INCH-POUND

National Aeronautics and
Space Administration

MSFC-STD-3744
BASELINE
EFFECTIVE DATE: JANUARY 21, 2021

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

ER41

MSFC TECHNICAL STANDARD

STRUCTURAL DESIGN AND TEST STANDARD FOR SOLID ROCKET MOTORS

Approved for Public Release; Distribution is Unlimited

CHECK THE MASTER LIST—
VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

DOCUMENT HISTORY LOG

Status (Baseline/ Revision/ Canceled)	Document Revision	Effective Date	Description
Baseline	-	01/21/2021	Baseline Release.

FOREWORD

1. This technical standard establishes limited baseline requirements for the structural design and testing of SRMs. Current NASA standards, such as NASA-STD-5001 or NASA-STD-5020, do not sufficiently address all aspects of the structural design and testing of cases, solid propellants, insulators, liners, and joint seals, ablatives and non-ablatives The intent of this standard is to bridge such gaps by providing some of the requirements cited in the Space Shuttle's Reusable Solid Rocket Motor (RSRM) Contract End Item (CEI) specification and lessons learned from other NASA SRM programs. Such requirements were not effectively transferred to any other active existing NASA Standards or the now cancelled MSFC-HDBK-505.
    a. The document utilizes lessons learned from extensive testing conducted on the Space Shuttle's RSRM to establish requirements and demonstrate compliance.
    b. Sealing joint design requirements are also included, as recorded in the RSRM CEI specification.
    c. Solid propellants, insulators, joint seals and liners, ablative and non-ablative, requirements are limited in scope at this time, but will be expanded to include viscoelastic analytical approaches and testing of Propellant, Liner, and Insulation (PLI) systems in future revisions.
2. Note that this Standard deviates from the NASA-STD-5001 metallic yield strength factor of safety.
3. This technical standard is applicable only to SRMs used in Expendable Launch Vehicles (ELVs), together with separation motors and igniters. Specifications have been directed toward motors that carry both internal and external vehicle loading. SRMs used in space, missiles and other weapon systems are not considered herein.
4. In general, no distinction is made in this document between SRMs to be used for transporting personnel and those used for transporting hardware only. SRM's for flight systems transporting personnel maybe subject to additional verification, including Non-Destructive Evaluation (NDE) and/or safety requirements that are consistent with the established risk levels for mission success and flight crew safety.
5. The responsibility of this document falls under the Propulsion Structures and Design Branch / ER41 that operates within the MSFC Propulsion Systems Department / ER01.

The framework of this standard was constructed from the proposed AIAA S-094-2001, Space Systems – Composite Solid Rocket Motor Cases. This was a collaboration of both the JANNAF and AIAA communities in response to a growing use of composites in SRMs and the need for top-level requirements for design and testing.

TABLE OF CONTENTS

APPENDIX

TABLES

1. SCOPE

1.1 Scope

This technical standard establishes baseline requirements for the structural design, and testing of SRMs. The requirements are limited to cases, solid propellants, insulators, liners, joint seals, ablatives and non-ablatives. These requirements may apply and be tailored to individual programs or projects with the agreement of the appropriate contractual and technical authorities in accordance with NPR 7120.5, *NASA Space Flight Program and Project Management Requirements*.

1.2 Applicability

This Standard is to be used to aid in the development of SRM design and test criteria. It meets the intent of higher-level NASA standards such as NASA-STD-5001.

This standard applies the following: all mandatory actions (i.e., requirements) are denoted by statements containing the term, “shall”, may” or “can” denote discretionary privilege or permission, “should” denotes a good practice and is recommended, but not required, “will” denotes expected outcome, and “are/is” denotes descriptive material.

2. APPLICALBE DOCUMENTS

2.1 Applicable Documents

The documents listed below provide requirements, specifications, standards, and procedures applicable to this standard to the extent specified herein. For each of these documents, the latest revision shall apply unless other revision levels are specifically authorized.

The following lists the documents containing relevant information approved for use by Government Agencies. Other documents used by the contractor as basis for SRM design, in addition to those listed, shall be made available to MSFC upon request.

2.1.1 Government Documents

NASA

NASA-STD-5001	Structural Design and Test Factors of Safety for Spaceflight Hardware
NASA-STD-5019	Fracture Control Requirements for Spaceflight Hardware
NASA-STD-5020	Requirements for Threaded Fastening Systems in Spaceflight Hardware
NASA-STD-6016	Standard Materials and Processes Requirements for Spacecraft
NPR 7120.5	NASA Space Flight Program and Project Management Requirements

SLS-PLAN-003 SLSP Systems Engineering Processes and Requirements

MSFC

MPR 7123.1 MSFC Systems Engineering Processes and Requirements

MSFC-STD-1800 Electrostatic Discharge Control for Propellant and Explosive Devices

MSFC-STD-3598 Foreign Object Damage/ Foreign Object Debris Prevention

2.1.2 Non-Government Documents

Other

CMH-17-1G Composite Materials Handbook Volume I – Polymer Matrix Composites Guidelines for Characterization of Structural Materials

2.2 Order of Precedence

Conflicts between this Technical Standard and other requirements documents shall be resolved by the responsible Technical Authority.

The requirements and standard practices established herein do not supersede or waive existing requirements and standard practices found in other NASA documentation.

3. DEFINITIONS

The following definitions of significant terms are provided to ensure precision of meaning and consistency of usage. In the event of a conflict, the definitions listed below take precedence.

Ablative Liner/Region: A component, or region of a component, that is intended to be thermally degraded, eroded, and/or potentially damaged as part of the design intent as a thermal protection system and is not required for structural strength.

Acceptance Test: A test performed to verify and demonstrate that an SRM is acceptable for flight and performs to specifications. It may also serve as a quality screen to detect deficiencies and to provide the basis for delivery of an end item(s).

SRM Burst Pressure: The pressure level at which rupture or unstable fracture of an SRM occurs.

Closing Joint: Joint gland/surfaces at the seal location that move towards one another during motor operation.

Composite or Bonded Structure: Structure (excluding overwrapped pressure vessels or pressurized components) of fiber/matrix configuration and structure with load-carrying nonmetallic bonding agents, such as sandwich structure or bonded structural fittings.

Damage Threat Assessment (DTA): An evaluation of potential sources of flaws in composite or bonded hardware that includes definition, quantification, and an assessment of the residual strength sensitivity to flaws.

Damage: Flaws, cracks, delamination, pitting, corrosion or other conditions that are potentially detrimental to structural strength**.**

Damage Tolerance (DT): The ability of an SRM to resist failure due to the presence of flaws, cracks, delamination's, impact damage, or other mechanical damage.

Design Safety Factor (DSF): A factor by which limit loads, including MEOP, or stresses, are multiplied by in order to account for the statistical variation of structural resistance and inaccuracies in structural analysis.

Detrimental Deformation: Structural deformation, deflection, or displacement that prevents any portion of an SRM from performing its intended function or that reduces the probability of successful completion of the mission.

Discontinuity Area: A local region of a composite or non-metallic structure consisting of thickness changes, built-up plies, dropped plies, chopped fiber or reinforced regions around fittings, joints, or interfaces. In these regions, the stress state and load distribution may be difficult to characterize by analysis.

Dynamic Joint: Joint gland/surfaces at the seal location that move away from each other a minimum distance greater than 0.001 inch (2 X 0.0005) during motor operation.

Failure: Rupture, collapse, excessive deformation, or any other phenomenon resulting in the inability of a structure to sustain specified loads, pressures, and environments or to function as designed.

Impact Damage: Mechanical damage caused when an object strikes an SRM.

Impact Damage Control: Processes and procedures intended to protect an SRM from damage due to potential impact events in the manufacturing, testing, transportation, ground handling, storage, and assembly.

Limit Load: The worst case anticipated load, or combination of loads, that an SRM may experience during its design service life under all expected conditions of operation.

Maximum Expected Displacement (MED): The maximum predicted increase in the seal gland height during motor operation.

Maximum Expected Operating Pressure (MEOP): The maximum pressure an SRM is expected to experience during its service life.

Maximum Initial Joint Pressure: The applicable pressure used in the determination of MED.

Pressurized Structures: Structures designed to carry both internal pressure and vehicle structural loads.

Proof Factor: A multiplying factor applied to the limit load and/or MEOP to obtain proof load and/or proof pressure for use in acceptance or qualification testing.

Proof Pressure: Application of proof pressure is used to demonstrate satisfactory workmanship and material quality. It is equal to the product of MEOP and the Proof Factor.

Proof Test: A test performed on flight hardware to verify workmanship, material quality, and structural integrity of the design.

Qualification Test: Any required formal contractual testing on flight-quality structures used to demonstrate that all specified design requirements have been achieved.

Residual Strength: The maximum pressure/load that a cracked or damaged structural component is capable of sustaining without rupture.

Residual Threat Determination: An assessment that defines the worst-case credible flaw conditions that composite or bonded hardware will be designed to endure, considering all applicable flaw detection and mitigation strategies that are implemented for flight hardware.

Sealing Joint: A joint between motor components, either fastened or pinned that contains the motor pressure during ignition and operation by preventing the escape of hot combustion gases.

Service Life: The period of time, or cycles, beginning with the manufacturing of an SRM and continuing through all acceptance testing, handling, storage, transportation, and ending with completion of the specified mission.

Static Joint: Joint gland/surfaces at the seal location that stay fixed or move away from each other a maximum distance of 0.001 inch (2 X 0.0005) during motor operation.

Solid Rocket Composite Motor Case (SRCMC): A SRCMC is filament wound case (FWC) design to reduce the weight of a solid rocket motor (SRM) while carrying both the internal pressure and external vehicle structural loads.

Ultimate Load/Pressure: The product of the Limit Load/MEOP and the ultimate design safety factor.

Ultimate Strength (Ftu): The maximum load or stress that a structure or material can withstand without incurring failure.

Virgin Material: A material portion within an Ablative Liners/Regions that has not experienced thermal degradation or loss of mechanical properties due to exceeding the materials glass transition temperature.

4. GENERAL REQUIREMENTS

This section provides the general requirements for the design, analysis, operation and maintenance for an SRM.

4.1 General Structural Assessment Planning

The following shall be developed and submitted as part of program/project documentation:

a. Establish and maintain effective Structural Test and Structural Assessment Plan (SAP) to assess and verify the structural integrity of an SRM.

The SAP should specify how the program's structural strength requirements are followed, the approach used for material allowables and property verification approaches, any alternate approaches, and other structural-related information pertinent to the particular program or project.

b. Ensure that an SRM is designed and constructed using the factors of safety specified herein by way of Section 9.

4.2 Loads and Environments

All relevant loads and environments shall be included in the analysis of SRMs as follows:

a. Anticipated loads, pressures and associated temperatures throughout the defined service life in accordance with specified mission requirements. Conditions considered, but not limited to, include acceptance hydrostatic proof test, ground handling, propellant loading, transportation, storage, integration to core vehicle, and all phases of flight.

b. Thermal effects – including temperatures, thermal gradients, thermal stresses and deformations – as well as changes in the physical and mechanical properties of the materials of construction.

4.3 Strength and Structural Integrity

SRM structural integrity shall be demonstrated by each of the following:

a. Positive margins of safety as determined by analysis and/or test at design ultimate and design limit levels, when appropriate, at the conditions specified herein via Section 4.2 Loads and Environments.

b. Successful operation at Ultimate Loads in the expected environments, including both pressurized and unpressurized conditions, without experiencing failure or damage.

4.4 Structural Stiffness

An SRM shall have adequate structural stiffness to satisfy each of the following items:

c. No detrimental deformation at limit load in the expected operating environments throughout the respective service life.
d. Minimum required stiffness to ensure stable elastic behavior of the vehicle, structural adequacy under transient dynamic loads, and the body-bending frequencies to within the limits imposed by the vehicle flight control system.
e. Acceptable axial growth is to be considered in the design.

4.5 Structural Joints

A structural joint can be a hybrid of both metallic and composite components that is intended to transfer the motor line load from one segment to another. Connections may either be pinned or bolted.

Structural joints shall comply with the following:

a. Minimum design and test factors for metallic components as defined in the agreed program standard.

b. Minimum design and test factors for composite components as given in Section 9 herein.

c. Composite build-ups used for joint transitions should not be classified as a discontinuity.

4.6 Structural Joints – Sealing Elements

The following design and functional requirements were derived from the Space Shuttle Full-Scale Redesigned Solid Rocket Motor Testing evaluation, which if met, would preclude solid rocket motor failure due to joint leaks. Testing included the Joint Environment Simulator (JES) test articles, the Nozzle Joint Environment Simulator (NJES) test articles, the Transient Pressure Test Articles (TPTA), the Development Motors (DM's), the Qualification Motors (QM's), and the Structural Test Articles (STA's) for both pinned and bolted joint configurations. These requirements are applicable to any structural joint with a potential motor leak path.

Joints should be designed to close or be static during motor ignition and operation. If achieved, tracking the displacement and rate will not be necessary

All of the following attributes for SRM structural joints and seals shall be complied with:

a. O-Ring seals are to be used for joints consisting of cylindrical hardware assembled with pins or bolts:

   (1) If the joint design permits, face seal configuration is the preferred orientation.

   (2) Joint gap displacements should be minimized for dynamic joints.

b. Redundant and verifiable seals provided for each SRM leak path, including:

   (1) Both the primary and secondary seals are to provide independent sealing capability through the entire ignition transient and motor burn without evidence of blow-by or erosion.

   (2) Sealing to accommodate any structural deflections that may occur during its service life.

   (3) Seals to be capable of operating within a temperature range resulting from all natural and induced environments as specified, all manufacturing processes, and any motor induced environments and the maximum specified assembly/storage time for the joint or motor.

   (4) The seal verification approach must not degrade the performance or integrity of the system.

   (5)

(6) Each seal maintains, without pressure assistance, sealing capability with a joint displacement equal to the appropriate tracking factor times the MED. *Displacement will be applied in direct ratio to motor pressure-time relationship.*

The 'tracking factor' of 2X displacement rate ensures that the response of the seal exceeds that of the joint and that seal contact is maintained with sealing surfaces during dynamic joint displacement events.

(7) A single O-ring is to be capable of retaining SRM MEOP, acceptance proof test pressure, and any qualification test pressure.

Design that can allow a single, credible failure of one component in a motor sealing system while still supporting safe motor operation.

c. Structural joints with sealing elements are to be protected from the environments that could impact performance and structural as specified in Section 4.2.

(1) The joint protection system function is to prevent accumulation of rain into the field joints from the time of assembly of the SRM until termination of flight.

(2) The field joint protection system is to remain intact throughout flight.

(3) Seal surface temperatures are not to exceed the limits determined by the seal material's structural and/or thermal capabilities

Bolted joint configurations must also consider:

d. Use NASA-STD-5020 for threaded fastening system design and joint separation in preloaded joints and document any alternative methods in the SAP.

(1) Threaded fastened joint factors of safety per NASA-STD-5001 Table 1.

e. Torque limits are to be established to ensure the following:

(1) Sufficient compression is applied to maintain sealing.

(2) Adequate volume exists at full compression to prevent loss of preload.

Torque may need to be re-applied after a predefined time period to allow the seal to relax and achieve the final torque value to ensure proper compression.

4.7 Structural Joints – Thermal Barriers

Thermal barriers ensure that no degradation to downstream critical joint components will occur during motor operation. Current O-ring requirements do allow "heat-effect" on the primary or secondary pressure seals. A thermal barrier is designed to minimize the direct exposure of the pressure seals to the hot combustion gases that are produced during motor operation. Thermal barriers are situated within the assembly gaps between the motor chamber and pressure seals. Common thermal barrier systems that may be used in pressurized joints are barrier O-rings, Carbon Fiber Rope (CFR), insulation rings, or J-legs. Joint fillers, such as polysulfide, Room Temperature Vulcanizing (RTV), etc. have been used as well.

Joints that use large elastomeric O-rings, as pressure seals, shall be designed to include a thermal barrier and meet the following criteria:

a. Combustion gas will not degrade the seals or downstream metal surfaces.

b. Capable of operating within a temperature range resulting from all natural and induced environments, all manufacturing processes, and any internal motor induced environments.

c. Minimize thermal effect of gas flow:

  (1) Evidence of erosion or heat effects on the barrier is allowed.

  (2) No heat effects are allowed on primary seals.

d. Accommodate any structural deflections, which may occur during motor operation.

e. Method of test and inspection will not degrade the performance or integrity of the system.

f. No shedding of fibrous or particulate matter during assembly, such that the system performance or joint seal performance is degraded.

g. Ensure system performance and joint integrity is maintained during the assembly process.

h. Thermal barriers constructed from insulation and CFR will control the thermal effects of combustion products with an appropriate margin as agreed to by MSFC.

4.8 Nozzle Non-Metallics

Due to the current inability to perform validated stress analyses for thermally degrading materials, the performance of Ablative Liners/Regions should be assessed by subscale and full-scale testing. It should be noted that testing may not necessarily demonstrate structural safety factors due to the inability to thermally overload representative configurations, however, this limitation should not prevent the verification of margin of the ablative material during all phases of manufacturing, transportation and handling prior to launch, and mechanical flight loads applied to an un-eroded profile. Furthermore, the structural analyses of virgin material contained within ablative liners are not always quantitatively accurate, but these analyses are useful for identifying areas for failures modes and effects assessments, dedicated analog testing, and for identifying areas for post-fire inspection of full-scale motors.

These materials can exhibit brittle fracture modes; therefore, thermal and residual stresses are intended to be treated as primary loads. Accordingly, the assessment of failure for propagation of a crack-like defect initiated in the Ablative Liners/Regions, into the Non-Ablative Liners/Regions and/or bond line is to be considered.

Any Nozzle non-metallic liners shall comply with the following requirements:

a. For Non-Ablative Liners/Regions:

  (1) Maintain a 1.40 factor of safety against failure.

  (2) No unstable initiation of crack-like defects such as de-bonds or delamination below 1.00 times limit load.

  No unstable initiation of crack-like defects such as de-bonds or delamination should occur at or below 1.40 limit load. Component specific interpretation should be documented in the applicable SAP.

  (3) All applicable thermal and residual stresses are to be included in the analysis.

b. For Ablative Liners/Regions:

(1) Ablative Liners/Regions will be identified in the SAP.

(2) Maintain a 1.40 factor of safety against failure due to mechanical loads (i.e. combined loads from pressure, inertia, residual, and vectoring) applied to an un-eroded profile.

(3) No unstable initiation of crack-like defects such as de-bonds or delamination below 1.00 times limit load.

No unstable initiation of crack-like defects such as de-bonds or delamination should occur at or below 1.40 limit load. Component specific interpretation should be documented in the applicable SAP.

(4) All applicable thermal and residual stresses are to be included in the analysis.

(5) No failure initiating from Virgin Material within Ablative Liners/Regions.

5. MATERIALS REQUIREMENTS

This section provides the general requirements, as outlined in NASA-STD-6016, for the design and analysis with respect to manufacturing and processing for an SRM.

5.1 Composite Material Selection

The composite materials selected for the design shall be evaluated with respect to the material processing, fabrication methods, manufacturing operations, refurbishment procedures and processes, operating environments and other pertinent factors which affect the resulting strength and stiffness properties.

Because of the close proximity to energetic propellants the mitigation of electrostatic discharge (ESD) is to be considered in the design of the SRM. MSFC-STD-1800B 5.3.2 states that composite motor cases should contain either graphite, or be coated with conductive paint, or contain conductive insulation, or other ESD shielding, and have a surface resistivity less than $10^9\ \Omega$ *per square.*

5.2 Composite Material Characterization

The properties of the composite materials selected shall be characterized in sufficient detail to permit reliable and high confidence predictions of the structural performance in their expected operating environments as cited in SAE CMH-17.

5.3 Composite Strength Design Allowables

SRM strength design allowables shall comply with the following:

a. Unless otherwise specified, composite material’s strength allowable values will be determined from burst testing of sub-scale rings, sub-scale pressure vessels or full-scale SRMs.

b. If data is used from other than full-scale motor cases, an analysis of test will be conducted to demonstrate the relevance of the data to full-scale SRMs

5.4 Composite Fabrication and Process Control

The composite fabrication process shall be controlled and documented to establish:

a. Certification and traceability of materials that demonstrate acceptable variable ranges to ensure repeatable and reliable performance.

b. Key process parameters that will be identified to control or eliminate detrimental conditions in the fabricated article.

c. Processing environments that will be specified for control of contamination and providing consistent development of final properties for composite components.

6. QUALITY ASSURANCE

6.1 General

An SRM shall comply with all Quality Assurance requirements:

a. A quality assurance program is to be established based on a comprehensive study of the product and engineering requirements.

   Procedural requirements are provided in MPR 7123.1 and are communicated through SLS-PLAN-003, system engineering management plan (SEMP) as required by contract, including nonconformance control as provided in section 8.5

   This will ensure that the necessary Non Destructive Evaluation (NDE) and acceptance testing are performed effectively and to verify that the hardware meets relevant requirements herein.

b. An Inspection Plan created and maintained to specify appropriate inspection points and techniques, the certification and training of inspectors, for use throughout the program that will include material procurement, fabrication, assembly, acceptance-proof test, propellant loading, shipment, storage, and operation.

   In establishing inspection points and inspection techniques, give consideration to material characteristics, fabrication processes, design concepts, contamination control, and accessibility for inspection of defects.

c. The program should demonstrate that materials will maintain structural integrity during the life of the hardware.

   Degradation is undesirable and could reduce margins of safety or impede the design intent. The overall life includes, but is not limited to, material processing, fabrication, inspection, acceptance testing, propellant loading, shipping, storage, launch pad assembly, or operational use.

d. If inspections reveal structural damage or defects exceeding permissible levels, the hardware must be assessed by a Material Review Board (MRB) for repair, refurbishment, or replacement. All repaired or refurbished hardware is to be re-certified by the applicable testing procedures to verify structural integrity and to establish suitability for service.

e. SRMs are to be protected against damage from the transportation and storage environments and reasonable threats, such as impact. Critical environments, such as temperature and humidity extremes, excessive vibration, and shock during transportation, will be recorded using proper instrumentation.

f. A foreign object debris prevention plan is to be development in accordance to MSFC-STD-3598 to ensure proper performance of all composite rocket motor materials and pressurized joint sealing systems

g. An ESD control program is to be prepared and submitted for approval in accordance to the requirements listed in MSFC-STD-1800 to protect against personnel injury, property damage, and/or loss of objectives due to discharge of electrostatic energy and subsequent initiation of propellant during all phases of manufacturing, test, inspection, handling, shipping and storage.

6.2 Impact Damage Control for SRCMC

a. SRCMCs shall comply with Impact Damage Control requirements as follows:An Impact Damage Mitigation Plan (IDMP) developed in accordance with NASA-STD-5019A Section 7.4.2:

   (1) Define, document, and implement impact protection and/or detection strategies that are used for the flight hardware to diminish targeted damage threats identified by the DTA.

   (1) Prescribe when and how impact protection and/or detection strategies are to be used for flight hardware to mitigate credible damage or threats.

7. STRUCTURAL ANALYSIS REQUIREMENTS

7.1 Strength Analysis

The hardware developer shall perform strength analyses and document them to clearly demonstrate that strength requirements have been fulfilled.

The strength analysis reports should clearly identify such items as geometric descriptions of each component, identification of all applied loads, types of materials and applicable strength allowables, environments and effects, proper identification of references for all analysis inputs, and a summary of all calculated margins of safety for representative failure modes.

7.2 Buckling Analysis

All structural items subjected to significant in-plane stresses (compression and/or shear) under any combination of ground loads, flight loads, or thermal loads shall be analyzed for buckling failure as follows:

a. Use Ultimate Loads to address any potential general, local, or panel instability.

b. If a loading condition tends to alleviate buckling, then use the un-factored load in combination with other factored loading conditions.

c. Account for any differences between idealized model geometry and the physical structure, including boundary conditions.

7.3 Material Allowables

Strength allowables and damage tolerance design values for use in the design of SRMs shall be determined as listed below:

Relevant Composite Materials: Fiber reinforced polymer matrix composites, sandwich construction (bonded metallics and non-metallics), bonds between metallic or composite parts, filament wound motor cases, and carbon-phenolic and carbon-carbon nozzles.

a. For composite materials:

   (1) Strength allowables used for qualification of flight hardware determined using A-Basis statistical techniques as defined in CMH-17 or an MSFC-approved equivalent approach.

   (2) Composite damage tolerance and no-growth threshold design values used for qualification of flight hardware determined from B-Basis statistical techniques as defined in CMH-17 or an MSFC-approved equivalent approach.

b. For metallic materials, strength allowables used for qualification of flight hardware determined using A-basis statistical techniques as defined in NASA-STD-6016 or an MSFC-approved equivalent approach.

7.4 Geometry

Stress calculations and analysis of structural members shall use worst-case thickness allowed by engineering drawing tolerances:

a. For rupture failure modes, use nominal or 1.10*minimum thickness, whichever is less.

b. For buckling failure modes, use nominal or 1.05*minimum thickness, whichever is less.

Careful consideration should be given to thicknesses and its contribution to the mode of failure. Furthermore, they are not necessarily a requirement for proof and testing in that thickness varies in production.

Using nominal thickness for composites is usually sufficient as the ultimate strength is defined by the fiber strength and matrix orientation.

7.5 Methodology Verification and Model Sensitivities

Analysis methods and model sensitivities shall be evaluated to establish the accuracies in the prediction of structural performance:

a. If un-conservative results are indicated, the analysis assumptions will be revisited, the final analysis re-evaluated, and risk mitigation actions established.

b. Model sensitivities should be examined to identify influential design parameters and non-linearity departure points.

7.6 Probabilistic Methods

Any proposed use of probabilistic criteria to supplement deterministic factors of safety shall be submitted for approval, on a case-by-case basis, to the appropriate contractual and technical authority.

Current standard structural verification criteria are deterministic and experience has shown these criteria to be adequate. These design factors of safety and test factors intend to compensate for any uncertainties related to strength analysis. The probabilistic method uses knowledge, or less conservatively, assumptions of the statistical variability of the design *variables to select design criteria for achieving an overall success confidence level. Statistical assessments of uncertainty in model inputs, design parameters, and measurement errors are generally expected to be incorporated as worst-case scenarios (i.e. "A" basis or 3-sigma bounding assumptions) into all structural and performance analyses and appropriately documented for MSFC engineering concurrence.*

7.7 Structural Joint Failure Modes Assessment

At a minimum, the following failure modes should be addressed:

a. Structural failure leading to inability to contain pressure or inability to allow proper vectoring for nozzle joints, caused by insufficient structural capability due to inadequate configuration, materials, or thermal protection.

b. Thermal failure leading to joint leakage, caused by sufficient gas flow to erode and burn through the sealing element(s) due to:

(1) Insufficient thermal protection and/or a gap between insulators that is too large or opens during motor operation.

(2) Thermal conduction heating of components which exceeds the structural thermal capability, resulting in "collapse" of the seal(s) or structural elements.

c. Seal performance failure leading to joint leakage caused by "blow-by" or a sustained leak due to:

(1) Large gap/deflection at the location of the seal(s) during motor pressurization, and insufficient seal material tracking capability at the extreme squeeze and temperature limits.

(2) A breach of the seal footprint due to defects or Foreign Object Debris (FOD) across the seal or seal surfaces.

d. Footprint breach failure caused by FOD or defect across the seal footprint when exposed to motor pressure, in turn caused by inadequate leak test or detection screening.

7.8 Structural Joint Maximum Expected Displacement

The MED for sealing joints shall be assessed by analysis with requirements as follows:

a. Analysis must be performed with joint pressure applied to the thermal barrier, Primary, and secondary seal glands.

(1) Primary and secondary analysis must use joint tracking factor listed in Table 1

(2) Thermal barrier analyses may use a joint tracking factor of 1.0.

The analysis assumes an upstream seal or barrier has been compromised allowing gas flow.

b. Analytical predictions are to use worst on worst conditions, unless otherwise agreed upon by appropriate technical authorities.

c. Application of maximum initial joint pressure is to be applied to the entire seal gland volume:

(1) No leakage or "blow-by" allowed at the barrier seal, pressure is to be applied to the barrier seal.

(2) If the barrier seal is allowed to leak or no barrier is present, pressure is to be applied to the primary seal.

(3) Pressure less than Maximum Initial Joint Pressure may be used between seals if verified by test.

d. MEOP is to be used for the Maximum Initial Joint Pressure, unless otherwise specified by seals design.

e. MED is to be assessed at the center of the seal groove.

(1) *MED evaluation are to include the influence of pressure, pressure penetration, geometries, joint stiffness, external loading, displacement convergences and frictional effects.*

(2) *Pinned joints are to include the effects from joint interference, clearance, and shims.*

(3) *Bolted joints are to include preloads and joint surface flatness.*

f. Tracking factors are to be applied to the MED analysis accordingly as shown below:

Table I. SRM Joint Tracking Factors

Joint Type	Analysis Type	Tracking Factor
Pinned or Non-bolted	Certification	2.0
Bolted	Certification	1.4
Bolted or Non-bolted	Independent Sealing	1.0

A Joint is classified as Pinned, bolted, or non-bolted. Non-bolted joints are the use of threads, adhesives, retaining rings, or other means of retention in place of pins or traditional bolts to provide the clamping force.

8. TESTING AND VERIFICATION REQUIREMENTS

Design verification requirements for all SRMs include margin of safety demonstration, , and qualification testing, including pressure cycling testing, leak check, and burst test.

8.1 General Requirements

All SRM testing shall comply with the following requirements:

a. Strength verification tests for structures designed to test factors of safety are given herein in Section 9, except where noted.

b. Test factors adjusted as necessary to account for differences between test and flight environments.

c. All test plans and requirements to be coordinated with and approved by the MSFC Engineering Directorate prior to implementation as required by contract per MPR 7123.1.

d. Test results and evaluations for certification are to be formally submitted to MSFC.

e. Results from development, component, and subscale structural tests are to be made available to MSFC upon request.

f. MED testing is to be performed on full scale hardware.

   (1) Measurements to be taken at or as close to the sealing location as permissible.

   (2) Displacement locations and number are to be carefully selected in order to provide statistically significant results to account for variations of geometry and assembly.

8.2 Test Loading

Test loads shall duplicate or envelope all flight loads and include pressure and temperature effects as follows:

Numerous components or elements are loaded by a combination of the inertia, dynamic pressures and temperatures during flight that cannot be faithfully simulated during testing, especially during static firings. It is understood that it is difficult to precisely duplicate the predicted flight loads, and equally difficult to simulate the reactions during flight. Engineering disciplines should work closely with their MSFC counterparts in the planning and development for such verification testing to ensure compliance.

a. Tests accomplished at the yield and ultimate levels specified by the factors of safety herein in Section 9.0.

b. No detrimental deformations beyond the elastic limit at or below yield load and no structural failure at or below ultimate load.

c. Test fixtures designed to permit application of loads or hydro-proof pressure without jeopardizing the flightworthiness of the hardware.

d. The test plan formulated to provide sufficient data to ensure proper application of input loads, pressures, environments, and vessel responses to allow assessment against accept/reject criteria.

e. Loads to be applied as close as practicable to actual flight loading time, with a dwell time not longer than necessary to record test data unless otherwise noted.

8.3 Acceptance Testing

All acceptance testing and procedures shall comply with:

a. All SRMs hydro-proof tested to include:

   (1) No leaks, rupture, or experienced damage during acceptance testing.

   (2) Acceptance proof tests performed at ambient temperatures and humidity conditions unless specific design conditions dictate otherwise.

   (3) A minimum hydro-proof pressure of 1.05 x MEOP.

   (4) A maximum hydro-proof pressure not to exceed 85% of average ultimate strength for composite motor cases.

This is to preclude the proof pressure causing SRM damage such as fiber breakage, interface debonding, delamination, and matrix cracking that cannot be adequately detected by presently available techniques.

a. SRMs subjected to visual inspection and NDE both before and after proof testing, per the Inspection Plan from Section 6.1b herein.

b. SRMs subjected to leak checks before and after hydro-proof testing, including:

   (1) Leak check pressure not to exceed MEOP.

   (2) The test duration will be sufficient to detect any leakage as defined in the planning

   (3) Leak check conducted using a certified and calibrated system.

c. Special considerations to include:

   (1) Environmental Correction Factor – If SRM strength is lower at the maximum use conditions, then the proof test pressure shall be increased to account for the effects of the flight environments on the mechanical strengths demonstrated by coupon tests.

   (2) External Loads – In cases where there are significant load conditions in addition to pressure, conduct a combined proof-pressure and external-loading test or increase the test pressure to encompass all loads.

8.4 Qualification Testing

All testing shall be performed in accordance with the following requirements:

a. Qualification tests of the flight article design requires separate units that are representative of the operational configuration, including all materials, manufacturing processes, and significant structural details

Specific rationale should be documented in the applicable SAP.

b. As a minimum, the following testing conducted on all new or modified SRM's:

   (1) Combined Loads and Pressurization Testing – Structures representative of flight hardware tested in accordance with Section 4.2 herein and a minimum demonstrated strength for combined loading of 1.4.

   (2) Bifurcation Testing – Structures representative of flight hardware tested in accordance with Section 4.2 herein and a minimum demonstrated strength for instability of 1.4.

   (3) Pressure Cycle Testing – Performed to include:

      i. SRMs to sustain a minimum design burst pressure of 1.4 x MEOP during qualification burst testing without collapse or rupture.

      ii. Application of external loads in combination with internal pressures during testing evaluated based on relative magnitude and/or destabilizing effect of stresses from external loads.

      iii. If the application of external loads is needed, the load shall be cycled to limit load level for four times the predicted number of cycles at the most severe design condition.

iv. If limit-combined tensile stresses are enveloped by test pressure stress/strain, the application of external loads may not be required.

(4) Burst Testing – Burst testing conducted to verify compliance to the requirements per Section 9.0 herein, to include:

i. A minimum design burst strength of 1.4 x MEOP.

ii. Upon completion of the hold period, increase pressure at a controlled rate until either case rupture or when pressures reaches a predetermined limit so as not to put the facilities or personnel at risk.

(5) Joint Strength Testing – Testing conducted to verify that the relevant structural test factor was achieved and then tested to failure to verify failure criteria.

(6) Joint Functionality Testing – Testing conducted to verify pinned joint movements such as rotation, expansion, growth, and gap openings. Independent sealing capability demonstrated by test for both primary and secondary seals.

8.5 Test Discrepancy and Retesting Criteria

A test discrepancy is a functional or structural anomaly that occurs during testing that either fails to meet the specified objectives or indicts the test validity. These may include – but are not limited to – premature operation, failure to operate, termination of operation before the prescribed time, not meeting functional performance, not following test procedures, or any issues related to test setup, test instrumentation, supplied power, and computer software.

All SRMs shall comply with the following test discrepancy and retesting criteria:

a. Retesting will be required under the following circumstances:

(1) If a test discrepancy occurs as described above.

(2) If there are significant design, material, or manufacturing changes made between the discrepant test article and flight hardware.

b. Retesting may be required under the following circumstances:

(1) Determining compliance of a test item to a specification or requirement.

(2) Assessing the readiness of test items for integrated system testing.

9. SAFETY AND TEST FACTORS

The general and qualification test factors of safety specified herein shall be the minimum for SRMs. Proposed safety factors different from those specified herein would require approval by the MSFC Engineering Directorate prior to use.

Table II. SRM General Factors of Safety

STRENGTH(1)					MATERIAL	DAMAGE TOLERANCE		
Design Ultimate Factor of Safety		Test Factor				Life		Damage Approach
Uniform	Discontinuity	Qualification	Proof Test Limits *Min.*	Proof Test Limits *Max.*(5)		Method	Factor	
1.40(2,4)	1.40(2,3)	1.40 1 w/ cycles	1.05	85% Ftu	A-basis (Structure) B-basis (DT)	Test and/or Analysis	4	Protection, DT, Demo of Burst

(1) Static strength factor of safety requirements applies throughout hardware service life.
(2) No unstable initiation of crack-like defects such as de-bonds or delamination below 1.00 times limit load. Component specific interpretation should be documented in the applicable SAP.
(3) Characterize strength by representative test.
(4) Joint structures tested to failure.

(5) Composite Only

Table III. Qualification Test Factors of Safety
(Burst, Proof and Pressure Cycle Requirements)

Test	Burst	Proof	Pressure Cycle
Article	DSF x MEOP* → Failure	DSF x MEOP	4 Service life cycles

**After demonstrating no burst at the design burst pressure test level, increase pressure to until burst or facility limits and record actual burst pressure.*

10. ALTERNATE APPROACHES

In the event that a particular requirement of this technical document cannot be met for a specific spaceflight structure or hardware component, an alternative or modified approach shall be proposed to verify the strength adequacy of the design. This includes:

a. A written assessment that justifies the use of the alternate approach to be prepared by the organization with primary responsibility for development of the hardware.

b. The assessment to be submitted to MSFC for approval prior to the implementation of the alternative approach.

APPENDIX A. ACRONYMS

CFR	Carbon Fiber Rope
CMH	Composite Materials Handbook
DM	Development Motors
DSF	Design Safety Factor
DT	Damage Tolerance
DTA	Damage Threat Assessment
ELV	Expendable Launch Vehicles
Ftu	Ultimate Tensile Strength
IDMP	Impact Damage Mitigation Plan
JES	Joint Environment Simulator
MED	Maximum Expected Displacement
MEOP	Maximum Expected Operating Pressure
MRB	Material Review Board
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NDE	Non Destructive Evaluation
NJES	Nozzle Joint Environment Simulator
NPR	NASA Procedural Requirements
QM	Qualification Motors
RSRM	Shuttle's Reusable Solid Rocket Motor
RTV	Room Temperature Vulcanizing
SAP	Structural Test and Structural Assessment Plan
SLS	Space Launch System
SRCMC	Solid Rocket Composite Motor Cases
SRM	Solid Rocket Motor
STA	Structural Test Articles
STD	Standard
TPTA	Transient Pressure Test Articles
VDT	Visual Damage Threshold