewed softgoods structure requires careful selection and statistical characterization of the softgoods materials and components, a robust and repeatable fabrication process, and a systematic and comprehensive test program that validates the performance of the design from component to full-scale article at a level of rigor consistent with human-rated spaceflight.

1.1 PURPOSE

To help guide NASA and industry in the development and certification of crewed softgoods structures, this document details the fundamental testing, data, and documents recommended for the evaluation of a softgoods inflatable designed for crewed occupation in a space environment. This is not a requirements document but supports NASA-imposed standards used for certification. This document is intended to support and guide the development of programmatic requirements to demonstrate a design has followed a systematic and comprehensive design, fabrication, and test program.

The focus of this document is on the structural layer(s) of the inflatable softgoods, holistically referred to as the restraint layer, however, guidance is included on other non-structural layers, components, and hard structure that interface with and affect the behavior of the primary structural layer(s). Reference documents are cited where prior heritage and standards already exist (e.g., in the development of typical crew support systems required of a habitable inflatable article and some of the non-structural layers used).

1.2 SCOPE

This document provides guidance in the critical areas used in the assessment of an inflatable design, its materials, and component/module testing. Guidance is also provided on the instrumentation and analysis that support the development and evaluation of crewed softgoods space structure certification. This document is intended to be broadly applicable to any habitable softgoods structure, but due to the breadth of possible architectures, supplementary testing or data may be necessary to support a specific mission application and/or environment. Due to the current lack of long-term flight data for softgoods inflatables used as primary structure on a crewed spacecraft, this document is expected to be updated periodically with new information and revised recommendations as experience is gained through use of these structures in service.

A typical inflatable layup is shown in Figure 2 and includes the following: a) inner liner layer, b) gas barrier bladder layer, c) structural restraint layer, d) micrometeorite and orbital debris protection layer, e) environmental protection layer, and f) deployment layer. This document provides guidance on the structural softgoods layers of a typical crewed inflatable architecture. Additional layers that are architecture specific, such as spacer layers or layers that are defined as part of a sub-system, are not covered in this document. These non-structural layers include the passive thermal insulation barrier and atomic oxygen barrier, both of which are parts of the environmental protection layer.

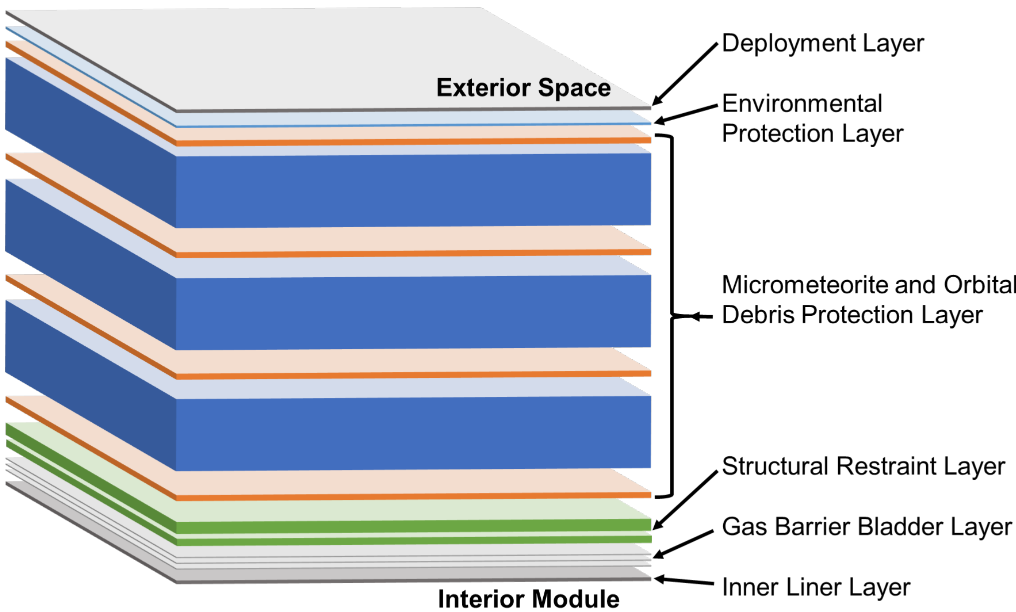

FIGURE 2 – TYPICAL CREWED SOFTGOODS SHELL LAYUP

Inflatable architectures commonly include both a softgoods structure and a rigid interfacing structure. This document is not comprehensive of all structural requirements but is intended to cover those areas unique to crewed inflatable softgoods. Metallic and composite components that interface with the softgoods should utilize their own set of requirements, such as NASA-STD-5001 – Structural Design and Test Factors of Safety for Spaceflight Hardware, and NASA-STD-5019 – Fracture Control Requirements for Spaceflight Hardware. Metallic and composite hardware have different factors of safety than softgoods and require a different qualification program. Softgoods are considered non-fracture critical; fracture control is applied only to rigid components as defined by NASA-STD-5019 and detailed in NASA-HDBK-5010.

The guidance and recommended testing in this document supports, but does not ensure, the overall safety of the habitable system for which the softgoods structure is the primary load-bearing structure. The final determination and certification of the overall system as human-rated for spaceflight will be based primarily on programmatic requirements and NASA-NPR-8705.2 – Human-Rating Requirements for Space Systems.

1.3 APPLICABILITY

This document is specific to crewed inflatable structures that are designed to support an internal breathable atmosphere. Alternative guidance and standards should be used for spacesuits, inflatable decelerators and other uncrewed inflatables that have separate and distinct requirements on loads, environment, and lifetime.

2.0 REFERENCES

The following documents include standards, guides, and test methods that are either directly cited in the recommendations or are listed as useful references.

TABLE 1: APPLICABLE DOCUMENTS

Document No.	Title
ASTM-D-123-15a	Standard Terminology Relating to Textiles
NASA-NPR-8705.2	Human-Rating Requirements for Space Systems
NASA-STD-4003	Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment
NASA-STD-5001	Structural Design and Test Factors of Safety for Spaceflight Hardware
NASA-STD-5002	Load Analyses of Spacecraft and Payloads
NASA-STD-5017	Design and Development Requirements for Mechanisms
NASA-STD-6016	Standard Materials and Processes Requirements for Spacecraft
NASA-STD-7012	Leak Test Requirements

TABLE 2: REFERENCE DOCUMENTS

Document No.	Title
AIAA-2015-1625	Creep Burst Testing of a Woven Inflatable Module
ASTM-D1434	Standard Test Method for Determining Gas Permeability Characteristics of Plastic Film and Sheeting
ASTM-D4158	Standard Guide for Abrasion Resistance of Textile Fabrics
ASTM-D5426	Standard Practices for Visual Inspection and Grading of Fabrics Used for Inflatable Restraints
ASTM-D6193	Standard Practice for Stitches and Seams
ASTM-D-6770	Standard Test Method for Abrasion Resistance of Textile Webbing (Hex Bar)
ASTM-D6775	Standard Test Method for Breaking Strength and Elongation of Textile Webbing, Tape and Braided Material
ASTM-D737	Standard Test Method for Air Permeability of Textile Fabrics
ASTM-F1342	Standard Test Method for Protective Clothing Material Resistance to Puncture
ASTM-F2878	Standard Test Method for Protective Clothing Material Resistance to Hypodermic Needle Puncture

Document No.	Title
CI-1500-02	Test Methods for Fiber Rope
GSFC-HDBK-8005	Guideline for Performing Risk Assessments
ISO-14624-1	Space Systems - Safety and Compatibility of Materials - Determination of Upward Flammability of Materials
ISO-14624-3	Space Systems - Safety and Compatibility of Materials - Determination of Offgassed Products from Materials and Assembled Articles
JSC-29353	Flammability Configuration Analysis for Spacecraft Applications
JSC-64399	Handbook for Designing MMOD Protection
JSC-65828	Structural Design Requirements and Factors of Safety for Spaceflight Hardware
JSC-65829	Loads and Structural Dynamics Requirements for Spaceflight Hardware
MIL-DTL-6645J	Detail Specification: Parachutes, Personnel, General Specification for
MIL-HDBK-17-1	Composite Materials Handbook: Guidelines for Characterization of Structural Materials
MSFC-HDBK-2221	Verification Handbook Parts I & II
MSFC-HDBK-3575	Outgassing Rate Measurements for Screening of Nonmetallic Materials
NAS-412	Foreign Object Damage (FOD) Prevention Guidance Document – Standard Practice
NASA-CR-4661 Parts I & II	Space Environmental Effects on Spacecraft: LEO Materials Selection Guide
NASA-HDBK-5010	Fracture Control Implementation Handbook for Payloads, Experiments, and Similar Hardware
NASA-HDBK-8719.14	Handbook for Limiting Orbital Debris
NASA-HDBK-8739.19-2	Measuring and Test Equipment Specifications
NASA-NPR-8705.5A	Technical Probabilistic Risk Assessment (PRA) Procedures for Safety and Mission Success for NASA Programs and Projects
NASA-NPR-8735.2A	Management of Government Quality Assurance Functions for NASA Contracts
NASA-SP-8043	Design-Development Testing
NASA-STD-5019	Fracture Control Requirements for Spaceflight Hardware
NASA-STD-6001	Flammability, Offgassing, and Compatibility Requirements and Test procedures
NASA-STD-7009	Standard For Models and Simulations
NASA-TM-2020-5005004	Development of a Compact, Low-cost Test Fixture to Evaluate Creep in High Strength Softgoods Materials under Constant Environmental Control

Document No.	Title
NASA-TM-2020-5005004 Supp	Creep Stand Fixture Drawings Package
NASA-TM-4527	Natural Orbital Environment Guidelines for use in Aerospace Vehicle Development
NASA-TN-D7610	Apollo Experience Report - Manned Thermal-Vacuum Testing of Spacecraft
NASA-TP-2003-210788	Meteoroid / Debris Shielding
PIA-4108E	Strength and Elongation, Breaking: Textile Webbing, Tape and Braided Items
SAE-AS9100	Quality Management Systems - Requirements for Aviation, Space, and Defense Organizations
SLS-SPEC-159D	Cross-Program Design Specification for Natural Environments (DSNE)
SMS-S-16	Test Requirements for Launch, Upper-stage and Space Vehicles
SSP-30425B	Space Station Program Natural Environment Definition for Design
SSP-30559C	Structural Design and Verification Requirements

3.0 ACRONYMS & DEFINITIONS

3.1 ACRONYMS

CISS .... Crewed Inflatable Softgoods Structures

DRA .... Damage Risk Assessment

ECLSS .... Environmental Control and Life Support System

FEA .... Finite Element Analysis

HVI .... Hypervelocity Impact

LOC .... Loss of Crew

LOM .... Loss of Mission

MDP .... Maximum Design Pressure

MMOD .... Micrometeoroid and Orbital Debris

PD .... Packaging and Deployment

QA .... Quality Assurance

RE .... Relevant Environment

SLA .... Structural Load Assessment

SVP .... Structural Verification Plan

TTF .... Time to Failure

UBP .... Ultimate Burst Pressure

UTS .... Ultimate Tensile Strength

3.2 DEFINITIONS

This section provides definitions of terms used in this document that may not be well known to the general aerospace community. For a more extensive list of terminology relating to softgoods and textiles please refer to ASTM D123-19 – Standard Terminology Relating to Textiles.

Article A sub-scale or full-scale inflatable pressure vessel with a shell constructed of softgoods components. Hard structure is often interfaced as part of an article and can include: bulkheads, windows, hatches, and internal or external secondary structure(s).

Bladder The primary hermetic barrier membrane(s). Can include redundant bladders, typically spaced apart with thin, low-friction fabric that allows free movement between bladder membranes.

Structural Bladder A structural bladder is an integral part of the restraint layer and acts as both a hermetic barrier and carries some in-plane stresses by design.

Component A structural softgoods element used in the construction of the restraint layer. This can include fabric, cordage, or webbing.

Cordage Any softgoods product with a nominally circular cross-section such as cords or ropes that have a twisted or braided construction.

Creep Time-dependent permanent deformation induced by load and thermal environment.

Fabric A broadcloth woven textile sheet consisting of warp and weft yarns that can carry biaxial loads.

Fiber A fiber is the same basic unit as a filament with a length-to-diameter ratio of at least 100.

Filament A long continuous fiber that is the basic unit that goes into fabrication of a yarn.

Prepared In the context of this document, this refers to a component that has flight-like spliced or stitched end terminations, in addition to any preconditioning or preload cycling performed as a part of their preparation for integration into an article.

Pristine In the context of this document, this refers to a component that is taken directly from the as-delivered roll/spool, without any pre-conditioning or additional workmanship.

Restraint Layer The primary load bearing layer of the inflatable softgoods article, which typically consists of fabric, cordage and/or webbing softgoods textile components.

Softgoods Any foldable or packageable material used in the multi-layer shell of an inflatable article. This typically includes but is not exclusive to: thin membranes (elastomeric polymer sheets, MLI, Kapton, and aluminized Mylar), and textiles (fabric, webbing, and cordage).

Textile Materials consisting of fibers and/or yarns that are woven, braided, or twisted into a softgoods product such as fabric, cordage, or webbing.

Webbing A flat woven softgoods product that includes straps or tapes, of limited width. Designed to take uniaxial loads, the yarn count in the warp direction is typically much higher than the weft direction.

Yarn A continuous strand of filaments or fibers that are twisted together. These are used to fabricate softgoods components.

4.0 RECOMMENDATIONS FOR FLIGHT CERTIFICATION

This section details the recommended minimum criteria for documentation, data and testing that facilitate the evaluation and certification of a human-rated softgoods structure designed for use in a space environment. Rationales are provided and additional information is given where appropriate for clarification. Since softgoods are considered a low heritage material for crewed spacecraft, their certification is currently based primarily on testing. The following flow chart, Figure 3, shows a nominal flow of documentation and tests outlined in this document for reference.

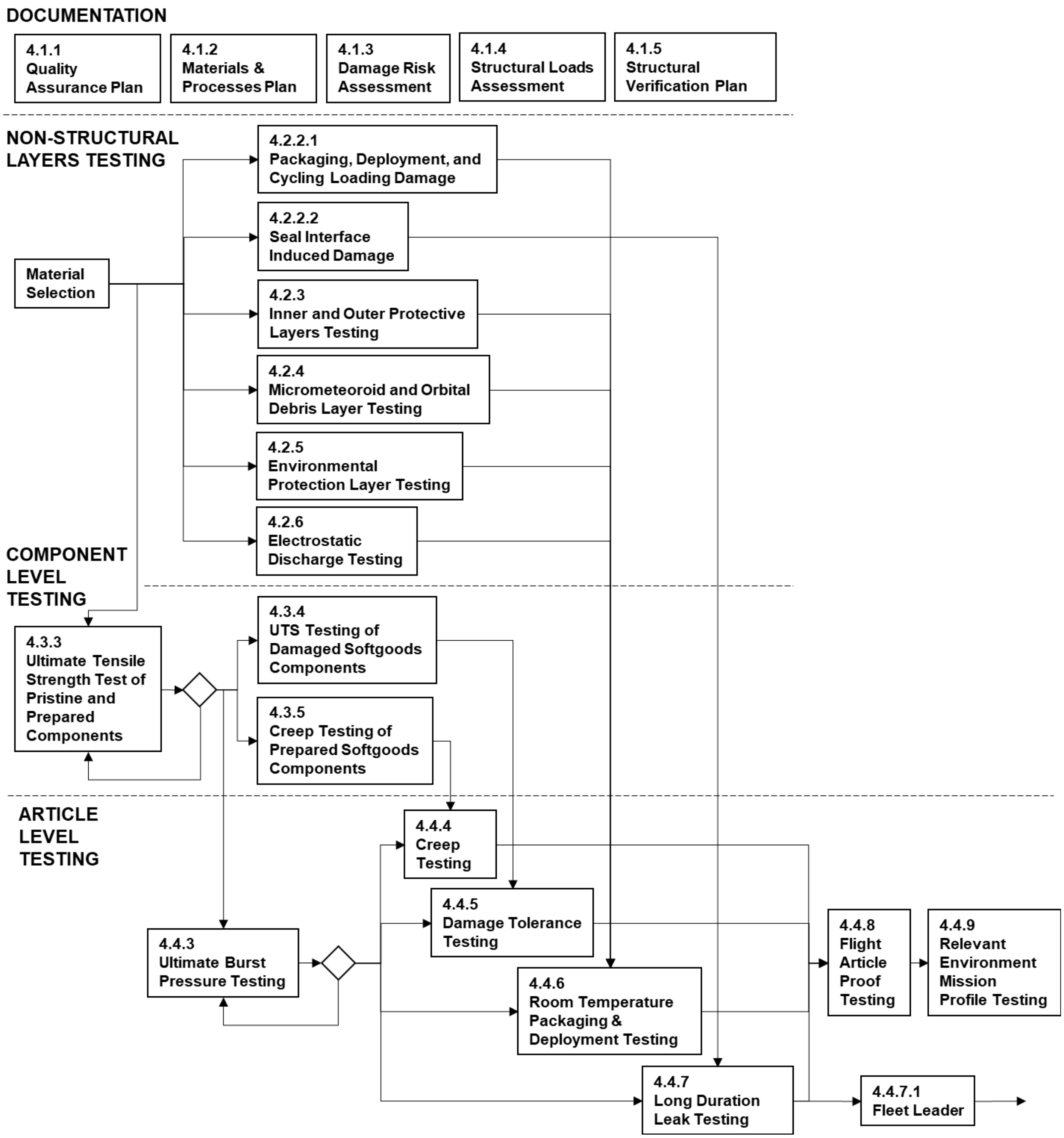

FIGURE 3 - TESTING FLOW CHART

4.1 RECOMMENDED DOCUMENTATION

4.1.1 Quality Assurance (QA) Plan

[CISS 01] A quality assurance (QA) plan should be provided that details the set of processes and controls that ensure the quality and repeatability of the inflatable design at a level appropriate for a human-rated space structure, and includes:

a) Witness coupon testing of as-fabricated components for each article under construction that ensures consistency of the fabrication process and verification of strength. Five samples of each prepared component taken from across the build process is recommended.
b) Specification of maintenance and periodic inspections of all machines and tooling used for fabrication.
c) A Foreign Object Debris (FOD) plan that covers both manufacture and packaging of the article.
d) A Storage plan for all materials and articles that covers prior to, during, and after fabrication.
e) A Transportation plan that incorporates and detail the processes for moving and transporting the articles both in and around the fabrication facility and between facilities, test sites, or flight integration site to mitigate damage.

Quality assurance and inspection is a central part of a robust and repeatable fabrication procedure and is a requirement for certification. It is expected that a QA process will be followed that inspects and maintains the condition of the materials and components used throughout the construction of the inflatable, provides for a repeatable, precise and robust fabrication process, and addresses any discovered discrepancies with a clear, well-documented solution approach.

The QA plan, when properly executed, reduces avoidable damage risks and provides mitigation approaches. Errors in fabrication, handling, and transport, can result in variable performance and life of the finished article, and possible early failure. The QA plan establishes the allowed damage thresholds and fabrication tolerances for acceptance or non-acceptance of materials, components, and the final article, and includes a repair strategy and rationale, if appropriate.

It is critical that all personnel involved in the acceptance, fabrication, transport, and testing of the softgoods article are knowledgeable of, and adhere to, the QA plan.

References: SAE-AS9100, NASA-NPR-8735.2, MIL-DTL-6645. (FOD) NAS-412.

Test Methods: (Inspection of fabrics) ASTM D5426-19.

4.1.2 Material and Processes (M&P) Plan

[CISS 02] All materials used in spaceflight hardware are required to be documented and reported in a Materials and Processes Selection, Control, and Implementation Plan, as defined by NASA-STD-6016 – Standard Materials and Processes Requirements for Spacecraft.

This plan will detail the specifications of each material, its heritage, manufacturing processes, implementation and how it meets the stated requirements. Common requirements for flight materials are specified in NASA-STD-6016, which includes NASA standards for flammability, off-gassing, microbial resistance, and thermal vacuum stability. All materials used in a crewed inflatable softgoods structure must meet these specifications, separate from any additional load or damage factors.

Other requirements may be specified by the program and will be both application and material-layer specific. Resistance to the space or planetary environment, material aging under mission conditions and damage as identified in the DRA (4.1.3) should also be evaluated for all softgoods layers.

Testing to meet these requirements can typically be performed on sample material coupons and may be met by material selection, if previous heritage testing or usage data is available and deemed applicable by the program. All testing processes and data should be included in the M&P plan.

References: NASA-STD-6016. (Flammability and Outgassing) NASA-STD-6001, JSC-29353B, MSFC-HDBK-3575. (Space Environment Effects) NASA-CR-4661 I&II.

Test Methods: (Flammability and Outgassing) ISO-14624-1, ISO-14624-3.

4.1.2.1 Softgoods Materials List

[CISS 03] A list of softgoods materials used in the inflatable structure should be provided as part of the M&P plan that includes the following minimum information:

a) Material type and construction specification, nominal strength, sizings/coatings/coloring used, manufacturing run length and unit roll/spool lengths, manufacturing dates, and labeling method that demonstrates traceability of this information to a regularly maintained database.
b) Company names, addresses, and length of time providing material type. Dates and explanation of change of vendor, if applicable.

This information provides the core component level specifications of the material system that drives the behavior of the whole article and guides the appropriate level of acceptance testing based on the lot size and type. It allows the components to be traced back to the specific lot and date of manufacture with all pertinent specifications. The company information provides the heritage of the products used in the article, whether any changes were requested and/or made and how long a relationship the inflatable fabricator has had with the manufacturer of their core components.

Softgoods component manufacturers may use different oils, sizings, manufacturing tensions, etc. Thus, for any change in vendor, even if the material specification is nominally the same, any changes in strength, stiffness or variability in those properties should be quantified along with their impact on performance at both the component and article level. Once certified for flight, any changes in the primary structure will require a recertification of that article based on the type and level of impact of that change.

4.1.2.2 Softgoods Inspection Samples

[CISS 04] Inspection samples of both the pristine and prepared flight article restraint layer materials should be set aside and controlled as flight hardware.

These are separate from the witness-coupon test samples that are recommended as part of the QA process (4.1.1). These samples should be provided on request for internal comparative testing at NASA. Qualification inspection samples are used for verification testing of the material properties to compare with the vendor's results, such as strength and load versus strain characteristics. This is part of the verification process in certifying a softgoods structure for flight. At minimum, five specimens of each type should be provided. Exact material quantities and sample position in material run should be negotiated as part of the QA plan (4.1.1) and M&P plan (4.1.2). If multiple material runs, or lots, are used in qualification and flight testing, additional samples may be requested for each material lot.

4.1.2.3 Material Lot Continuity

[CISS 05] It is highly recommended to use the same material lot for both the qualification test articles and the flight article(s) to maintain the greatest level of consistency and continuity between articles.

This ensures that the same test data can be used for qualification and certification of the flight article(s). If the same lot is not utilized, then additional testing should be completed to compare the performance of the material lots and address any potential impact on the qualification test results.

4.1.3 Damage Risk Assessment (DRA)

[CISS 06] All softgoods materials and components used in the inflatable structure and the overall article, should be included in an assessment of the damage risk to each, from initial material delivery through fabrication, transport, and use through the end of life. These activities include:

- Pre-mission: material storage, testing, packaging, and article storage.
- Ground Processing: transportation and launch vehicle integration.
- Flight: Launch, and transit to mission destination.
- Mission: Deployment, pressurization cycles and operations over the duration of the mission in the relevant mission environment.

Note, these are separate from expected knockdown factors due to the fabrication of the article itself, as described in 4.3.1.

A thorough examination and documentation of the lifetime use and risk profile for all softgoods elements is essential in evaluating both the requirements on the design and the structural test program. The DRA should be referenced in the comprehensive structural verification plan (4.1.5) generated for the inflatable structure seeking certification, which should include component testing of all pertinent damage sources.

Damage risks should be assessed as avoidable (mitigation plan used), unavoidable or inadvertent (materials will be selected and tested to quantify the damage effects) and known unknowns (identified but unable to quantify via test, requires robust design and structural health monitoring via personnel and/or sensors). The DRA should be rigorous, comprehensive, and conservative in determining both the probability and consequence of damage factors to help mitigate the likelihood of unforeseen damage events, and possible points of failure in the inflatable article over its entire lifetime.

Damage factors that are considered unavoidable or inadvertent fall into two primary categories: environmental and mechanical. The worst-case factors under both categories, and their impact, may be different for each material used in the structure. Some example factors are:

- Environmental factors: Temperature and humidity, atmospheric pressure or vacuum, dynamic particulates (for surface applications, e.g., dust and regolith), radiation, UV, atomic oxygen, and microbial exposure. Mission exposure levels should be corroborated with the program for the specific mission and application.
- Mechanical damage factors: Abrasion, folding / unfolding, cut / puncture, tearing, cyclical loading (e.g., for airlock applications), and creep.

Combinations or interactions between damage factors should be carefully considered. This includes combinations of mechanical factors, environmental factors, or both, and their effects on the behavior of the softgoods. Interactions between softgoods layers, and their interaction with internal or external secondary structure(s), should also be considered in the presence of, and possibly contributing to, these damage factors, especially during packaging and deployment.

References: (Risk Assessment) NASA-NPR-8705.5, GSFC-HDBK-8005. (Space Environment) SLS-SPEC-159D, SSP-30425B, NASA-TM-4527.

4.1.4 Structural Loads Assessment (SLA)

[CISS 07] An assessment of all load sources, magnitudes and frequencies on the structural softgoods should be performed that considers all stages of the article's life from material delivery through fabrication, transport, and use through the end of life, as defined by NASA-STD-5002 – Load Analyses of Spacecraft and Payloads.

A comprehensive examination of all possible load regimes and overload sources is essential to defining and guiding the design of the inflatable article, and the required testing and verification of the structure. For softgoods structures, the primary design loads may not be from the launch environment due to their packaged state. The uniformity of load distribution throughout the load bearing restraint layer should be evaluated to identify load factors on the ideal design state, in addition to any induced over-load or cyclical load conditions. Combinations of load states, such as mechanical and environmental, should also be evaluated to determine limit loads and uncertainty factors. Conservative factors should be used initially, with the understanding those factors may be reduced after testing, verification and experience through flight heritage with a design.

References: NASA-STD-5002, JSC-65829.

4.1.5 Structural Verification Plan (SVP)

[CISS 08] A structural verification plan should be provided, that details a comprehensive test and analysis program to characterize and certify all structural softgoods materials and components used in the inflatable structure, and the article itself, including at minimum the areas addressed in this document.

The SVP is used to evaluate the scope and depth of the test program, including applicability of prior tests and research, and the proposed methods to meet the requirements of the program. The SVP addresses characterizing the initial pristine behavior of the softgoods, the manufacturing knockdown strength, the behavior after exposure to the relevant environments, and any damage identified in the DRA (4.1.3), and in reference to the SLA (4.1.4) to identify relevant loads. The SVP should be discussed and agreed upon with the program prior to the start of any testing.

References: JSC-65828, NASA-SSP-30559, MSFC-HDBK-2221.

4.1.6 Softgoods Test Reports

[CISS 09] All material, component, and article-level softgoods tests should be documented and include the following:

a) Test facility / personnel: test facility, organization and operator(s) performing tests including any required operator certification.
b) Test setup: load frame(s), test fixture(s), end fitting(s), grip type(s), and instrumentation used, including any required calibration.
c) Test article preparation / history: description, lot, number, preparation method(s), method of storage and sampling from delivered material lots. Include any preconditioning, load cycling, and/or load, UV, temperature or humidity history, anomalies and/or repairs
d) Test environment: temperature, humidity, pressure, and any other pertinent environmental parameter if applicable. (Consistent conditions should be maintained for all replicate tests).
e) Test methodology: the industry recognized test standard(s) followed or a detailed test methodology and rationale for the chosen approach.
f) Test results: the raw test data, mean, standard deviation, and statistical design values (where applicable), failure location and mode, a summary of the results, and observations and explanations of any anomalous result(s); photographs

and/or video before, during, and after the test. For ultimate strength tests, load versus strain curves should be included. For creep or lifetime tests, load level as a percentage of the average breaking load versus time-to-failure data points should be plotted and presented, along with master creep strain versus time curves.

References: NASA-SP-8043, NASA-HDBK-8739.19-2. (Statistical Design Values) NASA-STD-6016-MPR37, MIL-HDBK-17-1.

4.2 NON-STRUCTURAL LAYERS TESTING

4.2.1 Integration and Packaging Effects of Non-structural Layers

[CISS 10] The impact of the integration of all non-structural layers with the restraint layer and with each other should be carefully evaluated as part of the DRA (4.1.3) and SLA (4.1.4) in packaged, deploying, and operational states.

Even though the non-structural layers are designed to not carry load during operation, their integration and physical connection to the restraint layer may cause local stress risers that can be more severe during packaging and deployment if not adequately accounted for in the design. The type and spacing of index stitching or bond patches is architecture specific, thus each design should evaluate and mitigate the structural impact of the connection points via component or article level testing.

Reference: (Stitching) ASTM-D6193.

4.2.2 Bladder Layer Testing

The bladder layer of a crewed inflatable works in conjunction with the structural restraint layer as a gas barrier to contain the internal atmosphere of the module. The bladder is typically oversized to fully transfer the pressure load to the restraint layer. In this configuration, the bladder does not carry in-plane loads and is considered non-structural.

There are some crewed inflatable architectures where the bladder layer does carry load and is considered as a structural bladder layer. In these configurations, the bladder layer material should undergo all the same component-level testing as the restraint layer to ensure evaluation of all structural materials used in the module.

4.2.2.1 Packaging, Deployment, and Cyclic Loading Damage

[CISS 11] Bladder materials should undergo representative testing that simulates the worst-case folding, packaging, deployment, and cyclic loading expected throughout the life of the inflatable. Both material permeability and mechanical strength should be evaluated before and after any loading, along with the following considerations:

a) The materials should be tested at the design stress level in a mission relevant thermal and pressure environment.
b) Simulated damage from folding/unfolding, cyclic loading, etc., should be representative of the expected damage from the DRA (4.1.3) and the predicted number of deployment cycles of a flight article as specified in the SLA (4.1.4).
c) The specific number of test cycles should also include additional safety factors per NASA-STD-5017 – Design and Development Requirements for Mechanisms.
d) The data collected should include size and location of visible damage, increase of permeability rate of air flow through the bladder material, and reduction in mechanical strength of the bladder material.

The material level permeability data can be compared to the results from the article level leak testing (4.4.7) and used to predict flight article leakage performance. The material level mechanical strength is a useful indicator of the suitability of the material to withstand any potential damage from folding, packaging, or cyclic loading. Even if the bladder is non-structural, the reduction of mechanical strength is valuable in determining material robustness.

Reference: NASA-STD-5017.

Test Methods: (Permeability) ASTM-D737-18, ASTM-D1434.

4.2.2.2 Seal Interface Induced Damage

[CISS 12] The effects of long-duration compression of the bladder layer at all softgoods-to-hard-structure interfaces used in the flight article should be evaluated.

The bladder layer in an inflatable must be sealed to any attached hard structure, such as a bulkhead, hatch, window, etc. If a compression seal is used between the bladder and the interfaced hard structure, the potential damage to the bladder should be evaluated. Compression seal lines put stress on the bladder material for the duration of the mission, potentially causing material creep, thinning, or structural failure.

4.2.3 Inner Liner and Outer Protective Layers Testing

[CISS 13] The innermost and outermost layers of a crewed inflatable should be tested to show resistance to damage, such as puncture, cut, and abrasion from objects or environments that may come into contact with the materials throughout its mission life.

Depending on the layup and architecture, the innermost and outermost softgoods layers may be used as protective layers to prevent damage to internal layers, such as the bladder layer. Potential sources of damage for consideration include sharp edges of hardware, tools and equipment with known cutting capability, and lunar or Martian regolith that may be present inside or outside of the inflatable. Any potential damage from the inside or outside of the module should be identified in the DRA (4.1.3) and the representative materials should be tested to show no detrimental damage to the layers or underlying layers they are meant to protect.

Test Methods: (Puncture) ASTM-F1342, ASTM-F2878. (Abrasion) ASTM-D4158, ASTM-D-6770-07.

4.2.4 Micrometeoroid and Orbital Debris (MMOD) Layer Testing

[CISS 14] The Micrometeoroid and Orbital Debris (MMOD) layer of the inflatable article should be tested to the probability of no penetration (PNP) limit specified by the program for the specific mission and application.

Hyper velocity impact (HVI) testing of the inflatable article's MMOD layers should show that the restraint layer will be undamaged by the mission's maximum predicted size, speed and angle of impactors. Primary damage to the restraint layer is covered under damage tolerance and creep testing and should not include MMOD damage.

The geometry and mounting of the test coupon MMOD panels detailed in the test report should show that they accurately represent the attachment and expected stress-level of the flight article MMOD layer, after packaging and deployment.

References: NASA-TP-2003-210788, JSC-64399, NASA-HDBK-8719.14.

4.2.5 Environmental Protection Layer Testing

[CISS 15] All softgoods materials providing environmental protection should be assessed to ensure their function meets their program requirements.

The environmental protection layer of a typical softgoods layup is a multi-functional layer used to protect the rest of the layers from the space environment. These layers commonly include a passive thermal layer, atomic oxygen protection, radiation protection, and regolith protection for surface applications. All layers should be tested to show that they meet their intended function.

A passive thermal layer is part of the vehicle's thermal management system and works in conjunction with the environmental control and life support system (ECLSS). The softgoods elements that make up this layer should be tested to verify that it meets the needs of the overall thermal system, and its performance is not degraded by packaging, deployment, or any other potential damage as identified in the DRA (4.1.3).

Each material should be evaluated for its inherent susceptibility to radiation damage, per the DRA (4.1.3), and any additional shielding layers required to protect those layers should be tested to ensure they provide adequate protection. Radiation shielding for the crew from Solar Particle Events (SPEs) or Galactic Cosmic Radiation (GCR) is typically mass prohibitive to add as one or more shell layers. SPEs and GCR is typically mitigated via additional local shielding around the crew quarters, wearable shielding, or possible biological countermeasures. This is an area of ongoing research.

References: SLS-SPEC-159D, SSP-30425B, NASA-TM-4527.

4.2.6 Electrostatic Discharge Testing

[CISS 16] Softgoods material electrostatic buildup should be considered as part of the overall vehicle's electrical bonding / grounding plan, as defined by NASA-STD-4003 – Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment.

The stack-up of softgoods materials can cause a buildup of electrostatic charge that could occur during deployment or operation, especially with transient loads or electromagnetic particles surrounding the structure. Conductive softgoods materials are often grounded together and to a vehicle ground point, such as the bulkheads or core structure. NASA-

STD-4003 provides guidelines and requirements for electrical bonding and should be used to guide any testing necessary to meet program requirements.

Reference: NASA-STD-4003.

4.3 STRUCTURAL COMPONENT-LEVEL TESTING

4.3.1 Fabrication Knockdown Factors

[CISS 17] To characterize and understand the baseline performance of an inflatable structure, knockdown factors should be calculated and reported at the component and article level that detail the percentage strength loss versus the tested average breaking strength, due to preparation and integration of the pristine softgoods layers into a built-up article.

The knockdown factors are used in the initial design and test cycles to make sure enough margin is being maintained to meet the required ultimate safety factor on burst for the final article to be certified. They also enable tracking of the performance for quality assurance purposes and improvements over time in structural efficiencies as a design is matured.

Knockdown factors are specific to an architecture and the softgoods materials selected, therefore reevaluation of knockdown factors should be performed if changes are made to materials, processes, or the architecture. Material selection, along with joining (e.g., stitching, splicing, bonding) and integration (e.g., layer-to-layer indexing) should be tailored and co-developed to maximize structural efficiency. Note that a material with superior pristine properties, may not perform as efficiently as another once prepared and integrated into an article. All layers of the article should be considered for their potential impact on each other, especially on the behavior of the restraint layer, due to joining, integration, indexing, packaging and deployment. Any structural health monitoring system or other instrumentation that is integrated as part of the architecture should also be included in the testing and calculation of knockdown factors.

The total knockdown factor is the as-built de-rating factor of the strength of the article, compared to the pristine tested material strength. These factors are separate from damage factors that may occur at any point during the life cycle of an article, as described in the DRA (4.1.3).

Reference: (Stitching) ASTM-D6193.

4.3.2 General Component-Level Test Guidance

The following recommendations apply to all component-level tests in this section:

Results of testing softgoods components can be influenced by the test parameters, grip type, number of specimens tested, instrumentation, and operator, among other factors. It is critical that testing is carried out in a consistent, precise, and standardized manner by experienced test personnel and documented properly. Improper test planning, setup, or execution can result in invalid or variable results, misinterpretation of data, and incorrect conclusions.

4.3.2.1 Wrap Grips for Pristine Component Tests and Slippage

[CISS 18] Split-capstan wrap grips are recommended for testing of softgoods components.

Wrap grips allow the testing of webbing and cordage without the necessity to add an end-termination loop or splice, and thus are most often used for determination of the pristine strength. Split-capstan grips provide excellent gripping force and load introduction for high-strength softgoods components and are available for both webbing and cordage. A valid failure should be away from the grips, however for split-capstan grips a failure at the tangent point at the ends of the free test section is considered a valid test if it is not a pinch point on the grip.

Slippage of low-friction materials in the grips can be mitigated via wrapping a high-friction strip of material of the same width with the wrapped tail of the specimen, such as rubber. Alternatively, a thin layer of spray paint can be applied to the wrapped tail section, that once tack dry can provide enough additional friction to mitigate slippage.

Reference: ASTM-D6775.

4.3.2.2 Pin-Grips and Prepared Component Tests

[CISS 19] The total length of the unseamed portion of the specimen in the test section should equal or exceed the total length of the seamed portions to avoid boundary influences on the test section.

For specimens with stitched or spliced end terminations, a pin-grip is most often used for strength testing and should be analogous to the attachment point on the article in terms of pin diameter. The length of the specimen should be determined based on the lengths of the stitched seam or splice used, so that the specimen behavior isn't governed by those sections. A rule of thumb is given above, but this should be evaluated versus the actual architecture used for the article and whether the component level behavior is actually heavily impacted by the number or density of stitches used.

4.3.2.3 Statistical Based Strength Values and Number of Specimens

[CISS 20] An appropriate statistical strength value is recommended to be calculated for both pristine and prepared specimens.

The number of specimens tested should be based on providing confidence in the measured variability in properties such that the statistical variation in strength of the core components and the probability distribution function can be characterized. A B-Basis is typically appropriate for a softgoods article, as it's used for structures with multiple load paths. It provides the strength above which 90% of the specimens will fail with 95% confidence. Materials that have high strength variance will require a larger number of tests to produce a reasonable B-Basis strength value, thus the selection of materials, material vendors and preparation of the softgoods components is highly impactful on the required test program and number of specimens. If the article does not have redundant load paths, then the selection of an appropriate confidence margin and basis strength criterion should be discussed with the program.

References: NASA-STD-6016-MPR37, MIL-HDBK-17-1.

4.3.2.4 Preconditioning of Softgoods Components

[CISS 21] Load cycling specimens to 25~50% of their average tensile strength three to five times is a recommended initial preconditioning range for high strength softgoods, but should be tailored to, and tested with, the selected softgoods components.

Applying a set preload to softgoods products during length setting is a common practice to normalize the effect of architectural strain from strap to strap or cord to cord. Multi-cycle preconditioning, which allows initial fiber/yarn alignment to achieve a more evenly loaded equilibrium condition, has been shown to reduce variability of strength and stiffness behavior which influences both the UTS and creep behavior of the softgoods.

4.3.2.5 Strain Measurement

[CISS 22] Recording strain data for ultimate load and creep tests is highly recommended to provide the most complete characterization of the materials for modeling, and component-to-module level comparisons and predictions.

Any strain or displacement measurement system used should be evaluated for its impact on the strength, stiffness, and failure mode of the softgoods component it is measuring. Non-contact measurement systems, such as photogrammetry, typically require a coating, paint, or target to be applied to the sample. Pin-extensometers attached elastomeric sensors, sensor wires/fibers and any other mechanically or adhesively attached sensors directly contact the softgoods. Both methods can affect the mechanical behavior. Strain calculation from grip displacement has been shown to be inaccurate and is not considered a valid strain measurement approach. Displacement measured at the grip interface should only be used as an approximate measurement unless the stiffness and movement in the grip section has been fully characterized. Any measurement system used should be referenced and verified against a second calibrated system.

4.3.2.6 Load Measurement

[CISS 23] Load measurement in softgoods articles from strain-to-load conversion or use of integrated sensors should be used with caution, due to the difficulty to verify results.

Load measurement for component tests can be taken directly from a calibrated load frame. Component load measurement at an article level can be achieved via in-line load cells, however they can only measure load at their integration site reliably and may not provide a good measurement of load along a component if there are additional crossing-elements, stitching, or friction with underlying or adjacent softgoods components. Load measurement via strain-to-load conversion, at an article level is highly challenging and likely to be inaccurate. The non-linear load vs. strain behavior of softgoods products is influenced by the number of load cycles applied, the peak load(s) and when the loading was applied (i.e., relaxation time), in addition to any 'built-up' effects of integration into the inflatable article. These all effect the initial calibration of strain-to-load. In addition, the initial zero strain point required for an accurate conversion is extremely difficult to determine for an article test as some initial pressure is needed for the article to hold its shape and the measurement system to be calibrated.

4.3.2.7 Photographic and Video Documentation of Testing

[CISS 24] Photo, video and/or high-speed video documentation of testing is recommended when possible, and highly recommended for module level tests.

Photographic images, and real-time and high-speed video all provide excellent insight and corroborative information on all levels of softgoods testing. They allow pinpointing of failure location and mode, damage propagation, and retroactive tracing of unforeseen events. They also provide a visual reference to cross-check with displacement, strain, or load readings. Lastly, given the low number, level of effort, and complexity of each article level test, use of this equipment is highly recommended.

4.3.3 Ultimate Tensile Strength Tests of Pristine and Prepared Components

[CISS 25] Ultimate tensile strength (UTS) tests should be performed on all softgoods, components used in the restraint layer, per NASA-STD-5001 [FSR 48], in both of the following conditions, and the results documented:

a) Pristine: taken directly from the as-delivered roll/spool.
b) Prepared: includes spliced or stitched end terminations or seams using the same preconditioning, manufacturing, and integration processes as the flight design.

Pristine material tensile behavior, as characterized by strength and load versus strain data, for off-the-roll and prepared softgoods components, provides the baseline information that is compared to data from damage tolerance and full-scale article testing. The pristine material behavior also quantifies the baseline variability in strength and stiffness behavior of each softgoods component and impacts the preparation of the softgoods components for the flight article. Material lot testing performed by the manufacturer of the softgoods does not typically include characterizing the load versus strain behavior. In-house or independent characterization testing should be performed for all softgoods used.

UTS testing should follow appropriate uniaxial or biaxial industry standard test methods, where applicable. Uniaxial tests are appropriate for webbing and cordage; whereas structural fabrics should be bi-axially tested under biaxial stress ratios appropriate to the geometry of the inflatable article. Uniaxial strip tests do not provide accurate strength or stiffness measurements for fabrics that will be biaxially loaded in use. In addition, caution should be used in applying uniaxial webbings and cordage data when modeling for inflatable architectures that are woven or attached together into a contiguous, biaxially loaded surface. These surfaces can act like a large fabric in transferring loads biaxially, creating stiffer behavior than is seen with just uniaxial testing of the components.

Reference: (Stitching) ASTM-D6193.

Test Methods: ASTM-6775, PIA-4108E, CI-1500-02.

4.3.4 UTS Testing of Damaged Softgoods Components

[CISS 26] Ultimate tensile strength (UTS) tests should be performed to characterize the reduction in strength due to the damage factors revealed in the DRA (4.1.3) for all softgoods components affected by those damage sources.

Damage factor testing is a critical part of quantifying the effects of environmental and mechanical damage factors on the behavior of the component softgoods. The results provide a measure of the significance and severity of each identified factor (strength knockdown) that can be combined with the likelihood of occurrence to produce a structural risk assessment matrix. Damage tests and article-level testing should demonstrate a fundamental understanding of the causes for reduced performance in the flight article versus the pristine component performance.

4.3.5 Creep Testing of Prepared Softgoods Components

[CISS 27] Real-time creep testing should be performed on specimens of all structural softgoods components used in the inflatable article that maintain a load over the duration of the mission, and should include:

a) Flight-like component preparation and stitching / splicing.
b) Grip-types selected to represent a flight-like interface where possible, such as pin-clevis. If testing a lap-seam or continuous loop section, then grips should be selected so the failure occurs away from the grips.
c) A minimum of 4 stress levels, between 50% and 90% of the average UTS of the prepared components (as tested in 4.3.3b), with a minimum of 5 specimens at each load level, for each type of load bearing softgoods component used in the inflatable article.
d) A minimum of 5 creep test specimens to act as fleet leaders at the maximum design load level.

Creep testing is the primary method of determining the lifetime load carrying capability of a softgoods structure and bounding the time-to-failure (TTF) at a given stress level (%UTS). Creep testing of the prepared components is used to predict suitable test times for sub-scale and full-scale article creep testing, with consideration of the additional knockdown factors from testing a built-up article. Creep testing should be performed on each type of primary softgoods component used in the article, as each have different TTF curves and bounds, and the component with the shortest time to failure is typically unknown prior to performing these tests.

It is suggested that a nominal level of damage, due to the factors identified in the DRA (4.1.3) is applied to the creep specimens to represent their condition more accurately, post-deployment.

If any softgoods component, such as a structural fabric / bladder, is specifically designed to operate at low stress levels (i.e. has a significantly higher safety factor than the required factor of 4), creep testing of that component may not be necessary. It should be noted that creep effects vary based on the material and component architecture selected, therefore a component with lower creep resistance may fail first, even at a lower %UTS than the other softgoods components.

Results of creep testing can be influenced by the test setup, grip type, instrumentation and test parameters as discussed in (4.3.2). It is critical that the test facility and setup is thermally and physically isolated to eliminate the potential influences of temperature, humidity, shock, and vibration on the test results.

It is highly recommended that displacement and/or strain in the specimens is measured so that master creep curves (strain versus time) can be generated. This data provides insight into the three stages of creep, as shown in Figure 4, including the steady state creep rate, and the total strain to failure that may better inform predictions and extrapolations of the recorded creep data and TTFs.

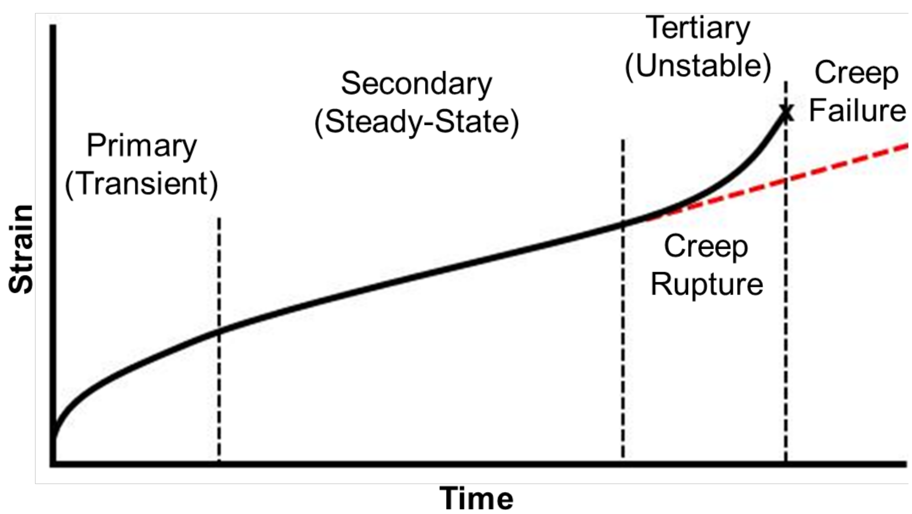

FIGURE 4 – TYPICAL THREE STAGE CREEP CURVE

Currently, no validated approach exists for accelerated creep testing of high-strength softgoods components, even though accelerated methods do exist at a fiber and yarn level for typical visco-elastic materials used in these components. Prior efforts have included both iso-thermal and iso-stress superposition techniques. Iso-thermal approaches are hampered by the secondary effects of heating and expelling the oils and sizing applied to the softgoods. These effects can influence the inter-fiber / inter-yarn behavior versus strict viscoelastic creep of the core materials. Iso-stress methods are affected by the non-linear, load-strain behavior of these materials. This includes a transition at low %UTS from architectural or constructional strain to mechanical strain. If a successful methodology is validated in the future, it should be used for augmentation, and not replacement, of real-time creep tests, which will still be required at minimum for validation of the accelerated methodology for the softgoods component(s) being tested.

Reference: NASA-TM-2020-5005004.

4.4 STRUCTURAL ARTICLE-LEVEL TESTING

4.4.1 General Article-Level Test Guidance

The following recommendations apply to all article-level tests in this document:

4.4.1.1 Max Design Pressure

[CISS 28] Crewed inflatable softgoods structures are considered Habitable Modules and should be designed and tested using the maximum design pressure (MDP), as defined by NASA-STD-5001.

Reference: NASA-STD-5001.

4.4.1.2 Sub-Scale Test Article Considerations

[CISS 29] For sub-scale test articles, the restraint layer architecture and components, fabrication methods, component stress levels, structural interfaces, and failure mode should be shown via design, analysis, and test to be consistent with the full-scale architecture, with the following considerations:

a) Any sub-scale article should use the same primary softgoods components that are used in the full-scale architecture, rather than substituting scaled components.
b) If rigid structures, such as bulkheads, hatches, windows, pass-throughs, and structural connections that interface with the restraint layer and bladder/liner are included in the flight design, they should be included in all article-level tests at a fidelity that demonstrably represents the flight article hardware dimensions, stiffness, and interface design.
c) Interfacing metallic hardware should be built as test hardware to withstand the loads expected during the test, which may be higher than the expected loads in flight.
d) Failure of the article should not occur at, or be instigated by, any integrated hard structure.

Performing tests on sub-scale variants of the architecture should be approached with caution and vetted through analysis and test. The mechanical behavior of high-strength softgoods does not typically scale uniformly or predictably, due to changes in the component architecture required to produce a different strength. Therefore, an additional suite of tests would have to be performed to characterize these scaled softgoods components.

Careful consideration should be given to the design of any rigid components integrated into, or interfacing with, a softgoods shell, as peak loads at attachment points may have higher variance than interfaces in a rigid shell due to non-uniform load distribution in the restraint layer.

Metallic and composite hardware are required to meet lower factors of safety for flight than softgoods. Therefore, for a softgoods to metallic interface, there will be hardware with two distinct capabilities. In a flight article, this interface should be designed according to the factors specified for both materials in NASA-STD-5001, but for a test article demonstrating the failure load of the softgoods, the metallic hardware should be designed to withstand the test loads.

Reference: NASA-STD-5001.

4.4.1.3 Workmanship Test

[CISS 30] As a workmanship test and to mitigate test facility safety concerns, it is recommended that every article-level build should undergo a low-pressure test after construction is complete to ensure the article has been properly manufactured and can inflate as expected. This could be part of the QA plan (4.1.1) to verify that manufacturing was completed according to the specifications.

4.4.1.4 Boundary Conditions

[CISS 31] Careful evaluation of the boundary conditions between the test article and test stand should be performed to verify that the article has free movement to expand and is representative of how the article will be restrained for its proposed application. In addition, the test stand should be designed with consideration of the dynamic failure of the article, as the pressure is likely to release in a non-uniform and directional manner that may impart high moments or torques in addition to axial loads to the test stand. These loads should also be evaluated with regards to the restraint hardware that connects the test stand to the test facility to meet structural safety standards for that facility and test.

4.4.1.5 Article Over-Pressure Design

[CISS 32] Spacecraft over-pressure scenarios should be evaluated on a vehicle level to understand how the softgoods structure carries additional load without catastrophic failure during an over-pressure event.

Traditional metallic habitable modules are designed to leak-before-burst, using common fracture control methods as described in NASA-STD-5019. Crewed softgoods, however, are not designed in the same manner. The two-part system is typically made of the bladder layer that contains the internal atmosphere and the restraint layer that carries the pressure load, both of which are designed with redundancy. In an over-pressure scenario, the vehicle architecture will use relief valves to reduce the pressure load on the inflatable as opposed to allowing for a leak in the pressure wall. This difference in methodology shows the importance of understanding how damage propagates through an inflatable architecture and how the structure responds.

Reference: NASA-STD-5019.

4.4.2 Structural Health Monitoring

[CISS 33] A Structural Health Monitoring (SHM) system should be integrated to enable tracking of strain and impact events over the life of the article.

Due to the complexity and low heritage of crewed inflatable softgoods structures, and the inaccessibility of the restraint layer during operation, it is highly recommended that an SHM system is integrated into the restraint layer. The restraint layer is typically non-repairable, or observable once integrated into the multi-layer shell. This introduces the risk of localized damage or long-term strain propagating toward a failure without the knowledge of the crew or mission control. To mitigate this risk an integrated SHM system should monitor the restraint layer and provide a warning if a critical event is detected to allow the crew enough time to evaluate the situation and evacuate if necessary.

4.4.3 Ultimate Burst Pressure (UBP) Testing

[CISS 34] Ultimate burst pressure tests should be performed on flight-like test articles of the inflatable design to demonstrate that the architecture meets or exceeds the ultimate design factor of safety specified in NASA-STD-5001 [FSR-49]. The test(s) should include the following considerations:

a) It is recommended that initial UBP testing is done at a sub-scale level, for ease of manufacturing and testing. Final testing of the flight design should be at full-scale. Multiple data points are recommended for UBP tests at any one scale.
b) At a minimum, two sub-scale and two full-scale tests of the locked-in design should be conducted.
c) All UBP tests should be taken to failure of the structural restraint layer, and the mode and location of the failure reported. If the failure mode or location is inconsistent or unexpected between tests, a root cause analysis should be performed and reported. One or more repeat tests may be necessary in this instance.

Demonstrating the architecture's ability to meet the required factor of safety through ultimate burst pressure testing is the primary structural requirement on a softgoods article seeking flight certification.

During the initial design and development phase, multiple UBP tests of a restraint layer should be conducted to prove repeatability in the results and failure modes. At the early stage, it is common to iterate upon the restraint layer design through multiple tests to achieve the desired safety margins. When test results show sufficient margins of safety above the required safety factors and any other relevant mission requirements, the restraint layer design for flight should be locked in. No additional iterations should be made at this stage and this design should be used for all subsequent article-level tests.

References: NASA-STD-5001, JSC-65828.

4.4.4 Creep Testing

[CISS 35] At minimum, three creep tests to failure should be performed on sub-scale test articles to predict the lifetime performance of the inflatable and show that the design meets the required life factor specified in NASA-STD-5001 [FSR 55]. The test(s) should include the following considerations:

a) The test article(s) should be built to the same specifications as the locked-in design from 4.4.3.
b) The %UBP levels for the creep failure tests should be based on estimates from the prepared component creep testing (4.3.5) time-to-failure results at the same % stress levels.
c) The %UBP levels for the creep failure tests should be calculated to provide time-to-failure data on the fabricated articles within the time frame of the test program. Time-to-failure recommendations for the test program are 100 hours, 1,000 hours, and 10,000 hours.
d) Following the test, the %UBP level, time-to-failure, failure mode, temperature and humidity versus time should be reported.
e) Creep tests should be performed in an environmentally controlled facility that maintains constant temperature and humidity around the test article throughout the duration of the test and provides reasonable accommodations to support testing operations during a power outage. Any effect from vacuum on the restraint layer strength should be tested at the component level, as recommended in 4.3.1, but it is not mandatory to perform these creep tests under vacuum.
f) Using input from the DRA (4.1.3), the SVP (4.1.5) should specify whether to include a single failed component in any of the creep test articles.

Creep is a primary source of long-term damage to the restraint layer once the article is deployed and pressurized. Article-level creep testing is critical to understanding any additional long-term knockdown factors of the built-up article that would not be observed in the component level or UBP tests. A minimum of three points on a %UTS versus time-to-failure plot is needed to create a lifetime projection of the softgoods structure at the operational pressure level. These tests must be carried out at elevated load levels to provide an estimation of the lifetime creep behavior within a reasonable test program, typically 1-2 years.

References: NASA-STD-5001, AIAA-2015-1625.

4.4.5 Damage Tolerance Testing

[CISS 36] At a minimum, one test of a flight-like inflatable article at operational pressure should be performed with an induced, instantaneous failure of a single restraint layer softgoods component that is representative of potential flight damage specified in the DRA (4.1.3). The test(s) should include the following considerations:

a) The test article(s) should be built to the same specifications as the locked-in design from 4.4.3.
b) The test should demonstrate, at a minimum, no damage to the underlying bladder layer that would cause an increase in leak rate above nominal and no propagation of the failure to adjacent structural components within a maximum crew response time, as specified by the mission con-ops emergency procedures.
c) The failed softgoods component should be in the group of components that have the shortest predicted creep life at the operational pressure, based on predicted stress levels in the components and the creep test results from 4.4.4.

d) The strain or load distribution before and after failure of the selected component, and those components adjacent to it should be recorded and presented in the test report. This data can help quantify both the peak and equilibrium loads in the surviving components to determine the design creep stress level in the presence of a single failure.

Human-rated softgoods articles should demonstrate at least single failure tolerance in the structural restraint layer. If a component fails due to damage during the mission, it is likely to be a dynamic and sudden failure. The structure should demonstrate robustness to this dynamic overload and the ability to maintain structural integrity long enough for the human crew to assess the situation and execute emergency procedures if necessary. The loss of crew (LOC) requirement will be specified by the program, and mission planners should specify if this testing should be expanded to include loss of mission (LOM) requirements, i.e., a long-term creep test article(s) with a single component failure.

4.4.6 Room Temperature Packaging and Deployment (PD) Testing

[CISS 37] Packaging and deployment cycles of a flight-like test article should be performed at room temperature that demonstrate a repeatable packaging scheme and a controlled deployment with the inflation of the article. The tests should include the following considerations:

a) The number and length of PD test cycles should be mission-specific and include any cycles from manufacturing, ground testing, pre-launch storage, in-space transit time, full deployment, through the duration of the mission, as specified in the SLA (4.1.4).
b) The article should be full-scale and use flight or flight-like shell layers that accurately represent the thickness and packaging characteristics of the inflatable shell.
c) If a deployment mechanism is employed in the design, it should be included in all PD tests and meet the requirements of NASA-STD-5017.

One of the primary features of inflatable structures is their ability to package compactly for launch and transit, and be deployed once at their mission station. The article may be in a packaged condition for many months prior to deployment while awaiting qualification testing and launch vehicle integration, and on the transit to the mission destination. To evaluate the packaging and deployment (PD) capability, testing should be conducted that simulates flight-like packaging, and tests the deployment and deployment mechanisms used in the design at room temperature.

The PD test should be documented and an overview of the packaging methodology, any deployment layer designs, and a detailed account of the deployment sequence with key activation steps provided. The reported results should include a detailed inspection of all softgoods layers prior to and after deployment, and note any malfunction or failure of the deployment mechanism if used. Any damage to the layers should be described and characterized, and include any reduction in strength in the restraint layer if found.

Reference: NASA-STD-5017.

4.4.7 Long Duration Leak Testing

[CISS 38] At least one long duration leak test should be performed on a full-scale, flight-like test article of the structural restraint and air barrier design, that are built using the locked-in design from 4.4.3. The test(s) should include the following considerations:

a) Prior to any leak test, the article should have gone through the predicted number of pressurizations, packaging, and deployment cycles of the flight article – from manufacturing and ground testing, through the duration of the mission, as specified in the SLA (4.1.4).
b) As an engineering design unit, only the air barrier, restraint layer, and flight-representative interfaces are recommended to be part of this test article.
c) The article(s) should be tested according to NASA-STD-7012 – Leak Test Requirements to generate an expected flight-like, steady-state leak rate used for engineering data. The chosen test method should be agreed upon with the program.
d) Leak tests should be performed in an environmentally controlled facility that maintains constant temperature and humidity around the test article throughout the duration of the test and provides reasonable accommodations to support test operations and data collection during a power outage. Internal and external temperature, humidity, atmospheric pressure, internal pressure, and leak rate versus time should be reported. It is not mandatory to perform this test under vacuum.
e) The articles should be tested at the operational design pressure for a duration that demonstrates the article reaches a steady-state leak rate after initial settling and maintains that steady state rate for at least the length of the initial settling period. The overall test duration should be agreed upon with the program.

This test is recommended as part of an engineering evaluation and is not meant to provide leak rate data for a program leak requirement. Those requirements often call for higher quality results in a vacuum chamber with short durations. This test is used for long duration results to evaluate the initial settling period of an inflatable and the subsequent pressure carrying capability.

Inclusion or not of a single failed component in any of the long-duration leak test articles should be based on information from the DRA (4.1.3) and SVP (4.1.5) and agreed upon with the program.

Reference: NASA-STD-7012.

4.4.7.1 Fleet Leader

[CISS 39] A flight-like, full-scale fleet leader article should be constructed and utilized to monitor the behavior of the article at the operational pressure over a period commensurate with the mission duration, according to the following considerations:

a) The fleet leader should be kept in a controlled environment with the ability for monitoring of the restraint layer over time.
b) The article should be inspected periodically for any signs of progressive damage such as yarn or stitch popping and fraying in the restraint layer throughout the mission, and any damage or failure should be reported to the program.
c) The test article developed for the long duration leak testing (4.4.7) can be utilized as the fleet leader article, assuming it represents a flight-like structural softgoods system.

The use of fleet leaders is a common practice for unique systems that are expected to be loaded for long durations. The fleet leader provides a ground-accessible representation of the flown structural system to monitor any degradation over the duration of the mission. While it is difficult to capture all expected loads or damage scenario that the flight article will endure during the mission, the fleet leader can provide an indication of the health of the structure over time in a static configuration.

4.4.8 Flight Article Proof Testing

[CISS 40] Flight articles should undergo a structural proof test that meets the habitable module factors of safety, per NASA-STD-5001 [FSR-47].

A structural proof test verifies that the article has been constructed according to the specifications and proves that it can hold pressure at the required proof test factor of safety. Typically, this test is done after construction of the softgoods and integration with the structural core, but before any internal flight systems are installed and outfitted. This test should be completed prior to the relevant environment mission profile testing (4.4.9) and for all subsequent flight builds.

Reference: NASA-STD-5001.

4.4.9 Relevant Environment Mission Profile Testing

[CISS 41] At minimum, one full-scale flight article should be tested in a relevant environment that simulates the launch packaging, ascent pressure ramp down, thermal soak, softgoods deployment, and pressurization to operational pressure. Once fully deployed in the simulated space environment, a leakage test should be conducted that verifies the article meets the mission specified leak rate requirement, following the guidelines of NASA-STD-7012.

All softgoods components, and release and deployment mechanisms should be flight or flight-like. Internal components and secondary structures if part of the flight deployment should also be included in this test.

Relevant environment testing on the full-scale article is one of the final steps required to elevate the article technology readiness level and certify the inflatable design for flight.

References: NASA-STD-5001, NASA-STD-5017, NASA-STD-7012, NASA-TN-D7610, SMS-S-16.

4.5 ANALYSIS AND MODELING

4.5.1 Structural Design, Verification and Validation of Test Results

[CISS 42] A report should be provided to the certifying program or agency that details the analytical and modeling capabilities used to size the primary components of the inflatable design, along with a description and results of any application of Finite Element Analysis (FEA) to correlate with component and/or article level test results.

Understanding the type and level of analyses used for design, optimization, and verification of a design helps establish the programmatic risk associated with the structure. Proven capability to verify and validate analysis models with test results provides significant risk reduction and increased confidence in the predictability of an inflatable design, given the relatively small number of full-scale article tests that are practical. It is strongly recommended to pursue the development of robust analysis techniques for an inflatable architecture.

It is expected that analysis and modeling should, at a minimum, be used to provide insight into critical areas of interest of the structure, such as load distribution and redistribution after a component failure, and the sensitivity of stresses and strains in the restraint layer to variation of key material and design parameters.

Softgoods structures are challenging to accurately model at the hierarchical structural level of a full-scale article due to typically non-linear, time- and load-dependent material behavior. Given the variance in the material behavior, analytical models should use statistical-based parameter inputs for material behavior and contact properties, based on actual component test data. Deterministic properties do not provide coverage of these variances and do not typically provide useful predictions of behavior.

Analyses should seek to include the effects of interactions between softgoods components (seams, index stitches, friction), and between softgoods and hard structure. In addition, the effects of the non-structural layers, and how their mass, connection points and frictional characteristics alter the mechanical behavior of the restraint layer, should be considered.

Reference: NASA-STD-7009.

5.0 APPENDICES

5.1 APPENDIX A – HUMAN-RATED SOFTGOODS APPLICATIONS

Human-rated softgoods structures have several applications for commercial and exploration missions in space and on the surface of other planetary bodies. The applications detailed below are the primary uses for which softgoods inflatables are expected to provide a significant benefit based on their ability to be compactly packaged and deployed. This list is by no means exhaustive, and it is anticipated, with the continued development and employment of these structures, that additional applications will be conceived of and implemented.

Habitats and Outposts

One of the first conceptions for the use of inflatables in space was for an in-space outpost consisting of many habitats connected together and compactly stowed on a single large launch vehicle. Inflatable habitats provide significant living volume versus their packaged state and can be designed to be comparable to composite shell structures in terms of mass. For Mars missions the ability to stow a habitat compactly behind a heat shield is a significant advantage for atmospheric entry. A habitat may be a standalone module or part of a larger assemblage such as an outpost on a planetary surface or in-space. Habitats are typically deployed once and should maintain their internal pressure for the entire duration of the mission. Once deployed the inner structural restraint and bladder layers see a relatively benign environment over the mission life, where creep is the primary long-term damage concern. Often an inner core or rigid end structure is used to integrate and offload primary systems and logistics to reduce the need for structural load-bearing interfaces in the shell. Habitats are critical primary structure, expected to protect and house the crew for the majority of the mission, and thus should meet the highest safety standards of any mission element.

Airlocks

An airlock is typically a smaller secondary module used to transit from a pressurized primary volume to the external environment. Many packaging options exist for an inflatable airlock as it is typically connected to a larger pressure vessel at an external hatch and can be packaged around the hatch interface, or around, or alongside the primary vessel. This reduces its impact on both the overall launch volume and dynamic loads. An inflatable airlock may be the primary EVA airlock or could act as a contingency airlock due to its packaged size. It could also be used on a surface rover and be required to package and deploy multiple times during its mission life, requiring a retraction mechanism to be integrated. Airlock applications have the advantage of not being required to maintain the full design pressure at all times (given the capability to vent and/or recapture the internal atmosphere), reducing the effects of lifetime creep. They do however see a full load cycle for each EVA performed. The interior of the shell is exposed repeatedly to the mission environment. This puts additional requirements on the inner layers, including the bladder and the restraint layer, which are not required of a habitat. Due to the small packaged and deployed size of an airlock, and to provide suited crew members space to maneuver, there is typically no core structure. A secondary support structure close to the inner shell is expected to be required to maintain the shape of the airlock when depressurized and can be used to provide reaction points for crew mobility. Consideration should be given to supporting reaction loads both internally and externally when designing the secondary support structure, including translational loads through the non-structural layers when crew members are performing an EVA. Inflatable airlocks are typically dominated by their hatch mass and integration hardware, thus careful consideration of the geometry of the shell and location of the hatches is crucial for both the efficiency and manufacturability of the airlock, and its ability to allow the suited crew members to maneuver themselves effectively and operate the hatches without undue effort or contortion.

Tunnels

A tunnel is a pressurized shell structure connecting two other pressurized vessels together to provide a transit path between them. Tunnels could be used between habitat elements of an outpost or space station, between a habitat and rover or other spacecraft, or as a connection between spacecraft or rovers. The purpose and requirements are similar to the inflatable airlock in that it protects the interiors of the primary pressure vessels being connected from exposure to the environment or depressurization. A softgoods tunnel could be stowed in a ring that is pre-integrated to the structure or installed via robot or astronaut to interfaces around the hatches of two vessels. Once installed, the hatches are opened and secured, and the tunnel can be used. This may only expose the interior of the tunnel to the environment during installation and would most likely be used for permanent connections between elements. The addition of an articulation mechanism would allow the positioning of the free end which could be useful on a rover where a temporary and adjustable connection is needed. Further modifications for a rover application could include the ability to retract and deploy the tunnel and/or add a hatch on the free end to provide an airlock capability. For gravity environments, the tunnel may have to be climbed, to go from rover to habitat for instance, thus the internal scuff layer may need additional reinforcement and mobility aids such as steps or boot interfaces. A secondary structure like that of the airlock may only be needed if the design is a hybrid tunnel/airlock, or if it is deemed necessary to provide reaction points for the astronauts. The height of the tunnel would also likely be required to be standing height in a gravity environment to allow the astronauts to walk through the tunnel without stooping, especially for any permanent outpost tunnels, thus affecting the geometry and volume required.

Space Hangars

An inflatable space hangar can be thought of as a much larger airlock, possibly many times bigger than a typical habitat structure, designed to provide a large in-space, shirt-sleeve environment for assembly, maintenance and upgrade of spacecraft and space systems. To date only the concept has been proposed, and this application is likely a longer-range goal for development after human-rated softgoods structures have been proven at a smaller scale. Inflatable structures provide one of the few approaches to creating such a large, contiguous habitable volume in space. The challenges of realizing such a large softgoods structure however are many including: fabricating, packaging and testing a single shell of that size on the ground, protecting it from damage, especially in low earth orbit from MMOD given its surface area, and integrating a hatch structure large enough to allow the ingress/egress of a spacecraft. The structural architecture of such a vessel may need to be fundamentally different to current habitats, airlocks or tunnels given the scale and logistics of a space hangar.