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CERTIFICATION GUIDELINES FOR CREWED INFLATABLE SOFTGOODS STRUCTURES

Engineering Directorate
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Compliance is Mandatory

National Aeronautics and Space Administration

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Baseline	08/03/2022	T. C. Jones	Via Signatures	Baseline Release (First release of document to support NextSTEP Appendix A: Habitation Systems and Commercial LEO Development Program)
Rev A	05/22/2025	T. C. Jones	Per EA MRCB EA CRD-0298	Updates and clarifications throughout document and added the following sections: 4.2.3 Localized Heat Source Material Degradation Testing 4.2.6 Thermal Profile Testing of Softgoods Shell 4.4 Structural Sub-Component Testing 4.4.1 Multi-Axis Testing 4.5.1 Module-Level Knockdown Factor 4.5.2.1 Test Facility Contingency Considerations 4.5.2.3 Stiffness Matching for Modules with Integrated Rigid Structures 4.5.6 Pressure Cycle Testing 4.5.9 Modal Testing

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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 module 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 module versus a composite or metallic shell structure, where component-level or small panel tests can typically be directly extrapolated to the behavior of the full-scale module, and for which a higher level of experience and heritage currently exists for human spaceflight applications.

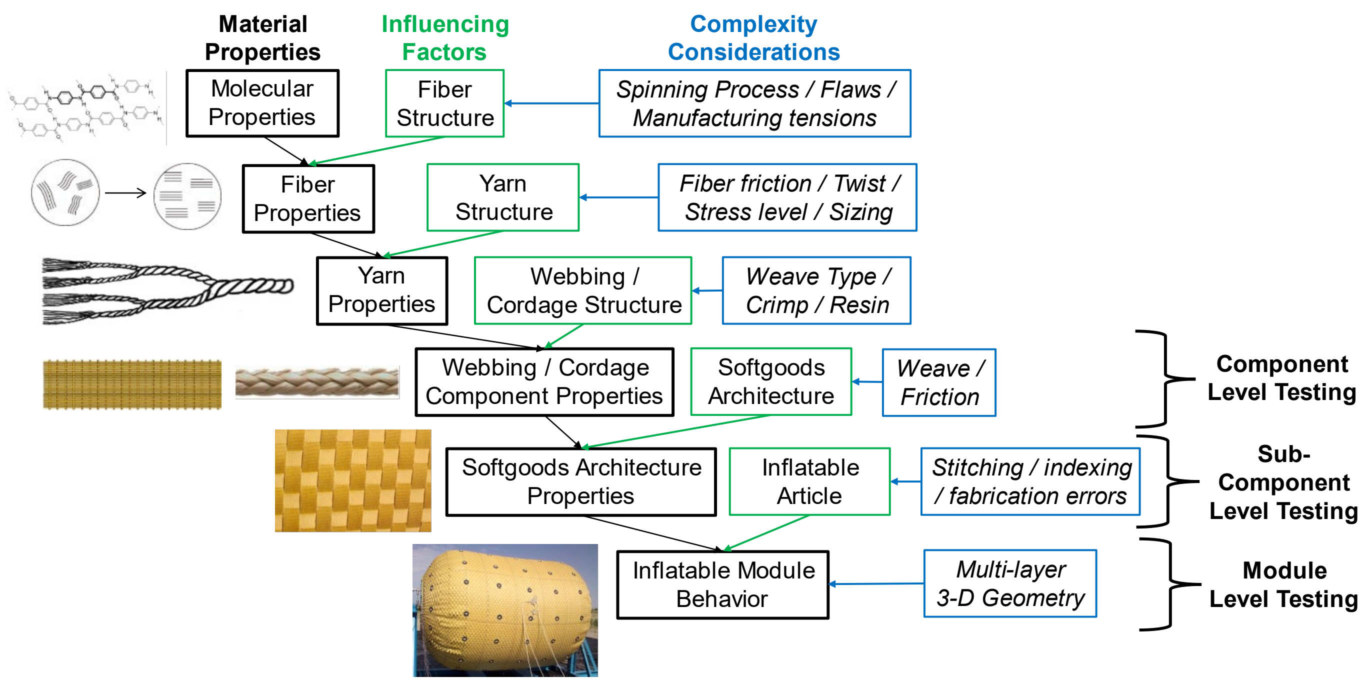

FIGURE 1 – STRUCTURAL HIERARCHY OF SOFTGOODS

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 module 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 qualification of a softgoods inflatable designed for crewed occupation in a space environment. This document is intended to support and guide a softgoods certification program that demonstrates a design has followed a systematic and comprehensive design, fabrication, and test program. While not written explicitly as such, the recommendations in this document may be levied directly as programmatic requirements or used to develop such requirements.

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 rigid 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.

1.2 SCOPE

This document provides guidance in the critical areas used in the assessment of an inflatable design, its materials, and component, sub-component, and 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) internal protection layer(s), b) gas barrier bladder layer(s), c) structural restraint layer(s), d) micrometeoroid and orbital debris protection layer(s), e) external protection layer(s), and
f) packaging layer(s). 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 external protection layer(s).

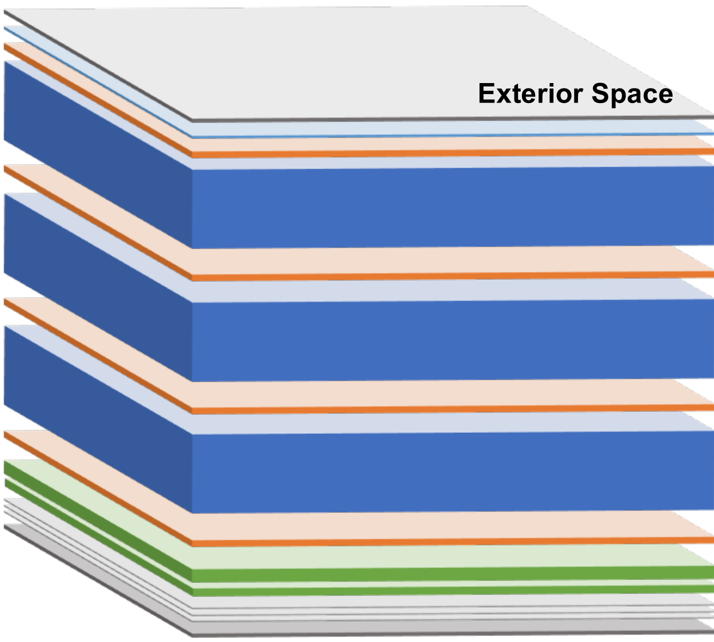

FIGURE 2 – TYPICAL CREWED SOFTGOODS SHELL LAYUP

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.

Fracture control, as currently defined by NASA-STD-5019, applies only to material systems that contain internal flaws, such as metallics and composites. Softgoods are considered non-fracture critical. However, the intent of fracture control, to prevent catastrophic events in human-rated space system through failure tolerance, should still be addressed. For softgoods, this is done with a Damage Risk Assessment (4.1.3) and relevant component (4.3.4), sub-component (4.4.1), and module-level (4.5.7) damage tolerance testing.

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-D123	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

Document No.	Title
ASTM-D6193	Standard Practice for Stitches and Seams
ASTM-D6770	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-E595	Standard Test Method for Total Mass Loss and Collected Volatile Condensable Materials for Outgassing in a Vacuum Environment
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
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-6645	DetailSpecification:Parachutes, Personnel, General Specification for

Document No.	Title
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-7005	Dynamic Environmental Criteria
NASA-HDBK-8719.14	Handbook for Limiting Orbital Debris
NASA-HDBK-8739.19-2	Measuring and Test Equipment Specifications
NASA-NPR-8705.5	Technical Probabilistic Risk Assessment (PRA) Procedures for Safety and Mission Success for NASA Programs and Projects
NASA-NPR-8735.2	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 Supplemental	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-4108	Strength and Elongation, Breaking: Textile Webbing, Tape and Braided Items
SAE-AS9100	Quality Management Systems - Requirements for Aviation, Space, and Defense Organizations
SLS-SPEC-159	Cross-Program Design Specification for Natural Environments (DSNE)
SMC-S-016	Test Requirements for Launch, Upper-stage, and Space Vehicles
SSP-30425	Space Station Program Natural Environment Definition for Design
SSP-30559	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
FOD .... Foreign Object Debris
GCR .... Galactic Cosmic Radiation
HVI .... Hypervelocity Impact
LOC .... Loss of Crew
LOM .... Loss of Mission
M&P .... Materials and Processes
MDP .... Maximum Design Pressure
MMOD .... Micrometeoroid and Orbital Debris
PD .... Packaging and Deployment
PFA .... Per- and Polyfluoroalkyl substances
PNP .... Probability of No Penetration
QA .... Quality Assurance
SHM .... Structural Health Monitoring
SLA .... Structural Load Assessment
SPE .... Solar Particle Events
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 – Standard Terminology Relating to Textiles.

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 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.

Flight-like Built with same drawings, materials, and processes as the flight unit.

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

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 a module. Preconditioning could include a thermal soak and/or outgassing procedures, and any cleaning or chemical treatment to remove oils or sizing prior to integration.

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 module, 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 module. This typically includes but is not exclusive to: thin membranes (elastomeric polymer sheets, MLI, Kapton, and aluminized Mylar), and textiles (fabric, webbing, and cordage).

Sub-Component A representative panel or portion of the inflatable pressure vessel softgoods architecture, that includes all or some of the elements used in fabricating the inflatable module, such as stitching, indexing, and rigid structure interfaces.

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 certification of a human-rated softgoods structure designed for use in a space environment. Rationales are provided and clarification is given where appropriate. Since softgoods are considered a low heritage material for crewed spacecraft, their certification is currently based primarily on testing. Flow chart, Figure 3, shows a nominal flow of documentation and tests outlined in this document. Once certified for flight, any changes in the module design may require a recertification of that module based on the type and level of impact of that change.

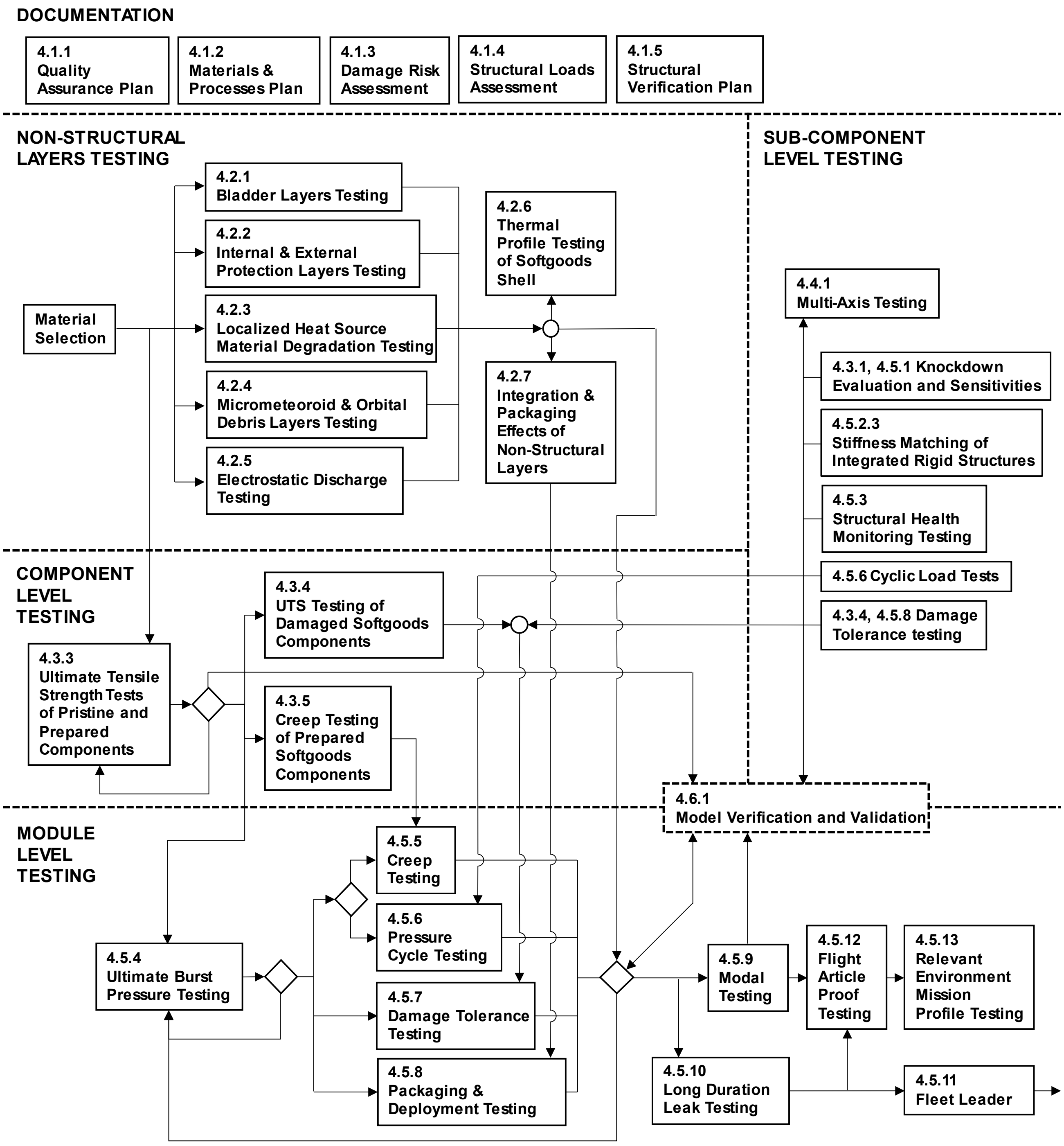

FIGURE 3 – TESTING FLOW CHART

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 module under construction that ensures consistency of the fabrication process and verification of strength. At least 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 manufacturing, packaging, and deployment of the module.
d) A storage plan for all materials and modules that covers prior to, during, and after fabrication.
e) A transportation plan that incorporates and details the processes for moving and transporting the modules both in and around the fabrication facility and between facilities, test sites, or the flight integration site to mitigate damage. If rigid structures that interface with the restraint layer and bladder/liner layer are included in the module, then all required hardware support structures should be included in the transportation plan.

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 module, 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 module, 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 module are knowledgeable of, and adhere to, the QA plan. Note that vendor internal QA documents may be requested for review in addition to the formal QA plan if additional detail is required in assessing the fabrication processes for certification.

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

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

4.1.2 Materials and Processes (M&P) Plan

[CISS 02] All materials used in a crewed inflatable structure 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, outgassing, microbial resistance, and thermal vacuum stability. All materials used in a crewed inflatable softgoods structure are subject to these requirements, separate from, and in addition to any load or damage factors.

Note that some softgoods materials that use or are treated with Per- and Polyfluoroalkyl substances (PFAs), commonly referred to as forever chemicals, may become restricted or discontinued due to increasingly stringent regulations on their usage. Therefore, to reduce recertification testing, it is recommended that all materials selected are non-PFA and minimize or eliminate reliance on PFA substances in their production.

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 Offgassing) NASA-STD-6001, JSC- 29353, MSFC-HDBK-3575. (Space Environment Effects) NASA-CR-4661 Parts I & II.

Test Methods: (Flammability and Outgassing) ASTM-E595, 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 any change of vendor, if applicable.

This information provides the core component level specifications of the material system that drives the behavior of the whole module 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 module, 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 module-level.

4.1.2.2 Softgoods Inspection Samples

[CISS 04] Inspection samples of both the pristine and prepared flight module 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 the material run(s) should be discussed 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 modules and the flight module(s) to maintain the greatest level of consistency and continuity between modules.

This ensures that the same test data can be used for qualification and certification of the flight module(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. To be considered in family with prior lot(s), enough specimens should be tested from the new lot(s) to show average strength and standard deviation is consistent within a B-Basis level of statistical confidence [Reference 4.3.2.3].

4.1.3 Damage Risk Assessment (DRA)

[CISS 06] All softgoods materials and components used in the inflatable structure, and the overall module, 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 module 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 module itself, as described in 4.5.1.

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 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). 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 module over its entire lifetime.

Damage factors that are considered unavoidable or inadvertent fall into two primary categories:

environmental and mechanical/chemical. 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 (including operating across a range of temperatures based on application/mission, and across interfaces with direct contact to the external environment), humidity, atmospheric pressure / vacuum, dynamic particulates (for surface applications, e.g., dust and regolith), radiation (including ultraviolet), atomic oxygen, and microbial exposure. Mission exposure levels should be corroborated with the program for the specific mission application.
- Mechanical and chemical damage factors: Abrasion, folding / unfolding, cut / puncture, tearing, cyclic loading (e.g., for airlock applications), and creep. Propellent venting or exhaust and outgassing from proximate materials.

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, interaction with internal or external secondary structure(s), and interaction with integrated rigid 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-159, SSP-30425, 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 module'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 module, 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(s) should be evaluated to identify load factors on the ideal design state, in addition to any induced over-load or cyclic load conditions. Combinations of load states, such as mechanical and environmental, should also be evaluated to determine limit loads and uncertainty factors. Conservative load factors should be used initially, with the understanding that those added factors may be reduced after testing, verification, and experience through flight heritage with a design. Note, these are in addition to the standard structural safety factors required on burst (4.5.4) and life (4.5.5).

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 module 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 agreed upon with the certifying 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, sub-component, and module-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 specimen 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, ultraviolet exposure, 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 tests, load/pressure level as a percentage of the average failure load/pressure versus log-time-to-failure should be plotted, along with master creep strain versus log-time curves.

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

4.2 NON-STRUCTURAL LAYERS TESTING

4.2.1 Bladder Layers Testing

The bladder layer(s) of a crewed inflatable work in conjunction with the structural restraint layer(s) 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(s). 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(s) carry load and are considered as structural bladder layer(s). In these configurations, the bladder material should undergo all of the same component-level testing as the restraint layer(s) to ensure evaluation of all structural materials used in the module. If a structural bladder is designed with significantly higher safety factors (e.g. a safety factor of 8 or greater), creep testing may not be necessary, but should be agreed upon with the certifying program.

4.2.1.1 Packaging, Deployment, and Cyclic Loading Damage

[CISS 10] 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 module as specified in the SLA (4.1.4).
c) The data collected should include size and location of visible damage, any change of permeability rate of air flow through the bladder material, and any change in mechanical strength of the bladder material.

The material level permeability data can be compared to the results from the module- level leak testing (4.5.104.5.9) and used to predict flight module 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.

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

4.2.1.2 Seal Interface Induced Damage

[CISS 11] If applicable, the effects of long-duration compression of the bladder layer(s) at all softgoods-to-rigid-structure interfaces used in the flight module should be evaluated.

The bladder layer(s) in an inflatable must be sealed to any attached rigid structure, such as a bulkhead, hatch, window, etc. If a compression seal is used between the bladder and the interfaced rigid 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.

4.2.2 Internal and External Protection Layers Testing

[CISS 12] The innermost and outermost layers of a crewed inflatable should be tested to demonstrate resistance to mission specific mechanical, chemical, and environmental damage that may be present throughout the mission life of the inflatable structure.

Depending on the layup and architecture, the inner and outermost layers are typically used as the first line of protection against damage to the softgoods layers in between, such as the bladder and restraint layer(s). Potential damage factors that can be mitigated with internal and external protective layers, include puncture, cut, and abrasion, from mechanical or external sources (e.g., lunar, or Martian regolith), ultraviolet radiation and atomic oxygen, the thermal-vacuum environment, and chemicals and/or propellent. Any potential damage from the inside or outside of the module should be identified in the DRA (4.1.3) and the relevant materials should be tested to assess their ability to protect the interior layers of the multi-layer softgoods shell.

Passive thermal layer(s) are part of the vehicle's thermal management system and work in conjunction with the active environmental control and life support system (ECLSS). The softgoods elements that make up these thermal layer(s) should be tested to verify that they meet the needs of the overall thermal system across the mission profile, and their performance is not degraded by packaging, deployment, or any other potential damage as identified in the DRA (4.1.3). Considerations should be made for consistent thermal control over the entire surface area, especially at areas with direct interfaces to the external environment such as at rigid connection points, passthroughs, bulkheads, windows, hatches, etc.

Each material should be evaluated for its inherent susceptibility to radiation damage, per the DRA (4.1.3), and any additional shielding 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 are therefore typically mitigated via local shielding and logistics placement around the crew quarters, wearable shielding, and/or possible biological countermeasures. This is an area of ongoing research.

Test Methods: (Puncture) ASTM-F1342, ASTM-F2878. (Abrasion) ASTM-D4158, ASTM- D-6770. (Environmental) SLS-SPEC-159, SSP-30425, NASA-TM-4527.

4.2.3 Localized Heat Source Material Degradation Testing

[CISS 13] The degradation of the shell layers due to a localized heat source should be evaluated through testing of a representative softgoods shell section.

The internal configuration of an inflatable module may lead to heat sources being placed near the inner walls of the softgoods shell. Sustained thermal radiation may heat up the inner liner, bladder(s) and/or restraint layer(s) and could lead to a potential increase in permeability or damage to the bladder layer, or failure of the restraint layer.

Additionally, an internal fire near the softgoods shell, could lead to rapid degradation of the softgoods layers. Even if the inner layers pass required flammability tests as part of M&P requirements (4.1.2), direct heating from a fire could cause permanent damage to the softgoods materials that reduces the useful life of the inflatable module. In order to evaluate all scenarios, potential heat sources and the sensitivity to proximity, intensity, and duration of heat application should be identified in the DRA (4.1.3).

Heat source testing should be conducted, to evaluate both material permeability and mechanical strength before and after the heat source is applied, along with the following considerations:

a) The materials should be tested at the design stress level in a mission relevant thermal, pressure, and atmospheric environment.
b) A representative heat source should be used as identified in the DRA (4.1.3).
c) The test fixture should provide the capability to adjust distance and duration of heat application to evaluate the sensitivity of the materials to those parameters.
d) The data collected should include size and location of visible damage, any change of permeability rate of air flow and any change in mechanical strength.

Test Methods: (Permeability) ASTM-D737, ASTM-D1434; (Flame Impingement) NASA STD-6001 Modified Test Method 1 with horizontally mounted specimen perpendicular to igniter.

4.2.4 Micrometeoroid and Orbital Debris (MMOD) Layers Testing

[CISS 14] The Micrometeoroid and Orbital Debris (MMOD) layers of the inflatable module should demonstrate by hypervelocity impact (HVI) testing that it meets the probability of no penetration (PNP) limit specified by the program for the specific mission and application, and that the restraint layer remains undamaged by the mission's maximum predicted size, speed, flux, and angle of impactors.

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 module MMOD layer, after packaging and deployment.

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

4.2.5 Electrostatic Discharge Testing

[CISS 15] The design of electrostatic buildup mitigation should meet the intent of NASA- STD-4003 – Electrical Bonding for NASA Launch Vehicles, Spacecraft, Payloads, and Flight Equipment, as part of the overall vehicle's electrical bonding / grounding plan.

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 interacting with 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.

4.2.6 Thermal Profile Testing of Softgoods Shell

[CISS 16] The thermal conductivity of the multi-layer softgoods shell should be quantified through thermal measurements in an environmental test of a softgoods shell section.

To understand the thermal performance and behavior of each material layer and the shell, a thermal model should be used. The conductivity and effective emittance values used in the model should be quantified through thermal-vacuum testing of a representative article. The shell thermal test can provide layer-specific temperature levels which should be used to understand the operating temperature of each layer and guide any material capabilities or further tests required for each material system.

The shell thermal testing should be conducted with the following considerations:

a) The test article should be representative of the flight-like shell materials and include all layers.
b) The test article should be insulated at all free edges in order to represent the acreage of the shell and sized such that edge effects do not influence the temperature measurement.
c) Each layer should include at least one thermocouple to measure the temperature distribution through the thickness of the shell.
d) The test conditions should represent a flight-like reduced atmospheric pressure / vacuum and thermal environment.
e) The test duration and cycles should be representative of the mission and include any

expected thermal soak periods.

f) The test article may require multiple configurations to represent different stages of flight operations (e.g., cold soak while packaged, cold and/or warm thermal gradient after deployment).
g) Additional testing may be needed to understand any degradation of thermal properties due to damage factors, as described in the DRA (4.1.3).

4.2.7 Integration and Packaging Effects of Non-structural Layers

[CISS 17] The impact of the integration of all non-structural layers with the restraint layer(s) 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 be non-load bearing during operation, their integration and physical connection to the restraint layer(s) 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 location 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 module-level testing.

Reference: (Stitching) ASTM-D6193.

4.3 STRUCTURAL COMPONENT-LEVEL TESTING

4.3.1 Component-Level Knockdown Factors

[CISS 18] To characterize and understand the baseline performance of an inflatable structure, knockdown factors should be calculated and reported for the components, defined as the ratio of stitched or spliced component strength over pristine strength (4.3.3). Preparation of softgoods includes any preload cycling, thermal soak(s) / outgassing procedures, and any cleaning or chemical treatment to remove oils or sizing.

The component-level knockdown factors are used in the initial design cycles, along with the intended inflatable geometry, to estimate the maximum module level performance, from which additional fabrication and integration knockdowns will be determined and applied (4.5.1). These component-level knockdown factors are unique to the softgoods materials and constructions used, and the specific stitch pattern or splice selected, therefore reevaluation of knockdown factors should be performed if any changes are made to the components.

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 may result in invalid or variable results, misinterpretation of data, and incorrect conclusions.

4.3.2.1 Wrap Grips and Slippage

[CISS 19] Split-capstan wrap grips are recommended for testing of softgoods components without stitched or spliced end-terminations.

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 (4.3.3). 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, such as rubber, of the same width with the wrapped tail of the specimen. Alternatively, a thin layer of spray paint can be applied to the wrapped tail section, that once tack dry can provide additional friction to mitigate slippage.

Reference: ASTM-D6775.

4.3.2.2 Pin-Grip Test Considerations

[CISS 20] Pin-grips are recommended for prepared specimen testing with stitched or spliced end terminations (4.3.3). The total length of the unseamed portion of the specimen in the test section should equal or exceed the total length of the spliced or stitched portions to avoid boundary condition influences on the test section.

For specimens with stitched or spliced end terminations, the pin-grip should be analogous to the attachment point on the module in terms of pin diameter. The minimum 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 module and whether the component level behavior is sensitive in its tested configuration to the size of the stitched or spliced regions.

4.3.2.3 Statistical Based Strength Values and Number of Specimens

[CISS 21] An appropriate statistical strength value should 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 recommended for use when testing softgoods, 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 test program and number of specimens required. If the module does not have redundant load paths, then the selection of an appropriate confidence margin and basis strength criterion should be agreed upon with the certifying program.

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

4.3.2.4 Preconditioning of Softgoods Components

[CISS 22] 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 component to component. 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. Note that handling, packaging, deployment, and the length of time between preconditioning and further loading may impact these effects.

4.3.2.5 Strain Measurement

[CISS 23] 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 or attached to the sample. Pin-extensometers, 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 load frame 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 24] Load measurement in softgoods modules from strain-to-load conversion should be used with caution, due to the high probability of the strain-load relationship changing with load history.

Load measurement for component tests can be taken directly from a calibrated load frame. Component load measurement at a sub-component or module-level can be achieved via commercially available in-line load cells, or custom designed sensors that integrate to or are within the softgoods interfaces. If custom load sensors are used, they should include the components of the interface they are attached to or integrate with. All sensors should be individually calibrated using an industry standard method that covers the calculated load range with margin of the test for which they are being used.

Load sensors 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 a module-level is highly challenging and likely to be inaccurate. The non-linear load vs. strain behavior of softgoods components 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 module. These all affect the initial calibration of strain-to-load. The initial zero strain point required for an accurate conversion is also extremely difficult to determine for a module test, as some initial pressure is needed for the module to hold its shape prior to the measurement system being activated.

Test Method: ASTM-E74

4.3.2.7 Photographic and Video Documentation of Testing

[CISS 25] 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 module-level test, use of this equipment is highly recommended.

4.3.3 Ultimate Tensile Strength Tests of Pristine and Prepared Components

[CISS 26] To verify the static strength of all structural softgoods via test, per NASA-STD- 5001, ultimate tensile strength (UTS) tests should be performed on all load bearing softgoods components, 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 using the same preconditioning (load/thermal cycling, outgassing, cleaning) and integration processes as the flight design.

Ultimate tensile behavior, as characterized by strength and load versus strain data, for pristine off-the-roll and prepared softgoods components, provides the baseline information that is compared to data from sub-component and module-level testing. The pristine material behavior also quantifies the baseline variability in strength and stiffness of each softgoods component and impacts their preparation for the flight module. 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 components; whereas structural fabrics should be biaxially tested under biaxial stress ratios appropriate to the geometry of the inflatable module. 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 webbing and cordage data when modeling 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. See section 4.4.1 on sub-component level biaxial testing.

Reference: (Stitching) ASTM-D6193.

Test Methods: ASTM-D6775, PIA-4108, CI-1500-02.

4.3.4 UTS Testing of Damaged Softgoods Components

[CISS 27] Ultimate tensile strength (UTS) tests should be performed to characterize the reduction in strength due to the damage factors identified 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, mechanical, and/or chemical 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 testing provides a fundamental understanding of the causes for reduced performance in the flight module versus the pristine component performance.

4.3.5 Creep Testing of Prepared Softgoods Components

[CISS 28] Real-time creep testing should be performed on specimens of all structural softgoods components used in the inflatable module that maintain a load over the duration of the mission, and should include:

a) Maintaining a constant load, temperature, and humidity throughout the tests.
b) Flight-like component preparation and stitching / splicing.
c) Grip types selected to represent a flight-like interface where possible, such as a pin-clevis. If testing a lap-seam or continuous loop section, then grips should be selected so the failure occurs away from the grips.
d) A minimum of 4 stress levels, between 60% 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 module.
e) A minimum of 5 creep test specimens to act as fleet leaders at the maximum design load level.

It is critical that the creep tests performed provide full coverage of the minimum recommended stress levels above, and that there is adequate separation between stress levels to bound and extrapolate the data more accurately. Additional test cases that expand the creep data set at each stress level and/or add data at lower stress levels is highly recommended. The ability to predict creep life with higher statistical confidence at the component level, directly affects predictions of both the flight lifetime creep performance and module-level creep test pressure predictions.

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. Creep testing of the prepared components is used to predict suitable test times for module-level creep testing, with consideration of the additional knockdown factors from testing a built- up module. Creep testing should be performed on each type of primary softgoods component used in the module, as each will have different TTF curves and bounds, and the component with the shortest time to failure is typically unknown prior to performing these tests. 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 if at a lower stress level than the other softgoods components used in the architecture.

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 safety factor of 8 or greater), creep testing may not be necessary, but should be agreed upon with the certifying program.

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 test stands are 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 vs. log-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. In addition, this data is invaluable for direct comparison to both module-level creep data and flight data for inflatable modules with integrated structural health monitoring, which could be used for supporting flight extension or determining the impact of observed increases in strain rate due to a detected off-nominal event.

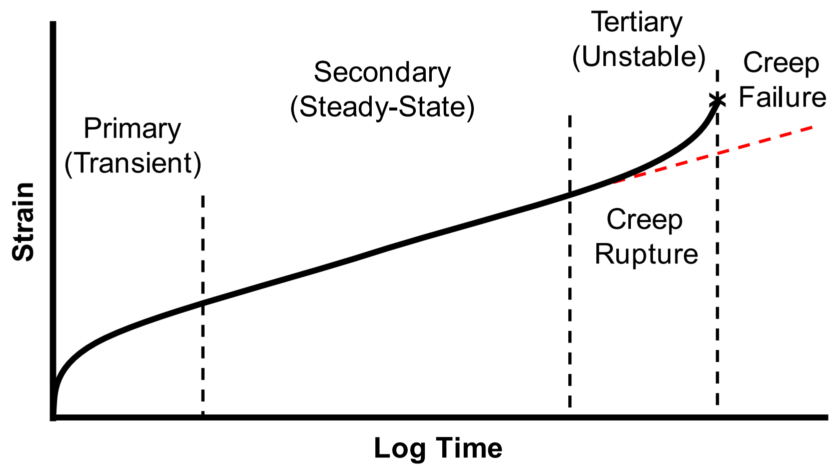

FIGURE 4 – TYPICAL THREE STAGE CREEP CURVE

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 viscoelastic 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 stress levels 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, NASA-TM-2020-5005004 Supplemental.

4.4 STRUCTURAL SUB-COMPONENT TESTING

4.4.1 Multi-Axis Testing

[CISS 29] For inflatable softgoods architectures that carry biaxial and/or shear loads, sub-component structural testing should be performed where uniaxial component tests do not provide suitable replication of the loading, and the number of test parameters and/or samples required make module-level testing unfeasible or cost prohibitive.

Most inflatables carry load biaxially in the circumferential (hoop) and meridional (axial) directions. The restraint layer loading and stiffness behavior is affected by the shape of the module, number of components, and whether they are woven or non-woven (layered). Component level tests provide the uniaxial behavior, but to build accurate models of an architecture (4.6.1), the nonlinear, load-dependent biaxial and shear stiffnesses need to be characterized. In addition, the strength of the architecture is affected by the fabrication and integration of the components, whose features can't be fully replicated in component testing. Module-level testing provides the holistic performance of an inflatable structure but is typically limited to a small number of test articles.

Sub-component testing of the restraint layer can provide both statistically significant performance data (4.3.2.3) for model development and validation, and testing of local effects that may have multiple influence parameters of interest, such as damage tolerance. Sub-component testing also provides a more efficient approach to developing or evolving softgoods architectures, including studying the effects of different load ratios (i.e., novel geometries, core versus no-core designs), and integrated hardware with tight control and monitoring of the environment and loading of the architecture, to maintain repeatability and consistency across test cases.

Recommended areas for sub-component structural tests are:

- Knock-down evaluation and sensitivities (4.3.1, 4.5.1) of an architecture
    - Rigid structure integration (4.5.2.3).
    - Test impact of local or global design changes in architecture.
    - Fabrication error / accuracy sensitivity for validation of QA approach.
    - Preconditioning effects at architecture level (4.3.2.4).
- Damage tolerance testing
    - Single Component Failure (4.5.7).

  - Cut, puncture, abrasion, etc. (4.2.2, 4.3.4).
  - Effects of folding/packaging (4.5.8).
- Cyclic load tests
  - Fatigue load cycling, to represent airlock inflation / depress cycles or operational pressure cycling over mission life (4.5.6).
- Structural Health Monitoring (SHM) sensor integration
  - Effects and correlation to high precision load/strain readings on the architecture (4.5.3).
- Model verification and validation
  - Biaxial and shear stiffness characterization for FEA (4.6.1).

4.5 STRUCTURAL MODULE-LEVEL TESTING

4.5.1 Module-Level Knockdown Factor

[CISS 30] To characterize and understand the performance of an inflatable structure, a module-level knockdown factor should be calculated, defined as the ratio of the tested burst pressure (4.5.4) over the calculated ultimate burst pressure based on geometry and component-level performance (4.3.3). This knockdown includes the effects of the fabrication and integration processes on the softgoods layers and any post-integration preparation prior to test or flight such as load cycling, thermal soak(s) / outgassing procedures, and any cleaning or decontamination treatment.

The module-level knockdown factor is separate from damage factors that may occur at any point during the life cycle of a module, as described in the DRA (4.1.3), and is specific to the softgoods materials selected, the architecture, and the assembly processes. A reevaluation of the knockdown factor should be performed if any changes are made in these areas. Materials and methods used in the module integration (e.g., layer-to-layer indexing) should be carefully documented for quality assurance purposes and for tracking the sensitivities of those parameters and the impacts they have on the knockdown factor.

Note that selected materials may not perform as efficiently once prepared and integrated into a module. Index stitching is considered non-structural and therefore should be of lower strength / higher elasticity than structural stitching which is typically the same material as used for the structural components. All layers of the module should be considered for their potential impact on each other, especially on the behavior of the restraint layer(s), 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 the module-level knockdown factor.

4.5.2 General Module-Level Test Guidance

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

4.5.2.1 Test Facility Contingency Considerations

[CISS 31] Facilities used to conduct module-level testing should meet or exceed the specific test requirements outlined for each test type. A successful test relies on a facility that supports the test goals without influence or interruption. In addition to the nominal test specifications, the facility should address the possibility of off-nominal events by including the following capabilities:

a) Backup power and/or network capabilities to support critical test operations and data collection during a power and/or network outage.
b) Physical access to data acquisition hardware and/or computer systems during long duration tests that allow for physical troubleshooting if systems fail during test operations.

4.5.2.2 Max Design Pressure

[CISS 32] 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.

4.5.2.3 Stiffness Matching for Modules with Integrated Rigid Structures

[CISS 33] Any inflatable module with one or more rigid structures integrated within the restraint layer(s) should validate, via analysis and test, a repeatable approach to matching stiffnesses across those interfaces to equilibrate structural loads at any target pressure.

Rigid structures, such as hatches and windows that are integrated directly in-line with restraint layer components may produce uneven loading in the restraint layer due to differences in the combined stiffness of those elements. Typically, the stiffness curves of the rigid structures will not match the softgoods components they interface with, therefore the softgoods must be sized so that the stiffness curves intersect at a target pressure, and an even loading can be achieved in the restraint layer. For the flight module, this target pressure should be the operational pressure, but for module-level tests, the target pressure will vary. Given that burst test modules will target an expected ultimate pressure, and creep test modules will target a range of pressures between operational and burst, there are multiple target pressures at which the restraint layer loading must be equilibrated using a stiffness matching approach. In addition, the integrated rigid structures may also vary in stiffness between the test and flight hardware, due to the required higher structural factors on test hardware. It is therefore recommended that testing is performed at a sub-component or sub-scale level first to validate the efficacy of the stiffness matching approach at a range of load states that represent the target pressures. Data should be gathered during each applicable test to support validation of the approach used for the flight module that ensures equal loading at operational pressure.

4.5.2.4 Sub-Scale Test Module Considerations

[CISS 34] For sub-scale test modules, 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 module 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 module-level tests at a fidelity that demonstrably represents the flight module 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 are likely to be higher than the expected loads in flight.
d) Failure of the module should not occur at, or be instigated by, any integrated rigid structure.
e) The sub-scale module should represent a conservative distance between interfaces versus the full-scale module. I.e. based on the scaling factor, the actual distance between interfaces should be the same as or smaller than for the full- scale. Particular attention should be given to multiple interfaces in-line with the same critical softgoods components, i.e., multiple rigid structures interfaced along the same hoop component(s).
f) If rigid elements are staggered axially or radially then that should be reflected in calculating the appropriate spacing of interfaces for sub-scale modules.
g) The size of the sub-scale may need to be increased to incorporate an appropriate representation of the rigid structures included in the full-scale module(s) versus a similar module with fewer or no integrated rigid structures. In addition, the stitch/ splice lengths are typically fixed for a given component target stress level, which may also affect the required size of the sub-scale so that the design isn't influenced by the position or percentage of stitched/splice areas versus a full-scale module.

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 be required to characterize these scaled softgoods components.

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.

NASA-STD-5001 specifies lower factors of safety for rigid components made of metallic and/or composite materials versus the softgoods restraint layer. For a flight module, the rigid structure should be designed for operational loads, but for a test module intended for restraint layer failure, the rigid structure should be designed to withstand the expected test loads with margin. If two different rigid structures are designed, one for test operations and one for flight operations, then the physical interface to the softgoods should remain consistent between the two designs (i.e. pin diameter for a pin-clevis), and the resized hardware should be evaluated for any ancillary impact on the flight article softgoods, packaging, transport, and deployment.

Reference: NASA-STD-5001.

4.5.2.5 Workmanship Test

[CISS 35] As a workmanship test and to mitigate test facility safety concerns, it is recommended that every module-level build should undergo a low-pressure test after

construction is complete to ensure the module has been properly manufactured and can inflate as expected. It is recommended that this be included as part of the QA plan (4.1.1) to verify that manufacturing was completed according to the specifications.

4.5.2.6 Boundary Conditions

[CISS 36] Careful evaluation of the boundary conditions between the test module and test stand should be performed to verify that the module has free movement to expand and is representative of how the module will be restrained for its proposed application. In addition, the test stand should be designed with consideration of the dynamic failure of the module, if it is anticipated to burst, as the pressure is likely to release in a non-uniform and directional manner that may impart high moments, torques, and/or 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.

4.5.2.7 Module Over-Pressure Design

[CISS 37] Spacecraft over-pressure scenarios should be evaluated on a vehicle level to ensure the softgoods structure does not carry additional loads during an over-pressure event.

Traditional metallic habitable structures are designed to leak-before-burst, using common fracture control methods as described in NASA-STD-5019. Crewed softgoods, however, are typically designed as a two-part system consisting of the bladder layer(s) that contain the internal atmosphere, and the restraint layer(s) that carry the pressure load. In an over- pressure scenario, the vehicle architecture should use relief valves to limit the pressure load on the inflatable as opposed to allowing for a leak in the pressure wall.

Reference: NASA-STD-5019.

4.5.3 Structural Health Monitoring

[CISS 38] A Structural Health Monitoring (SHM) system should be integrated to enable tracking of strain and impact events over the life of the module.

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 a SHM system is used to monitor the restraint layer during operation. Direct strain or load measurement of critical components of the restraint layer are recommended. Any SHM system should be evaluated as part of the DRA to determine its impact on the performance of the structural layer(s), or ancillary impact on the other layers due to its integration.

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. The system should also be used to monitor strain over time to compare with strain vs. log-time curves as generated in creep testing (4.3.5) and (4.5.5). This information provides data for model correlation and will be required for any life extension assessment and recertification of an existing module.

Additionally, monitoring of non-structural layers, for impact detection of the MMOD shield and leak detection of the bladder layer(s) for instance, is highly recommended as a further risk mitigation to the crew, and to provide advance warning of any adverse event.

4.5.4 Ultimate Burst Pressure (UBP) Testing

[CISS 39] Ultimate burst pressure tests should be performed on flight-like test modules of the inflatable design to demonstrate that the architecture meets or exceeds the Ultimate Design Factor of Safety for Critical Structural Softgoods of 4.0, per NASA-STD-5001. The test(s) should include the following considerations:

a) It is recommended that initial UBP testing is done at a sub-scale level, for efficiency 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 scale.
b) The structural restraint layer(s) and associated interfaces are considered the unit- under-test and should be flight-like. Other non-structural layers can be considered test layers and are not required to be flight-like as long as they do not alter the flight-like behavior of the structural layers.
c) At a minimum, two sub-scale and two full-scale tests of the flight-like design should be conducted.

d) 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.
e) For each test, redundant internal pressure sensors are recommended, and the minimum pressure reading should be used as the burst pressure of record.

Demonstrating the architecture's ability to meet the required factor of safety through ultimate burst pressure testing is one of the primary structural requirements on a softgoods module 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. 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 factors of safety 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 module-level tests.

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

4.5.5 Creep Testing

[CISS 40] At minimum, three creep tests to failure at a constant pressure should be performed on sub-scale test modules to predict the lifetime performance of the inflatable and show that the design meets or exceeds the minimum service life factor of 4.0, per NASA-STD-5001. The test(s) should include the following considerations:

a) If the structural layer is specifically designed to operate at low stress levels (i.e. has a safety factor of 8 or greater), creep testing may not be necessary, but should be agreed upon with the certifying program.
b) The test module(s) should be built to the same specifications as the flight-like design from 4.5.4.
c) The structural restraint layer(s) and associated interfaces are considered the unit- under-test and should be flight-like. Other non-structural layers can be considered test layers and are not required to be flight-like as long as they do not alter the flight-like behavior of the structural layers.
d) The pressure 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, and adjusted if needed as module-level creep data is acquired.
e) The pressure levels for the creep failure tests should be calculated to provide time- to-failure data on the fabricated modules 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. These time points are not specific minimums or maximums but suggested to provide statistically significant separation between data points on the log-time plot used for creep life prediction.

f) Following each test, the pressure level, time-to-failure, failure mode, %UBP stress level (based on average UBP of the module (as tested in 4.5.4), temperature and humidity versus time should be reported. If any components fail prior to ultimate rupture of the module, the time and location of each should also be reported.
g) Creep tests should be performed in an environmentally controlled facility that maintains constant temperature and humidity around the test module throughout the duration of the test. Any effect from reduced atmospheric pressure / vacuum on the restraint layer strength should be tested at the component level, as recommended in 4.3.1, but is not required for the module level creep tests.
h) The DRA (4.1.3) and/or SVP (4.1.5) should specify whether to include a single failed component in any of the creep test modules.

Creep is the primary source of long-term damage to the restraint layer once the module is deployed and pressurized. Module-level creep testing is critical to understanding any additional long-term knockdown factors of the built-up module that would not be observed in the component level or UBP tests.

A minimum of three well separated points on a stress versus log-time-to-failure plot is needed to create a lifetime projection of the softgoods structure at the operational pressure level. These tests are typically 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.

4.5.6 Pressure Cycle Testing

[CISS 41] Cyclic load testing should be performed to verify fatigue lifetime performance of the inflatable and show that the design meets or exceeds the minimum service life factor of 4.0, per NASA-STD-5001. The test(s) should include the following considerations:

a) If the inflatable is expected to maintain a constant pressure throughout the lifetime of the mission, and the static pressure variation is small, then a cyclic test may not be necessary. This should be agreed upon with the certifying program.
b) The test module(s) should be built to the same specifications as the flight-like design from 4.5.4.
c) The structural restraint layer(s) and associated interfaces are considered the unit- under-test and should be flight-like. Other non-structural layers can be considered test layers and are not required to be flight-like as long as they do not alter the flight-like behavior of the structural layers.

d) The tested pressure cycles should be representative of the expected service life of the inflatable and include all applicable pressure changes, depress/repress cycles, and static pressure variations around the nominal operating pressure.

References: NASA-STD-5001.

4.5.7 Damage Tolerance Testing

[CISS 42] At a minimum, one test of a flight-like inflatable module 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 module(s) should be built to the same specifications as the flight-like design from 4.5.4.
b) The structural restraint layer(s) and associated interfaces are considered the unit- under-test and should be flight-like. Other non-structural layers can be considered test layers and are not required to be flight-like as long as they do not alter the flight-like behavior of the structural layers.
c) 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 the structure maintains its integrity for a period equal to or longer than the maximum crew response time, as specified by the mission con-ops emergency procedures.
d) 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 4.5.5.
e) 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 thesurviving components to determine the design creep stress level in the presence of a single failure.

Human-rated softgoods modules 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 module(s) with a single component failure.

4.5.8 Packaging and Deployment (PD) Testing

[CISS 43] Packaging and deployment cycles of a full-scale, flight-like test module should demonstrate a repeatable packaging scheme and a controlled deployment with the inflation of the module. 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 module should use materials that accurately represent the thickness and packaging characteristics of the flight 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.
d) This test can be performed at room temperature.

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 module 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.

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, characterized, and include any reduction in strength in the restraint layer if found.

Reference: NASA-STD-5017.

4.5.9 Modal Testing

[CISS 44] Modal survey testing of a pressurized, flight-like test module should be conducted to verify the frequency, modes, and stiffness characteristics of the inflatable module used in a spacecraft dynamic model, per NASA-STD-5002.

Dynamic characteristics of a pressurized inflatable are required for vehicle-level dynamic models. Modal survey testing is used to verify these characteristics and should include the following considerations:

a) The test module(s) should be built to the same specifications as the flight-like design from

4.5.4, and tested in the configuration(s) that represent the targeted dynamic cases (e.g. packaged for launch, deployed in operation, depressurized or at partial pressure, such as an airlock).

b) The structural restraint layer(s) and associated interfaces are considered the unit- under-test and should be flight-like. Other non-structural layers can be considered test layers and are not required to be flight-like but should have mass and stiffness properties that represent the flight configuration.
c) Modal surveys should be done at all expected operating pressures of the module to fully understand the effect of pressure on the module's stiffness.
d) If the module is planned to be operated without any pressure (e.g. as an airlock), then any planned secondary structure should be included in the modal test to provide an accurate flight-like representation of the module's stiffness.
e) Mass simulators should be used where appropriate to represent hardware or logistics that will be attached to the inflatable shell or core that could affect the dynamic behavior of the system.
f) Modal testing may be done on the inflatable module itself or as part of a larger vehicle-level test with other interfacing hardware.

References: NASA-STD-5002, NASA-HDBK-7005.

4.5.10 Long Duration Leak Testing

[CISS 45] At least one long duration leak test should be performed on a full-scale test module built using the flight-like structural restraint design from 4.5.4, but with the flight- like air barrier design. The test(s) should include the following considerations:

a) Prior to any leak test, the module should have gone through the predicted number of pressurizations, packaging, and deployment cycles of the flight module – 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 module. All materials and interfaces should be flight-like to provide an accurate representation of the expected flight leak behavior of the unit.
c) The module(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 certifying program.
d) Leak tests should be performed in an environmentally controlled facility that maintains constant temperature and humidity around the test module throughout the duration of the test. 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 in a reduced atmospheric pressure / vacuum.

e) The modules should be tested at the operational design pressure for a duration that demonstrates the module 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 certifying 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 (see 4.5.13). 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 modules should be based on information from the DRA (4.1.3) and SVP (4.1.5) and agreed upon with the certifying program.

Reference: NASA-STD-7012.

4.5.11 Fleet Leader

[CISS 46] A full-scale, flight-like test module should be used as a fleet leader to monitor the behavior of the module at the operational pressure over a period commensurate with the mission duration, according to the following considerations:

a) The test module developed for the long duration leak testing (4.5.10) can be utilized as the fleet leader module, assuming it represents a flight-like structural softgoods system.
b) The fleet leader should be kept in a controlled environment with the ability for monitoring of the restraint layer over time, and could be used as a ground comparison and long duration test of any integrated SHM system.
c) The module 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.

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 module will endure during the mission, the fleet leader can provide an indication of the health of the structure over time in a static configuration.

4.5.12 Flight Module Proof Testing

[CISS 47] Flight modules should undergo a structural proof test that meets the Proof Test Factor of Safety for Habitable Modules of 1.5, per NASA-STD-5001.

A structural proof test verifies that the module 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 (4.5.13) and for all subsequent flight builds.

Reference: NASA-STD-5001.

4.5.13 Relevant Environment Mission Profile Testing

[CISS 48] At minimum, one full-scale flight module 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 module 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 module is one of the final steps required to elevate the module technology readiness level and certify the inflatable design for flight.

References: NASA-STD-5001, NASA-STD-5017, NASA-STD-7012, NASA-TN-D7610, SMC-S-016.

4.6 ANALYSIS AND MODELING

4.6.1 Model Verification and Validation

[CISS 49] 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, sub-component, and/or module-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 module tests that are practical. It is strongly recommended to pursue the development of robust analysis techniques for an inflatable architecture, supported by component and sub-component-level tests for verification and validation.

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. FEA modeling will also likely be required to provide a dynamic model of any inflatable module that will be attached to a larger space system or vehicle, for which stiffness (4.4.1) and modal properties (4.5.9) would be needed.

Softgoods structures are challenging to accurately model at the hierarchical structural level of a full-scale module 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 and biaxial sub-component level test data. Deterministic properties do not include 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 rigid 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.

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

One of the first conceptions for the use of inflatables in space was for a space station 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 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 extravehicular activity performed. The interior of the shell is exposed repeatedly to the mission environment. This puts additional requirements on the internal protection layers, 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 wall of the 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 extravehicular activity. 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 protection 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 or rover. 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.