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Evaluation and Test Requirements for Liquid Rocket Engines

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Jeffrey Murphy[1], Nacer Thomas[1], Zachary Kier[2], James Tuck-Lee[3], and Vinay K. Goyal[4]
[1]Propulsion Department, Vehicle Performance Subdivision
[2]Thermostructures, Structures Department
[3]Structures Department, Structural Mechanics Subdivision
[4]Launch Systems Division, Launch and Enterprise Operations

Prepared for:
United States Space Force
Space Systems Command
483 N. Aviation Blvd.
El Segundo, CA 90245-2808

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Jeffrey J. Murphy, Nacer Thomas, Zachary Kier, James P. Tuck-Lee, Vinay K. Goyal

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The Aerospace Corporation
Vehicle Systems Division
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14. ABSTRACT

Liquid propellant rocket engines enable rocket vehicle design and space launch capability. These systems are susceptible to numerous potential failure modes, which can produce catastrophic results. Furthermore, engine testing and test hardware costs have historically represented a major portion of engine development program costs. For these reasons, an engine development test and evaluation standard was developed to convey best practices and establish consistent requirements across the industry to support the successful development and qualification of liquid rocket engines. Non-binding guidelines (JANNAF-GL-2012-01-R0, Test and Evaluation Guidelines for Liquid Rocket Engines, Joint Army Navy NASA Air Force Liquid Propulsion Subcommittee Test Practices and Standards Panel, December 2012) were previously developed, and the release of TR-RS-2017-00026 (SMC-S-025) established requirements. This is an update to TR-RS-2017-00026, incorporating lessons learned from collaboration with launch vehicle and liquid rocket engine contractors subsequent to the initial release. These lessons draw upon historical guidelines and recent experience to provide best-in-class liquid rocket engine qualification practices.

15. SUBJECT TERMS
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Document History

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TR-RS-2017-00026, 16 Jun 2017 (SMC-S-025, 26 Jul 2017)	Original release of *Evaluation and Test of Liquid Rocket Engines* standard.
TOR-2021-01879, 10 May 2022	First version of proposed update to SMC-S-025, including documentation of the internal Aerospace Corp. stakeholder review of the updates that took place from 25 Aug 2021 through 15 Oct 2021. The following is a summary of the changes: § 4.1 – General Test Considerations Clarified that testing should encompass potential variation in propellant composition and have flight-representative interfaces § 4.4 – Number of Total Tests Clarified guidance regarding onset of engine qualification testing relative to completion of development testing § 4.6.1 – Material Selection Clarified guidance regarding properties considerations for additive manufacturing § 4.6.2 – Loads Clarified recommended practice for analytically establishing Maximum Design Condition Loads § 4.6.3 – Factors of Safety Clarified fitting factor recommendation to address non-uniform loading occurring in a group of fasteners, guidance with respect to qualification by analysis, and acceptability of local yielding during proof § 5.3 – Strength Assessment Clarified guidance regarding characterization of multi-axial states of stress § 5.3.4 – Joints and Seals Modified requirement for NASA-STD-5020A under [5.3.4-2]; added clarification regarding locking or secondary retention features; added requirement [5.3.4-4] regarding leakage during qualification test program § 5.4.3 – Damage Tolerance (Safe-Life) Assessment Updated requirement [5.4.3-1] damage tolerance (safe-life) verification approach, and added guidance regarding damage tolerance evaluation approach § 5.6 – Bellows Complete update on requirements to reflect bellows “lessons learned” since initial release, and clarified guidance regarding fatigue testing, as well as post-proof destructive testing (initially and during production) to identify hardware damage from testing and manufacturing process drift § 7.2.5 – Thrust and Mixture Ratio Excursion Tests Clarified guidance regarding flight box definition, MR/PL bin development, and guidance regarding development of “worst

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	case" conditions to ensure realistic (and not overly conservative) bounding of engine service life conditions § 7.3.5.4 – Shutdown Transients Clarified guidance on development of adequate data to characterize shutdown transients (shutdown impulse) § 7.9.2 – Post-Test Inspections Added requirement regarding inspection procedure development in [7.9.2-1]; clarified guidance regarding safe-life assessments relative to NDE of flaws during inspection Appendix B Added new section describing definition of "keep-out" zones
TOR-2022-01071, 5 Apr 2022	Update to TOR-2022-01879 based on internal review comments. In addition to a number of changes to improve the clarity of requirements and guidance, the following changed were made: § 4.3.1 – Number of Verification Engine Samples Clarified definitions of "qualification" and "verification" engine and edited section to ensure consistent use of terms; separated out qualification engine characteristics into separate requirement [4.3.1-1] § 4.6 – Material Selection Further clarified guidance on materials properties for additively manufactured materials; clarified requirement [4.6.1-6] § 4.6.2 – Loads Updated reference to SMC-S-005 to new version (TR-RS-2022-00005, in preparation) § 5.1 – Structural Model Updated [5.1-1] to be more explicit regarding characteristics of "valid" numerical models § 5.6 – Bellows Updated flow-induced vibration analysis/testing requirement, [5.6-4] § 6.12 and § 7.6.5 – Electromagnetic Compatibility Tests Added direct reference to SMC-S-008 test requirements § 7.3.5.4 – Shutdown Transients Added guidance that testing should address in-flight abort § 7.6.1 – Thermal Environment Clarified requirements and guidance on what constitutes a "correlated" thermal model § 7.9.4 – Gas Liquefaction Control Moved demonstration of insulation repair process into a separate requirement for clarity § 7.9.5 – External Icing Requirement [7.9.5-2] rewritten for clarity § 7.10.2 – Mass Properties Reference to AIAA mass properties standard removed from requirement

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This document	Version of TOR-2022-01071 for release. No external review comments were received. References to TR-RS-2022-00005 were updated to TR-RS-2023-00005 to reflect actual numbering upon release of that standard.

Background

Liquid propellant rocket engines enable rocket vehicle design and space launch capability. These systems are susceptible to numerous potential failure modes, which can produce catastrophic results. Furthermore, engine testing and test hardware costs have historically represented a major portion of engine development program costs. For these reasons, an engine development test and evaluation standard was developed to convey best practices and establish consistent requirements across the industry to support the successful development and qualification of liquid rocket engines. Non-binding guidelines (JANNAF-GL-2012-01-R0, Test and Evaluation Guidelines for Liquid Rocket Engines, Joint Army Navy NASA Air Force Liquid Propulsion Subcommittee Test Practices and Standards Panel, December 2012) were previously developed, and the release of TR-RS-2017-00026 (SMC-S-025) established requirements.

This is an update to TR-RS-2017-00026, incorporating lessons learned from collaboration with launch vehicle and liquid rocket engine contractors subsequent to the initial release. These lessons draw upon historical guidelines and recent experience to provide best-in-class liquid rocket engine qualification practices. In the General Requirements section there is new information and references pertaining to additive manufacturing, and maximum expected operating pressure requirements. In the Structural Analysis section there is new information regarding factors of safety, damage tolerance, and bellows requirements. In the Engine Requirements section there is added information regarding the definition and qualification of the flight/trim box and testing requirements. Additionally, there are numerous clarifications and editorial revisions made throughout the document.

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1. Scope of this Standard

This Standard establishes test and evaluation requirements related to the development, qualification, and production unit acceptance of liquid propellant rocket engines and associated propulsion systems. Requirements include those associated with integrity, strength, life, interface conditions, and functional performance. These requirements should be understood and applied early in the design phase to enhance success in the development, test, and evaluation phases. Tests generally include component-level testing, engine system-level testing, and vehicle stage-level testing. Development is addressed herein largely to the extent that it increases the likelihood of successful qualification and/or provides additional necessary verification samples. Thus, development requirements outside those applicable to minimum verification requirements are treated less rigorously. Evaluation includes relevant and appropriate analyses for verification of requirements. In some cases, requirements are expressed by reference to other standards.

1.1 Purpose

The requirements in this Standard should be used to define a test program, primarily for qualification and production acceptance, that will appropriately verify the design, identify latent defects, ensure adequate functional performance, and help ensure a high level of confidence in achieving successful launch missions. It is expected that the overall program will include a thorough development program and use other good engineering practices to help maximize the success of the test program.

1.2 Application

This document is intended for compliance in government acquisition programs, and the requirements herein are to be flowed, as applicable, throughout the supply chain. The test requirements herein focus on design verification and the identification of latent defects to help ensure a high level of confidence in achieving successful space missions. Unless otherwise specified by the Approval Authority, the requirements herein are intended to apply to new or modified liquid rocket engine (LRE) designs, new or modified LRE unit designs, use of existing LRE designs in a new application or environment, and procurement from a new supplier or manufacturing location.

This Standard applies to LREs and associated propulsion systems for expendable and re-usable applications. Relevant LREs include those using pump-fed or pressure-fed designs, with various propellant combinations including hydrogen/oxygen, hydrocarbon/oxygen, storable, and monopropellants. This Standard addresses development, qualification, acceptance, and pre-launch testing for main propulsion systems (i.e., steady-state, non-pulsing, thrust greater than 4,500 N / 1,000 lbf) for space launch vehicles (including booster, upper stage, and in-space propulsion). This Standard focuses on testing of an LRE at the individual engine and integrated propulsion system levels but includes lower-level testing where warranted. Here, the LRE is defined to include those components from the engine inlet flanges to the thrust chamber nozzle, including all interface connections to the launch vehicle and launch facility.

This Standard is intended to be used with other mission assurance documents listed in Section 2, including TR-RS-2014-00016 (SMC-S-016) [1] and TR-RS-2023-00005 [2]. The requirements in this Standard take precedence over documents referenced in Section 2 in the event that conflicts are encountered. Within the nomenclature of TR-RS-2014-00016 [1], an LRE is categorized as a subsystem. Within the nomenclature of TR-RS-2023-00005 [2], an LRE is categorized as a pressurized system, meaning there are pressure-containing elements within the LRE. This Standard uses these documents and provides more detailed and specific requirements applicable to LREs and their integration.

All requirements in this document are numbered and indicated by the word "shall," thereby differentiating requirements text from explanatory or guidance text. All guidance text is presented in italics.

1.3 Tailoring

The requirements contained herein may be tailored based on the project-specific acquisition situation/environment, design complexity, design margins, vulnerabilities, technology state of the art, in-process controls, mission characteristics/criticality, lifecycle cost, number of vehicles involved, prior usage, and acceptable risk. All tailoring of requirements must achieve the intent of this Standard. As part of the tailoring process, sufficient rationale with supporting technical data for each tailored requirement must be documented. Tailoring rationale should include risk assessment per the process detailed in MIL-STD-882E [15]. The tailoring rationale and risk assessment shall be subject to review and acceptance by the Approval Authority. Otherwise, the requirements of this document stand as written.

Herein, requirements for engines used on vehicles transporting personnel are intended to be the same as those for engines used on vehicles transporting only hardware. Engines used on vehicles transporting personnel, however, may have additional program-specific verification and/or safety requirements to be consistent with the established program-specific risk levels for mission success and flight crew safety.

2. Reference Documents

2.1 Applicable Documents

The following documents, of the issue identified, form a part of this Standard to the extent specified herein. The documents are listed in order of occurrence within this Standard. Where conflicts exist between the requirements of other documents and this Standard, the requirements of this Standard take precedence.

1.	TR-RS-2014-00016	*Test Requirements for Launch, Upper Stage and Space Vehicles*, The Aerospace Corporation, 25 Jun 2014. (SMC-S-016, Air Force Space Command Space and Missile Systems Center Standard, 5 Sep 2014.)
2.	TR-RS-2023-00005	*Space Flight Pressurized Systems*, The Aerospace Corporation, 5 Jan 2023. (Expected to supersede SMC-S-005, Air Force Space Command and Missile Systems Center Standard, 28 Feb 2015.)
3.	CPIA Publication 655	M. D. Klem and R. S. Fry, *Guidelines for Combustion Stability Specifications and Verification Procedures for Liquid Propellant Rocket Engines*, The Johns Hopkins University Chemical Propulsion Information Analysis Center, Jan 1997.
4.	ANSI/AIAA S-080A-2018	*Space Systems* - *Metallic Pressure Vessels, Pressurized Structures, and Pressure Components*, American National Standard, 20 Mar 2018.
5.	AIAA S-110-2005	*Space Systems – Structures, Structural Components, and Structural Assemblies*, American Institute of Aeronautics and Astronautics, 12 Jul 2005.
6.	ANSI/AIAA S-081B-2018	*Space Systems – Composite Overwrapped Pressure Vessels (COPVs)*, American National Standard, 20 Mar 2018.
7.	AIAA S-113A-2016	*Criteria for Explosive Systems and Devices on Space and Launch Vehicles*, American Institute of Aeronautics and Astronautics, 28 Nov 2016.
8.	AIAA S-114A-2020	*Moving Mechanical Assemblies for Space and Launch Vehicles*, American Institute of Aeronautics and Astronautics, 14 Jun 2021.
9.	TR-RS-2015-00011	*Parts, Materials, and Processes Control Program for Expendable Launch Vehicles*, The Aerospace Corporation, 21 May 2015. (SMC-S-011, Air Force Space Command Space and Missile Systems Center Standard, 31 Jul 2015.)

10.	TR-RS-2003-00004	*Independent Structural Loads Analyses of Integrated Spacecraft / Launch Vehicle Systems*, The Aerospace Corporation, 22 Aug 2003. (SMC-S-004, Air Force Space Command Space and Missile Systems Center Standard, 13 Jun 2008.)
11.	NASA-STD-5020A (W/ CHANGE 1)	*Requirements for Threaded Fastening Systems in Spaceflight Hardware*, National Aeronautics and Space Administration, 2 Nov 2019.
12.	NASA MSFC-DWG-20M02540	*Assessment of Flexible Lines for Flow Induced Vibration*, Rev. E, National Aeronautics and Space Administration, 15 Jan 1992.
13.	NASA MSFC-SPEC-626	*Test Control Document for Assessment of Flexible Lines for Flow Induced Vibration*, NASA Marshall Space Flight Center, 11 May 1990.
14.	TR-RS-2008-00008	*Electromagnetic Compatibility Requirements for Space Equipment and Systems*, The Aerospace Corporation, 1 Jan 2008. (SMC-S-008, Air Force Space Command Space and Missile Systems Center Standard, 13 Jun 2008.)

2.2 Guidance Documents

15.	MIL-STD-882E	System Safety, Department of Defense Standard Practice, 11 May 2012.
16.	AS6500	*Manufacturing Management Program*, SAE International, 2014.
17.	TOR-2014-02537-REV A	*The Test Like You Fly Process Guide for Space, Launch, and Ground Systems*, The Aerospace Corporation, 20 Sep 2016.
18.	AS9103	*Variation Management of Key Characteristics*, SAE International, 2012.
19.	JANNAF-GL-2012-01-R0	*Test and Evaluation Guidelines for Liquid Rocket Engines*, Joint Army Navy NASA Air Force Liquid Propulsion Subcommittee Test Practices and Standards Panel, Dec 2012.
20.	AFI 91-217	*Space Safety and Mishap Prevention Program*, Air Force Instruction, Department of the Air Force, 17 April 2014.
21.	NASA-STD-5012B	*Strength and Life Assessment Requirements for Liquid-Fueled Space Propulsion System Engines*, National Aeronautics and Space Administration, Jun 2016.

22.	NAFEMS Guidelines	*Management of Finite Element Analysis – Guidelines to Best Practice*, National Agency for Finite Element Methods and Standards (NAFEMS), Glasgow, UK, 1 Feb 1995.
23.	NASA SP-8007A	*Buckling of Thin-Walled Circular Cylinders*, National Aeronautics and Space Administration, Jan 2021.
24.	M. J. Manjoine	"Damage and Failure at Elevated Temperature," *Journal of Pressure Vessel Technology*, volume 105, pages 58–62, Feb 1983. https://doi.org/10.1115/1.3264240.
25.	NASA-STD-5019A W/ CHANGE 3	*Fracture Control Requirements for Spaceflight Hardware*, National Aeronautics and Space Administration, 14 Aug 2020.
26.	NASA-STD-5009A	*Nondestructive Evaluation Requirements for Fracture-Critical Metallic Components*, National Aeronautics and Space Administration, Jun 2018.
27.	M. Singh, J. Vargo, D. Schiffer, and J. Dello	*Safe Diagram – A Design and Reliability Tool for Turbine Blading*, Dresser-Rand Company, 2002.
28.	NASA SP-8123	*Liquid Rocket Lines, Bellows, Flexible Hoses, and Filters*, National Aeronautics and Space Administration, Apr 1977.
29.	C. E. Brennen	*Hydrodynamics of Pumps*, Concepts ETI, Inc. (ISBN 0-933283-07-5), pp. 67–69, 1994.
30.	A. Mulder	*Water Flow Characterization of the Unsteady Environment Upstream of the Space Shuttle Main Engine Low Pressure Fuel Pump with Flow Liners*, JANNAF paper 2005-0356BA (available by request to the Center Asst. Export Administrator, NASA MSFC, MC: US01, Marshall Space Flight Center AL 35812).
31.	R. B. Randall	*Vibration-based Condition Monitoring*, Wiley (ISBN 978-0-470-74785-8), 2011.
32.	ANSI/AIAA S-120A-2015 (2019)	*Mass Properties Control for Space Systems*, American Institute of Aeronautics and Astronautics, 23 Nov 2015.
33.	LE-S-010	*Supplemental Requirements for Reusable Launch Systems*, Air Force Space Command Space and Missile Systems Center, 27 Mar 2019.
34.	LE-P-018	*Guide for Reusable Launch Systems*, Air Force Space Command Space and Missile Systems Center, 1 Apr 2019.

3. Acronyms and Definitions

3.1 Acronyms

ALF	allowable load factor
ATP	acceptance test procedure
CDI	cumulative damage index
CMP	critical manufacturing process
COPV	composite overwrapped pressure vessel
DDT&E	design, development, test, and evaluation
DOP	detailed operating procedure
ECF	environmental correction factor
ELCF	external load correction factor
EOM	end of mission
FAF	fatigue analysis factor
FID	failure identification
FoS	factor of safety
GG	gas generator
HCF	high-cycle fatigue
Isp	specific impulse
KC	key characteristic
KPP	key process parameters
LCC	launch commit criteria
LCF	low-cycle fatigue
LEFM	linear elastic fracture mechanics
LRE	liquid rocket engine
LRU	line replaceable unit
MCC	main combustion chamber
MDC	maximum design condition
MDCL	maximum design condition load
MEOP	maximum expected operating pressure
MMA	moving mechanical assembly
MMPDS	Metallic Materials Properties Development and Standardization
MR	mixture ratio
MS	margin of safety
NAFEMS	National Agency for Finite Element Methods and Standards

NDI	non-destructive inspection
NPSP	net positive suction pressure
PB	pre-burner
Pc	chamber pressure
PL	power level
SAFE	Singh's advanced frequency evaluation (see Singh et al. [27])
SCC	start commit criteria
SL	service life
TLYF	test-like-you-fly
TPA	turbopump assembly
TPS	thermal protection system
TVC	thrust vector control
UF	uncertainty factor
$\mathbf{X}_{\mathbf{LB}}$	demonstration factor with respect to the longest burn
$\mathbf{X}_{\mathbf{SL}}$	demonstration factor with respect to the service life

3.2 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 here apply.

A-Basis Allowable: The mechanical strength values such that 99% of the population will meet or exceed the specified values with a confidence level of 95%.

Acceptance Test (or Acceptance Test Procedure, ATP): The required formal tests (or procedures) conducted to demonstrate acceptability of an item for delivery. The tests are designed to demonstrate performance to specified requirements and to act as quality control screens to detect deficiencies of workmanship, material, and quality.

Allowable Load Factor: Ratio of the allowable load to the Maximum Design Condition Load (MDCL); ALF × MDCL = load resulting in failure.

Ambient Environment: The actual external environment surrounding an engine or subsystem. The environment will vary depending on whether operation is during ground test or flight test. Unless otherwise noted, the reference ambient environment for a ground test is defined as temperature of 23 ± 3 °C (73 ± 5 °F), atmospheric pressure of 101 +2/–23 kPa (29.9 +0.6/–6.8 in Hg), and relative humidity of 50 ± 20%. Actual ground test ambient environmental conditions should be documented, particularly when they are outside of this range.

Analysis Validation: Quantification of the accuracy of analysis results through comparison to experimentally measured data, and subsequent confirmation that the model's accuracy is satisfactory for its intended use.

Analysis Verification: The process of determining the correctness of model input data, the numerical accuracy of the solution obtained, and the correctness of the output data for a particular simulation.

Assembly: An integrated set of subassemblies and/or units that comprise a well-defined part of a subsystem.

B-Basis Allowable: The mechanical strength values such that 90% of the population will meet or exceed the specified values with a confidence level of 95%.

Booster: The lowest stage of a multi-stage launch vehicle that lifts the vehicle off of the launch pad and injects an upper-stage space vehicle and satellite into a trajectory (typically sub-orbital).

Bootstrap: The portion of an LRE start transient where the engine cycle becomes self-sustaining.

Breadboard: Component assembly in a laboratory or facility test environment that is representative of the functional relationship of the final system but is not in the final system configuration and/or omits some components.

Buckling and Crippling: A failure mode in which an infinitesimal increase in the load could lead to sudden collapse or detrimental deformation of a structure.

Burst Factor: A multiplying factor applied to the maximum expected operating pressure (MEOP) to obtain the design burst pressure. Burst factor is synonymous with ultimate pressure factor. The factor is adjusted to account for differences between test and flight conditions.

Burst Pressure: The minimum pressure level at which failure of the pressurized hardware item occurs. Burst pressure can be estimated by analysis and/or measured by test. The burst pressure is greater than or equal to the *design burst pressure*.

Chamber Pressure (Pc): Force per unit area within the enclosed chamber where combustion takes place, between the injectors and throat. Often referenced as injector-end Pc (static pressure at the injector face), or nozzle stagnation Pc (calculated from injector-end Pc and Rayleigh losses).

Chilldown: Process for a cryogenic engine, prior to start, that cools engine components down to the cold temperatures needed to avoid excessive propellant boiling, facilitating proper pumping and bootstrap; typically most important for the turbomachinery of cryogenic LREs.

Component: A functional unit that is viewed as an entity for the purposes of analysis, design, manufacturing, testing, maintenance, configuration management, or recordkeeping (e.g., valve, injector, chamber, turbopump).

Critical Manufacturing Process (CMP): A process that creates or substantially affects a key or critical characteristic. (Source: AS6500 [16]).

Cyclic Stress-Strain Curve: The stress-strain curve that describes the cyclically stable response of a material after accounting for transient work-hardening or work-softening that may occur in a material under cyclic loading.

Damage-Tolerance Life (Safe-Life): The required period of time or number of cycles that the structure, containing the largest crack undetectable by the implemented NDI, is shown by analysis or testing to survive without leaking or failing catastrophically in the expected service load and environment.

Demonstrator (or Prototype) Program: Program to increase confidence in the likely success and provide risk reduction for proposed new designs, concepts, applications, or technologies prior to a full development program.

Design Burst Pressure: The pressure that a pressurized hardware component will sustain without rupture in the applicable operating environment; equal to MEOP times burst factor.

Design, Development, Test and Evaluation (DDT&E): The phase of a program during which a new design or concept is initiated, refined, and implemented up to manufacturing of qualification or flight hardware. Activities during this phase will provide confidence that the new design and concepts will accomplish mission objectives. See also *development phase*.

Design Service Life: See *service life*.

Detrimental Yielding or Deformation: Deformation, distortion, deflection, or displacement that prevents any portion of a structure from performing its intended function, that interferes with the intended function of other components, or that reduces the probability of successful completion of the mission.

Development Hardware (or Development Test Article): Vehicle, subsystem, or unit hardware dedicated to providing design requirement information; generally full scale and similar to the flight hardware. Design changes are often required during the development program as information is collected, but by the time the development program is completed, the test articles should be equivalent or nearly equivalent to the flight hardware in all aspects of flow-path and design. Development test articles are not intended for flight.

Development Phase: The development phase usually provides the first true demonstration of the capabilities of a proposed design. Development testing is used to identify problems early in their design evolution so that any required corrective actions can be taken prior to starting formal qualification testing.

Development Test: Test conducted on a representative article to assess design concepts, characterize engineering parameters, gather data, and/or validate the design approach.

Ductile (or Ductility): The ability of a material to withstand large plastic or permanent deformations and redistribution of load around regions of peak stress without fracture. Generally, ductile materials can maintain >3% allowable elongation across the entire operating range after accounting for temperature effects and triaxial states of stress.

Duty Cycle: See *service life*.

Engine: See *liquid rocket engine*.

Engine Cycle: The thermodynamic cycle that describes how liquid propellants are used within the engine to generate thrust. Common LRE cycles include pressure fed, expander, gas generator (GG), and staged combustion.

Engine System: A term used to describe the liquid rocket engine (LRE) portion of the integrated stage, whether it is a single engine or a multi-engine configuration.

Environmental Correction Factor: A multiplying factor applied to account for changes in material properties associated with differences between test and operating (i.e., flight) conditions.

Expendable Engine: An engine that is discarded after use on a single mission.

External Load Correction Factor: A factor applied to the structural test loads to compensate for differences in test configuration (e.g., loads, boundary conditions) between test and flight conditions.

Factor of Safety (FoS): A multiplying factor applied to the maximum expected operating conditions (e.g., structural or thermal loads) for analytical assessment (design factor) and/or test verification (test factor) of design adequacy. The FoS is used to account for build-to-build hardware variability, uncertainty in internal load paths and stress/strain levels, and uncertainty in ultimate failure modes.

Fatigue: The process of progressive, localized, and permanent structural change occurring in a material subjected to fluctuating stresses and strains, and which may culminate in cracks or complete fracture after a sufficient number of cycles. Fatigue failure can occur at stress levels less than the static yield strength of the material.

Fatigue Analysis Factor (FAF): A factor to account for uncertainty in predicted stress level to protect against scenarios when large changes in life occur due to small changes in stress. It is applied to the alternating stress/strain before entering the stress versus cycles to failure (S-N) design curve to determine the fatigue life.

Fatigue-Crack Growth: The portion of the fatigue process between crack initiation and crack instability, where a crack grows or extends under cyclic loading.

Flight Design: Final production design intended for the “as-flown” hardware.

Flight Operational Phase: This phase begins at launch. It includes test flights prior to the first mission and the actual mission flights themselves. Flight data generated during this phase may be used to generate performance reconstructions and detailed post-flight data reviews, with the goal of verifying in-flight specification performance, interface compatibility and predictions (e.g., engine and vehicle operating environments), calibration/control, and the ability to meet future mission requirements. The accumulation of flight data generally leads to refinement of flight simulations and revision of expected flight dispersions.

Functional Test: A test performed to assess the operability and/or capability of an item within the boundaries established by design requirements. For example, the test may screen for malfunctions, failure to execute, sequence of action, interruption in continuous function, or failure in cause and response. Functional tests are conducted in the most applicable environment.

Hazard: A real or potential condition that could lead to an unplanned event or series of events (i.e., mishap) resulting in loss of personnel capability; injury, illness, or death to personnel or the public; damage to or loss of system, equipment, or property; or damage to the environment.

High-Cycle Fatigue (HCF): A fatigue failure mode that results from a relatively large number of small elastic strain cycles. It is usually convenient to describe high-cycle fatigue capability of a material in terms of a stress-life curve due to the elastic behavior, but it may also be described in terms of a strain-life curve.

Hot-Fire Test: A test of the engine propulsion systems and components that includes actual ignition and combustion of propellants within the engine, simulating flight conditions to the extent possible.

Impulse: Integral of thrust over a specified time period.

Key Characteristic (KC): The features of a material or part whose variation has a significant influence on product fit, performance, service life, or manufacturability. (Source: AS9103 [18]).

Key Process Parameters (KPP): Those minimum attributes or characteristics of a manufacturing process that are considered most essential to control for a successful outcome.

Line Replaceable Unit (LRU): Within this standard, a unit (e.g., igniter or closed-loop control valve) that may be removed and replaced by a separate unit without requiring engine removal or repeating a hot-fire test.

Liquid Rocket Engine (LRE): Launch or space vehicle propulsion subsystem utilizing a combination of components and liquid phase chemical reactants to provide thrust; generally this includes the nozzle, thrust chamber, pumps, valves, regulators, and plumbing.

Loads: Any condition such as pressure, force, moment, thermal environments, or moisture that can produce a non-zero stress state in a structure.

Low-Cycle Fatigue (LCF): A fatigue failure mode that results from a relatively low number of cycles, which includes plasticity.

Margin: Capability in excess of worst-case operating conditions.

Margin of Safety (MS): A metric that predicts the structural integrity of an engine element based on the required factor of safety (FoS) and the predicted worst-case conditions against allowable limits. Equivalently, MS expresses the predicted structural capability above the design safety factor.

Maximum Design Condition (MDC): The most severe environment specified for the engine and its components.

Maximum Design Condition Load (MDCL): The worst loads or combination of loads and environments that the engine and its components are expected to experience and survive without failure. All phases in the life of the hardware, including fabrication, assembly, testing, transportation, ground handling, flight, and recovery/reuse are to be considered in defining the MDCL. Note that MDCL may refer to different combinations of loads depending on the failure modes being evaluated.

Maximum Expected Operating Pressure (MEOP): The highest pressure that pressurized hardware is expected to sustain during its service life and retain its functionality, in association with its applicable operating environments (includes worst-case dispersions).

Maximum and Minimum Expected Temperatures: The highest and lowest temperatures that an item can experience during its service life, including all test and operational modes.

Mixture Ratio (MR): Ratio of the oxidizer mass flow rate to the fuel mass flow rate. Engine MR is measured at the engine inlets.

Non-Destructive Inspection (NDI): Methods of inspection for integrity that do not impair serviceability, life, or performance.

Operability: The ability to support required flight rates and schedules and to meet a variety of operational characteristics while minimizing cost and risk.

Operating Envelope: Outer boundaries of conditions to which hardware may be subjected during intended operation, encompassing all possible intended variations of a set of parameters with dispersions (e.g., thrust and mixture ratio boundaries).

Operating Environment: Thermal, pressure, dynamic and/or electromagnetic conditions to which the system is exposed during its operational life.

Operational Life: The total allowed starts and run-time, including ground acceptance testing, on-pad firings/aborts, and flight exposure.

Part: A single piece, or two or more pieces joined together, that are not normally subject to disassembly without destruction or impairment of the design use. Examples are resistors, integrated circuits, relays, and roller bearings.

Physical Envelope: Dimensional boundary which encompasses the component or system.

Pogo: Self-excited, sustained oscillations (typically associated with vehicle axial motion) due to interaction between the structural dynamic behavior of the launch system, the fluids of the propulsion system, and engine thrust.

Powerpack: Subsystem test article which typically includes turbomachinery and major combustion devices. It is intended to test these items in combination as risk mitigation prior to or in parallel with full-up engine testing.

Prelaunch Operational Phase: This phase begins when the flight hardware and software are received at the launch site and continues until launch. It includes all preparatory operations and checkout testing to verify flight readiness. It may also include separate flight readiness static firings and/or autonomous engine health monitoring and checkout during the engine startup and main stage operation immediately prior to lift-off. It is intended to ensure the readiness of the hardware, software, personnel procedures, and mission interfaces to support launch and the program mission. On some occasions, the prelaunch operations may include unexpected or out-of-sequence inspection, testing, or modification of flight hardware to resolve identified concerns after the hardware has been delivered to the launch site.

Prelaunch Tests: Testing following system delivery to a vehicle factory or launch site prior to launch. These tests are intended to verify system readiness for integration, system integrity, safety, and performance.

Pressure Component: A component in a pressurized system, other than a pressure vessel, a pressurized structure, or special pressurized equipment, that is designed largely by the internal pressure. Examples include lines, fittings, valves, and bellows with no significant external load.

Pressure-Loaded Component/Structure: A component/structure not intended to store a fluid under pressure but experiencing a combination of internal pressure and external loading. The pressure-loaded component/structure is generally considered to be part of the engine. Examples include pump housings, main propellant lines/valves, and combustion chambers.

Pressure Vessel: A container designed primarily for the storage of pressurized fluids, and which (a) contains stored energy of 19,307 joules (14,240 ft-lbf) or greater, based on adiabatic expansion of a perfect gas; or (b) contains gas or liquid which will create a mishap (accident) if released; or (c) will experience a MEOP greater than 700 kPa (100 psi).

Pressurized System: A system that consists of pressure vessels and/or pressurized structures, with other pressure components such as lines, fittings, valves, and bellows, that is exposed to and structurally designed largely for the acting pressure. Electrical or other control devices required for system operation are not included. Pressurized systems on the engine may store and/or supply pressurized hydraulic, pneumatic, purge fluid, or gas for the actuation of engine system components or other system functions.

Proof Factor: A multiplying factor applied to the MDCL or MEOP to obtain the proof load or proof pressure for a proof test. The proof factor is adjusted using an environmental correction factor and external correction factor to account for differences between test and flight conditions.

Proof Load: Value established by taking the calculated maximum design condition (e.g., MEOP) and multiplying it by the proof factor.

Proof Pressure: Pressure equal to the product of the MEOP and the proof factor, where the proof factor has been adjusted for differences between test and flight conditions. Proof pressure is the pressure used to give evidence of satisfactory workmanship and material quality and/or establish maximum initial flaw sizes for damage-tolerance life (safe-life) demonstration. Synonymous with *proof load* for pressure tests.

Proof Test: A static load or pressure test performed as an acceptance workmanship screen to prove the structural integrity of a unit or assembly. The proof test gives evidence of satisfactory workmanship and material quality by the absence of failure or detrimental deformation. The proof test load and/or pressure compensates for the difference between test and flight conditions, if applicable.

Propulsion System: The system producing thrust, which includes the engine system; propellant tankage and feedlines; off-engine valve, fill, vent, purge, chilldown and drain systems; pogo suppression devices; and propellant tank pressurization systems, as applicable. A propulsion subsystem within TR-RS-2014-00016 (SMC-S-016) [1] is termed a propulsion system within this document.

Prototype: A preliminary version of part of the hardware or software of a system that serves as a model for later stages or for the final, complete version of the system. Frequently, the prototype will be focused on replicating only specific parameters of interest because its purpose is to guide future development, permit customer evaluation, and demonstrate critical new technologies.

Prototype Phase: This phase precedes development and may also be referred to as feasibility, risk reduction, or demonstration testing. Tests in this phase are intended to assist design definition by providing engineering data to confirm analyses and/or help define expected operating conditions. Often this testing is intended to explore and/or validate new technologies that might be beneficial to the engine system. Prototype hardware is typically designed to be more robust with greater margins compared to flight hardware because the design and operating conditions have higher uncertainty during this phase. The hardware may contain facility components in place of flight components, modified components from earlier engine models, or component simulators to gain the engineering information needed to complete the initial flight design. Breadboard and/or bench-level type engines or subsystems may be used in some cases, and subscale testing is also common.

Qualification Hardware: Production articles that go through a series of qualification tests to demonstrate readiness for flight operation. Qualification hardware is to be produced using the same materials, tooling, manufacturing processes, and level of personnel competency as will be used for actual flight hardware. Often the qualification engines are the first engines off the production line.

Qualification Phase: The qualification phase includes the production and testing providing the formal verification that the final design, manufacturing processes and facilities, and acceptance program produce flight hardware/software that meet specification and performance requirements with adequate margin to accommodate variations in hardware and engine operation. It generally follows completion of the development test program. This phase includes validation of test techniques, procedures, equipment, instrumentation, and software, as well as potential rework and repeat test cycles.

Qualification Test: The formal tests (typically to satisfy contractual requirements) intended to demonstrate that the final design, manufacturing, assembly, and acceptance testing yield hardware designs conform to specification requirements. Qualification testing verifies compliance to engine specification requirements and vehicle interface requirements over the range of expected operating conditions, including worst-case conditions for all intended applications. Required margin conditions (e.g., operating life margin, thrust margin) are also verified.

Quasi-Static Load: A time-varying load in which the duration, direction, and magnitude are significant, but the rate of change in direction or magnitude, and the dynamic response of the structure, are not significant.

Restart: Engine start after previous shutdown, without interruption of the environment, or modification of the hardware or setup.

Reusable Engine: An engine that is to be used for multiple space launch missions. The service life of a reusable engine includes all testing, initial use and reuses (mission operation times), refurbishment, and retesting.

Reusable Item: A unit, subsystem, or vehicle that is to be used for multiple missions. The service life of reusable hardware includes all testing, initial use and reuses (mission operation times), refurbishment, and retesting.

Reuse: Recovery and use of an item for another space launch mission after completion of a prior space launch mission.

S-Basis Allowable: The minimum property value specified by a governing industry specification or federal or military standards for the material.

Safe Life: See *Damage-Tolerance Life (Safe-Life).*

Safety Factor: See *factor of safety*.

Scatter Factor: A factor used to describe the measured variability in the number of cycles to initiation or failure that a material can withstand at a given level and under constant amplitude loading.

Separation-Critical Joint: A joint that would fail to function as required if separated. Examples of separation-critical joints include, but are not limited to, joints that must maintain contact to enable proper function of a system (e.g., thermal, electrical, fluid) or joints whose dynamic stiffness is unacceptably reduced due to separation.

Service Life (SL): The SL of an item starts at the completion of fabrication and continues through all acceptance testing, handling, storage, transportation, prelaunch testing, all phases of launch, orbital operations, disposal, re-entry or recovery from orbit, refurbishment, retesting, and reuse that may be required or specified.

Service Life Factor: A multiplying factor to be applied to service life when performing an assessment of design adequacy in fatigue or creep.

Similarity: The process of assessing by review of prior data, hardware configuration, and applications that the article is similar or identical in design and manufacturing process to another article that has been previously qualified to equivalent or more stringent specifications.

Specific Impulse (Isp): Engine Isp is the instantaneous total thrust divided by the instantaneous total mass flow rate of propellants through the engine inlet, at a specific altitude (e.g., sea level and/or vacuum conditions).

Steady State: Operation during which key engine performance parameters are no longer varying significantly over time or are slowly changing at a constant rate.

Storage Life: The time that a unit can be stored after acceptance tests without replacement of parts, with subsequent successful operation within specification limits.

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

Structural Integrity: The ability of the structure to meet the structural requirements.

Subassembly: An item containing two or more parts, capable of disassembly or part replacement.

Ultimate Load (Design): The load that the structure must withstand without rupture or collapse in the expected operating environments. Equal to the product of the maximum design condition load and the ultimate design FoS.

Ultimate Pressure Factor: See *burst factor*.

Ultimate Strength: The maximum load or stress that a structure or material can withstand without incurring rupture, collapse, or cracking.

Unit: A functional item (hardware and, if applicable, software) that is viewed as a complete and separate entity for purposes of manufacturing, maintenance, record keeping, and environmental testing.

Upper-Stage Vehicle: A vehicle that has one or more stages of a flight vehicle capable of injecting a space vehicle or vehicles into orbit from the sub orbital trajectory.

Validation: To show to be accurate and correct (as in, validate requirements or validate results). Validation can be by inspection, demonstration, or analysis.

Verification: Confirmation that ground and flight hardware and software are in compliance with design and performance requirements (as in, verify capability). Verification can be done by inspection, test, or analysis.

Verification Engine: An engine sample used for required verification testing. All qualification engines are verification engines. Other engine samples (e.g., development engines) that are of the flight design or structurally and functionally equivalent to the flight design may be used as verification engines.

Yield Strength: The load or stress that a structure or material can withstand without incurring permanent deformation. (The 0.2-percent offset method is usually used to determine the load/stress.)

4. General Requirements

The primary objective of any test program is to maximize the probability, within programmatic constraints, that the flight design will function properly and successfully when used in actual service for the intended application. Flight risks are mitigated via prudent and effective analysis and testing. While analysis can sometimes be used in place of test, analysis techniques should always be rigorously validated and supported with test data. The combination of analysis and test verification is used for both qualification of the liquid rocket engine (LRE) designs as well as workmanship verification of each LRE flight unit.

4.1 General Test Considerations

Certain tenets of testing have served the liquid propulsion test community well as it has tried to accomplish the above objective. Foremost, testing should demonstrate engine operation with flight-representative hardware and under flight-representative conditions, including expected worst-case conditions. This is consistent with the "Test-Like-You-Fly" (TLYF) process, intended to produce operationally realistic tests that are mission execution driven, as described in TOR-2014-02537-REV A [17]. The general test considerations that follow are intended as guidance in defining a test program offering a high likelihood of successful LRE qualification.

The test program should expose the flight design to as much of the operational flight envelope as possible to avoid operating any particular hardware configuration under any particular set of conditions for the first time in flight. This includes propellant composition, with qualification test propellant composition range encompassing that which may be experienced operationally. The test configuration should provide flight-representative interface hardware and utility (propellants, power, purges) conditions. Some flight environments (e.g., acceleration) cannot be replicated during ground test. For booster engines, the engine should be in the same orientation relative to gravity as flight for qualification testing. Margin testing with respect to the expected flight conditions should be included to protect against known and unknown uncertainties in the flight conditions (e.g., ground-to-flight dispersions), as well as known, anticipated, and unknown hardware variations (e.g., manufacturing tolerances, non-conformances, and undetected deficiencies).

If it is impractical to test or simulate a particular flight condition on the ground, then additional margin may be appropriate. Furthermore, testing should consider and account for engine hardware experience and exposure throughout all phases of the required lifecycle, including manufacturing, acceptance testing, transportation, handling, storage, vehicle integration, checkout testing, launch preparations, aborts, liftoff, flight, recovery, and reuse. Exceptions to this approach should be carefully evaluated and include a risk determination. LREs deliberately designed to provide margins greater than those specified in this Standard have a higher likelihood of test and flight success.

Equally important to thoroughly exploring the flight envelope during qualification is ensuring that flight operations remain within demonstrated ground-tested and qualified regimes, and that design and process differences between qualification test hardware and flight hardware should be minimized and ideally avoided. A successful development and qualification program will anticipate all potential flight conditions and ensure those conditions are validated by a robust test program. If an engine has multiple applications, the engine should be developed and qualified to the most demanding requirements; programmatic considerations may, however, dictate a phased approach.

Hot-fire testing to verify that an LRE design is ready for flight typically consists of four phases of major program activity: prototype testing, development testing, qualification testing, and integrated system testing. The first three test phases typically occur at the component level as well as the engine level. The integrated system testing phase is performed at the propulsion system and/or vehicle level. After an LRE *design has completed the qualification program (i.e., entered the production phase), each individual flight engine is acceptance tested by hot-fire to verify that specific engine's suitability for flight. Prelaunch operational testing is performed prior to engine start and liftoff to verify readiness for launch.*

Specific requirements are placed upon qualification, production unit acceptance testing, and integrated system testing. There is an allowance, in fact an expectation, that engines not meeting the full requirements for a qualification engine will be used as part of the overall design verification effort. The term "verification engine" is used to encompass both qualification engines and these additional engine samples, which must all be structurally and functionally equivalent to the flight design. Prototype and development tests are not required herein, but it is strongly recommended that qualification be preceded by a significant number of development engine samples, with associated testing, to increase the likelihood of success in the qualification phase.

4.2 Verification Approach

There are four critical aspects of an LRE test program related to verification of the design and build: (1) The total number of verification engine samples, which includes qualification engine samples, (2) the number and duration of tests on each verification engine, (3) the specific test and safety factors used in test and analysis margin assessments, and (4) the degree of reliance on, and maturity of, the analysis. The specifics of each of these elements are discussed in the following sections.

Table 4-1 lists the parameters and required conditions yielding Baseline risk for a typical LRE using turbomachinery. Requirements for other LRE configurations will be noted in the corresponding text if they are different. Tailoring of Table 4-1 must balance engine complexity with the program risk posture, cost constraints, and schedule constraints. Further guidance on tailoring of requirements (including Table 4-1) is contained in Appendix A.

[4.2-1] An LRE test plan satisfying the requirements of this Standard shall be developed, reviewed and approved by the Approval Authority, and executed.

Table 4-1. LRE Verification Engine Samples and Margins/Demonstration Factors

Parameter	Section	Samples/Factors
Unit & Subscale Test and Evaluation		
Fatigue and Damage Tolerance Factor	6.11	$4\ X_{SL}$
Unit Single Burn Operation Demonstration Factor[1]	6.13.2	$1.1\ X_{LB}$
LRE Test and Evaluation		
Minimum Verification Engine Samples	4.3.1	4 engines[2]
Minimum Qualification Engine Samples	4.3.1	2 engines
Thrust/MR Margin Demonstration	7.2.6	2%
Life Demonstration Factors (duration and starts)	7.7.1, 7.7.4	4 engines[2]: $4\ X_{SL}$ on 1, and $2\ X_{SL}$ on 3
Single Burn Endurance Demonstration Factor[1]	7.7.2	$1.1\ X_{LB}$
Nozzle Operational Demonstration Factor	7.7.3	$1.2\ X_{SL}$ on 4 samples (ablative) $1.1\ X_{SL}$ on 4 samples (non-ablative)

(1) Applied to the maximum expected single burn duration in flight.
(2) Includes the 2 qualification engine samples.

4.3 Engine Samples

Few aspects of a development and qualification program have as great an influence on its scope, cost, and schedule as the number of engine samples and number of tests (see JANNAF-GL-2012-01-R0 [19]). Cost will also be affected by differences in engine cycle, physical size, flowrates, and pressures.

The complexity of a rocket engine design results in sensitivities to hardware dimensional variances, which drive the requirement for testing multiple engine samples. Despite careful attention to identifying and controlling critical tolerances in the design phase, engine testing will often identify significant engine-to-engine variations in operating conditions and other responses. Common examples include pump cavitation characteristics, turbine blade responses to excitation, bearing loading, pump chilldown characteristics, ignition effectiveness, and self-induced vibration. Adverse responses to variations can cause lower margins than desired. Therefore, one key objective of the test program is to provide insight into engine-to-engine variations, and to verify that these variations are acceptable for the given design and intended application(s).

Multiple engine samples demonstrating a test objective are required to provide adequate confidence that the engine operation and its variations are well understood. A significant number of development engines should be included in the program to define and reduce risk for the final flight design. The optimum number will depend on design complexity, heritage, and risk tolerance. Some verification test objectives may be satisfied by the earlier development efforts (e.g., combustion stability bomb tests), provided that the development design is sufficiently similar to the final flight design for the specific test objectives being accomplished.

It is acceptable for some verification activities to use rebuilt engines to reduce costs, but at the disadvantage of reducing the extent of normal variation that will be observed and characterized. If an engine includes reused parts, determination of whether that engine sample is "unique" depends on a valid engineering assessment based on knowledge of the engine build history and the specific objective under consideration. For example, an ignition test sample would be unique if the igniter and injector were changed during an engine rebuild, and the uniqueness of the turbopump would be of interest for a pump chilldown test sample. Furthermore, any major hardware changes (e.g., to resolve a failure or to incorporate a desired improvement) may reset the test engine sample count, depending on how the specific design features relate to given test objectives. Even small hardware changes must be considered carefully, as there are numerous examples where seemingly trivial changes had significant unintentional consequences.

One or more engine samples (new or reused from engine-level testing) should undergo additional testing at the integrated system level. In addition, as acceptance and flight data become available, they should be thoroughly assessed to verify that the engines being flown are still in family with those used in the qualification program.

4.3.1 Number of Verification Engine Samples

The number of verification engine samples, which includes designated qualification engines as well as other engines used in verification activities, must be large enough to characterize effects of build-to-build variation to a high level of confidence. The required sample sizes are based upon experience, Weibull statistical analysis, and other reliability calculations, and have been successfully employed on past programs. Each verification engine may be associated with different test objectives, thus introducing some leeway regarding specific hardware configuration. Further guidance on the basis of the number of engines and rationale that may be used during tailoring is provided in Appendix A.

[4.3.1-1] Verification engines shall be unique engine samples that are structurally and functionally equivalent to the flight design.

Different test objectives may use different engines to satisfy this sample requirement. Determinations of what is "structurally and functionally equivalent to the flight design" should focus on aspects applicable to the specific objective(s)/requirement(s) being verified and are subject to review by the Approval Authority.

[4.3.1-2] Qualification engine samples shall be of the flight design, produced using the same materials, tooling, processes, and level of personnel competency as the flight hardware.

[4.3.1-3] The minimum number of qualification and verification engine samples shall be as specified in Table 4-1.

Qualification engine samples are included in the total count of verification engine samples.

[4.3.1-4] All engines used for verification activities shall include a common instrumentation suite (i.e., same type, location, and sample rate).

The instrumentation suite should be sufficient for evaluation of general verification objectives (i.e., should include most measurements such as pressure, temperature, accelerometer, pump speed, etc.). Additional instrumentation may be added for tests with specialized objectives (e.g., combustion stability verification), and does not need to be replicated across all engine samples. Modifications to or expansion of the instrumentation are allowed and encouraged if deemed advantageous based on test results from earlier engine samples.

[4.3.1-5] Each engine utilized to satisfy the total engine sample number (Table 4-1) shall successfully complete testing, including hot-fire tests, while encompassing and formally verifying required functional requirements, including propellant condition and interface conditions, representative operating duty cycles, and performance (consistent with Table 4-2).

[4.3.1-6] Engine activities that result in failures or anomalies requiring modification of the engine design shall not be considered as part of the number of engine samples specified in Table 4-1, although credit for specific objectives may be granted by the Approval Authority based upon high confidence engineering analysis showing independence from the cause of the failure/anomaly and the subsequent engine modification.

Repair and rework performed during engine verification testing should be thoroughly evaluated, as these modifications may (and typically do) invalidate life demonstration. Specific objectives of the testing will be detailed in later sections.

It is recommended that an earlier development phase include engine samples beyond the requirements of Table 4-1. Development engines typically have additional instrumentation and are tested to an additional margin. For a new engine, additional engine samples are commonly necessary to effectively evolve the initial design to the final flight design. There are no requirements herein for these additional engines, but the total number of development engine samples should be sufficient to facilitate successful verification tests as defined by subsequent sections, with consideration of the following:

a. *The requirements of tests such as transient (power-level transition) development, margin demonstration, and mixture ratio (MR) and inlet box exploration may consume the useable life or cycles of initial development engines more rapidly than later testing.*
b. *Early failures will probably occur.*
c. *Major design iterations may be required.*
d. *Catastrophic failures could occur.*

e. Contingency engines should be available to continue testing in the event of a problem with a particular engine or test series.

4.4 Number of Total Tests

It is difficult to determine the number of tests needed to sufficiently verify all the requirements. Experience, analytical capabilities, and deviation from known, highly matured technologies/practices all play a role. Furthermore, there will be programmatic influences that shape the test campaign. There may be several paths available to obtain the necessary data to verify and qualify the design depending upon these influences. Test campaigns should be optimized to accomplish as many objectives as possible on a given test without making the tests overly complex, and without allowing one objective to interfere with implementation/verification of another.

[4.4-1] The test program shall verify each of the specific engine system performance requirements and functional objectives in Table 4-2 on the specified number of unique engine samples for each objective.

Accomplishing multiple objectives on any single test is allowed, provided each objective does not interfere with verification of the others.

Prior test programs indicate the not-surprising-characteristic that more test failures or problems occur early in the test campaign than later (see Figure 4-1). This trend has continued into more recent test programs (JANNAF-GL-2012-01-R0 [19]). The fact that several recent programs have used a lower total number of tests compared to the predecessor programs without increasing flight failure instances suggests that a learning curve exists for the key factors which play a role in understanding the physical system and its interactions. Some of the benefits more recent programs have over the predecessors can be attributed to the increased analytical capability and experience base. The complexity of the Space Shuttle Main Engine (SSME) and its long-lasting ground test programs have allowed modeling of physical systems to evolve significantly, along with computing power. Cost-driven aspects, however, have limited technology development and the associated impetus for additional development tests.

Because problems during testing may affect schedule and engine sample applicability for subsequent testing, it is recommended that the qualification portion of the test program be initiated only after development is complete or mostly complete. There is often an interest in attempting to shorten test program duration by running engines in parallel at multiple facilities. Program management should balance the anticipated benefit of schedule reduction against increased risk to cost and schedule due to late-surfacing failures that may require design changes, invalidating a portion or all of the preceding qualification effort. To illustrate this point, Figure 4-1 shows historical trends in percentage of cumulative failures experienced in development relative to a percent of cumulative development tests completed for F-1, J-2, and SSME programs. This historical data for robust development programs shows, for example, that 80% completion of development testing typically encompasses 90% of failures. If the decision is made to proceed with qualification before completion of development, potential adverse effects are most effectively mitigated by commencing qualification towards the latter portion of the development program, after successfully completing key testing to explore each of the functional and durability requirements and incorporate necessary design changes or operational refinements.

There are multiple test planning approaches that may be used to establish the total numbers of tests. It is recommended to follow a "functional objectives-based" approach. Whichever technique is used, the Approval Authority must carefully weigh programmatic requirements and constraints versus acceptable risk levels as each program has different amounts of technology development and design heritage to consider. Total numbers of engine-level tests should be discussed in the context of a full engine development plan, which is expected to address the component-, subsystem-, and engine-level test and evaluation approach, in concert with modeling and simulation capabilities.

Table 4-2. LRE Verification Engine Objectives and Minimum Unique Engine Samples Required

Objective	Section	Min Number of Unique Verification Engine Samples
Performance	7.2	
Steady-State Performance Characterization	7.2.1	4
Repeatability	7.2.2	3
Run-Time Trends	7.2.3	3
Steady-State Analytical Models	7.2.4	4
Thrust and Mixture Ratio Excursion Tests	7.2.5	2
Thrust and Mixture Ratio Margin Demonstration	7.2.6	1
Ignition System	7.2.7	3
Turbomachinery	7.2.8	4
Combustion Devices Performance and Stability	7.2.9	2*
Contamination and Debris Tolerance	7.2.10	4
Functional Characteristics	7.3	
Cold Shock Tests	7.3.1	4
Cold Flow Tests	7.3.2	0
Acceptance Propellant Conditions	7.3.3	4
Engine Propellant Inlet Conditions	7.3.4	4
Transient Characterization	7.3.5	
Start Transients	7.3.5.1	4
Restart Transients	7.3.5.2	4
Throttle Transients	7.3.5.3	4
Shutdown Transients	7.3.5.4	4
On-Pad Abort Shutdown Transients	7.3.5.5	1
NPSP Margin and Cavitation	7.3.6	2
Pogo and Pump Compliance Characterization	7.3.7	4
Ancillary Systems	7.3.8	2
Thrust Vector, Gimballing, and Deployment	7.3.9	2**
Structural Tests	7.4	1
Pressure and Leak Testing	7.5	4
Environments	7.6	
Thermal Environment	7.6.1	4
Climatic Tests	7.6.2	0
Vibration, Shock, and Acoustics	7.6.3	1
Vehicle Interface Loads	7.6.4	4
Electromagnetic Compatibility Tests	7.6.5	1
Life	7.7	
Operational Lifetime and Durability	7.7.1	4
Burn Duration Endurance Testing	7.7.2	1
Nozzle Endurance	7.7.3	4
Life Starts	7.7.4	4
Acceptance Test Procedure Validation	7.7.5	4

Table 4-2, continued.

Objective	Section	Min Number of Unique Verification Engine Samples
Controls	7.8	4
Operations	7.9	
Pre-Test Inspections and Checkouts	7.9.1	2**
Post-Test Inspections	7.9.2	2**
Drying and Heated Purges	7.9.3	4
Gas Liquefaction Control	7.9.4	2
External Icing	7.9.5	4
LRU Demonstrations	7.9.6	1
Reusability Operations	7.9.7	2
Operability	7.9.8	4
Preflight Procedures and Flight Sequences	7.9.9	2**

* 1 or 2 engines, depending on the approach in CPIA Publication 655 [3] taken.

** These should be performed on the 2 qualification engines.

Note: where 0 engine samples are required, demonstration should be pursued during development and/or via analytical validation.

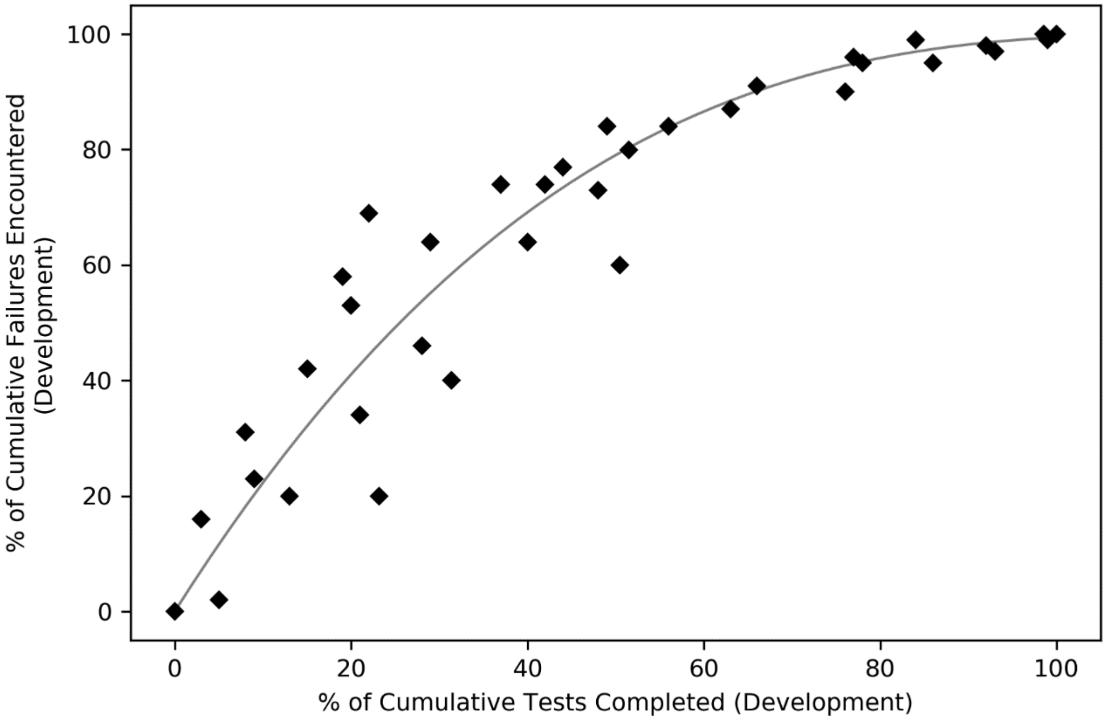

Figure 4-1. Percentage of failures encountered as a function of development test program completion for the F-1, J-2, and SSME programs (see JANNAF-GL-2012-01-R0 [19]).

4.4.1 Functional Objectives-Based Approach

The goal of the functional objectives-based approach is to verify all specific engine system performance requirements and functional objectives as efficiently as possible in the minimum number of tests. Enough tests should be performed, however, to adequately exercise the full range of engine operating conditions, including nominal, off-nominal, and extreme conditions (with margin where practical). Furthermore, it is recommended that enough tests be performed for each of the various conditions to adequately characterize the normal variability of the engine system for those conditions. Because this approach generally will not include sufficient test samples to statistically demonstrate reliability requirements against failure modes (such as random and wear-out failure modes), it is necessary to verify significant margin against various key engine performance aspects, requirements, and operating conditions to ensure adequate robustness in the design, and to identify any design flaws and failure modes that might exist. If sufficient margin is demonstrated, the functional objectives approach provides additional protection against unknowns.

Margin is relative to the extremes of the expected operating conditions. It may include a change in level, expansion of range, increase in duration or cycles of exposure, or any other appropriate increase in severity. A global margin requirement is impractical to apply for an LRE due to the complex and often very non-linear interactions in these systems result in vastly differing conditions throughout the engine. Thus, the test margin conditions must be carefully selected to demonstrate robustness for critical aspects of the engine, while avoiding excessive over-test of other parts. Margin requirements for specific objectives and design aspects of LREs are discussed within the sections that follow.

4.4.2 Modeling and Simulation

Modeling and simulation are critical complements to testing. Therefore, acquisition of data to validate and calibrate analytical models, for the "by analysis" element of development and qualification verification of requirements, should be a major test objective. One of the fundamental purposes of testing is the validation and calibration of physics-based models. Much effort is placed in this area to increase fidelity of the initial design, based upon experience, and to apply it to new or evolved propulsion system designs. Analysis efforts that are inherently lower risk can be initiated earlier in the design, development, test, and evaluation (DDT&E) effort and provide the capability to explore many aspects of the design prior to hardware manufacture and assembly. However, test data is necessary to validate the analytical assumptions; there is no substitute for test.

There are test objectives tied to validating and anchoring models so they can be extrapolated or interpolated with confidence to verify functionality and performance. The goal is to reduce the number of tests necessary to provide confidence for flight, as well as to analyze flight conditions that cannot be adequately simulated via ground test, although extrapolation should be minimized to the extent possible.

Modeling and simulation serve several important functions. First, they provide early design guidance and system characterization. Second, they give preliminary analytical indication of functional performance and integrity, which helps maximize the probability of successful verification during subsequent testing. Finally, in specific cases, they may provide sufficient analytical verification without testing. This is especially critical for those aspects of engine performance and operation that are impossible or impractical to adequately test on the ground. Furthermore, with the evolution of more powerful computing capabilities, advanced simulation tools, and improved manufacturing processes, recent engine development and qualification programs can shorten the typical (and costly) "test-fail-fix" design cycle during development that has plagued many past programs. This allows an earlier entry into the verification phase of the test program. Nevertheless, sufficient testing is required to verify the design because any design result is subject to the validity of assumptions and proper consideration of all potential failure modes. Improved analyses coupled with customary design test verifications can yield *better reliability for the same cost, or they can be coupled with a reduced level of design verification to yield lower cost for the same level of reliability.*

4.5 Relationship to Other Standards

An LRE may contain units that are covered under other standards documents. This section indicates the relationship between this Standard and these other standards documents. The relationship with TR-RS-2014-00016 (SMC-S-016) [1] is handled separately within Sections 6, 7, and 8 of this Standard.

4.5.1 Systems Safety

Launch systems are required to comply with MIL-STD-882E [15] regarding systems safety, and AFI 91-217 [20], which includes both system safety and requirements for reentry or disposal at the end of the mission. These requirements pertain to the design and development phase and must be considered during the test and evaluation phase to ensure that requirements are being met appropriately.

4.5.2 Pressure Vessels and Pressurized Structures

Storage of propellant and pressurant is within a pressurized structure or pressure vessel. For the purposes of this document, requirements for pressurized structures and pressure vessels are relevant only when those units are considered part of the LRE.

[4.5.2-1] Metallic pressurized vessels and pressurized structures within an LRE shall comply with AIAA S-080A-2018 [4] and AIAA S-110-2005 [5] for both qualification and acceptance.

[4.5.2-2] Composite overwrapped pressure vessels within an LRE shall comply with AIAA S-081B-2018 [6] for both qualification and acceptance.

4.5.3 Pressure and Pressure-Loaded Components

Many elements of an LRE are considered pressure components and require pressure and leak testing. Although AIAA S-080A-2018 [4] contains a section for pressure components, that section is incomplete for an LRE application. As such, this Standard modifies some of the requirements within AIAA S-080A-2018 [4].

[4.5.3-1] Pressure components and pressure-loaded components shall comply with AIAA S-080A-2018 [4] for both qualification and acceptance testing, with the exceptions as specified herein for structural analysis methodology (Section 5), unit structural requirements (Section 6.11), and amended design factors (Section 4.6.3).

4.5.4 Ordnance

Ordnance is typically not part of an LRE but can be. Ordnance is considered a unique unit type and has its own compliance document.

[4.5.4-1] Ordnance within an LRE shall comply with AIAA S-113A-2016 [7].

4.5.5 Moving Mechanical Assemblies

LREs may contain moving mechanical assemblies (MMAs). Some LRE components and subassemblies, such as turbomachinery, may meet the MMA definition but have unique requirements which are specified in this Standard. Other MMAs, including valves, actuators, electric motors, servos, gimbals, gimballed *joints and ducts, and deployment mechanisms, are subject to the requirements of AIAA S-114A-2020 [8] and TR-RS-2014-00016 (SMC-S-016) [1], both of which include tailoring provisions.*

[4.5.5-1] MMAs within an LRE shall comply with AIAA S-114A-2020 [8].

4.5.6 Pressurized Systems

Per the nomenclature of TR-RS-2023-00005 [2], the LRE is a pressurized system with requirements pertaining to material selection, load definition, margin factors, and test of the LRE.

[4.5.6-1] LRE qualification and acceptance shall conform to the TR-RS-2023-00005 [2] requirements for a pressurized system with the exception of structural (TR-RS-2023-00005 Section 4.2) and proof pressure test (TR-RS-2023-00005 Section 4.4.2) requirements. In the event of conflict with TR-RS-2023-00005, this Standard takes precedence.

4.6 General Structural Requirements

Requirements for test and analysis to verify the thermo-structural capability presuppose that proper materials have been selected and appropriate loads and margin factors are utilized.

4.6.1 Material Selection

Structural elements have additional design requirements where both the operational environment and the manufacturing processes relate to the material selection.

[4.6.1-1] Engine materials shall meet the requirements in TR-RS-2015-00011 (SMC-S-011) [9].

[4.6.1-2] Temperatures of structural components and bonded interfaces shall remain within material temperature limits specified to ensure their structural integrity.

[4.6.1-3] Materials shall be compatible with fluids used in test and operation.

[4.6.1-4] Physical, thermal, mechanical, strength, fracture, creep, fatigue, and any other properties required for a thermo-structural analysis, shall be either determined from characterization testing or selected from validated sources, corresponding to service environments.

An example of a validated source is the Metallic Materials Properties Development and Standardization (MMPDS) handbook.

[4.6.1-5] Material properties shall include changes due to manufacturing processes such as temper, product form, casting, welding, thermal environments and conditioning, chemical environments (cleaning agents, fluorescent penetrants, etc.), coatings, and test fluids.

The manufacturing process for additively manufactured materials includes the specific machines used and the specific build plan. Properties for these materials are highly sensitive to the build process and may exhibit a degree of orthotropic behavior relative to the build direction. As such, material properties such as strength, fatigue, and fracture need to be obtained for each direction from coupons produced using a manufacturing process consistent with production parts. Manufacturing process control is discussed in Section 7.10.1. Witness coupons are also used to verify consistency between as-built production units and what has been characterized and qualified. During development or qualification testing, the consistency between those witness coupons and delivered part-level properties should be verified.

[4.6.1-6] For all engine elements that are either primary structures, fracture-critical, or not fail safe, A-basis strength values at the operating environments (e.g., moisture and temperature) shall be used in analytical assessments.

[4.6.1-7] For components not covered by [4.6.1-6], A-basis or B-basis strength values, evaluated at the operating environments (e.g., moisture and temperature), shall be used in analytical assessments.

If neither A-basis nor B-basis properties are available, S-basis may be used for metallic hardware provided that each lot of material used in production is tested to verify consistency with those allowables.

[4.6.1-8] The mean curve shall be used to evaluate engine design for fatigue, creep, and damage tolerance.

The fatigue database may not account for surface finish, size effects, residual stress, and loading configuration. Additive manufacturing, for example, is known to result in parts with rough surface finish and may have process dependent material properties. Therefore, material data should consider the as-built material properties, directional dependence, and surface finish of the part. The material databases may be incomplete and unable to adequately characterize uncertainties in fatigue scatter expected for well-controlled samples. Although use of the mean curve is required only to evaluate fatigue, creep, and damage tolerance, it is recommended that minimum properties or increased factors of safety be used when possible to increase the likelihood of a successful engine test program. It may be challenging to define a single minimum curve. In these instances, the curve enveloping the majority of the material scatter should be used.

[4.6.1-9] Material properties for environmentally induced degradation mechanisms such as stress corrosion cracking, hydrogen embrittlement, or hydrogen-assisted cracking shall be obtained from characterization tests.

Prior characterization testing may be used to satisfy this requirement if applicable data are available.

4.6.2 Loads

There are two relevant load terms utilized within this Standard: Maximum Expected Operating Pressure (MEOP) and Maximum Design Condition Load (MDCL). MEOP is part of MDCL. MDCL is the most critical combination of load conditions, and includes steady-state, vibration, and shock loads. The MDCL is the worst-case combination of loads that a structure may experience during its service life in the specified environments. Steady-state loads may include a combination of residual stresses, pre-loads and other assembly loads, pressure loads, and external loads. Pressure loads may be uniform or non-uniform due to aerodynamics, combustion gas flow, flow separation, and over-pressure. Steady and transient thermal loads also require consideration, such as aerodynamic or combustion gas heating (flow or shock impingement, flow separation and reattachment, circumferential flow, shock recompression and shock formation, shock-shock interaction, plume-plume interaction, recirculation, etc.). For nozzles operating with exit plane pressure less than 50% of the ambient (atmospheric) pressure, sub-scale nozzle flow testing is recommended to determine the appropriate MDCL accounting for potential separation and/or side loads. Further validation should occur on full-scale component and/or with engine tests.

[4.6.2-1] The MEOP of the LRE and its respective units shall comply with the requirements for MEOP within TR-RS-2023-00005 [2], including both static pressure and transient pressure increases (Requirements [4.1.1-1] through [4.1.1-9] in TR-RS-2023-00005).

[4.6.2-2] The MDCL shall be the most critical condition(s) considering all loads, including external loads and combinations of loads and environments, that an engine and its elements will experience throughout its service life, including pre-launch operations, launch, ascent, re-entry, descent, and landing. When a statistical estimate is applicable, this load corresponds to a 99% enclosure with a 90% confidence level.

A good practice for developing MEOPs in support of establishing MDCLs is to perform a Monte Carlo simulation using the engine balance model to assess maximum and minimum conditions. To help ensure that bounding environments are established, this simulation encompasses the uncertainties associated with performance (such as turbine efficiencies, pump efficiencies, injector efficiencies, and pressure drops), fabrication (e.g., component dimensional variation) and operations (such as propellant inlet conditions, power level, mixture ratio, and run time/life dependent attributes). Historical data, such as that from early development hardware or relevant analogous heritage hardware, are helpful in establishing realistic bounds for performance and fabrication uncertainties. Qualification test conditions beyond what can be experienced during flight operations, such as those needed for margin demonstration (Section 7.2.6) and combustion stability testing (Section 7.2.9), are not included when determining MEOP. However, these should be considered in the engine design for survivability to successfully meet verification objectives.

[4.6.2-3] MDCL shall include thrust vector control, ignition, thrust, vibration, maneuvering loads, and loads determined by coupled system flexible body structural dynamic analysis, corresponding to the external load environment.

Note that in systems with flexible bellows or flexhoses, variations in as-built stiffness may change the predicted loads, such as during gimbaling or from flexible body dynamics. As such, allowable ranges of stiffness for these components should be considered as part of the MDCL definition.

[4.6.2-4] In evaluating the low- and high-cycle fatigue life of an engine element, the load spectra definition shall consider the component load history, including the number of cycles or time at each load level based on requirements of service life (flight and non-flight loads), and sustained loads such as pressure and thermal loads.

4.6.3 Factors of Safety

The required factors of safety for LRE engine elements are provided in Table 4-3. Application of damage tolerance (safe-life) on pressure components and pressure-loaded components allows the use of lower factors of safety (FoS) on proof and ultimate. The design factor is used to account for build-to-build hardware variability, uncertainty in internal load paths and stress/strain levels, and uncertainty in failure modes.

There may be applications where it would be impractical to conduct a structural qualification test and a proof test to required levels. One example is an integrated nozzle with cooling channels. In such an instance, structural integrity is verified by engine life testing, fatigue analysis, and strength analysis. The final verification of the flight unit is accomplished with a comprehensive NDI to verify that all flaws are within acceptable limits during the service life of the engine.

For weight and practical considerations, a yield factor lower than the proof factor may be used. In this case the proof test could cause permanent changes to the hardware, which could lead to subsequent leakage or accelerate fatigue failure. Therefore, a yield design factor lower than the proof factor is allowed when material is ductile (>3% elongation across the expected operating range), fatigue requirements are met, and no new failure modes are introduced.

[4.6.3-1] At a minimum, design analysis and test factors of safety (FoS) in Table 4-3 shall be used in the evaluation of engine structural elements.

These minimum factors are intended for well-controlled processes and may need to be increased to encompass process variations. For lines and fittings, qualification by analysis is an acceptable alternative to qualification testing if using the FoS in Table 4-3 under the "Pressure Components and Pressure-Loaded Components without Safe-Life" classification.

[4.6.3-2] Fitting factors, casting factors, and joint efficiency factors, all greater than or equal to 1.0, shall be included in addition to the design analysis factors of safety when calculating structural margins.

A fitting factor of 1.15, in addition to the ultimate factor of safety, is typically used to address non-uniform loading occurring in a group of fasteners. Other factors that may be considered in a design are casting factors, which are employed due to the inherent variability in strength properties caused by the manufacturing process.

Table 4-3. LRE Structure and Pressure Component Design Factors of Safety

	Applicable Loads	Yield	Proof	Ultimate
Unpressurized Metallic Structures (1)				
Qualification by Analysis Only (2,3)	MDCL	1.25	Not applicable	2.0
Qualification by Analysis and Test	MDCL	1.2[4]	1.2	1.4
Pressure Components and Pressure-Loaded Components *with* Safe-Life	MDCL	1.2[4]	1.2	1.4
Pressure Components and Pressure-Loaded Components *without* Safe-Life				
Lines and Fittings, Diameter < 1.5 inch	MDCL	1.5	1.5	4.0
Lines and Fittings, Diameter ≥ 1.5 inch	MDCL	1.5	1.5	2.5
Fluid Return Sections	MDCL	1.5	1.5	3.0
Fluid Return Hose	MDCL	1.5	1.5	3.0
Other Pressure Components	MDCL	1.5	1.5	2.5
Other Structures *with* Safe-Life				
Joints (welds, brazes, bonds)	MDCL	1.2[4]	1.2	1.4
Composites	MDCL	Not applicable	1.2	1.4
Rotary Components	MDCL	1.2[4]	1.2	1.4
Joints and Seals (5)	MDCL	Not applicable	1.1 or 1.2	1.2 or 1.4
TPS Structural Evaluation	MDCL	Not applicable	1.2	1.4
Buckling (2)	MDCL	Not applicable	Not applicable	1.4
Inadvertent Contact (2)	MDCL	Not applicable	Not applicable	1.4

(1) Unpressurized metallic additively manufactured structures are required to be qualified by Analysis and Test.

(2) Acceptance test and structural test are not required.

(3) Qualification by analysis should only be used on simple, determinate structures, where load paths, interfaces, and failure modes are straightforward and well understood and the hardware uses well-established manufacturing processes.

(4) Local yielding during proof with a design factor of safety for yield is acceptable when material is ductile, fatigue requirements are met, there is no effect on function, and no new failure modes are introduced.

(5) See Section 5.3.4 for clarification of which factors to use.

5. Structural Analysis Requirements

The thermo-structural qualification approach for engine structural elements requires a combination of analysis, test, acceptance, and inspection verification. This Standard provides a comprehensive and complete set of structural requirements, similar to NASA 5012B [21]. This section provides the requirements for the thermo-structural analytical verification of engine elements. While there are analytical models used with test to verify propulsion performance and functional requirements, this section is specific to the thermo-structural analyses. Structural requirements for test are included within the unit and engine requirement sections (Sections 6.11 and 7.4, respectively). No distinction is made between engines to be used for transporting personnel and those used for transporting only cargo.

The role of analysis is to demonstrate design robustness relative to dispersions in geometry, material properties, strength, fatigue, and creep data. Design integrity of structural elements can be demonstrated by analysis alone in instances where there is high confidence in the analysis for fatigue, fracture, buckling, and creep. Due to complexities associated with the vibratory-thermal-structural environments the engine experiences during operation, engine-level tests (hot-fire tests) are required as part of structural qualification and constitute the primary approach to fatigue life demonstration. Fatigue analysis is still required, as the total stress in the engine element can be a combination of stresses induced by the launch vehicle system, in addition to stresses self-induced by the engine due to combustion roughness, moving assemblies, thermal gradients, thermal expansion variations, etc.

Thermo-structural analyses of engine elements are typically performed using finite element models. Structural analyses are conducted to evaluate failure modes of the engine using the most appropriate solution procedure, which could include buckling, static, linear, nonlinear, and transient dynamic analyses. Structural dynamic and stress models are used in evaluating engine components. Engine structural dynamic models are integrated into coupled system models of the launch vehicle; these system models are coupled with the payload and are used to predict launch vehicle and payload launch and flight loads. The launch vehicle loads predictions include engine loads. Internal stresses are computed from stress models by imposing thermal loads, pressure loads, external loads, and inertial loads. Because of the complexity of the structural dynamic and stress models, test data are required to adequately develop the high-fidelity models.

The role of structural qualification tests is to verify and validate analytical models and verify the flight design. In the absence of a workmanship issue, the structural qualification test increases the likelihood of a successful proof test. An engine element that does not undergo a rigorous structural qualification test program can result in a failure or damage of the test article during a proof test. As such, engine elements may be accepted for flight as long as the component passes a comprehensive proof test, with no damage detected from a thorough post-proof inspection.

Analysis is used to ensure a successful structural qualification test, to define acceptance flaw criteria, and to demonstrate that the proof test does not cause detrimental yielding. There are several qualification strategies for engine elements, as illustrated in Figure 5-1. An environmental correction factor (ECF) and external load correction factor (ELCF) are applied to adjust for differences between the test and flight conditions. An alternate qualification strategy is to qualify an engine component by similarity to a previously qualified engine element. Whenever analysis is relied upon, specifically for fracture assessments, a test-anchored analysis approach should be used. Analysis validation is even more important for Option 4 in Figure 5-1, where no NDI is implemented.

[5.0-1] Engine elements shall comply with the structural qualification strategies in Figure 5-1, unless qualified by analysis only (per Table 4-3) or by similarity (Section 5.7).

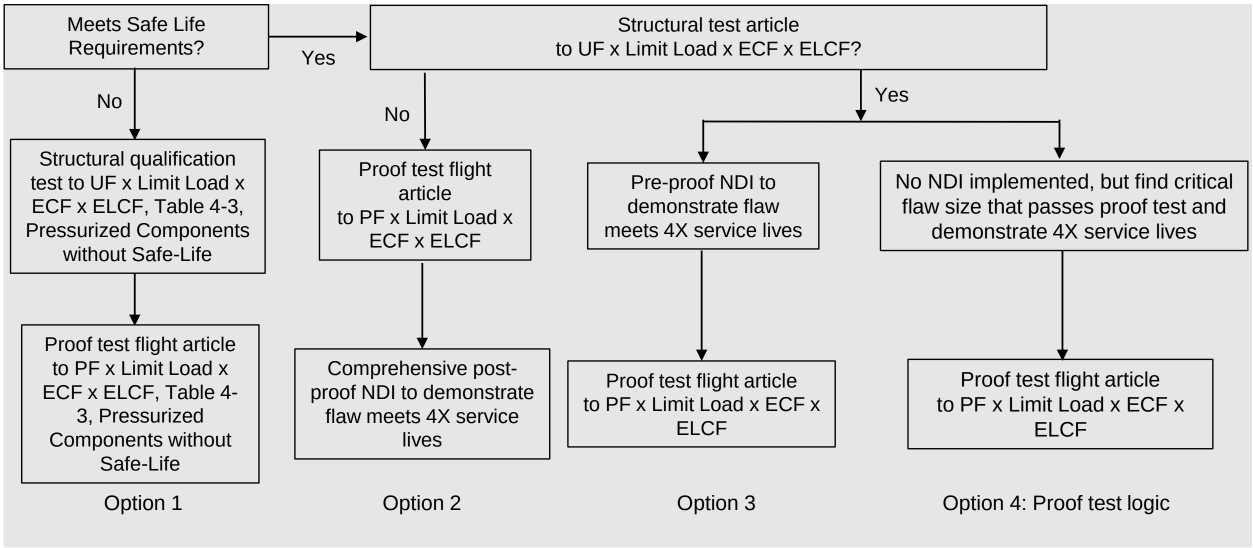

Figure 5-1. Qualification strategies for engine elements, excluding qualification by analysis (no test option) and by similarity. ECF – Environmental correction factor, ELCF – External load correction factor, UF – Ultimate Factor, PF – Proof Factor. For options relying on fracture analysis, particularly Option 4, the analysis methods should be validated by test.

5.1 Structural Model

Local stress models should include sufficient modeling fidelity in areas of rapidly varying stresses or strains and follow modeling "best practices" such as those described in Management of Finite Element Analysis – Guidelines to Best Practice [22]. The contributions of stress concentration factors should be included in the final assessment of the engine element.

[5.1-1] Numerical models used in design and analysis of the LRE shall meet the following criteria:

a. The geometry, material properties, mass, finite element selection (e.g., beams, shells, solids), boundary conditions, loading conditions, and stiffness representation of adjoining structures are representative of flight hardware.

b. Element quality checks pass for all cases where a violation could lead to invalid stress or strain results.
These checks include aspect ratio, Jacobian, skew, and warpage.

c. The mesh is converged.
Numerical methods such as finite element method, boundary element method, and finite differences are sensitive to mesh density and element type. Mesh convergence is demonstrated when stress or strain values remain insensitive to further refinement.

Closed-form or classical solutions are acceptable if the design geometry and loading conditions are simple enough to warrant their application.

Test articles should be instrumented sufficiently to measure load, deflection, and strains for model correlation and to identify failure modes. A typical static correlation goal is that model predictions be within ±10% of the test measurements. Deviations from these goals should be investigated because they can affect structural evaluation during the design phase, proof test definitions, and accurate evaluation of non-conformances.

Manufacturing complexities for engine components (e.g., small radii, thin walls) typically result in significant geometric variations, and the severe engine environments mean that even minor geometric variations may significantly affect operation. These aspects may not be covered by a standard factor of safety, and if not evaluated, they could result in unexpected failures during structural qualification testing or engine testing.

Engine components are subject to extremely high and/or extremely low temperatures, with large thermal gradients through parts, making it impractical to apply a FoS to the thermal portion of the thermo-mechanical load. Other examples of impractical application of FoS include cases where the load is limited by deflection. To address this challenge, the dimensions within drawing tolerances that result in minimum margins should be selected along with a minimum stress-strain curve in a nonlinear analysis.

[5.1-2] When analysis is used as a verification method, it shall use the following:

a. Typical or mean values for physical properties at the service environments (e.g., modulus of elasticity, thermal expansion, Poisson ratio, etc.).

b. Dimensions for strength and life calculations such that the calculated structural margin is the minimum.
If nominal dimensions are used, accounting for minimum dimensions may be possible by scaling the stresses.

c. Stress-strain curves based on A-Basis or S-Basis properties, except the nominal stress-strain curve is used in stress-based high-cycle fatigue predictions.

[5.1-3] The structural dynamics model of the engine shall meet the requirements in TR-RS-2003-00004 (SMC-S-004) [10].

The model should have sufficient fidelity to capture the dynamic behavior in the relevant frequency range and TR-RS-2003-00004 provides the mode survey test and model correlation criteria.

5.2 Failure Modes

When calculating the structural margins of the system, the most applicable failure metric (e.g., stress, strain, applied load) and failure criteria (e.g., strength allowable, strain allowable, buckling load) should be used for each failure mode of the structural component. In certain cases, analysis approaches for complex joints (such as adhesively bonded, mechanically fastened, welded, or brazed) are of low confidence. These analyses should be anchored to representative coupon or subscale tests that bound the expected manufacturing variability.

[5.2-1] An uncertainty factor (UF) greater than or equal to 1.0, and determined by test data of similar failure modes on prior designs or published data, shall be applied as a multiplier to the design factor of safety when analyses of composites and complex joints (e.g., bonded joints, braze joints) are not directly anchored or correlated to test data.

It is common to apply an uncertainty factor of 2.0 for structural discontinuities to account for the uncertainties in predicting failure of joints.

5.3 Strength Assessment

[5.3-1] The structural margin of safety, MS = ALF/(FoS × UF) – 1, shall be greater than zero with the FoS specified in Table 4-3, where the allowable load factor (ALF) is a calculated non-dimensional multiplier to the MDCL that produces the mode of failure (e.g., A-Basis ultimate strength, A-Basis yield strength, A-Basis elongation, buckling, etc.).

[5.3-2] When calculating the ALF, factors applied to the portions of the MDCL definition that increase the structural margin shall be set to 1.0.

As an example, internal pressure typically has a beneficial effect on buckling failure modes, so a unit factor would be applied to that portion of the load. Furthermore, the value of the alleviating load should be a mean or minimum expected value of that load, rather than MDCL, which if used would result in an unrealistically high margin. For loads such as the internal pressure, the minimum expected value should be used as a conservative lower bound for the buckling margin. There could be other instances where using the mean expected value for the alleviating load is more appropriate.

Structural analysis of engine components usually necessitates nonlinear structural analysis, including both geometric and material nonlinearities. The structural margin calculation in requirement [5.3-1] applies to both linear and nonlinear analyses. Engine structural elements, subject to high temperatures, will often require a nonlinear material and geometric analysis. To the extent practical, the FoS should be applied to the mechanical and thermal portions of the loading, as long as these loads are non-relieving. Incorporating the FoS on the thermal portion of the loading may be impractical in a nonlinear analysis. In some cases, applying the FoS on deflection-controlled loads, such as engine gimballing, may be impractical. Therefore, it is important to analyze engine elements following the requirement in [5.1-2].

Multi-axial states of stress can lead to a reduction in strength and elongation compared to uniaxial conditions. To account for this effect, the following empirical correction factor C_{TF} is applied to the elongation of the material.

$$\frac{\text{von Mises effective strain allowable}}{\text{Uniaxial tensile elongation allowable}} = 2^{1-TF} = C_{TF},$$

where the Triaxiality Factor (TF) is defined as follows:

$$TF = \min\left(1,\ \frac{\sigma_1+\sigma_2+\sigma_3}{\frac{1}{\sqrt{2}}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]^{1/2}}\right),$$

and $\sigma_1, \sigma_2, \sigma_3$ are the principal stresses at a given location. For further background on TF, refer to Manjoine [24].

5.3.1 Strength and Yielding

The peak stress or peak strain should be used in determining whether failure can initiate at the outer surface of the component and propagate through the thickness of the part. Many engine structural components can have (1) unique geometric features, such as sharp radii or abrupt changes in geometry, (2) extreme thermal gradients, and (3) non-uniform stresses that cause bending. These features are typically the initiators for cracking. Plastic correction factors, plastic bending, and fracture mechanics may be used to evaluate the risk of failing the hardware when the material allowable is exceeded.

[5.3.1-1] The structural margins of safety shall be positive when the engine element is evaluated using the peak strain or peak stress at the ultimate load. Negative local yield margins of safety are acceptable when all the following conditions are met:

a. The structural integrity of the component is demonstrated by adequate analysis and/or test.

b. The deformations do not adversely affect the component/system function.

c. The service life (fatigue and creep) requirements are met.

Unlike many components of a launch vehicle, metallic engine components may undergo yielding. In these cases, it is necessary to ensure that yielding does not adversely affect function and structural integrity of the hardware. Examples of adverse effects include unexpected contact between components, unexpected stiffness (flexibility) of hardware, reduced performance capability, or new failure modes (e.g., buckling or fatigue).

5.3.2 Buckling

[5.3.2-1] Engine structural elements shall demonstrate positive margins of safety against local instability, global instability, and crippling using the factors of safety in Table 4-3.

[5.3.2-2] In instances where buckling is statically stable, the post-buckling deformation at MDCL shall not degrade the function of any system.

[5.3.2-3] Geometric and material properties, dimensions, and imperfections in the analytical model shall be chosen so that calculated margins are at a minimum while enveloping the actual flight hardware condition.

Buckling assessments may use either linear or non-linear analytical methods, whichever is more appropriate.

[5.3.2-4] For linear buckling analysis at MDCL, ALF shall be taken as the most critical buckling eigenvalue multiplied by an imperfection knockdown factor, which accounts for the difference between classical theory and empirical instability loads.

Typical knockdown factors, as listed in NASA SP-8007A [23] or other validated sources, may be used.

[5.3.2-5] For non-linear buckling analysis, ALF shall be (1) calculated as a multiplier factor to MDCL corresponding to the point of collapse initiation, and (2) a bounding factor resulting from an exhaustive study that considers geometric imperfection amplitude, in conjunction with buckling modes, and the combination of modes or other imperfection geometries deemed more critical.

Buckling, or some other instability, can be precipitated by local yielding in the structure, and this yield point can exhibit statistical scatter. To ensure that this effect is accounted for in the buckling analysis, it is necessary to use a minimum stress-strain curve.

5.3.3 Inadvertent Contact

[5.3.3-1] Intended clearances to prevent impact under all conditions (e.g., with the engine fully gimbaled) shall be greater than zero to prevent inadvertent contact under at least one of the following assumptions:

Option A: Nominal tolerances, deformations, and thermal effects at 1.4 × MDCL (e.g., with the engine fully gimbaled),

Option B: Worst-case stack-up tolerances, deformations, and thermal effects at MDCL.

5.3.4 Joints and Seals

[5.3.4-1] Separation-critical joints shall remain in contact under loads up to 1.4 × MDCL for joints leading to a catastrophic structural failure, and 1.2 × MDCL otherwise, when subjected to worst-case stacking tolerances, environments, and minimum preload.

[5.3.4-2] All requirements in NASA-STD-5020A [11] shall be met with the following modifications:

a. Threaded fastening system hardware shall be designed using a separation factor of safety of 1.0 when it has been confirmed, for the range of permitted tolerances, that (i) unacceptable environments do not occur as a result of gapping, and (ii) the joint does not need to contain pressurized fluid; otherwise a separation factor of safety ≥ 1.2 shall be used, even when seals are employed.

b. All instances of "NASA" in this document shall be replaced by "Approval Authority."

Locking or secondary retention features are important for engine systems, as high vibrations can cause fasteners to back out. These locking features, however, do not eliminate preload loss that should be accounted for in analysis and measured during testing. In some cases, unanticipated measured reductions in preload during testing may require changes in initial installation torque procedures, updates to analysis, and/or changes to design to maintain intended design function and sufficient safety factors with positive margin.

[5.3.4-3] Seals shall be capable of accommodating structural deflections and operating across the entire expected temperature range resulting from all environments, manufacturing processes, and any engine induced environments, without rupture or a leakage rate that leads to a violation of leakage, performance, and/or safety requirements.

[5.3.4-4] Leakage shall be acceptable only if demonstrated to have all the following characteristics:

a. Non-hazardous in terms of contamination, corrosion, fire, etc.

b. Stable across engine operation (additional starts/duration demonstrate stability)

c. Not the cause of unacceptable loss of system or mission performance

5.3.5 Failure Modes of Ablative Thermal Protection System (TPS)

Key to the overall TPS structural integrity assessment is ensuring that the ablated structure (i.e., the end of mission state without the eroded material) can withstand the ultimate loads. The evaluation should include assessment of temperature extremes. Often, the char regions of the TPS will experience cracks because material properties are reduced significantly.

[5.3.5-1] The structural margins for all structural failure modes relevant to the TPS and adjacent components shall be greater than zero at 1.4 × MDCL (including worst-case heat loads and external loads). TPS regions which are above their charring temperature may be excluded from this requirement.

5.4 Life Assessment

Analytical assessments of thermo-structural life include fatigue, creep, and damage tolerance (safe-life) aspects. Fatigue analysis is performed assuming no initial defects, while damage tolerance assumes an initial flaw size set by the non-destructive inspection (NDI) limit. In the fatigue analysis, a fatigue analysis factor (FAF) is applied to account for uncertainty in stress level near the endurance strength, where small changes in stress can have significant implications in the life predictions, and the typical service life factor of 10, alone, is ineffective. Fatigue stresses are often dependent on the line-up of natural frequencies with forcing functions, as well as uncertainties in characterizing forcing function magnitudes, damping, and temperatures. FAF also provides protection in the higher cyclic strain amplitude regime where the typical service life factor of 4 may not be sufficient. A higher FAF is used for rotating components due to the higher uncertainty surrounding these fatigue predictions.

5.4.1 Fatigue

[5.4.1-1] The predicted number of service lives shall be greater than one, using a service life factor of 10.0 for High Cycle Fatigue (HCF) failure modes, and 4.0 for Low Cycle Fatigue (LCF) failure modes.

Stress-life fatigue models are appropriate for evaluating HCF failure modes when cyclic loading remains in the linear-elastic regime; otherwise, strain-life models should be used. Strain-life analyses should be used for the evaluation of LCF failure modes when plastic strains occur but can also be used to evaluate HCF failure modes. Higher factors should be used if the material exhibits high fatigue scatter from the median.

For service lives that include variable amplitude loading, including elastic- and plastic-strain ranges, both LCF and HCF failure modes should be evaluated. In addition, when the service life includes non-proportional loading, critical-plane fatigue models that account for changes in principal stress directions should be considered in place of uniaxial fatigue analysis models.

[5.4.1-2] The fatigue analysis factor (FAF) of 1.25 for rotating components or 1.15 for nonrotating components shall be multiplied by the alternating stress before starting the stress-life fatigue assessment, or by the strain range before starting the strain-life fatigue assessment.

[5.4.1-3] Mean stress effects shall be accounted for in the evaluation of HCF and LCF failure modes.

The evaluation of LCF failure modes should also consider the potential for larger strain ranges stemming from material-specific characteristics (such a cyclical softening, etc.).

[5.4.1-4] The cumulative damage index (CDI) shall be less than 1.0 for the entire service life using standard methods such as Miner's method after including the FAF, mean stress/strain corrections, and the required service life factors (i.e., 10 for HCF failure modes and 4 for LCF failure modes).

5.4.2 Creep

[5.4.2-1] The predicted number of service lives for the creep failure mode shall be at least 10.0.

[5.4.2-2] The stress or strain shall include stress concentration factors when applicable.

[5.4.2-3] The stress or strain shall be multiplied by a minimum factor of 1.15 before entering the design creep curve to determine life.

5.4.3 Damage Tolerance (Safe-Life) Assessment

Engine structural elements are generally classified as fracture critical. While NASA-STD-5019A [25] requirements are not imposed in this Standard, they may be used as guidance to assess fracture criticality. Pressurized components and pressure-loaded components may also be subjected to damage tolerance (safe-life) verification to allow reduced yield and ultimate FoS (see Table 4-3). These requirements supplement strength requirements to prevent catastrophic failure due to material flaws under operational loads.

Safe-life analysis has successfully mitigated structural failures in ships, pressure vessels, aircraft, and launch vehicles. For a part to meet safe-life requirements, cracks smaller than the NDI detection threshold must not grow to unstable conditions over the required life of the structural component. There have been instances where a flaw smaller than the minimum detectable flaw size propagated to failure during the life of a component. Flaw growth can be accelerated by environmental (e.g., hydrogen embrittlement, hydrogen assisted cracking, etc.) and metallurgical (e.g., large grains) factors, and therefore these need to be carefully considered in the material fatigue characterization. Stable crack growth could cause a leak before catastrophic failure; in these cases the leak is only acceptable when the leak is non-hazardous, stable, and does not cause unacceptable loss in performance.

[5.4.3-1] For Qualification Strategies in Figure 5-1, Options 2–4, damage tolerance (safe-life) verification shall be performed by evaluating the largest undetectable crack in a part (consistent in size with the proof test limits or sensitivity of the applied NDI) and demonstrating by analysis or test that it remains stable when the part is subjected to cyclic and sustained loads to at least 4 times the service life. For reusable parts (e.g., reusable engines), the applicable service life definition for this requirement is based on the inspection interval (i.e., safe-life assessment is based on the last inspection).

Note that more than 4 times the service life may be required if this does not adequately cover the actual fatigue scatter.

[5.4.3-2] If proof test logic is used, then the upper bound fracture toughness shall be used to define the initial flaw size prior to the safe-life assessment.

The intent of this requirement is to ensure that the largest flaw size that could survive proof test loads is used in the safe-life assessment.

[5.4.3-3] NDI shall be performed before and after proof testing for hardware following Option 2 or Option 3 of Figure 5-1.

[5.4.3-4] NDI techniques shall demonstrate a 90% probability of detection and 95% confidence level for the detection of cracks or crack-like defects assessed in [5.4.3-1].

Acceptable flaw sizes include those from Table 1 from NASA-STD-5009A [26], which provides minimum detectable crack sizes based on the NDI technique, or alternate flaw sizes based on rigorous probability-of-detection studies.

Damage tolerance evaluation may be verified by analysis using linear elastic fracture mechanics (LEFM) if the engine element is in the elastic range throughout its service life and other LEFM assumptions are valid. In instances where an inelastic response is present, an accurate analysis necessitates fatigue-crack growth data in the nonlinear elastic regime and a nonlinear elastic analysis with accurate plastic cycling. In these cases, a test program to demonstrate damage tolerance may be more appropriate.

5.5 Turbomachinery Operation

Campbell diagrams are typically used to assess the dynamics of turbomachinery. A Campbell diagram relates frequency to the rotation speed of the shaft. Natural frequencies corresponding to a mode and Engine Order (EO) excitations are drawn against the rotation speed of the shaft. A necessary condition for an EO excitation to excite a bladed disk is that the EO frequency coincides with the natural frequency of the structure. At the intersection between the nth EO line and the line of natural frequencies of a mode characterized by n nodal diameters, a possible resonant condition can be found. Singh's advanced frequency evaluation (SAFE) diagrams (Singh et al. [27]) may also be used in the assessment.

[5.5-1] The minimum frequency separation margin between each combination of component natural frequency and primary excitation source frequency, as established by Campbell or SAFE diagrams (or an equivalent approach), shall be 20% in the operating speed range.

Secondary and higher-order harmonics of driving sources may also cause failures, so they should be considered and evaluated. The requirement addresses only primary frequencies because it becomes very challenging to maintain 20% separation across the board when multiple harmonics are included. For primary frequencies, separation margin less than 20% may be acceptable with test verification and concurrence of the Approval Authority.

[5.5-2] Campbell or SAFE diagrams (or an equivalent approach) shall include, as a minimum, an evaluation of rotating blades, stationary vanes, turbine disks, and impellers, and consider modes subject to excitations driven by the known forcing functions.

Generally, the assessment includes the dynamic assessment of shaft modes, with consideration of interactions with bearings, seals, imbalance, shaft curvature, and hydrodynamic forces.

5.6 Bellows

Bellows structural analysis is usually not of high confidence due to manufacturing variations in convolute geometry, difficulty in developing a material model consistent with manufacturing, plasticity occurring in thin ply regions, complex contact interaction between plies, and potential contact between convolutes. Therefore, verification of bellows components is primarily by test.

Bellows are susceptible to fatigue failures, buckling, corrosion failure, handling damage, failure due to pressure surge, flow induced vibration (FIV), fluid entrapment, and contaminants (NASA SP-8123 [28]). Depending on the significance of external loads, bellows may be considered either pressure components or pressure-loaded components. In many applications, those external loads are highly dependent on the stiffness of the bellows itself. As such, verification of bellows stiffness is often a requirement to verify consistency of the as-manufactured unit relative to predicted MDCL.

[5.6-1] Bellows design shall meet the proof and ultimate factors in Table 4-3.

[5.6-2] Fatigue capability and damage tolerance life of bellows shall be verified by test consisting of cyclic loading to a minimum of 4 times the service life, including all load and deflection cycles.

It is recommended to perform fatigue testing on multiple hardware units to verify fatigue behavior is within a 4× scatter factor. In absence of testing multiple units, it is recommended that damage tolerance be performed using bellows hardware manufactured with a pre-cracked defect at a ply location corresponding to the maximum expected fatigue damage. Specific unit test requirements for fatigue and damage tolerance (safe-life) testing are discussed in Section 6.11.

[5.6-3] Bellows shall meet the requirements in ANSI/AIAA-S-080A-2018 [4], except as superseded by the requirements herein.

For example, a unit stiffness test (ANSI/AIAA-S-080A-2018, Paragraph 10.4.13) is required for bellows whose stiffness would change the predicted MDCL.

[5.6-4] Bellows that are not fully lined shall be evaluated for flow-induced vibration (FIV) by (1) analysis according to NASA MSFC-DWG-20M02540 [12] or an equivalent method that demonstrates separation between the coupled fluid-structural modes and the fluid excitation frequencies, or (2) flow testing conducted according to NASA MSFC-SPEC-626 [13].

Fully lined bellows designs mitigate FIV failure modes and do not require evaluation. If the design has partially lined bellows, the technique prescribed in NASA MSFC-DWG-20M02540 [12] does not apply, and either an alternate technique must be developed and employed, or a flow test must be conducted according to NASA MSFC-SPEC-626 [13].

A post-proof destructive inspection of bellows on the first article and articles from subsequent production lots is recommended to verify nominal manufacturing and testing procedures are not introducing unintended hardware damage. Particular attention should be paid to inner convolutions that are fluid-contacting or not nominally accessible for post-proof inspection. Periodic repeat of these destructive inspections helps to screen for potential process drift.

5.7 Structural Qualification by Similarity

Successful qualification, production, and flight experience with the heritage design of an engine element may be used to develop qualification rationale for minor design changes to an engine element, or for a candidate engine element design. Only minor differences should exist between the heritage engine element and the candidate design. Because structural modeling is relied upon for the evaluation of the candidate design, it is imperative that the structural analysis for the heritage design has been validated. Design dissimilarities resulting from addition or subtraction of piece parts and particularly moving parts, ceramic or glass parts, crystals, magnetic devices, and power conversion or distribution equipment usually compromise qualification based on similarity.

[5.7-1] Qualification by similarity rationale for a candidate engine element shall meet criteria (a) – (i) in Paragraph 4.10.1 of TR-RS-2014-00016 (SMC-S-016) [1] and criteria (j) – (l) as follows:

j. All design changes are thoroughly evaluated, and anticipated failure modes remain identical.

k. The candidate element produces environments on other engine components that are within the limits of those produced by the heritage design.

l. The margins of safety for each failure mode being qualified by similarity is greater than or equal to the margin of safety for the same failure mode in the heritage design that was tested.

5.8 Structural Approach Documentation

The approach used for structural verification is termed the structural assessment plan (SAP) and will contain plans for both analyses and test. Fracture critical elements necessitate a fracture control plan.

[5.8-1] The SAP shall be provided to document how the particular engine program intends to satisfy the requirements of this Standard, including development, qualification, and acceptance approaches; analysis methods; and the applied FoS.

[5.8-2] A Fracture Control Plan and/or Impact Damage Control Plan shall be provided either in the SAP or separately, documenting the hardware-specific fracture control methodologies and procedures.

These plans are typically produced at the beginning of a program, before the test and evaluation phases begin, but they are essential to successful test and evaluation phases.

6. Unit Requirements

The objective of the qualification test program is to substantiate that the flight design, manufacturing processes, and acceptance program produce flight hardware and software that meet specification and performance requirements, allowing adequate margin to accommodate normal hardware variations. Acceptance tests verify the performance against the specification and demonstrate acceptable workmanship in manufacturing.

The generic unit test requirements in TR-RS-2014-00016 (SMC-S-016) [1] are applicable, and in some cases expanded in this Standard to specifically address application to LRE unit testing. This Standard takes precedence in the event of any conflict with TR-RS-2014-00016. Units acting in concert with other elements may defer testing to a higher assembly level as long as test objectives and test perceptiveness for requirement verification are maintained. Depending upon the unit, a mix of functional and performance tests are typically conducted prior to its delivery to the next higher level of assembly.

6.1 Unit Verification by LRE Test

Because engines are hot-fire tested for acceptance, installed components will receive additional testing beyond the unit acceptance test procedure (ATP). This reduces the risk of a future failure due to manufacturing and assembly issues. Component acceptance testing at the bench level serves to reduce risk for engine testing, but it often cannot adequately simulate the engine environments.

A line replaceable unit (LRU) is one that may be removed and replaced within an LRE without adversely affecting the performance verification of the LRE or one that will affect performance only within some understood and properly allocated uncertainty. Example LRUs are igniters and isolation valves. To be considered an LRU, the unit's interaction with the LRE must be fully characterized via LRE testing.

[6.1-1] All components of an LRE shall be hot-fire tested on an engine, except in cases where unit-level acceptance testing can replicate the engine environment and/or adequately screen components, or the component is designed for a single use: exclusions require Approval Authority concurrence.

LRUs may be substituted into an engine without requiring that particular engine to undergo repeat hot-fire testing, but the LRU must still have undergone hot-fire test on an engine with adequate instrumentation to verify the component is acceptable.

[6.1-2] An LRU shall be verified by testing to have either a trivial effect on LRE performance and reliability, or a known, well-characterized, and predictable effect on LRE performance and reliability.

Units excluded (with Approval Authority concurrence) from engine hot-fire testing are typically restricted to those unaffected by the thermal-pressure-vibration environment of the engine (which is difficult to replicate), simple components with high structural margins, or those that are designed for a single use (e.g., ablative nozzles or pyrotechnic igniters).

6.2 Unit Inspection

[6.2-1] Units within an LRE shall comply with the inspection requirements of TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 4.6, for unit qualification and unit acceptance.

6.3 Unit Performance Requirements

This section describes LRE performance requirements; LRE functional requirements are detailed in Section 6.4.

Performance of a unit includes many aspects with requirements specific to the various types of units. For example, contamination control, while a design aspect, is verified by cleanliness tests. These cleanliness tests are considered part of performance verification. Qualification performance testing includes showing margin beyond the expected maximum and minimum conditions. The amount of margin varies; the appropriate value is specific to the unit type and application.

[6.3-1] Units within an LRE shall comply with the performance requirements of TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 6.3.2, for unit qualification and unit acceptance.

Additional requirements are included in the following sections for LRE-specific components and aspects.

6.3.1 Ignition System

Significant unit or subsystem testing should be conducted on ignition systems to minimize risk to engine-level testing. The environment of the start condition is important, and the type of ignition system will affect the parameters of interest (including mixture ratio, temperature, pressure, and input voltage). Unit testing can verify compliance to unit design specifications, but ignition system verification for an LRE ultimately must occur at the engine level (see Section 7.2.7).

6.3.2 Turbomachinery

Analytical models for steady-state performance use turbomachinery performance maps to predict overall engine performance. These maps are initially predicted analytically and need test validation. Ideally, the testing would span the ranges of the statistical variation (e.g., 99% enclosure, 90% confidence level) of the expected operating band with some excursions outside of that range. Consideration must be given to performance over time in a single burn as well as over the engine's life expectancy. Engine performance predictions will depend on turbine and pump efficiencies and net positive suction pressure (NPSP) performance. Inherent inefficiencies drive the need for additional turbine drive power requirements for the system. Turbine flow area can carry uncertainty that affects engine performance and prediction capability. The secondary flows (bearing coolant flows, thrust balance fluid pressures, inter-propellant seal purges, etc.) also need validation, as these can affect system performance, functionality, and margins.

Turbomachinery is technically a combination of several units that function together. Performance testing requires the full combination of units acting together, although limited functional testing at the individual unit level is still possible. For engines with turbomachinery, subscale testing of the turbine and pump, flowing air and water, respectively, is recommended. These lower-level tests verify turbine flow path and pump/inducer performance. Full-scale turbomachinery tests are performed to obtain mapping information for engine performance. These tests are typically either performed in a dedicated turbomachinery test rig or facility, or at the engine level during development hot-fire testing. For tests performed in a turbomachinery test facility, the test facility will have some method to drive the turbomachinery and control speed that may not match the turbine drive on the engine. The pump may or may not pump the same fluid as the engine. The test drive gas and pumping fluid should be matched to the engine to the maximum extent practical. This testing may include "powerpack" type configurations, which typically include turbomachinery and major combustion devices in an integrated package, to provide supplemental characterization prior to, or in parallel with, the full engine development test program.

[6.3.2-1] For engines with turbomachinery, a full-scale turbomachinery test shall be conducted to obtain mapping information for engine performance across the entire range of expected operating conditions, including expected excursions and sensitivities to secondary flow variations.

These tests may be performed in a dedicated turbomachinery test rig or facility, or at the engine level during development.

Temporal and spatial variations/distributions in gas temperature at the turbine inlet should be characterized, then verified by test at the component and/or engine level.

6.3.3 Combustion Devices and Combustion Stability

Combustion device performance is ultimately verified at the engine level for the operating conditions (see Section 7.2.9). At the component level, subscale testing is used to characterize combustion efficiency and injector pressure drop. Calorimeter spool pieces may be used to estimate combustion chamber heat loads/fluxes. Component testing is used to reduce risk to the engine test program. A full-scale component test for stability verification is recommended as risk reduction prior to the engine-level test verification effort. Ultimately, combustion stability must be verified at the engine level per [7.2.9-2].

Turbine drives for LRE cycles with a pre-burner (PB) or gas generator (GG) may be sensitive to temperature distributions at the inlet, which may necessitate design features in the associated PB or GG to minimize the effect.

PBs and GGs, if present in the LRE cycle, should undergo component-level testing to verify combustion efficiency, injector delta pressure, and temperature distributions entering the turbine.

6.4 Unit Functional Characteristics

6.4.1 Cold Flow Tests

[6.4.1-1] Cold flow tests, using either the engine working fluids or suitable alternatives, shall be conducted on units within the flowing system to characterize their behavior. Test results are to be compared to predictions to verify that resistances, pressure drops, temperatures, and flow rates are within expectations and design requirements.

6.4.2 Transient Characterization

Due to the complexity and severity of environments in LRE systems, it is challenging to properly characterize the engine transient environment at the component level. However, unit resistances can be characterized as a risk reduction step for powerpack and engine-level testing. Units may include valves, injectors, and flow restrictions. Unit testing may include "powerpack" type configurations, which typically include turbomachinery and major combustion devices in an integrated package, to help develop and establish the proper start transient control sequencing and timing prior to engine-level testing. Ultimately, acceptable transient behavior must be verified at the engine level (see Section 7.3.5).

[6.4.2-1] Components (e.g., pumps and control valves) that significantly influence the transient characteristics of the engine shall be unit tested to characterize their transient behavior, including start-up and shut-down, and reduce risk for engine-level testing.

In addition to verifying specification requirements, the test results are to be compared to predictions and should be used in engine system models and verification steps.

6.4.3 Net Positive Suction Pressure (NPSP) Margin and Cavitation

NPSP is the pressure difference between the total pressure and vapor pressure of a liquid propellant at a given temperature. For engines with liquid pumps, this is a key parameter needed to quantify suction performance. This parameter must be thoroughly understood and characterized during development. Low inlet pressure to a pump can lead to significant cavitation, which can reduce pump performance with a corresponding reduction in discharge pressure (commonly referred to as head fall-off, where acceptable head fall-off is typically no worse than ~2-3% degradation in pump discharge pressure), and/or damage or fail hardware. In addition, cavitation can lead to fluid-structure interaction and pogo instability if other conditions are present. Lower tank operating pressures for vehicle systems are desirable to reduce tank weight, but a minimum NPSP must be maintained to avoid significant pump cavitation. The margin is analytically predicted, along with the turbopump performance maps anchored to test data, and incorporated into engine steady-state performance and transient models.

Component-level pump tests are often conducted using subscale hardware at scaled speeds using simulant fluids (such as water) that may not adequately represent the true flight operating environment. Even full-scale turbopump component tests pumping flight propellants may not identify all cavitation issues due to the variety and complexity of possible cavitation phenomena and the potential for unknown engine system effects. For these reasons, component-level testing is useful to identify expected engine-level suction performance but does not satisfy the requirement for turbomachinery powerpack and/or engine-level testing, which is required to validate the component-level findings (see Section 7.3.6).

Pump conditions, equivalent to the engine operating range, should be mapped in terms of the dimensionless pump parameters that govern cavitation behavior, namely cavitation number and flow coefficient, accounting for uncertainties derived from measurement uncertainties, hardware variation, and ground-to-flight differences.

[6.4.3-1] For engines with liquid pumps, adequate steady-state pump performance and acceptable head fall-off with decreasing NPSP shall be verified by test, including margin testing outside of the pump inlet box and below the specified minimum NPSP requirement for each propellant.

Test durations at the minimum NPSP condition should be sufficiently long to collect steady-state performance data. See the last paragraph of Section 7.3.6 for margin selection guidance.

[6.4.3-2] For engines with liquid pumps, cavitation behavior testing shall cover (with sufficient resolution) the entire range of flow coefficients and cavitation numbers (i.e., cavitation space) corresponding to the entire range of specification-allowed and expected engine operating conditions, including expected excursions and ground-to-flight differences.

[6.4.3-3] Cavitation mapping information shall describe the structure (alternate blade, high-order surge, high-order rotating, etc.), strength (vibratory and/or pressure fluctuation amplitudes), and extent (operating parameter range) of cavitation instabilities.

[6.4.3-4] The NPSP margin and cavitation testing implementation plan shall include the following elements:

a. Proper location of propellant inlet temperature, pressure, and flow rate measurements for determination of cavitation number and flow coefficient. These should be located as close as possible to flight measurement locations or corrected to flight measurement locations. Inlet pressure measurements should be sufficiently far upstream to prevent erroneous pressure readings that may be caused by local backflow near the inducer inlet.

b. Proper location of axial and radial accelerometers on the pump housings to quantify the strength and oscillation frequencies associated with cavitation instabilities. Also, if possible, one or more close-coupled dynamic pressure transducers should be included at or near the inducer inlet.

c. Sufficient frequency response and sample rates of accelerometers and pressure transducers to resolve the frequencies associated with the highest frequency cavitation instabilities (which are typically 10–12 times the rotor shaft speed).
d. Employment of pressure transducer arrays (e.g., circumferential array) if cavitation instabilities are observed, to identify the structure and rotation rate of the cavitation disturbance.
e. Working fluid cleanliness and dissolved gas content levels representative of flight conditions.
f. Flight-representative feedline geometries.

[6.4.3-5] Testing shall verify design robustness and life margin against any observed cavitation or flow instability behavior that cannot be eliminated by accumulating 4× worst-case exposure duration (4× exposure service life) to that instability.

[6.4.3-6] Acceptance testing shall verify characteristic cavitation responses of production engines, and ensure that high-cycle fatigue damage potential at the end of production engine service life will be bounded by qualification with margin per [6.4.3-5].

[6.4.3-7] Post-test integrity of critical hardware (e.g., inducer and impeller blades) shall be verified via sufficient inspection methods (e.g., dye penetrant inspection), either periodically throughout the test series or at the end of the test series.

Additional rationale and guidance can be found in JANNAF-GL-2012-01-R0 [19], Paragraphs 4.4.5, 4.4.5.1, and 4.4.5.2. The following references may be helpful in establishing placement and selection of instrumentation: For assessing backflow near inducer inlet, "Hydrodynamics of Pumps" by C. E. Brennen [29]; for close-coupled pressure transducer location, "Water Flow Characterization of the Unsteady Environment Upstream of the Space Shuttle Main Engine Low pressure Fuel Pump with Flow Liners" by A. Mulder [30]; and for accelerometer selection and placement, "Vibration-based Condition Monitoring" by R. B. Randall [31].

6.4.4 Pogo and Pump Compliance Characterization

Pogo is a fluid-structural instability that can cause catastrophic loss of a vehicle. Characterization of engine compliance by testing becomes an important part of anchoring the analytical models and helps determine if a pogo accumulator is required. Ultimately, compliance characterization must be done at the engine level (see Section 7.3.7), but pump characteristics should be determined through pump unit testing.

6.4.5 Engine Controls

The engine control system acts as the nervous system. It sends commands throughout the engine and communicates with the stage/vehicle. It also collects and distributes engine data as necessary. This subsystem is a vital contributor to the engine as a whole. Functional tests are initially run separate from the LRE (at unit or a subsystem level), often in a laboratory environment (e.g., hardware-in-the-loop). Vehicle commands and other communication may be simulated.

[6.4.5-1] Tests of engine controls shall use integrated software and electronic hardware to verify the engine control system can reliably and accurately satisfy specification requirements for startup, steady-state operation, throttling, shutdown, and aborts.

[6.4.5-2] Tests of engine controls shall verify data collection and transfer characteristics, and verify response time characteristics (i.e., response time between receipt of command and actual physical response of fluid, mechanical, or electronic devices).

[6.4.5-3] Tests of engine controls shall include standard command and control type activities and data transfer activities in relation to engine health management (EHM) validation.

6.5 Unit Leak Test

Leak testing is relevant to units and subsystems that maintain pressure as part of their functional operation (e.g., pressure vessels, pressurized structures, and pressure components). Unit leakage must be limited to within design-allowable values that have been carefully developed with consideration of system-level requirements. Sections 4.5.2 and 4.5.3 require pressurized units within an LRE to comply with AIAA-S-080A [4] or AIAA-S-081B [6], both of which require leak testing. TR-RS-2014-00016 (SMC-S-016) [1] specifies how to perform leak testing.

[6.5-1] Units within an LRE shall comply with the leakage requirements of TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 6.3.3, for unit qualification and unit acceptance.

Joints and seals, such as those within turbomachinery, must prevent leakage under structural loading to specified requirements.

[6.5-2] Tests shall demonstrate acceptable separation leakage at 1.4 × MDCL for a leakage leading to a catastrophic event and 1.2 × MDCL otherwise. Analyses verifying requirements in Section 5.3.4 that preclude joint separation are an acceptable alternative to testing when seal deflection modeling tools are anchored to seal test data.

The failure mode under consideration is rupture of a seal or leakage rate leading to mission degradation.

For many LRE unit types this testing would be impractical, requiring that special tooling be designed to load and check seals at all locations on an LRE. Seal deflection modeling tools, anchored to seal test data, have alternatively been used successfully.

6.6 Unit Shock Test

Shock testing is not always applicable, and is termed Evaluation Required within TR-RS-2014-00016 (SMC-S-016) [1]. Units where the test is not relevant still require a one-time justification document detailing the rationale. Unit-level shock environments should be verified against engine-level test and flight data when they become available.

[6.6-1] Units within an LRE that have been evaluated to require unit-level shock testing shall comply with the shock requirements of TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 6.3.4, for unit qualification and unit acceptance.

6.7 Unit Vibration and Acoustic Test

LREs contain vibration-sensitive components such as actuators, mission critical sensors, valves, electric components, and bellows. Per Section 6 of this Standard and TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 4.4.1, unit-level testing may be deferred to a higher assembly-level test or engine-level test with appropriate rationale (see Section 7.6.3) and concurrence of the Approval Authority. Unit-level environments should be verified against engine-level test and flight data when they become available.

[6.7-1] Units within an LRE that have been evaluated to require unit-level vibration and/or acoustic testing shall comply with the vibration and acoustic requirements of TR-RS-2014-00016 (SMC-S-016) [1], Paragraphs 6.3.5 and 6.3.6, for unit qualification and unit acceptance.

[6.7-2] The maximum expected environments used in vibration testing shall envelop all phases of flight.

6.8 Unit Acceleration Test

Acceleration testing is Evaluation Required and may not be applicable for many units.

[6.8-1] Units within an LRE that have been evaluated to require unit-level acceleration testing shall comply with the acceleration requirements of TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 6.3.7, for unit qualification.

6.9 Unit Thermal Test

Per Section 6 of this Standard and TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 4.4.1, unit-level testing may be deferred to a higher assembly-level test or engine-level test with appropriate rationale, and concurrence of the Approval Authority.

[6.9-1] Units within an LRE that have been evaluated to require unit-level thermal cycle and thermal vacuum testing shall comply with the thermal cycle and thermal vacuum requirements of TR-RS-2014-00016 (SMC-S-016) [1], Paragraphs 6.3.8 and 6.3.9, for unit qualification and unit acceptance.

6.10 Unit Climatic Test

[6.10-1] Units within an LRE shall comply with the climatic requirements of TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 6.3.10, for unit qualification.

6.11 Unit Structural Test Requirements

Verification of structural integrity includes static-load testing, and may also include tests for buckling, fatigue, and damage tolerance (safe-life) when analyses are insufficient. The test articles are manufactured using representative processes, and with established process controls. The purpose of proof test is to screen for gross workmanship flaws, and it should be defined to be worse than the flight environments. The proof factor provides margin relative to flight conditions for both analysis uncertainty and workmanship variability. It is often prudent to perform proof tests at the component or subassembly-level to screen out issues before rework or repairs become difficult or expensive. The proof test compensates for differences between flight and test conditions. Differences may include loads, environments, and boundary conditions.

If there is only low or moderate confidence in analysis results, then tests are needed to achieve high confidence in the verification of structural capability. Tests may be needed when analysis methods for a design must be extrapolated to a domain beyond which they have been validated, when analysis or environmental inputs are not adequately characterized, or when complex fluid-structure interactions play a significant role in the state of stress.

[6.11-1] Ultimate strength tests shall be conducted on dedicated qualification engine components, including rotors, pressure vessels, and pressurized components, using the loads and factors listed in Table 4-3.

[6.11-2] Proof tests shall be conducted on flight engine components, including rotors, additively manufactured hardware, pressure vessels, and pressurized components, using the loads and factors listed in Table 4-3.

[6.11-3] The boundary and loading conditions applied to the test article shall produce flight-like stress states in the appropriate environment.

[6.11-4] The applied loads shall compensate for differences between test and flight conditions including missing loads, environmental conditions (e.g., temperature, moisture), and boundary conditions.

When pressures, thermal gradients, or other complex loads are present, it may be challenging to define a proper room-temperature proof or structural test. In these instances, it is important to ensure that the proof test is exercising the failure mode in a manner consistent with flight conditions. When differences between test and flight conditions are considered, the effective proof factor should follow the values specified in Table 4-3. The effective proof factor may be readily established by analyzing the proof test and flight configurations.

[6.11-5] No failure shall occur at or below the ultimate load or the specified margin factor beyond the service life (i.e., 10× for HCF failure modes, and 4× for LCF failure modes).

[6.11-6] For strength and buckling tests, when a load component alleviates failure under combined load conditions, a unit factor shall be applied to that load component of the MDCL condition instead of the ultimate factor of safety.

See Section 5.3 for additional guidance on the application of a unit factor on the load that alleviates the mode of failure.

[6.11-7] Buckling tests shall not fail at or below ultimate load using test articles that include worst-case load eccentricities and/or geometric imperfections based on measured data (e.g., laser scan, etc.). Analysis is an acceptable alternative to buckling tests when the stiffness and load-path is anchored to structural tests.

Testing is performed with an article that incorporates the worst-case imperfections expected during the life of the program, or bounding imperfections allowed by the drawing(s).

The primary approach for fatigue verification is engine qualification tests to 4× starts and 4× duration. Ground engine qualification tests may not fully envelop the self-induced vibrations and launch vehicle vibrations. Analytical approaches for evaluating fatigue become key in the structural assessment process and should employ an applicable material fatigue database (e.g., surface finish, loading condition, and environments).

[6.11-8] Fatigue tests shall be conducted at the most severe environments using a load spectra definition that includes alternating and mean stresses applied to the test article to at least 4 times the number of service lives (Fatigue and Damage Tolerance Factor in Table 4-1). Analyses meeting the requirements in Section 5.4.1 are an acceptable alternative to tests when the analysis methodology is anchored to test data.

An example of a low-to-moderate confidence engine structural component is bellows. These are typically qualified separately as described in Section 5.6.

[6.11-9] Damage tolerance (safe-life) testing shall be conducted with the load spectra applied to the test article to at least four times the number of service lives (the Fatigue and Damage Tolerance Factor in Table 4-1). Analyses meeting the requirements in Section 5.4.3 are an acceptable alternative to tests when the analysis methodology is anchored to test data.

Note that damage tolerance (safe-life) testing has additional requirements in Section 5.4.3 relative to demonstrating allowable defect sizes and NDI.

6.12 Unit Electromagnetic Compatibility Test

Electromagnetic compatibility (EMC) testing is Evaluation Required within TR-RS-2014-00016 (SMC-S-016) [1] as these tests are only applicable certain types of units. TR-RS-2014-00016 defers to TS-RS-2008-00008 (SMC-S-008) [14] for EMC test requirements.

[6.12-1] Units within an LRE which have been evaluated to require unit-level EMC testing shall comply with the electromagnetic compatibility (EMC) test requirements of TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 6.3.13, and TR-RS-2008-00008 (SMC-S-008) [14] for unit qualification and unit acceptance.

6.13 Unit Life and Wear-in Test

Qualification of an engine for flight includes showing margin to the maximum expected operational life. This is one aspect of demonstrating hardware robustness. Life-limited parts are expected and can drive engine maintenance intervals and total life. Acceptance tests will not include life testing but are to include wear-in tests to detect material and workmanship defects that occur early in the unit life.

6.13.1 Operational Lifetime

TR-RS-2014-00016 (SMC-S-016) [1] requires life testing as part of unit qualification. LRE units are also required to verify life as part of qualification, but operational life testing of some LRE units may be performed at a higher level of assembly. Life verification with regards to fatigue and damage tolerance is within Section 6.11. Life verification of nozzles is done at the engine level per Section 7.7.3.

[6.13.1-1] Qualification for units (other than nozzles) with life limitations set by phenomena other than fatigue shall include life testing per TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 6.3.14, but may defer unit-level life testing to a higher-level assembly.

6.13.2 Single Burn Operation Duration

[6.13.2-1] Unit qualification shall include sustained operation for a duration greater than or equal to the maximum expected mission single-burn duration, with margin as specified in Table 4-1 for Unit Single Burn Operation Demonstration Factor.

6.13.3 Operational Life Starts

Engine starts are a significant hardware durability driver and a major component of life calculations, especially for LCF damage. Starting and stopping of units within an engine causes significant thermal and pressure gradients in a very short period, stressing the hardware. Start capability limited by fatigue effects is covered under Section 6.11 for unit qualification. Start capability verification of nozzles is done at the engine level per Section 7.7.3.

[6.13.3-1] Unit qualification for start capability limitations, other than fatigue effects (and not including nozzles), shall be tested per TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 6.3.14, but unit-level life testing may be deferred to a higher-level assembly.

6.13.4 Unit Acceptance Wear-In

Wear-in is an aspect of unit ATP.

[6.13.4-1] Units within an LRE shall comply with the wear-in requirements of TR-RS-2014-00016 (SMC-S-016) [1], Paragraph 6.3.1, for unit acceptance.

7. Engine Requirements

The objective of the overall development and qualification test program is to substantiate that the flight design, manufacturing processes, and acceptance program produce flight hardware/software that meet specification and performance requirements with adequate margin to accommodate engine variations. The LRE test program (together with appropriate analyses) verifies requirements compliance. Engine-level testing is necessary because of the significant component-to-component interactions, unknown environments, and nonlinearities that cannot be adequately predicted nor replicated at lower system levels. The LRE includes all primary subsystems (e.g., TPA) as well as all major components (e.g., valves and combustion devices). Engine-level testing is critical to design verification because there are significant interactions between the various components and subsystems that cannot otherwise be simulated or characterized. Furthermore, it is difficult and often impossible to test components and subsystems in the actual engine environment other than through their testing at the engine level itself. Component testing may address individual environmental stresses and the effects on functional capability, whereas the engine level introduces systems interactions and combined environments (engine self-induced). Most of the test requirements will be pertinent to this level of testing. Development testing is required to achieve design maturity, demonstrate capability, and reduce risk to the qualification program. Qualification testing is required to formally verify compliance of the flight design with requirements. Acceptance testing verifies the flight worthiness of each specific deliverable unit.

Per the nomenclature of TR-RS-2014-00016 (SMC-S-016) [1], the LRE is a bus subsystem. Bus subsystem test requirements are in Tables 7.3-1 and 7.3-2 of TR-RS-2014-00016 (SMC-S-016) [1] but are generically written for any subsystem. This Standard includes further specific requirements in the sections indicated in Table 7-1.

7.1 Test Types

Even though requirements levied upon a propulsion system can vary from system to system, the types of tests are relatively well known. These tests establish the basic functionality and overall robustness of an engine or integrated propulsion system. This section identifies the different test types with the following sections providing the detailed requirements for each type.

Table 7-1. Relationship between TR-RS-2014-00016 (SMC-S-016) [1] Bus Subsystem Requirements and this Standard

TR-RS-2014-00016 Bus Subsystem Test Requirements			LRE Standard
Test	**Qualification**	**Acceptance**	**Section**
Inspection	R	R	7.9.1 and 7.9.2
Performance	R	R	7.2 and 7.3
Static Load	R	ER	7.4
Pressure and Leak	ER	R	7.5
Shock	ER	ER	7.6.3
Random Vibration or Acoustic	ER	–	7.6.3
Thermal Vacuum	ER	ER	7.6.1
Separation and Deployment	R	R	7.3.9
Electromagnetic Compatibility	R	ER	7.6.5
Mode Survey	R	–	5.1

R = Required; ER = Evaluation Required

7.1.1 Development

Development tests are conducted for the following reasons:

- *Validate new design concepts or the application of proven concepts and techniques to a new configuration*
- *Assist in the evolution of designs from the conceptual phase to the operational phase*
- *Validate design changes*
- *Expand, update, and anchor models*
- *Reduce the risk involved in committing designs to the fabrication of qualification and flight hardware*
- *Develop and validate qualification and acceptance test procedures*
- *Investigate problems or concerns that arise after successful qualification*

Development test conditions should encompass worst-case conditions for the intended application. In addition, the development program is used to verify margin, outside the operating envelopes, by test. Margin testing will allow a successful development program to identify weak aspects in the design; identify, eliminate, and/or mitigate failure modes prior to beginning qualification; and ultimately yield a much more robust design. However, development testing should avoid conditions that violate acceptable safety margins or cause unrealistic modes of failure.

Development testing is not explicitly required but is expected and recommended because its omission is likely to result in increased qualification test failures, as well as a lack of understanding of the design weaknesses and limitations. Furthermore, per Section 4.3 and Table 4-1, a certain number of development engine samples may be used to help satisfy the required number of verification engine samples, provided that those units are structurally and functionally equivalent to the qualification and flight design, and meet the instrumentation requirements (see [4.3.1-1] and [4.3.1-4]).

7.1.2 Qualification

Qualification testing provides formal verification that the final design, manufacturing processes, and acceptance program produce flight hardware/software that meet specification and performance requirements with adequate margin to accommodate expected variations in hardware and engine operation. It generally follows completion (or near-completion) of the development test program to reduce program risk at this phase. Testing should validate the planned acceptance program, including test techniques, procedures, equipment, instrumentation, and software, as well as potential rework and repeat test cycles.

Qualification engine samples are typically the first engines off the production line to demonstrate readiness for flight operation. Manufacture of the qualification units should use the same materials, tooling, manufacturing processes, level of personnel competency, and quality control as will be used for actual flight hardware. Limited deviations are permitted, but only if required to accommodate benign changes that are necessary to conduct the testing (e.g., adding instrumentation to record functional parameters for engineering evaluation). Other deviations may be proposed to, and potentially accepted by, the Approval Authority.

Qualification testing verifies satisfaction of design requirements, especially margin and product robustness for designs that have no demonstrated history. A full qualification validates the planned acceptance program, in-process stress screens, and retest environmental stresses resulting from failure and rework. Qualification testing verifies compliance to engine specification requirements and vehicle interface requirements over the entire range of expected operating conditions. Overall qualification test *conditions should encompass worst-case conditions for all intended applications. Selected margin conditions (e.g., operating life margin, thrust margin, mixture ratio margin) are also verified to demonstrate robustness. However, qualification testing should not create conditions that violate acceptable safety margins or cause unrealistic modes of failure.*

[7.1.2-1] LRE qualification test requirements shall be verified by testing on flight design engine samples (i.e., verification engine samples).

Verification engines include qualification engines but may also include development engines that are structurally and functionally equivalent to the qualification units and flight design. Additional leeway exists in relation to specific verification tests. For example, verification of the ignition system requires that the engine under test have a flight-design ignition system and related elements, but the engine could conceivably have other elements that are not flight-like. Such a unit could satisfy ignition system verification but would not count toward the total number of engines required per Table 4-1 (see also Section 4.3).

7.1.3 Acceptance

LRE acceptance tests are conducted to demonstrate the acceptability of each deliverable item to meet performance specification and demonstrate acceptable workmanship in manufacturing. Acceptance testing of an LRE includes hot-fire testing to ensure the article is acceptable for delivery. Because of the combination of complex components, significant dependency on functional timing, and strict performance bands, engine testing is a necessary part of acceptance of flight propulsion systems. The criticality and complexity of LREs require that performance be calibrated and measured. Verified performance parameters include thrust, mixture ratio, and flow rate (for derivation of Isp). In addition, selected critical operating conditions, key interface conditions, and other specification requirements must be demonstrated. Verification of workmanship is a critical aspect of the acceptance hot-fire test because discrepancies are not always detected during the build process. The extreme thermal, pressure, and dynamic environments during engine operation can cause failure if workmanship flaws exist. Acceptance testing is intended to stress-screen hardware items to nominal operational levels to precipitate incipient failures due to latent defects in parts, processes, materials, and workmanship prior to flight.

[7.1.3-1] Acceptance testing, to include hot-fire testing, shall be conducted on each LRE to verify that engine environments and performance are within qualified bounds, and to provide calibration data required for engine flight operations.

[7.1.3-2] Successful acceptance testing shall exclude structural failures and detrimental structural conditions.

Generally, acceptance test operating conditions should remain well within the operating envelope. Because the hardware being tested is intended for flight and should not be significantly overstressed, margins are tested only for certain aspects. For example, operating margins may be exercised (1) during a structural or pressure test conducted on the flight article to levels higher than maximum design condition (MDC), maximum expected operating pressure (MEOP), etc., to verify material quality and workmanship; (2) for confidence building against specific technical issues; and/or (3) to verify that the flight unit behaves similarly to the qualification units at specific off-nominal conditions. The appropriate numbers of starts and duration is a trade between obtaining sufficient ground test time to accurately establish performance and reliably screen workmanship issues versus minimizing the expenditure of operating life. The most appropriate starts/duration will depend on the engine design, performance repeatability, and manufacturing maturity, as well as the number and severity of any unique persisting technical issues that require special testing to resolve prior to flight.

The acceptance series functionally checks critical systems and performance. Engine-level acceptance tests should closely resemble key portions of the intended, or typical, mission profiles in terms of thrust, mixture ratio, power level transition rates (start, throttle, shutdown), etc. Associated test parameters and instrumentation are expected to align with the development and qualification experience. The goal is to acquire enough data and characterization to confidently show the engine performs within required limits, to confirm normal operational behavior, and to quote expected flight performance (i.e., performance tag) utilizing the acceptance test results.

7.2 Performance

Test programs should conduct enough testing to sufficiently characterize the different performance parameters and their sensitivities. Thrust, specific impulse, and mixture ratio are all examples of performance parameters that must be measured or computed/derived from measured data during engine test, to thoroughly validate analysis models over a range of input variations, and to minimize extrapolation to flight operation outside the family of ground test data. Accurate measurement and characterization are necessary as the vehicle requires characterization of engine performance over the flight profile to properly calculate propellant load and reserves, and to calculate vehicle guidance, navigation, and control parameters, etc.

7.2.1 Steady-State Performance Characterization

Steady-state operation refers to a condition or state in which key parameters of interest (e.g., thrust) are either constant or slowly changing at a constant rate. There may be some small noise-like variation, but no rapid time dependency. Typically, thrust, pressure, and temperature must all reach this condition for engine operation to be considered steady state, although some engine designs may achieve steady-state thrust prior to steady-state thermal conditions prevailing. The test purpose must be considered when establishing which parameters must be steady state.

Most commonly, the ultimate objective is to characterize how well the actual flight performance of the engine corresponds to the intended, commanded, and/or predicted performance. As an example, if mean thrust remains unchanged with time (having only noise-like or minor roughness variation) after 60 seconds of operation following a commanded transition event (e.g., start command or throttle transition), then 60 seconds could be considered the minimum operating duration to reach steady-state thrust after said commanded event. Because noise-like variations do occur, however, steady-state conditions should be time-averaged over a finite dwell period of steady operation, thereby necessitating operating times longer than the minimum to determine the steady-state thrust behavior. In most cases, different engines will require different durations after a commanded event to reach steady state.

Steady-state performance should be thoroughly characterized by varying parameters across the expected acceptance test and flight regimes to validate analytical models, minimize uncertainties, and minimize flight risks. The engine physics-based steady-state model should be validated and anchored by test data such that "3-sigma" conditions, including build-to-build and run-to-run variations, can be evaluated and shown to still fall within requirement limits. Establishing and validating engine gains and "influence coefficients" related to interface conditions are inherently part of this model validation activity. To accomplish this, multiple engine tests on each design are expected. Performance measurements are expected to occur during steady-state time slices during a test where no commanded changes occur, or enough time has elapsed to reach steady-state conditions.

[7.2.1-1] LRE hot-fire testing shall include measurements of steady-state thrust and steady-state propellant flow rates.

[7.2.1-2] LRE hot-fire testing shall include diagnostic measurements, including critical pressures and temperatures within the engine to characterize normal variability, and verify appropriate LRE behavior and health.

It is typical to see engine performance data adjusted to a set of standard propellant conditions at the engine interface.

[7.2.1-3] LRE qualification hot-fire testing shall include steady-state performance measurements at all power levels within the allowed range of steady-state operation, with emphasis at power levels where the engine spends a significant portion of the mission.

[7.2.1-4] LRE qualification hot-fire testing of continuously throttleable engines shall include performance measurements across all allowed throttling ranges.

This may be accomplished by tests that include throttling or by testing multiple discrete conditions across the throttling range per [7.2.5-2].

[7.2.1-5] When significant run-time trends or sensitivities are identified during qualification, LRE acceptance testing shall be of sufficient duration to demonstrate that the production engine's run-time trends are bounded by, or in family with, qualification.

[7.2.1-6] If an engine trim adjustment (e.g., orifice change, valve position change, or other configuration adjustment) is made after hot-fire acceptance testing, then the final configuration shall be validated with another hot-fire acceptance test, unless performing the change without retest has been previously qualified.

For example, LRU demonstrations are required to characterize any performance effects resulting from hardware changes occurring without a validation hot-fire acceptance test run on the flight engine (see Section 7.9.6).

Sometimes the full flight nozzle may not be acceptance tested with the LRE due to a nozzle's intended single-use application (e.g., ablative nozzle) or test facility limitations (e.g., no vacuum test capability for a high expansion-ratio nozzle). Furthermore, sometimes the LRE may instead be acceptance tested with a truncated nozzle (intended to characterize nozzle wall heat transfer characteristics for the specific injector environment, and/or to provide an intermediate expansion ratio within facility capabilities). In these cases, the measured thrust and Isp for the LRE, without the full flight nozzle, must be adjusted to properly account for the truncated ground test configuration.

[7.2.1-7] If the LRE is not ground acceptance tested with the flight nozzle, LRE qualification shall provide sufficient performance data, for both the intended flight configuration and acceptance test configuration, in order to develop sufficiently accurate correlations, in conjunction with validated analytical tools and methodologies, to correct ground acceptance test thrust and Isp, measured without the full flight nozzle.

7.2.2 Repeatability

Run-to-run and engine-to-engine variations in thrust, mixture ratio (MR), Isp, and other key engine operating parameters are to be evaluated during the test program. The objective is to gain sufficient test data to understand the typical variation and ensure that the variation is controlled well enough such that an engine can be effectively tuned to meet performance and functional requirements. Three tests on a given engine sample are required to provide a reasonably low uncertainty (three times lower than for only two data points) in the flight prediction. This is consistent with the engine performance repeatability guidelines in JANNAF-GL-2012-01-R0 [19].

[7.2.2-1] LRE run-to-run variability shall be characterized during qualification by performing at least three tests on the same engine sample, with each test including periods of identical stabilized test conditions (e.g., engine control set points, propellant inlet conditions, other interface conditions).

[7.2.2-2] For engine designs with multiple power levels or continuous throttling capability, the "stabilized test conditions" in [7.2.2-1] shall include the most critical performance regimes based upon the intended and specification usage profile(s) (e.g., thrust, mixture ratio).

Additional sets of repeated tests should be performed, if needed, to cover the full operational range of the engine.

[7.2.2-3] Engine-to-engine variability shall be characterized by performing qualification hot-fire tests on three unique engine samples using the same "stabilized test conditions" as the tests in [7.2.2-1].

Inclusion of the test series across all verification engine samples and within development testing is preferred to maximize the data available for unit-to-unit variability characterization.

[7.2.2-4] To verify consistency of the run-to-run variability with qualification, at least two LRE hot-fire acceptance tests, both including at least one period at identical stabilized test conditions (i.e., the entire test need not be repeated), shall be performed on each production engine.

After obtaining sufficient operational history to demonstrate repeatability in acceptance testing of production engines, the supplier may delete the acceptance repeat test [7.2.2-4] if the Approval Authority concurs.

7.2.3 Run-Time Trends

Run-time trend data are an important diagnostic to identify any uncommanded and/or unintended time varying operating conditions that might exist for thrust, Isp, MR, shaft speeds, pressures, temperatures, or component efficiencies, such that they can be properly considered and accommodated.

[7.2.3-1] LRE hot-fire qualification and acceptance testing shall monitor time-dependent parameter trends, and account for them, if significant.

[7.2.3-2] Significant unexpected trends and/or extrapolations that suggest potential exceedance of specification limits or qualified engine operating conditions shall require further disposition and/or corrective actions.

7.2.4 Steady-State Analytical Models

Steady-state analytical models predict engine internal operational conditions (e.g., pressures, temperatures, and flow rates) based upon specified input conditions and known or expected hardware characteristics. Preferably a model is based on physical hardware measurements, and exercising the model by varying the input parameters results in influence coefficients that represent incremental changes in various engine performance parameters given the incremental change in input. Modeling and determination of dependent parameters are expected to be initiated during the development phase.

[7.2.4-1] LRE qualification testing shall determine and verify influence coefficients based on inlet conditions, valve positions if applicable, and other interface conditions for steady-state LRE performance (e.g., thrust, Isp, MR) and key operating conditions (e.g., shaft speeds, chamber pressures and temperatures, pump discharge pressures) across the entire intended operational regime. Actual parameters will vary depending upon the engine design.

7.2.5 Thrust and Mixture Ratio Excursion Tests

The thrust (e.g., power level) and mixture ratio excursion test campaign should characterize the engine hardware sensitivity to operating point variations. Doing so will help characterize engine behavior and verify hardware durability. Depending on engine configuration and vehicle application, significant power level and mixture ratio variation may be a desired and/or deliberate functionality. However, the engine also has to accommodate variations due to vehicle stage operation, such as variations in propellant inlet conditions (e.g., run box variations). Some systems may have control features to minimize variations (closed-loop control), but others may elect to tolerate these external variations (open-loop control).

For a trimmed engine, Figure 7-1 details the allowable control limits as the "trim box." Worst-case dispersions, biases, and variations (pump inlet conditions, run-time trends, hardware replacements, etc.) can drive those limits further in flight to the extent of the "flight box." The flight box bounds the full range of power levels and mixture ratios that may be seen in flight and must be thoroughly tested. The flight box includes all instances of LRE operation, including reentry and recovery for an LRE to be reused. Margin should also be demonstrated against the flight box, per Section 7.2.6. For engines with open-loop control, worst-case pump inlet conditions will result in power level and MR conditions that are more extreme. For engines with closed-loop control, the engine operating parameters will become more extreme when worst-case inlet conditions are applied. Note that for engines with closed-loop control on both thrust and MR, the Trim and Flight Boxes can become nearly the same box boundary, differing only by run-to-run variability (or control uncertainty).

To support a comprehensive qualification program, the MR and PL bin requirements should be formulated to accommodate the full range of potential Service Life scenarios (such as multiple mission profiles and allowance for contingency operations such as re-acceptance tests) as well as uncertainty in, or evolution of, mission profiles. Future significant operational changes that are unanticipated and untested likely will pose increased mission risk or require delta-qualification.

[7.2.5-1] Worst-case conditions for LRE qualification hot-fire testing shall account for all significant dispersions and biases (and be included in the [4.2-1] test plan), including specification limits, run-to-run variations, measurement uncertainty, ground-to-flight dispersions, operating biases (e.g., extreme inlet conditions), run-time trends, and potential post-test engine hardware replacements.

[7.2.5-2] The flight box of allowable power levels and mixture ratios shall be discretized into bins spanning no greater than 5% of maximum power level, and no greater than 5% of nominal MR (unless confident analysis establishes other bin increments are more appropriate), which represent operating points for testing.

[7.2.5-3] The perimeter bins of the flight box shall be defined relative to the trim box such that when the engine is commanded to the maximum or minimum power level and/or MR of the trim box, with nominal inlet conditions, the engine will be operating within a perimeter bin.

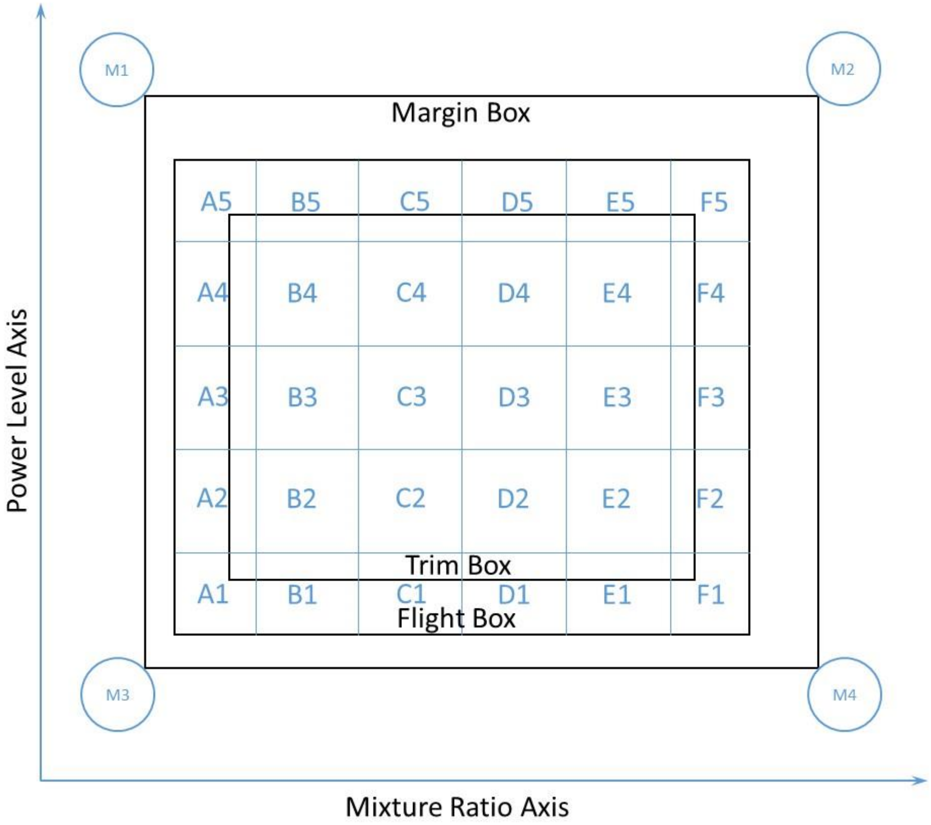

Figure 7-1. Notional diagram of power level versus mixture ratio trim box, flight box (with internal and perimeter bins), and margin box (showing margin demonstration locations).

[7.2.5-4] At least 50% of the operating time in perimeter bins shall be performed with worst-case pump inlet conditions applied, or at equivalent engine conditions achieved by other means (demonstrated as equivalent via an evaluation comparing the engine response [e.g., critical parameters such as shaft speed, chamber temperature, valve delta-pressure] with respect to that driven by worst-case inlet conditions), unless bin-specific engine operating conditions (e.g., shaft speed, chamber temperature, and valve delta-pressure) are bounded by the flight box margin demonstrations of [7.2.6-1].

[7.2.5-5] The qualification hot-fire tests for each bin of [7.2.5-2] shall accumulate a duration of at least one times the bin-specific service life (for example, in Figure 7-1, the bin C5 service life may be 400 sec, and the bin E2 service life may be 20 sec.), including at least one continuous steady-state dwell enveloping the longest instance of continuous dwell operation within that bin over the engine's service life.

[7.2.5-6] The sum of qualification hot-fire test operation at a given power level (for example, at the lowest thrust level, the accumulated duration in bins A1, B1, C1, … , F1 in Figure 7-1) shall accumulate duration at least two times the engine service life specific to that power level (for example, at the lowest thrust level, the sum of the bin-specific service lives of bins A1, B1, C1, … , F1 in Figure 7-1).

"Worst-case" conditions should be encompassing without being unrealistic. This requires thoughtful consideration of realistic operating parameters and conditions that may be encountered at a moment in time over the service life of the engine, with emphasis on flight conditions. "Worst-case" does not entail stacking the extreme values for each parameter irrespective of when they occur during service life. For example, early in flight, when power levels are typically higher, both the allowable range and dispersions of propellant conditions and mixture ratio may be considerably narrower than later in flight, when power levels may be lower due to acceleration limiting. Regardless, the engine specification should be consistent with, or be revised to be consistent with, the actual qualified MR/PL and associated operating conditions. If not, then a formal waiver must be generated to document where and how the actual qualification and verification excluded parts of the existing specification for the present application, such that it remains clear that delta-qualification is required if a future application does exercise a previously excluded part(s) of the specification.

Selection of MR/PL bins should account for engine behavior sensitive to MR at a given PL. Any tailoring of MR/PL binning requirements must demonstrate the ability to adequately encompass atypical conditions potentially associated with the tailored regime.

7.2.6 Thrust and Mixture Ratio Margin Demonstration

The objective of the thrust and mixture ratio margin demonstration is to envelop extreme operating conditions and verify engine robustness via margin testing on thrust and MR beyond expected worst-case flight box conditions. Certain margin condition combinations may be deleted from the test series, provided that those deleted combinations can be confidently shown to be well bounded by the combinations that are tested with respect to engine robustness/health (e.g., maximum shaft speeds, peak pressures, minimum cooling, extreme valve positions) and functional capability (e.g., achievable thrust level).

[7.2.6-1] The verification hot-fire testing shall include a minimum margin factor, as indicated in Table 4-1, for testing beyond the flight box envelope, where worst-case demonstration test points are usually defined beyond each corner of the margin box (M1, M2, M3, and M4 in Figure 7-1), with alternatives approved by the Approval Authority.

The margin factor specified in Table 4-1 is consistent with heritage and experience.

[7.2.6-2] Minimum test duration at a particular margin condition (e.g., high MR with high thrust, test point M2 in Figure 7-1) shall be at least 10% of the maximum expected cumulative flight duration (based on vehicle tank capacity), unless confident analysis establishes a more appropriate dwell duration, with Approval Authority concurrence.

Testing of greater margin during development testing is recommended to increase the likelihood of successful qualification testing. Deliberate testing outside of the specification limits is desirable as it helps understanding of the engine's off-design performance and sensitivities, but it is recognized that significant testing outside the specification limits may pose unrealistic conditions that are more likely to damage the engine hardware and/or the test facility. In other words, specific test margin conditions should be considered carefully to reduce flight risk while minimizing significant unwarranted test risks.

For the purposes of overall engine qualification, a single qualification engine sample with the prescribed margin is considered adequate for thrust and mixture ratio margin demonstration, based on successful heritage and experience. Testing in Section 7.2.5 explores the entirety of the flight box, which incorporates worst-case dispersions tested at worst-case propellant conditions to bound potential flight conditions on multiple engine samples. This margin test deliberately overstresses the engine, providing confidence that the engine is not operating at the edge of incipient failure during worst-case flight conditions. As such, it does not expand the qualified engine operating space beyond the flight box.

Additional margin testing or engine samples may be required if the planned margin testing identifies concerns with engine robustness.

7.2.7 Ignition System

Hot-fire verification of the ignition system includes demonstration that adequate energy is produced to ignite each and all combustion devices reliably, under nominal, off-nominal, and worst-case propellant conditions (including mixture ratio, temperature, and pressure), input voltage (if electronic excitation is required), and hardware environments (or equivalently, chilldown conditions).

Worst-case propellant conditions typically occur (for a fuel-rich combustor) when a minimum amount of oxidizer (low mixture ratio) is present at the igniter; for cryogenic propellants this typically occurs at minimum oxidizer NPSP. Very low pressure and cold propellants generally require more available energy to ignite, so vacuum testing under conditioned environments is recommended for upper stage engines. Extreme hardware environments may exist, particularly for upper stage engines when multiple restarts are required. Cold propellants at high pressure may also be difficult to ignite because more exciter power is required to produce a spark (i.e., Paschen's Law). Other factors that may affect the amount, density, quality, or mixture ratio of propellants in the vicinity of the ignition location must be considered and tested appropriately (e.g., purges, known potential leaks).

For hypergolic ignition systems, the quantity of the hypergol delivered, its associated timing (e.g., characteristic fill times, valve actuation times), and potential effects on propellant delivery in the vicinity of the ignition location (e.g., purges, known potential leaks) must be considered and tested appropriately. For dual and multi-engine stages, the period when ignition is permitted must be both long enough to assure ignition reliability and short enough to support vehicle controllability.

[7.2.7-1] The LRE qualification hot-fire testing shall verify reliable ignition across the range of allowed conditions (nominal and off-nominal) as well as worst-case conditions with margin, to include the variation in fluid conditions (including mixture ratio, temperature, and pressure), chilldown conditions, start transient timing, input voltage (if electronic excitation is utilized), and hardware temperatures.

[7.2.7-2] Testing of ignition systems shall be conducted at flight-like ambient pressure levels, referenced to flight altitude at ignition.

[7.2.7-3] Tests for worst-case conditions shall include ignition system variables with margin beyond engine operational limits, as determined by demonstrated sensitivities and heritage.

Large margins (near 20% or higher) may be warranted where ignition sensitivities exist.

[7.2.7-4] Tests for worst-case conditions shall be conducted on a minimum number of unique engine samples of the flight design as indicated in Table 4-2.

[7.2.7-5] For engines with electronic igniters, reliability and margins of the ignition window (i.e., when ignitable conditions exist in the vicinity of the ignition location) shall be demonstrated by spark delay testing.

[7.2.7-6] Hypergolic ignition systems shall be qualified to encompass the full range of variation in flow rate, temperature, duration, and timing of fluid introduction.

[7.2.7-7] Pyrotechnic ignition systems shall be qualified to encompass the full range of variation in the pyrotechnic device's loading, timing, and operating temperature.

7.2.8 Turbomachinery

As discussed in Section 6.3.2, test-validated turbomachinery performance maps are needed to predict overall engine performance. The maps and performance predictions must consider the statistical variation (e.g., 99% enclosure, 90% confidence level) of the expected operating band, potential further excursions, time varying performance over a single burn and over the engine's life expectancy, turbine and pump efficiencies, NPSP performance, turbine flow area, and secondary flows (bearing coolant flows, thrust balance fluid pressures, inter-propellant seal purges, etc.). Final verification of turbomachinery maps and performance must occur at the engine level.

[7.2.8-1] LRE qualification hot-fire testing shall verify acceptable pump and turbine performance across the entire range of expected operating conditions, including excursions and ground-to-flight differences.

[7.2.8-2] If secondary flows are controllable (e.g., with an orifice change), they shall be varied (e.g., by swapping out the orifice) during LRE qualification to identify sensitivities, and if any sensitivities are found, to demonstrate adequate tolerance against them.

[7.2.8-3] LRE acceptance hot-fire testing shall verify acceptable pump and turbine performance for all conditions tested.

[7.2.8-4] Engines shall be instrumented to record the data necessary to verify mapping information, efficiencies, and engine performance.

7.2.9 Combustion Devices Performance and Stability

Most performance characterization must occur during system-level engine testing, where the self-induced environments that couple to the combustion devices are fully present. Transient priming and purging characteristics should be explored thoroughly (including nozzle side-loads). Gas-ingestion testing falls into this category as it has historically affected combustion stability and performance (both steady state and transient), particularly in pressure-fed systems.

All operational power levels and chamber mixture ratios, including expected extreme variations, should be explored and characterized. This includes all instances of liquid rocket engine (LRE) operation, including reentry and recovery for an LRE to be reused. Combustion efficiency, injector pressure drop, heat load/fluxes, and coolant channel and/or film cooling effectiveness are typically modeled analytically and need validation/anchoring to match steady-state performance predictions. Testing of "powerpack" type configurations, which typically include turbomachinery and major combustion devices in combination, may provide supplemental characterization prior to, or in parallel with, the full engine development test program.

[7.2.9-1] Combustion device performance under nominal, off-nominal, and worst-case propellant conditions (including mixture ratio, temperature, and pressure), chilldown conditions, input voltage (if electronic excitation is utilized), and hardware temperatures, shall be verified by qualification hot-fire tests.

Specific performance metrics to be verified include combustion efficiency, injector pressure drop, heat load/fluxes, and coolant channel and/or film cooling effectiveness.

Combustion stability must, in most cases, be verified at the engine level. The exception is when unit-level testing is flight-like, and its substitution is approved by the Approval Authority.

[7.2.9-2] Combustion stability shall be verified by engine test using an implementation plan based on the definition of stable operation and the test conditions listed within CPIA Publication 655 [3], and included in the approved test plan required by [4.2-1].

7.2.10 Contamination and Debris Tolerance

Domestic and Foreign Object Debris (DOD/FOD) can either be self-generated or come from the vehicle and/or facility. It can be introduced as residual after cleaning processes, flowing propellants, general operations (functional check-outs like valve cycling), or through open interfaces during handling. Requirements pertaining to contamination control aspects within an LRE are included within Section 4.3 of TR-RS-2023-00005 [2] (required per [4.5.6-1]). Self-generated particles due to wear (e.g., gear teeth, turbine seals) will naturally exist within the system during engine operation.

Demonstration of tolerance to self-generated particles due to wear (e.g., gear teeth, turbine seals) is done via the testing of multiple engines well past the expected operational life. Testing and operational procedures verify that system maintenance procedures are adequate, that manufacturing and assembly processes deliver clean parts, and that propellant quality and in-place filters are adequate. Inspections looking for significant FOD/DOD are part of Sections 7.9.1 and 7.9.2.

7.3 Functional Characteristics

7.3.1 Cold Shock Tests

Cold shock is normally performed upon initial integration of the test facility and hardware to be tested.

[7.3.1-1] After initial exposure to cryogenic propellants, the LRE shall be inspected for leaks, thermal distortions, and material compatibility issues.

7.3.2 Cold Flow Tests

Cold flow tests may be performed at the LRE assembly level if unit-level testing (see [6.4.1-1]) is insufficient to meet the needs to characterize flow rates and feed system pressure drops, and to verify model results and predictions as risk reduction prior to hot-fire. These tests are most likely to occur during the development phase.

7.3.3 Acceptance Propellant Conditions

Because acceptance testing includes hot-fire tests, there are opportunities to validate chilldown characteristics, start and run propellant conditions, and shutdown propellant conditions. The idea is not to significantly vary conditions, but rather to promote consistency to understand build-to-build variations as flight production continues.

[7.3.3-1] LRE acceptance tests shall verify proper functionality of chilldown systems including tracking the flow rates and times pertaining to thermal conditioning.

[7.3.3-2] LRE acceptance tests shall replicate nominal vehicle start conditions.

[7.3.3-3] If an LRE is sensitive to changes in inlet pressure(s), the inlet pressure(s) shall be varied during acceptance testing to characterize the sensitivity within run box conditions.

Inlet pressures would still be held steady at defined standard conditions for a portion of the test for performance tagging.

[7.3.3-4] LRE acceptance tests shall maintain consistent shutdown conditions to enable build-to-build and run-to-run variation characterization.

7.3.4 Engine Propellant Inlet Conditions

Through each phase of operation, it is important to characterize the propellant conditions expected. Prior to start, it is important to thermally condition the engine hardware to minimize thermal shock that could be detrimental to hardware durability. LRE start transients are sensitive to propellant conditions due to NPSP sensitivities on turbomachinery, injector priming, pressure variations, and two-phase flow associated with the initial phase of starting a cryogenic engine. This carries over to steady state where inlet conditions can vary over time due to stage propellant control systems and heat load into the tank. At the end of burn, shutdown propellant conditions may deviate from the dominant part of the burn due to tank heat loads, ullage temperature, and pressure control bands.

[7.3.4-1] LRE qualification hot-fire tests shall verify proper and reliable operation for all propellant conditions at the engine inlet that might be supplied by the vehicle in flight.

Vehicle feed systems should be replicated as closely as practical during propellant inlet condition testing. Differences between ground and flight feed systems should be well-understood through adequate instrumentation and modeling.

Most vehicles will have a specification or interface control document that explicitly describes the expected and allowable propellant inlet condition boxes that the vehicle propellant feed system must deliver to the inlet of the engine. Such propellant inlet boxes are typically defined as regions within prescribed temperature and total pressure boundaries. Further background is provided in JANNAF-GL-2012-01-R0 [19].

Prior to start of an LRE, the engine should be bled and chilled (cryogenic engine) to eliminate or minimize vapor, thermally condition the hardware, and achieve the specified engine inlet temperature and pressure. However, exposure to cryogenic fluids can cause significant thermal loads that may damage hardware if not regulated properly.

[7.3.4-2] LRE qualification hot-fire tests shall verify the prestart chilldown and other conditioning procedures intended for prelaunch and flight operations through characterization of proper chilldown system operation (e.g., flow rates, temperatures, valve operations), acceptable hardware thermal condition variability (i.e., temperature versus flow rate over time), and acceptable hardware temperatures prior to start.

[7.3.4-3] Hardware temperatures prior to engine start shall be verified to meet requirements by qualification hot-fire tests under minimum, nominal, and maximum chilldown durations, pressures, temperatures, and flow rates, including worst case combinations (e.g., minimum chilldown duration and flowrates with maximum predicted initial temperature).

[7.3.4-4] For altitude start engines, chilldown shall be demonstrated at flight-like ambient pressure levels, or in simulated conditions that are shown to be representative of flight conditions.

While chilldown covers the conditions when the hardware is thermally conditioned, start propellant inlet conditions refers to the small window that holds conditions in the "start box" where the tanks are pressurized to start pressures. The start box (see also Section 7.3.5) tends to reside within the "run box," which is related to steady-state propellant conditions.

[7.3.4-5] LRE qualification hot-fire tests shall verify successful starts with inlet conditions throughout the start box, including propellant feed pressure "slump" (from feed system inertance and resistance), possible variation in local temperature conditions due to low circulation flow rates and feedline heat loads, and the relative operating boxes of various ancillary systems of the LRE.

Typically, there is no "shutdown box," and it is expected that the LRE can perform a safe shutdown (see also Section 7.3.5) from any conditions throughout the "run box." Engine and vehicle performance, as well as engine durability, may be very sensitive to MR, and shutdown MR may be very sensitive to end-of-burn propellant tank conditions, so tolerance to expected MR variation is important.

[7.3.4-6] LRE shut-down behavior shall be characterized by qualification hot-fire tests throughout the run box, including expected end-of-burn mixture ratio variation and ancillary system conditions, unless shutdown conditions are otherwise restricted by engine specifications.

7.3.5 Transient Characterization

Transients are critical to explore during the development of a rocket engine as they affect hardware durability, analytical modeling, and interactions between components/subsystems. Thrust transients are also critical for system-level coupled loads analyses, and until flight data becomes available these thrust transients have to be developed from ground-test data. Significant effort should be spent characterizing the variations that could occur during any given flight by varying propellant conditions (primary and secondary) and valve command timing.

7.3.5.1 Start Transients

Start transient modeling is a significant portion of the hardware design criteria. This modeling must be physics based to best represent the predicted hardware characteristics. Testing must validate and anchor the start transient model, similar to that done for the steady-state performance models.

[7.3.5-1] LRE qualification hot-fire testing shall verify that the final startup sequence produces a start transient that satisfies all requirements, under all expected variations in regards to propellant conditioning and associated inlet start conditions (both primary and secondary/ancillary), hardware thermal conditioning, electric power, valve command timing, ignition timing, valve slew rates, flow orifices, and ambient conditions.

[7.3.5-2] LRE qualification start transient testing shall include margin beyond worst-case conditions, established upon the criticality of, and sensitivity to, start characteristics determined from specification requirements, development testing, and validated modeling, where treatment of worst-case conditions considers various factors as applicable, including bootstrap rates (e.g., fast and slow), available start energy as a function of resistances (e.g., turbomachinery starting torque margin), and severity of thermal transients.

[7.3.5-3] LRE qualification start transient test data shall be used to accomplish the following:

a. Verify thermal conditioning process simulations
b. Develop forcing functions for structural dynamics loads analyses
c. Define/validate control valve timing
d. Establish purge system schemes, timing, and flow rates (e.g., to mitigate potential reverse flow and/or determine acceptable limits)
e. Determine ignition overpressure and structural loads environment
f. Establish effective start commit criteria (SCC) and launch commit criteria (LCC)

[7.3.5-4] LRE qualification start transient verification tests/evaluations shall include the following:

a. Verify specification limits are met
b. Verify acceleration rates, flow rates, propellant consumption, and side forces are acceptable
c. Validate initial spin-up and/or bootstrap method (if applicable)

[7.3.5-5] LRE acceptance testing shall include (at least at nominal or standard conditions) start transient characterization, with a comparison against qualification data to ensure it is within family.

7.3.5.2 Restart Transients

Depending on the mission usage role, some engines may be restarted one or more times during flight; if restart is required, it must be properly verified.

[7.3.5-6] For LREs whose concept of operations includes restart in flight, qualification hot-fire testing shall verify restart capability at nominal, off-nominal, and worst-case (with margin) conditions (actual or simulated), to include such effects as heat soak back, propellant settling, and propellant slosh.

7.3.5.3 Throttle Transients

Some engines are intended to operate with continuous throttling capability or multiple steady-state power levels. For these, test demonstration should characterize throttle rates and control capability during the intended continuous throttling periods and/or transitions between the specific intended discrete steady-state power levels, according to specification requirements and expected operation. Throttle transient characterization testing may be incorporated into tests with other objectives.

[7.3.5-7] For LREs intended for continuous throttling or multiple discrete steady-state power levels, qualification hot-fire testing shall characterize engine throttle transients, including all specified and expected throttle rates, power level transitions, and control capability, while simulating relevant external flight influences (e.g., rapid inlet pressure changes due to acceleration changes).

[7.3.5-8] For LREs intended for continuous throttling or multiple discrete steady-state power levels, acceptance hot-fire testing shall characterize engine throttling behavior to thoroughly exercise the control systems, verify specification requirements and expected operation, and compare behavior to the production family.

7.3.5.4 Shutdown Transients

Repeatable shutdown transients are desirable to ensure structural integrity and aid flight control. Like the start transient and steady-state performance models, testing must anchor shutdown transient models. Because of variability in the performance of engines during shutdowns, data need to be collected during development and qualification to characterize variability until sufficient hot-fire and flight data are available to develop a statistically adequate family of forcing functions. If the engine is to be operated until either the fuel or oxidizer is allowed to deplete, data need to be collected to properly define the thrust transients that would result.

[7.3.5-9] LRE qualification hot-fire testing shall characterize impulse ranges and repeatability of a baseline shutdown sequence.

[7.3.5-10] LRE qualification hot-fire testing shall verify the final shutdown sequence, including the range of expected variations based on power level conditions, propellant inlet conditions, mixture ratio, repressurization flows, purges, hardware thermal conditions (cold versus hot components), and control system parameters (e.g., voltage, pressure, valve timing, valve slew rates, and flow orifices), including combinations of conditions that produce the slowest and fastest shutdown transient.

Tests for worst-case conditions should include program-specific margins. The actual margin values are dependent on the type and application of engines being tested. These values should be determined during development testing, be in compliance with specification requirements, and be tailored to the specific engine system being tested. Engine shutdown related to in-flight abort scenarios should also be included in these tests, if applicable.

[7.3.5-11] LRE qualification and acceptance hot-fire testing of the shutdown sequence shall verify that deceleration rates, flow rates, propellant consumption, shutdown impulse, impulse repeatability, and side forces are acceptable, and that spin-down rates and dynamic responses (e.g., chugging, “pops”) are within allowable limits.

7.3.5.5 On-Pad Abort Shutdown Transients

Abort scenarios are specific to the vehicle and the stage for which the engine is designed. Complex systems tend to fail in complex ways; therefore, modeling all possible abort shutdown scenarios is rather difficult. The Failure Modes and Effects Analysis (FMEA) and other hazards documentation should be examined at all levels to best understand the reasonable failure modes to test and evaluate. The test program should incorporate abort scenarios to better anchor models that may be extrapolated to satisfy safety concerns.

[7.3.5-12] LRE qualification hot-fire testing shall verify the ability to safely abort and shutdown while on the pad using launch site abort logic and shutdown procedures, with interfaces simulating those of the launch environment, including demonstration of planned post-abort safing, inspections, and turnaround activities.

7.3.6 NPSP Margin and Cavitation

As detailed in Section 6.4.3, NPSP is the pressure difference between the total pressure and vapor pressure of a liquid propellant at a given temperature. For engines with liquid pumps, this is a key parameter for quantifying suction performance, and must be thoroughly understood and characterized. Low inlet pressure to a pump can lead to cavitation, which can reduce pump performance with a *corresponding reduction in discharge pressure (commonly referred to as head fall-off) and may damage or fail hardware. Lower tank operating pressures for vehicle systems are desirable to reduce tank weight, but a minimum NPSP must be maintained to avoid significant pump cavitation. NPSP margin is analytically predicted, along with the turbopump performance maps anchored to test data, and incorporated into engine steady-state performance and transient models.*

Pump conditions over the engine operating range should be mapped in terms of the dimensionless pump parameters which govern cavitation behavior, namely cavitation number and flow coefficient, accounting for uncertainties derived from measurement uncertainties, hardware variation, and ground-to-flight differences. Operating excursions on the full engine and/or powerpack (if flight representative) are required to validate and verify adequate performance and reliable operation, although this may be supplemented by information obtained from component-level testing (Section 6.4.3). The core requirements of this section are identical to Section 6.4.3, with the addition of:

[7.3.6-1] Any conditions not verified at the engine level shall be explored at the component level (Section 6.4.3).

[7.3.6-2] If there are significant unit-to-unit variations in any important cavitation characteristics (e.g., strength or operating parameter range), then LRE acceptance hot-fire testing shall verify acceptable pump performance and environments for the most pronounced cavitation conditions as identified during qualification.

A separate NPSP margin demonstration test is recommended for each propellant (rather than simultaneous margin testing on multiple propellants) to reduce risk of system interactions and potential over test conditions. Test durations at the minimum NPSP condition should be sufficiently long to collect steady-state data. Also, the minimum NPSP test point should be sufficiently low to collect data that explores the effects of potential single-point system failures (e.g., failed pressurization branch), but generally not much lower than the 2% head falloff region. Actual margin values should consider development testing results and the type of engine being tested.

7.3.7 Pogo and Pump Compliance Characterization

Pogo is a fluid-structural instability that can cause catastrophic loss of a vehicle. Characterization of engine parameters by testing becomes an important part of anchoring analytical models and helps determine if a pogo accumulator is required to reduce or eliminate the possibility of pogo. Accumulators may be engine-mounted or stage-mounted.

Only engine testing offers an environment that sufficiently simulates vehicle-provided inlet conditions. Verification of the pogo model of engine oscillatory behavior requires special engine testing to determine frequency response functions over the full range of engine operating conditions. These frequency response functions express the amplitude and phase of the engine inlet, pump discharge, and chamber pressures as functions of frequency per unit of sinusoidal flow oscillation upstream of the engine inlet.

Ideally, the overall test feed-system should include a replication of the flight feed-system, or as close as practical. The upstream facility system should be dynamically decoupled from the flight-representative feed-system by using an isolation accumulator to create a dynamic pressure null at the accumulator position. A pre-test dynamic model of the overall test system should be created and the design requirements for the facility accumulator determined.

Special pressure instrumentation should be included with data acquisition ranged to accurately determine small-amplitude oscillations in the frequency range of interest. The pump inlet pressure *amplitude should be intentionally kept below a level sufficient to ensure that its dynamic response is linear with amplitude. The downstream pressure amplitudes are normally smaller than the inlet pressure. After determining the frequency responses by test, parameters of the test system dynamic model should be adjusted to best match the test data. Important parameters to be verified are pump cavitation compliance and flow gain as functions of cavitation index and flow coefficient at the pump inlet.*

[7.3.7-1] LRE qualification hot-fire testing (or development testing with flight design hardware) shall be used to determine pump compliance and flow gain as functions of cavitation index and flow coefficient at the pump inlet, to facilitate vehicle pogo modeling with parameters derived using pogo pulse testing and analytical modeling.

[7.3.7-2] If engine-mounted pogo accumulator hardware is used, LRE qualification hot-fire testing shall be performed with the pogo accumulator hardware installed and operating as designed for flight.

The accumulator can affect pump cavitation dynamics. For helium filled accumulators, helium ingestion during operation may affect pump performance and combustion roughness. These issues tend to be more acute for accumulators mounted directly to the engine.

7.3.8 Ancillary Systems

Ancillary systems are mechanical, hydraulic, pneumatic, and/or electrical systems that enable the engine to function. These systems, which tend to make up the majority of the interfaces with the stage, perform functions that are no less significant than the primary flow path items, influencing performance and functionality of the engine. Like the primary propellants, there are operating boxes defined for each ancillary system.

[7.3.8-1] Each ancillary system operational band within an LRE shall be characterized in qualification hot-fire testing.

Flight-like component-level testing may be substituted if it is impractical to test the full range of values on the LRE.

Autogenous pressurization is when a small amount of the primary propellant is heated, expanded, and then returned to the vehicle to be used for tank pressurization. Inert gases may also be used to pressurize tanks.

[7.3.8-2] LRE qualification hot-fire testing shall verify autogenous and inert gas pressurization requirements and determine the influence on engine operation using nominal and worst-case engine operating conditions with margin on flow rates.

The appropriate margin value for flow rates is dependent on the type and application of the system.

Variations in ancillary systems' functional parameters can affect engine performance. For example, variations in conditions for valve actuation directly affect repeatability of start and shutdown transient characteristics, so efforts would be justified to vary working fluid temperatures and pressures to the maximum and minimum values, to characterize engine transient behavior over those extremes.

[7.3.8-3] LRE qualification hot-fire testing shall verify that electrical, pneumatic, and hydraulic operational box minimums and maximums do not significantly affect engine or stage operation, or if they do, that effects are well understood and acceptable. Flight-like component-level testing may be substituted if it is impractical to test the maximum and minimum values on the LRE.

Purging ensures the engine remains clean prior to operation (prevents contaminants from entering), and inerts the engine at the end of operation (expels remaining propellants). Proper sequencing and flowrates are key to start and shutdown characteristics of the engine.

[7.3.8-4] LRE qualification testing shall develop the appropriate purge schemes, flow rates, and timing.

[7.3.8-5] LRE qualification hot-fire testing shall validate purge effectiveness using dew point measurements or other appropriate means at minimum, nominal, and maximum purge flow rates, temperatures, and pressures for operational sequences and abort situations.

Electrical power typically is supplied by the stage/vehicle. These systems have power quality requirements. Engine electrical systems include the engine controller, data systems, valve control, and ignition systems. Variations in power quality can impair engine functionality. It is intended that qualification should demonstrate functionality of engine-mounted electrical components over the range of allowable engine/vehicle interface conditions (power supply as well as environmental).

[7.3.8-6] Electronics functionality verification, including end-to-end and valve sequence checkouts, shall be performed prior to LRE qualification and acceptance hot-fire tests.

7.3.9 Thrust Vector, Gimballing, and Deployment

Thrust vector control (TVC) includes engine gimbal and roll control systems, or differential throttling in non-conventional configurations such as aerospike engines. Engine nozzles may also be configured with deployable elements prior to flight usage. When testing these elements, vehicle interfaces should be simulated as close as possible to the flight design, including the stiffness at attach points. If vehicle structural components (e.g., heat shields, boots, or a boat tail) are significant in defining the interfaces or clearances, then those components should also be included or simulated.

[7.3.9-1] LRE qualification testing shall verify that TVC, gimballing, or other deployment functional capability meets system requirements, including maximum control range, slew rate, acceleration, loads, and frequency response.

[7.3.9-2] LRE qualification hot-fire testing shall include tests at worst-case combination propellant conditions for loading of TVC, gimballing, or deployment mechanisms, and at minimum and maximum thrust levels.

[7.3.9-3] LRE qualification hot-fire testing shall include tests with the engine or chamber (as appropriate) gimbaled to, and functionally operated at, its limit positions, slew rates, and accelerations.

[7.3.9-4] LRE qualification non-firing testing of gimbal elements shall include functional and hardware clearance checks.

[7.3.9-5] LRE qualification testing of gimbal elements shall include functional operation of roll control elements (if applicable) at limit positions during non-firing testing, and during hot-fire testing.

[7.3.9-6] LRE qualification testing of TVC and deployment mechanisms shall be at the appropriate altitude environment (sea level and/or vacuum). Component qualification of vacuum sensitive TVC and deployment mechanism elements may be used in place of LRE test verification.

[7.3.9-7] LRE qualification testing of TVC and deployment mechanisms shall verify that the engine induced heat flux on adjacent surfaces during hot-fire TVC testing is within acceptable limits.

[7.3.9-8] LRE qualification testing of TVC and deployment mechanisms shall validate the engine envelope clearance analyses at limit positions.

The recommended minimum clearance under dynamic conditions, and with flight conditions applied, is 1.0 inches (25.4 mm). Smaller clearances may be considered acceptable upon review of the uncertainties associated with the analysis of the differences in the ground to flight clearances.

[7.3.9-9] LRE qualification testing of TVC and deployment mechanisms shall verify gimbal block and roll control (if applicable) interface compatibility for mechanical (e.g., bearings), hydraulic, and electrical connections under minimum and maximum control parameters.

[7.3.9-10] LRE qualification testing of TVC and deployment mechanisms shall verify thrust vector alignment characteristics (arc minutes and offset), utilizing thrust measurement systems with lateral measurement capability.

[7.3.9-11] LRE acceptance testing shall measure thrust vector alignment during hot-fire.

[7.3.9-12] TVC systems, if present, shall meet the requirements of TR-RS-2014-00016 (SMC-S-016) [1].

[7.3.9-13] TVC actuation systems, if present, shall meet the requirements for moving mechanical assemblies (AIAA-S-114A [8]), electrical components, or pressurized vessels (AIAA-S-080A [4] or AIAA-S-081B [6]), as appropriate.

Applicability of the above standards depends on the type of actuator.

Dry, ambient hardware conditions can be used to check functionality of systems and fits/clearances of hardware. Hot-fire conditions can be used to help check proper TVC maximum control range at expected slew rates, accelerations, loads, and frequency response.

Acceptance testing of TVC or roll control actuators on the engine is not required if the unit-level acceptance testing is robust. It may be preferred to include such units in engine-level testing for acceptance, particularly if the actuators are supplied by the engine manufacturer.

7.4 Structural Tests

Whenever feasible, structural verification of LRE components should be performed at the unit (component) level, as it is often challenging to apply these loads at the engine level.

[7.4-1] Engine-level structural tests shall be performed on engine components that were not subject to unit-level ultimate load tests.

[7.4-2] Interface loads and relevant loads acting on the engine (e.g., actuators, etc.) shall be simultaneously applied to an engine test sample, equivalent to flight design, to the ultimate MDCL.

[7.4-3] Detrimental deformation of the LRE shall not occur at the proof factor times MDCL (e.g., excessive yielding leading to thrust angle change).

Fatigue verification at the LRE level is accomplished by the performance and functional testing using the margin factors specified in Section 7.7.

7.5 Pressure and Leak Testing

Proof and burst pressure testing are not typically performed at the engine level due to the large pressure gradients throughout the engine during operation. Proof and burst testing are reserved for the unit level as a part of manufacturing and assembly (see Section 6.11). Analytical verification of pressure capability of the LRE is described in Section 5.3.

Leak checks are conducted to ensure that the system will not leak beyond its specified limits during pre-launch and flight/operation. There are various ways to perform leak tests, and there may be different approaches at different locations across the engine depending on hardware configuration and operating pressures.

Leak tests of the LRE, including all pressurized systems such as pneumatics and hydraulics within the LRE, are part of compliance to TR-RS-2023-00005 [2], within Section 4.4.3 of that document (see [4.5.6-1] of this Standard). The method used to detect and/or measure leakage is purposely left unspecified within TR-RS-2023-00005 [2] and is expected to be set by the program as applicable.

7.6 Environments

Natural and induced environments are key factors in the design of hardware. This section outlines the tests necessary to validate analytical models used to define induced environments, and to verify compatibility with natural environments under both operating and non-operating conditions.

Environmental testing investigations are done during development and qualification. However, some level of screening is incorporated into the acceptance test series, even if it is not a specific objective during engine hot-fire. Accelerometers, strain gages, skin temperatures, etc., are all utilized to characterize each engine's response. Engine environments during hot-fire operation are typically the most extreme environments on engine hardware.

Hot-fire tests are a valuable screen for hardware acceptance, but this does not justify elimination of the component ATP; rather, engine hot-fire acceptance is additive. For upper stage or in-space propulsion, there are other significant and unique environments that exist, driving design features that need additional testing over and above engine hot-fire. Many times, the engine hot-fire can still serve as a useful screening environment. Engine environments should be appropriately measured during acceptance for comparison back to qualification experience.

7.6.1 Thermal Environment

The TR-RS-2014-00016 (SMC-S-016) [1] requirement for a thermal vacuum test of the engine subsystem is replaced by hot-fire testing of the LRE. Thermal environments of the LRE are initially modeled at various levels. Vehicle analysis flows down natural and vehicle-induced environments to lower levels of assembly.

[7.6.1-1] An analytical thermal model of the engine subsystem shall be developed, including natural, vehicle-induced, and self-induced thermal environments, for all phases of the service life of the engine.

[7.6.1-2] The LRE thermal model shall be validated against LRE qualification test data using thermocouples, resistive temperature devices (RTDs), and skin temperatures to convey the thermal profile of the engine.

A thermal model is considered correlated if measured values are within ±11 °C (±20 °F) *of predictions. If larger differences are observed, then measurements rather than predictions should be used to define thermal conditions used in design and analysis.*

7.6.2 Climatic Tests

The engine must be robust against, or adequately protected against, expected exposure to salt, fog, sand, and dust. This requirement is handled at the unit level (see [6.10-1]) although testing may be performed at higher levels of assembly to verify capability.

7.6.3 Vibration, Shock, and Acoustics

Space launch vehicles experience severe vibration environments during liftoff, atmospheric flight, and space flight that can impose substantial dynamic loads on vehicle components and payloads. LREs also experience self-induced vibration environments inherent to high-speed and high-power turbomachinery, high flow rate fluids, and complex combustion devices.

[7.6.3-1] LRE qualification testing (or analysis, where impractical to test) shall address all applicable dynamic environments, including the external excitation requirements of TR-RS-2014-00016 (SMC-S-016) [1], and engine self-induced vibration, followed by functional test and hot-fire of the LRE in a flight simulation to verify acceptable performance.

Appropriate test requirements are described in TR-RS-2014-00016 (SMC-S-016) [1]. Predicted environments usually are derived from flight and ground test data. In this manner, the test article is subjected to fatigue damage potential enveloping that experienced by the flight hardware. The duration of exposure required to adequately demonstrate durability is determined based on margin requirements and service life (SL), including acceptance testing and flight duration.

In cases where LRE environments are dominant, on-engine qualification may be performed as a demonstration of design robustness for LRE components. For some component types (typically more complex components involving sensitive electronics), it is necessary to demonstrate design margin with respect to LRE vibration and shock amplitude in addition to fatigue. If amplitude margin cannot be applied in a straightforward manner at the LRE level, testing at the component level is recommended (see Sections 6.6 and 6.7). In these cases, it is necessary to account for allowable component acceptance vibration testing when considering appropriate qualification margin and duration. Component test requirements should be derived from LRE accelerometer data acquired during engine-level testing. If data for the configuration in question are not available, then analysis or scaled data from a similar LRE configuration may be used.

Determination of self-induced vibration will necessitate the engine turbopump and other critical components being instrumented with accelerometers to characterize the dynamic environment during the development and qualification program. The resulting accelerometer test data represent the qualified environment for self-induced engine vibration. Self-induced environments for LREs can be quite severe and are highly complex, often including a large number of discrete-frequency and narrow-band random excitations spanning a wide frequency range. It is highly recommended that narrowband spectral analysis be applied to known LRE self-induced discrete forcing functions, given their narrowband nature. Additional analysis and consideration of forcing function characteristics should be used in determining whether the resulting environment is harmonic or random. During subsequent hot-fire testing and flight, *in the event of an out-of-family observation at a critical accelerometer location(s), an assessment should be performed to (1) determine the cause of the observation, (2) quantify the sensitivity of the engine design to the observation, and (3) evaluate any potential degradation of design margins.*

[7.6.3-2] LRE qualification testing shall include extended duration engine operation (per Table 4-1) under operating conditions representative of production acceptance and flight to verify durability of the engine hardware to self-induced vibration.

7.6.4 Vehicle Interface Loads

Vehicle-to-engine interfaces include structural, mechanical, and fluid-structural response characteristics. Significant structural loading is transferred from the engine to the stage/vehicle at the primary thrust take-out points (i.e., through a gimbal bearing or other thrust structure). At the other interfaces there can be fluid loading from propellant flow, secondary structural loading, and mechanical loading from gimballing. All these conditions are to be taken into account in engine models, and then flowed to component-level designers for detailed design. These models need anchoring from engine testing for engine-generated loadings.

[7.6.4-1] LRE qualification testing shall verify interface environments are within the Maximum Predicted Environments (MPE) by characterizing frequencies and amplitudes at the interfaces during engine testing.

7.6.5 Electromagnetic Compatibility Tests

Electronics are critical elements of flight systems, which depend on these items to control and manage engine functionality (engine health and status, valve controls, data, etc.).

[7.6.5-1] LRE qualification shall verify conformance of all electrical components to the EMC requirements in TR-RS-2014-00016 (SMC-S-016) [1] and in TR-RS-2008-00008 (SMC-S-008) [14].

In addition, ordnance, deployment systems, and fuel systems should be protected from, or made impervious to, inadvertent activation due to high electric field strengths, electrostatic discharge (ESD), and lightning. Specific EMC requirements should be made more stringent, if necessary, to verify acceptability for the worst-case inclement weather allowable for the launch. In addition, fuel lines need to have low enough resistivity and adequate bonding to surrounding structures to avoid surface electrostatic charging and discharge.

7.7 Life

Qualification of an engine for flight includes showing margin against each operating condition utilized over the service life. This is one aspect of demonstrating hardware robustness. The intention is to show this on multiple engines throughout the DDT&E program to build confidence in manufacturing processes and build-to-build variation.

7.7.1 Operational Lifetime and Durability

In verifying lifetime capability, the engine cannot merely be fired at one particular operating condition to accumulate a total duration. Duration with appropriate margin is applied on all expected operating conditions to the extent practical. Higher test margins during earlier development are recommended to *provide greater confidence of success going into verification testing. Any tailoring and/or exceptions must be dispositioned and properly justified.*

[7.7.1-1] Life testing of each verification engine sample, as specified in Table 4-1, shall encompass the entire range of specification (and expected, if different from specification) thrust, mixture ratio, propellant inlet boxes, and other conditions (i.e., life is not separated from operation across the range of allowed conditions).

[7.7.1-2] Life testing to a total duration with margin over the service life firing time shall be conducted on each of the required verification engine samples with minimum demonstration factors as specified in Table 4-1, Life Demonstration Factors, and to the extent detailed in Section 7.2.5, Thrust and Mixture Ratio Excursion Tests.

The entirety of these test series is also used for structural verification against fatigue.

[7.7.1-3] Each engine sample of the total listed in Table 4-1 shall be sufficiently instrumented to gather vibration data for evaluation of the dynamic environments relative to flight conditions and strain data for analysis correlation.

[7.7.1-4] If inspection of any verification engine sample produces evidence of fatigue damage, the engine sample with the fatigue condition shall be hot-fired for additional duration/starts to four times service life, with intermediate inspections to demonstrate stable damage progression (e.g., crack growth remains in Regime II of Paris Law fatigue relationship).

Any observed damage also necessitates a sufficient understanding of the potential root cause(s) to provide confidence that the test engine is representative of the fleet. Visual inspection may not be adequate, so an inspection approach should be selected that adequately characterizes the damage. A sufficient number of inspection points is needed, after damage detection, to ensure damage growth has stabilized.

Acceptance tests are used to verify durability and confirm that production hardware is in family with qualification hardware.

[7.7.1-5] LRE acceptance testing shall include pre- and post-test inspections to be used with the hot-fire data to verify that the hardware is not degrading faster than rates experienced and accepted during qualification.

7.7.2 Burn Duration Endurance Testing

Endurance tests show that the engine does not have issues meeting maximum burn durations, as well as indicating tolerance to several successive firings as expressed in the operational life and durability tests.

[7.7.2-1] LRE qualification shall include sustained operation for the maximum expected single-burn duration plus margin, as specified in Table 4-1, using flight-representative thrust and mixture ratio profiles.

This test demonstrates and characterizes run-time trends, and verifies that no failure modes exist that may not materialize until after an extended run.

[7.7.2-2] For multi-burn applications, LRE qualification tests shall demonstrate margin on cumulative mission duration in a series of single-burn tests.

Where practical, the burns should be sequential, with simulated coast periods between burns. If it is not practical to replicate the flight-like thermal conditions corresponding to long-coast periods in vacuum, it is acceptable to simulate the end-state using other means (such as cold or hot purges, etc.), and the sequence of coast events may be modified, provided all critical sequences are tested.

Similar to the thrust and mixture ratio margin testing in Section 7.2.6, the single burn endurance test deliberately overstresses the engine beyond maximum flight burn duration. Multiple qualification engine samples are demonstrating nominal burn durations at flight-bounding conditions in establishing qualified operating conditions. Therefore, a single qualification engine sample is considered acceptable for this test. Additional engine samples and/or testing may be required if single burn endurance test results identify concerns with engine robustness, such as unexpected or unstable behavior dependent upon burn duration.

7.7.3 Nozzle Endurance

For nozzles, erosion and char depth margin are typical concerns. Life testing is used to verify acceptable structural interface and liner interface temperature margins at the end of the extended duration, including during the soak-back heating at shutdown.

[7.7.3-1] Life testing for ablative and non-ablative nozzles shall be to a duration above the worst-case nozzle operational duty cycle, with at least one nozzle sample on each verification engine with the minimum margin specified in Table 4-1, Nozzle Operational Demonstration Factor.

[7.7.3-2] Post-test dissection inspections of qualification test nozzle samples shall verify nozzle erosion is acceptable.

[7.7.3-3] If a truncated ablative nozzle is to be used during acceptance testing to characterize the injector environment for flight units, the qualification test program shall establish correlations of erosion characteristics between the truncated nozzle versus the full-scale flight nozzle, with sufficient full and extended duration testing to determine engine-to-engine and nozzle-to-nozzle variability effects.

[7.7.3-4] Ablative nozzle erosion shall be evaluated for uniformity, following duration testing, to rule out flow protuberance erosion enhancement.

[7.7.3-5] While failures in charred regions of ablative nozzles may be acceptable, structural failures shall be precluded in non-charred regions unless evaluated to be non-catastrophic.

[7.7.3-6] For engines with nozzle extensions, operational life testing shall include a worst case duty cycle test that includes sufficient post-firing duration to ensure that all elements of the structure are exposed to temperatures that bound the flight environment.

For engines with restart capability and nozzle extensions, this requirement may necessitate a test sequence with simulated coast periods.

[7.7.3-7] Nozzle post-test inspections shall verify no seal blow-by or seal erosion.

7.7.4 Life Starts

Engine starts are a significant hardware durability driver and a major component to life calculations. Starting and stopping the engine tends to put significant thermal and pressure gradients across the engine in a very short period of time, stressing hardware significantly. Rocket engine life is typically quoted in starts and seconds (run time). Higher test margins during earlier development are recommended to provide greater confidence of success going into verification testing.

[7.7.4-1] Life testing for a total number of starts with margin over the SL starts shall be conducted on each of the required verification engine samples with minimum demonstration factors as specified in Table 4-1, Life Demonstration Factors.

7.7.5 Acceptance Test Procedure Validation

The qualification test series is also used to establish the ATP to be used for acceptance test of flight engines.

[7.7.5-1] LRE qualification hot-fire testing shall commence with the acceptance test sequence to validate the test techniques, processes, procedures, equipment, instrumentation, and software that will be used in production, as well as potential allowable rework and repeat test cycles.

ATP burn times should be sufficient to screen for early-life failure issues and exercise the engine to ensure that it is within qualification family with sufficient life remaining for possible stage ground test and flight with margin.

7.8 Controls

The engine control system sends commands throughout the engine and communicates with the stage/vehicle. It also collects and distributes engine data as necessary.

Functional tests are initially conducted off of the LRE. Control system malfunction logic checks are conducted on the LRE. Vehicle commands and similar communication may be simulated.

[7.8-1] LRE qualification testing shall verify the engine control system can reliably and accurately satisfy specification requirements for startup, steady-state operation, throttling, and shutdown.

This verification is typically satisfied in parallel with other objectives.

[7.8-2] LRE qualification testing shall verify data collection and transfer characteristics, and verify response time characteristics (i.e., response time between receipt of command and actual physical response of fluid, mechanical, or electronic devices).

This verification is typically satisfied in parallel with other objectives.

[7.8-3] LRE qualification testing, in combination with controller testing with flight-like interfaces, shall demonstrate fault detection and accommodation for engine control system faults by verification of proper identification of malfunctions followed by acceptable engine, engine controller, and control hardware responses, including channel switchover during the start transient, steady state, throttling, and shutdown for systems with redundancy.

[7.8-4] LRE qualification testing shall validate that the engine control system communicates with the vehicle, accepts commands, transmits data, directs engine operational functions based on commands, provides engine closed-loop control if so configured, provides condition monitoring data, and manages engine health if so configured.

7.9 Operations

7.9.1 Pre-Test Inspections and Checkouts

Pre-test inspections and checkouts primarily refer to visual inspections and functional checks. Checklist items must be performed on both the facility and test article in preparation for test. These include understanding the hardware configuration going into test, condition of hardware, removal of covers/closures where appropriate, review of hardware changed/altered since previous test, functionality checks including cycling the valves, and end-to-end electrical checks.

[7.9.1-1] LRE qualification testing shall validate the inspection procedures utilized prior to test, including, but not limited to, visual examination of configuration, visual inspections for damage, visual examination of fits and clearances, verification of safety precautions/requirements, verification of facility system readiness, and confirmation of adequate consumables. If inspection procedures have not been established prior to qualification testing, then inspection procedures are to be developed and validated as part of the qualification program.

[7.9.1-2] Prior to test of any LRE, engine-to-facility interfaces shall be inspected to verify compliance with dimensional and surface finish requirements.

[7.9.1-3] Main propellant line internal areas shall be inspected to verify absence of foreign object debris (FOD) when the lines are opened or if inlet covers are removed.

[7.9.1-4] Interfaces associated with internal components sensitive to moisture intrusion shall be verified to be dry.

[7.9.1-5] Test preparation shall include verification that all test procedures to be implemented are applicable for the intended test objectives and are of the correct version, that all facility and engine software to be used are the correct versions with the correct inputs, and that all relevant checksums have been performed.

[7.9.1-6] Prior to test, all specified functional checkouts shall be performed, to include manual or commanded operation/movement of mechanical systems, electrical integrity verification, control system checks, abort system readiness, data system readiness, and turbopump torque checks. Any redundant systems are functionally checked independently.

7.9.2 Post-Test Inspections

Inspections after a test provide valuable insight that can help explain or elaborate on any unexpected data, hardware life/durability concerns, etc. Depending on the test objective, the set of inspections conducted can vary during the DDT&E program. However, there will be a set of inspections that will be standardized for production engines to validate the condition of hardware and show the engine is ready for flight. These must be rehearsed and demonstrated to be a sufficient screening mechanism for flight preparation. A repeated acceptance test may also prove useful to characterize shifts in performance, which may be correlated with observed physical changes in the engine.

Post-test inspection requirements for individual tests are defined below. In general, the qualification test program should use the same requirements intended for the flight units during acceptance testing. Activities in addition to the normal activity intended for flight units are acceptable if required for specific risk mitigation for subsequent testing. But if the normal activity for flight units is found to be deficient, then it must be improved and re-validated.

[7.9.2-1] LRE qualification testing shall validate the inspection procedures and periodic inspection schedules used after test, including but not limited to visual inspections for damage, visual examination of fits and clearances, evaluation of combustion chambers and nozzles for evidence of unacceptable hot spots or erosion, and evaluation of chamber cracks and leakage against allowable values. If inspection procedures have not been established prior to qualification testing, then inspection procedures are to be developed and validated as part of the qualification program.

As described in Requirement [5.4.3-1], the initial flaw size in the safe-life assessment is based on the results from the last inspection, while the service life definition used in the damage tolerance life assessment is based on the inspection interval. The inspection for safe-life assessments requires validated NDI techniques (Requirement [5.4.3-4]). The ability of the NDI techniques and visual inspections to detect damage can be demonstrated via bench testing and qualification engine testing.

LRE qualification testing validates the inspection procedures and inspection schedules utilized after test, (Requirement [7.9.2-1]), including those used on flight engines. Inspection procedures used on the flight engine hardware are of equal or greater sensitivity than those used on the qualification hardware, as it is essential that the extent of damage acceptable for flight be enveloped by the extent of damage qualified by the engine test program with appropriate margin. The extent of damage acceptable for flight is addressed via the combination of the qualification engine test program (Requirement [7.7.1-4]) and the safe-life assessment (Requirement [5.4.3-1]).

[7.9.2-2] The general checkouts identified by [7.9.2-1] shall be performed after LRE acceptance testing, engine testing for operational life, MR excursion testing, and thrust/MR margin demonstration testing, correlating the condition of the engine as a function of its test exposure.

[7.9.2-3] After completion of a qualification test series (e.g., all the testing for a single engine sample), a detailed LRE teardown and inspection shall be conducted in which disassembly is to the piece-part level, and inspections include examinations for any signs of distortion, damage, excessive wear, or any other unexpected discrepancies.

7.9.3 Drying and Heated Purges

Drying and heated purges are intended to minimize the moisture (water) in the system. This is especially a concern with cryogenics and propellants expected to operate below the dew point of water vapor. Icing of sense lines during engine hot-fire may block pressure measurements or affect feedback control. Icing of injector elements may cause local maldistribution of propellants. Exposure to residual moisture may also cause material swelling (e.g., in seals) or stress corrosion cracking (e.g., in bearings). The elevated temperature used in purges must consider the material properties used within the system.

[7.9.3-1] LRE qualification testing shall validate the purge flow and drying procedures to maintain or return engines to specification limits, including checks of dew point at purge exit points at designated times. If purge flow and drying procedures have not been established prior to qualification testing, then these procedures are to be developed and validated as part of the qualification program.

[7.9.3-2] Acceptable hardware conditions after purges shall be verified by post-test inspections and/or subsequent successful hot-fire.

7.9.4 Gas Liquefaction Control

This testing refers to liquid air formation and control of detrimental amounts generated by cryogenic systems. Typically, foam insulation techniques are used for vacuum jackets. However, liquid air can still form in areas, leading to dripping onto electrical components, cryo-pumping, and insulation damage. Control and mitigation methods need testing to demonstrate durability, repair techniques, etc.

[7.9.4-1] LRE testing shall demonstrate, on a minimum of two engines, the life and durability characteristics of insulation applied for gas liquefaction control, accounting for process variations and design sensitivities.

[7.9.4-2] If insulation applied for gas liquefaction may be repaired, LRE testing shall demonstrate the effectiveness of the repair processes and that the life and durability of the repair is equivalent to the original material.

7.9.5 External Icing

Ice formation on the external surface of the hardware can change the thermal and dynamic characteristics of the hardware [19]. Environmental testing should simulate vehicle environments to mimic the atmospheric moisture conditions, pre-start conditioning, etc.

[7.9.5-1] External icing shall be characterized during LRE qualification testing, with potential ground-to-flight differences identified.

[7.9.5-2] Based on the testing in [7.9.5-1], areas of ice accumulation on the engine shall be identified and assessed for potential effects (i.e., changes in thermal and/or vibrational environments) in flight, accounting for TLYF exceptions.

7.9.6 LRU Demonstrations

LRUs are components that are interchangeable and do not pose a threat to the understood performance of the engine. Typically, an LRU is a component that, when removed and replaced within an LRE, either has a trivial effect on LRE performance and reliability, or a known, well-characterized, and predictable effect on LRE performance and reliability. Example LRUs are igniters and isolation valves. An LRU can be changed after final LRE acceptance testing without requiring that LRE to repeat the hot-fire test.

With few exceptions, however, the LRU itself must have undergone acceptance hot-fire testing on another LRE (see [6.1-1]). A long list of components allowed as LRUs helps provide flexibility in maintaining engine delivery schedules when a concern is raised about a particular component installed on an LRE that has already completed acceptance testing. Appropriate cost-benefit trades should be performed to help define the intended list of LRUs.

[7.9.6-1] The LRE qualification shall validate each LRU and its replacement procedures, including comparisons of resultant performance variation due to unit replacement compared to relevant performance uncertainty requirements, via direct and individual replacement of each LRU while minimizing any other test-to-test changes that might affect performance.

7.9.7 Reusability Operations

Reusability of an LRE adds unique requirements.

[7.9.7-1] The LRE qualification shall demonstrate two sets of two complete mission flight sequence simulations, with the first set at a nominal turnaround time and the second set at a minimum turnaround time, with inclusion of the following:

a. Demonstration of engine system start, steady-state operation, and shutdown over a complete flight sequence simulation during engine operation
b. Testing to simulate fly-back/return environments/loads exposure, if applicable
c. Verification of turnaround capability using specific procedures for the engine and countdown
d. Demonstration of any required between-flight hardware or software modifications
e. Inclusion of standard post-flight checkout and inspections, required health monitoring data reviews, and pre-flight checkout using the same access limitations and restrictions, including limitations on vertical and horizontal access, as applicable, and confined spaces
f. Demonstration of engine system re-start, steady-state operation, and shutdown over a repeated complete flight sequence simulation during engine operation
g. Final post-flight checkout and inspections, required health monitoring and data reviews to verify the LRE successfully meets all criteria

Documents LE-S-010 [33] and LE-P-018 [34] provide additional context for reuse requirements related to National Security Spaceflight Launches procured by the U. S. Space Force.

7.9.8 Operability

The term operability is used to describe the ability to conduct operational procedures in a timely and effective manner, such as minimizing the level of effort required to change LRUs when necessary, conducting pre- and post- test checkouts, and conducting electrical and mechanical checkouts. This also manifests itself in operational timeline optimizations. Test demonstrations help determine the allowed time to perform the multitude of operational tasks on an engine.

[7.9.8-1] LRE qualification testing shall determine and verify practical servicing procedures, operational readiness capabilities, maintenance access requirements, and availability and suitability of alternate parts/processes.

Access to the propulsion system for verification should be similar to actual flight-related operations and replicate the engine servicing environment expected during full operational status. Engine-related operability verification should be performed according to the intended engine servicing configuration (e.g., mounted on the flight vehicle, or removed and replaced) and orientation (e.g., vertical or horizontal) during flight-related operations. Operability verification demonstrations should include or replicate vehicle elements, and use available resources, including on-ground maintenance equipment and logistics support infrastructure, as close as possible to the intended standard launch operations.

7.9.9 Preflight Procedures and Flight Sequences

This includes pre-flight countdowns and hardware preparation and configuration for flight. Many vehicle operations are performed remotely at this point. However, there may be some flight-day or near-flight-day activities that require personnel around the engine or vehicle.

Because DDT&E tends to occur a significant time before first flight, the procedures known at that point are typically of significantly lower fidelity than what will be used on flight day. However, notional procedures can be put in place based on the known vehicle architecture and concept of operations. Interfaces with vehicle-simulated command and data systems should be part of the facility configuration.

[7.9.9-1] LRE qualification testing shall demonstrate preflight procedures and operational procedures, followed by verification of acceptable operation during a simulation of the flight sequence of events.

Where practical, the burns (if more than one) should be sequential, with simulated coast periods between burns. Long coast periods experienced in flight should be simulated as part of this test. If this is impractical, the engine may be conditioned to match the thermal environment at the beginning of each burn and the sequence of coast events may be modified, provided all critical sequences are tested.

7.10 Process Controls

7.10.1 Manufacturing

Because manufacturing processes are also being qualified, the test program must identify expectations regarding hardware discrepancies and how they can play into hardware durability, data from testing, etc. This is an important part of the DDT&E effort as some manufacturing issues of varying criticality are likely to occur during development due to low production levels.

[7.10.1-1] Key (design) characteristics (KCs) and their associated critical manufacturing processes (CMPs) shall be identified and qualified.

[7.10.1-2] Key process parameters (KPPs) for each CMP (including repair procedures) shall be identified, documented, and strictly controlled.

For example, these would include laser speed, laser power, and powder specification for additively manufactured parts.

[7.10.1-3] In-process inspection or process monitoring shall be used to verify the setup and acceptability of critical parameters during the fabrication process/procedure, especially for additively manufactured parts.

[7.10.1-4] Traceability shall be maintained on all fracture-critical structural items throughout their development, manufacturing, testing, and service.

[7.10.1-5] Inspection reports, which include type of NDI and sensitivity level, material and condition, and part number, shall be maintained throughout the life of the program, with periodical review and assessment to evaluate trends and anomalies associated with the inspection procedures.

[7.10.1-6] Volumetric NDI shall be required for welds, cast parts, and for parts susceptible to internal flaws resulting from manufacturing.

[7.10.1-7] LRE testing shall identify and track hardware or operational discrepancies, anomalies, or deficiencies, including but not limited to cracks, material erosion/ discoloration, part deformation, unexplained elevated vibration, and unusual operating characteristics.

7.10.2 Mass Properties

Engine and engine component masses, centers of mass, and mass moments of inertia must be understood, measured, and provided to vehicle controls analysts, to trajectory analysts, and for development of structural and structural dynamic models of the engine.

[7.10.2-1] Engine mass, center of mass, and mass moments of inertia shall be measured for each verification engine in the as-tested configuration.

The measurements should be performed using the same procedures that will be used for the flight engines. Mass properties control and verification procedures typically follow AIAA-S-120A-2015 (2019) [32].

7.11 Unique Requirements

7.11.1 New or Mission-Unique Requirements

[7.11.1-1] New requirements or mission-unique requirements levied on the LRE following completion of qualification shall require a combination of evaluation and test (including the option of not requiring delta-qualification) to qualify the engine for the new requirements, with concurrence of the Approval Authority.

7.11.2 Delta-Qualification Requirements

Qualification testing should be performed on the final design, manufacturing processes, procedures, and acceptance program to be used for flight units.

[7.11.2-1] Deviations following completion of LRE qualification shall require that the system be re-qualified (i.e., “delta-qualification”) via combination of evaluation and test (including the option of not requiring delta-qualification), with concurrence of the Approval Authority, where deviations include configuration changes, modified processes, new suppliers, new facilities, or revised procedures.

8. System Requirements

One or more LREs will be integrated into a launch vehicle stage, and the stages are integrated into the complete launch vehicle. TR-RS-2014-00016 (SMC-S-016) [1] terms the complete launch vehicle as a system.

8.1 Stage and System Test

Stage-level testing verifies engine operation within an integrated flight-like system. Such testing is a specific instance of an end-to-end performance test necessary to verify the engine and associated subsystems. Unlike other end-to-end performance tests identified in TR-RS-2014-00016 (SMC-S-016) [1], it does not need to be repeated prior to, during, or after environmental testing. However, the operating conditions, environment, and command sequence should be carefully selected to verify the system interactions in flight-like conditions.

[8.1-1] Engine qualification shall include an engine-integrated stage test to verify system interactions and control during engine prestart, start, dwell, and shutdown, including, for engine cluster type stage configurations, stage functional and performance demonstration of the design-maximum engine-out capability.

[8.1-2] For multiple engine (cluster) vehicle configurations, integrated testing or relevant analysis shall be completed to ensure engine interactions are acceptable.

[8.1-3] Qualification testing of TVC and deployment mechanisms shall verify through real-time observation and post-test inspection that all thermal protection shields, flexible boots, gimbal hardware, and adjacent structures remain properly configured/intact through all physical movement.

8.2 Pre-Launch Validation and Operational Tests

General prelaunch requirements are defined in TR-RS-2014-00016 (SMC-S-016) [1]. The scope of these tests covers everything from receiving a stage at the launch site to launch. Additional requirements are noted in the following sections.

8.2.1 General Requirements

[8.2.1-1] The LRE shall comply with TR-RS-2014-00016 (SMC-S-016) [1] requirements for Prelaunch Validation and Operational Tests, Paragraphs 9.1, 9.2, 9.3, and 9.4.

8.2.2 Receiving Inspection

[8.2.2-1] An external inspection of the condition of hardware shall be conducted to include the following:

a. All discrepancies noted and dispositioned.
b. State of all desiccants, covers, closures, acceleration monitors, and support equipment/cradles/etc., that “touch” flight articles are verified, with the focus on understanding if the condition of the hardware has changed as a result of transportation and handling.
c. If main propellant inlets covers are removed, condition of the internal area verified to be FOD free.

8.2.3 Purges

Purges are often necessary to maintain the engine internal environment (desired cleanliness and moisture levels) whenever any protective covers and closures have been removed. While performing final vehicle assembly and maintenance, limited periods of exposure without purges may be allowed. To ensure the propulsion system internal environment remains acceptable, however, a sequence of purges and moisture checks should follow to validate the internal environment. In preparation for launch, including tanking and loading of propellants and pressurants, purges are necessary on a more continuous basis to provide the confidence that the hardware internal environment is maintained. Purge sequences are usually automated, and rules for moving from one sequence to another are well established and software controlled.

[8.2.3-1] Purge operations shall be validated against requirements (see [7.9.3-1]) by verification of pressures, temperatures, flow rates, and fluid quality (grade, moisture content, etc.).

8.2.4 Vehicle Readiness Test

The vehicle readiness test is intended to verify readiness of the assembled vehicle by performing a simulated flight sequence using control parameters at nominal operating values.

[8.2.4-1] Engine control system functional checks shall be performed through the airborne flight control system with control parameters at nominal values per the flight sequence.

[8.2.4-2] Engine control system functional checks shall verify through real-time observation and post-test inspection that all thermal protection shields, flexible boots, gimbal hardware, flexible ducting, lines, cabling, and adjacent structures function as intended and remain properly configured/intact, through all physical movement.

[8.2.4-3] Vehicle readiness testing of TVC and deployment mechanisms shall validate the engine envelope clearance analyses at TVC limit positions. Dry, ambient hardware conditions may be used for this test.

[8.2.4-4] Vehicle readiness testing of TVC and deployment mechanisms shall verify gimbal block and roll control (if applicable) interface compatibility for mechanical (e.g., bearings), hydraulic, and electrical connections under nominal control parameters.

8.2.5 Vehicle Tanking Test

This test is intended to verify readiness of the assembled vehicle and interfacing ground support equipment. This test is intended to go as far into the pre-launch countdown procedures as feasible, including loading of propellants, without igniting the propulsion systems. The test is not intended for hypergolic propellants.

For engine architectures involving Earth-storable hypergolic propellants, it is desirable to not load and subsequently unload hypergolic propellants in the associated flight propulsion system under nominal operating conditions. As such, the identified guideline for a vehicle tanking test is not recommended for systems utilizing these storable hypergolic propellants. This avoids or reduces the potential for inadvertent air/ground atmosphere and propellant reactions, as well as propellant reaction product precipitate issues within the flight propulsion system.

[8.2.5-1] Preflight procedures and launch timelines shall be demonstrated by the vehicle tanking test. Operational procedures should be used to the extent possible.

[8.2.5-2] The vehicle tanking test shall include use of the preflight sequence, including any functional health checks such as TVC and valve slewing, and engine controller checkout.

[8.2.5-3] The vehicle tanking test shall exercise thermal conditioning processes and procedures, and verify performance of engine system passive and active thermal control (including chilldown, warming purges, heaters, etc.).

[8.2.5-4] The vehicle tanking test shall verify that engine start commit criteria (SCC) can be satisfied prior to commit time.

[8.2.5-5] The vehicle tanking test shall demonstrate the TVC operational envelope prior to introducing propellants, as well as after propellant load and engine thermal conditioning.

[8.2.5-6] Following the vehicle tanking test, post-test inspections shall be performed to verify that the post-test hardware condition is satisfactory and ready for flight.

8.2.6 Prelaunch Countdown

The same steps used in the Vehicle Tanking Test are conducted leading up to actual launch (except for post-test inspections [8.2.5-6]). Additional checks may be included to verify propulsion system health immediately prior to liftoff. Primarily, this consists of review of the launch commit criteria (LCC) and detailed operating procedure (DOP) prior to executing the launch command. No failure identifications (FIDs) should be left without disposition. Hardware must be thermally conditioned and in proper configuration for launch.

Appendix A. Tailoring Guidance

The values in Table 4-1 are derived from experience and reliability analyses, and are generally consistent with JANNAF-GL-2012-01-R0 [19]. The total unique verification engine samples listed (4) are to have similarity with the flight design, but may be considered development, qualification, or even flight units. Each engine may have different test objectives associated with it, provided the specific variation does not compromise any other objectives, thus allowing some leeway in hardware configuration. The intent is to achieve a sample size large enough to begin to establish build-to-build variation with a quantifiable level of confidence. The total number is supported by Weibull reliability analysis and has been used successfully.

Careful consideration should be given to hardware configuration, and what is considered to be a valid sample. Hardware changes (due to a failure, intended improvements, convenience, or any other reason) generally invalidate earlier samples for the components changed, as well as for all other interrelated engine components, unless it can be confidently demonstrated that the changes had a benign effect on their environments and interactions. Combinations of component-level and system-level testing should also be considered when determining sample sizes at the engine level.

Furthermore, the engine design should be evaluated relative to design heritage. The appropriateness of the four samples may be significantly influenced by heritage, evolutionary, or clean sheet designs. However, there are many examples where seemingly "small changes" have had significant adverse unintentional and unexpected consequences, so careful consideration must be taken on how to apply any heritage data to reduce the sample population. The following sections discuss examples where the test numbers and factors have been modified, as shown in Table A-1 (versus Table 4-1). Justification and implications to realized risk levels, which are different from the standard recommendation, are provided for each case.

As noted previously, the recommended minimum of four verification engine samples (Table 4-1) is based, in part, on Weibull reliability analysis. Weibull reliability functions (50% confidence bounds, using rank regression) are shown in Figure A-1 for this sample size requirement, with no failures. The value of beta represents the type of failure mode and is manifested as the slope of the line on a Weibull plot. The high beta (high slope) failure modes, which represent wear-out failure modes, are most affected by the 4 × SL engine sample. The low beta (low slope) failure modes, which represent early life failure and random

Table A-1. Example Alternate LRE Verification Engine Samples and Margins/Demonstration Factors, which have Different Associated Risk Levels than the Standard Recommendation

Parameter	A.1	A.2	A.3*
Engine Samples			
Minimum Total Engine Samples, 4.3.1	6	4	2
Minimum Qualification Engine Samples, 4.3.1	2	2	1
Unit & Subscale Test and Evaluation			
Unit Life Margin Factor, 6.13.1, 6.13.3	4×	4×	2×
LRE Test and Evaluation			
Thrust / MR Margin Factor, 7.2.6	2%	2%	2%
Life Demonstration Factors, 7.7.1, 7.7.4	2× on 6	4× on 1, 2× on 1, 1× on 2	2× on 2

* Note that this option is for a pressure-fed engine, i.e., a simpler design.

failure modes, are most affected by the three 2 × SL engine samples. That said, the predicted failure rate for all the betas analyzed is not favorably small. For example, the analysis (with 50% confidence bound) predicts 10% of engines will fail by the end of 1 service life (1 × SL) for beta = 0.5 (early life failure modes), and 7% of engines will fail at 1 × SL for beta = 1 (random failure modes). This baseline case emphasizes the fact that engine qualification testing is not the only factor that determines overall engine reliability. Robust material screening/quality control processes and acceptance testing are absolutely required for high reliability. Furthermore, high reliability, particularly for early life failure and random failure modes, requires much more cumulative engine test experience than 4 engines. For beta = 3 (early wear-out modes) and beta = 6 (later wear-out modes), the 4 × SL engine qualification sample has a very significant effect on reliability, with predicted failure rates of 0.8% and 0.02% at one service life (50% confidence bound). Robust designs and defect screening procedures will also help improve reliability, as will unit-level component testing to 4 × SL.

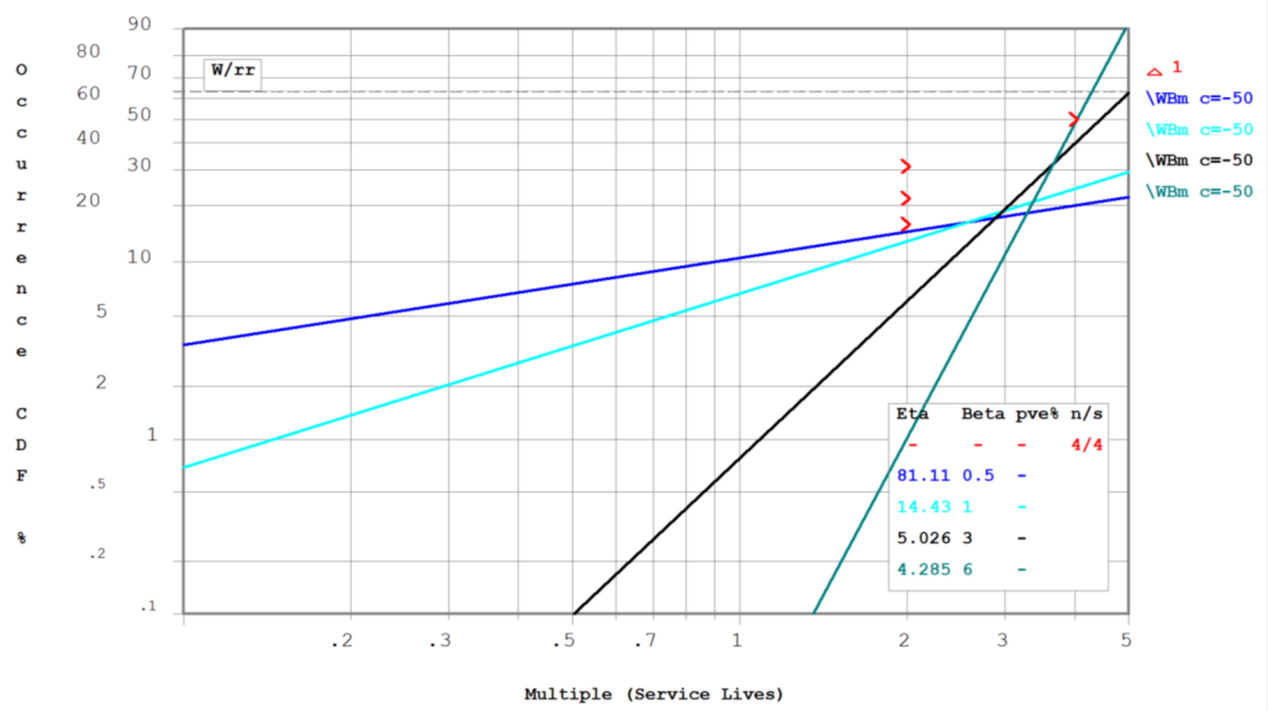

Figure A-1. Weibull analysis of a qualification program with one engine sample taken to 4 × SL, and three engine samples taken to 2 × SL, with no failures.

A.1 More Engines Tested, But Lower Qualification Demonstration Factor

If, rather than testing four verification engines per Table 4-1 (one to 4 × SL, and three to 2 × SL), six engines are tested to 2 × SL each, the Weibull analysis at a 50% confidence bound will change, as shown in Figure A-2. Note that the reliabilities at one service life for beta = 0.5 (early life failure modes) and beta = 1 (random failure modes) are improved over the requirements in Table 4-1. That is because this tailoring results in more cumulative engine experience (6 engines at 2 × SL/engine = 12 × SL total engine experience, as opposed to 1 engine at 4 × SL + 3 engines at 2 × SL/engine = 10 × SL total engine experience). The failure rates for beta = 3 and 6 (wear-out failure modes) went up significantly, in comparison. That predicted rise in failure rate would need to be offset by other factors, such as improved unit-level testing (4 × SL) and/or improved fidelity in the analytical predictive capability for those failure modes using test-anchored analyses. It is typically quite challenging to use analyses to confidently address the wear-out failure modes associated with fatigue of complex turbomachinery typical of LREs, and unit acceptance testing is usually inadequate to screen for fatigue issues.

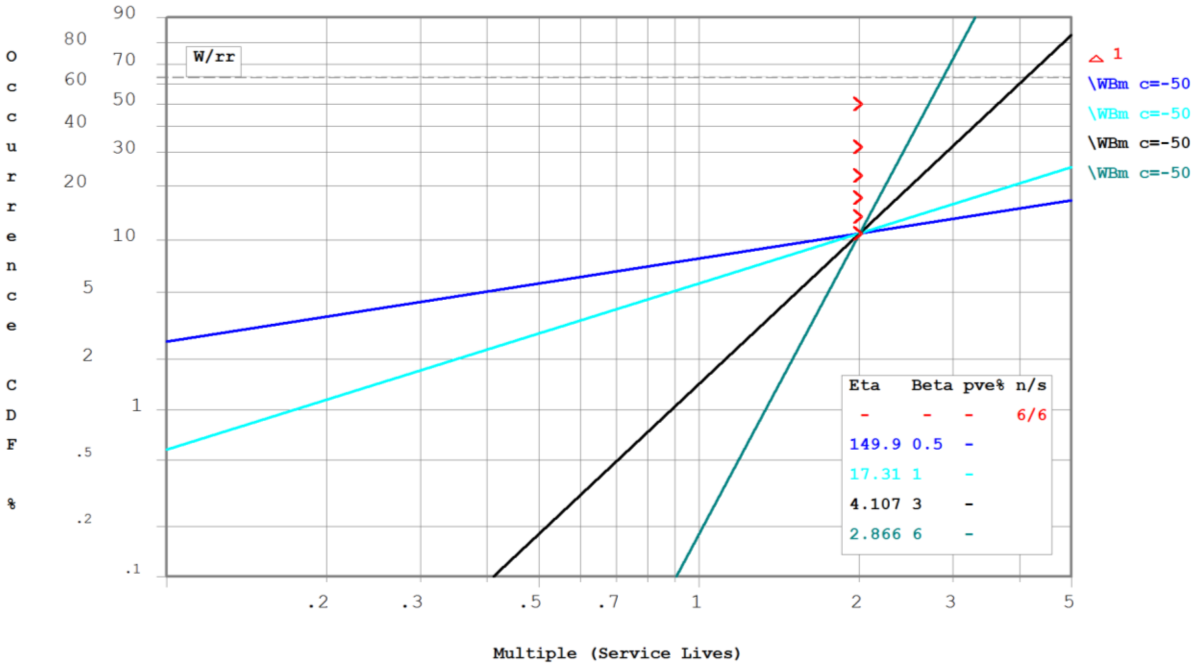

Figure A-2. Weibull analysis of a qualification program with six engine samples taken to 2 × SL (no failures).

A.2 Accepting Increased Risk

If, rather than testing four verification engines per Table 4-1 (one to 4 × SL, and three to 2 × SL), one engine is tested to 4 × SL, one engine is tested to 2 × SL, and two engines are tested to 1 × SL each, the Weibull analysis at a 50% confidence bound will change, as shown in Figure A-3. The reliability at one service life for beta = 6 (late wear out failure modes) is essentially driven by the 4 × SL qualification engine, and is unchanged. The reliabilities for the other failure modes are slightly degraded, now with only 8 × SL cumulative engine test experience. A program may be willing to accept higher initial risk for some failure modes coming out of qualification, recognizing that future risk for some modes may improve as greater test and flight experience is gained. If flight engines are utilized as samples, additional flight instrumentation may be required to help demonstrate that no failure modes have been experienced. It may not be possible, however, to adequately verify post-firing health of those engines (particularly imminent failures), unless the engines are brought back and inspected.

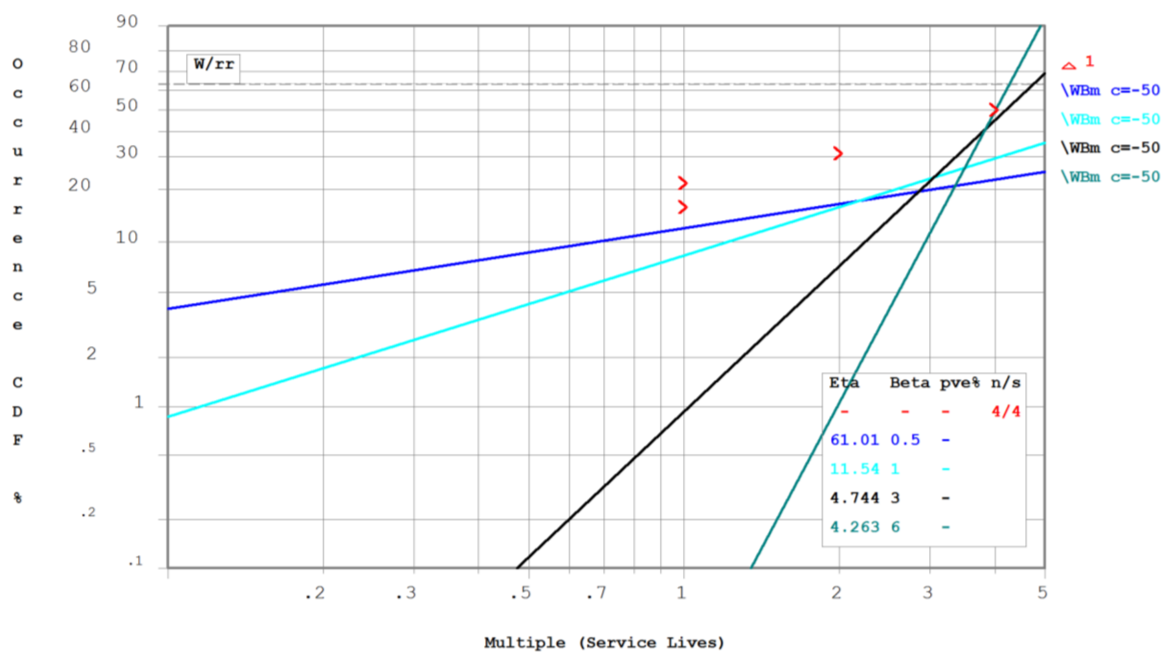

Figure A-3. Weibull analysis of a qualification program with one engine sample taken to 4 × SL, one engine sample taken to 2× SL, and two engine samples taken to 1 × SL (no failures).

A.3 Pressure-Fed Engine Design

The simplest LRE designs, such as pressure-fed engines, may be more amenable to reductions in engine samples without drastic increase in risk. The justification for the reduction is because pressure-fed engines can have less significant system interactions than pump-fed engines, and the load environment is more predictable. A minimum of two verification engine samples, including one qualification engine, may be appropriate for a new pressure-fed engine design. Size-scaling of existing engine designs may be considered as equivalent to a new engine design for many objectives. For comparison, Figure A-4 shows predicted reliability (50% confidence bound) for two verification engines tested to 2 × SL. Reliability is significantly degraded, based upon the test engines alone, in comparison with the requirement outlined in Table 4-1, so high fidelity test-anchored analysis with robust margins, robust material screening/quality control processes, reliable acceptance testing, etc. is absolutely essential for high flight reliability.

Where influence of build variability on local engine thermal conditions and distributions is not well characterized, additional verification engines should be tested until sufficient data are obtained to characterize the influence of build variability. Additional consideration should be given to build variability, especially as it pertains to injectors, fluid control, and cooling systems, that could affect the global or local mixture ratio and corresponding material thermal conditions. While pressure-fed engines benefit from the simplicity of removing turbomachinery, build variability affecting the injector and cooling systems remains. Additionally, "simple" systems may contend with larger overall mixture ratio variability that must be accounted for in qualification testing.

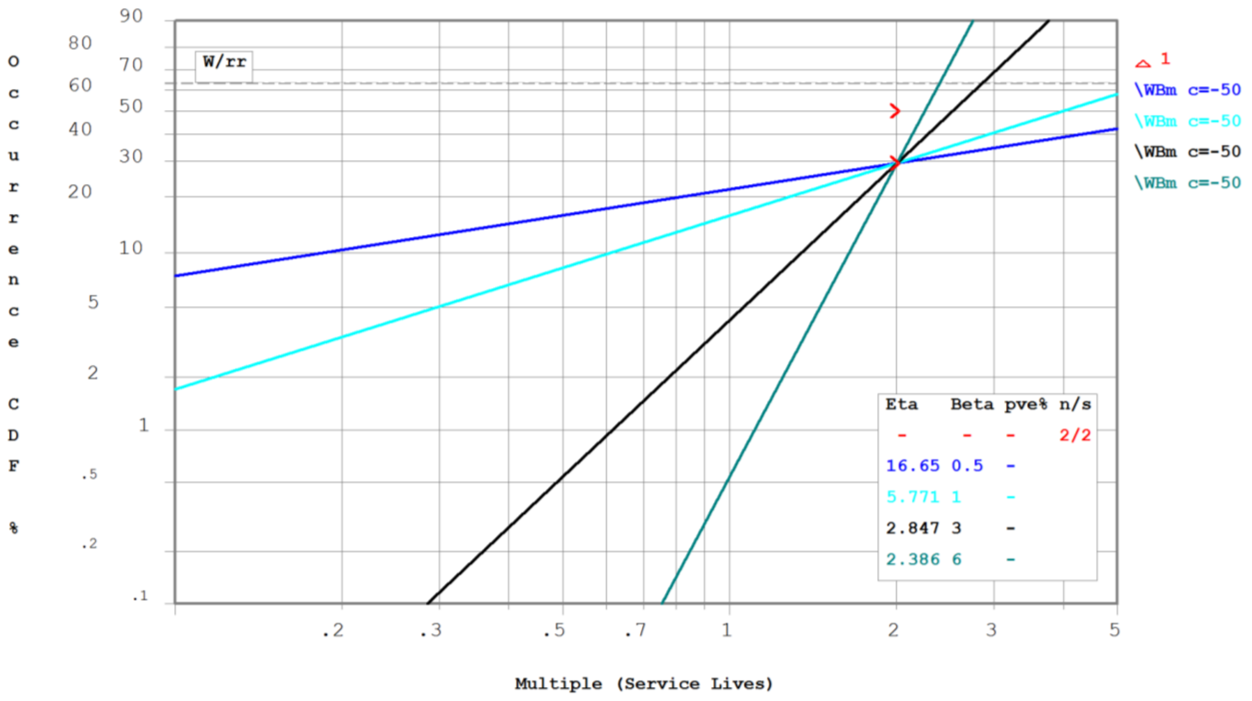

Figure A-4. Weibull analysis of a qualification program with two engine samples taken to 2 × SL (no failures).

Appendix B. Operational Keep-Out Zones

Engine development and qualification testing may reveal certain operating regimes where instability or accelerated fatigue are experienced. Examples include turbomachinery rotor-dynamic instabilities, combustion instabilities, and engine self-induced vibration. When these are encountered, "keep-out zones" may be incorporated into engine operational profiles to preclude significant operation at these potentially damaging conditions. The LRE qualification program should demonstrate transit through, and operation around, these keep-out zones consistent with LRE service life.

In the following example, Figure B-1 illustrates the power level/mixture ratio binning definition for an engine with continuous throttle capability. The table is also annotated to capture notional turbomachinery resonance keep-out zones where operation is restricted. These areas of expected rotor-dynamic instability should be characterized during the engine development and qualification phases to ensure adequate margin is maintained relative to potentially harmful operating regimes during engine operation. The qualification program should perform margin testing inside the boundaries of the keep-out zones in a manner similar to margin demonstration outside the boundaries of the flight box. The margin should reflect operational uncertainty (for example, shaft speed) as well as hardware modal variation.

Figure B-1. Power Level/Mixture Ratio Binning Definition.

Figure B-2 shows a notional flight profile designed to restrict the engine from operating in the keep-out zones. The qualification program should demonstrate that the engine control algorithm is capable of quickly and safely throttling the engine through the restricted areas and preventing dwelling for durations beyond demonstrated experience.

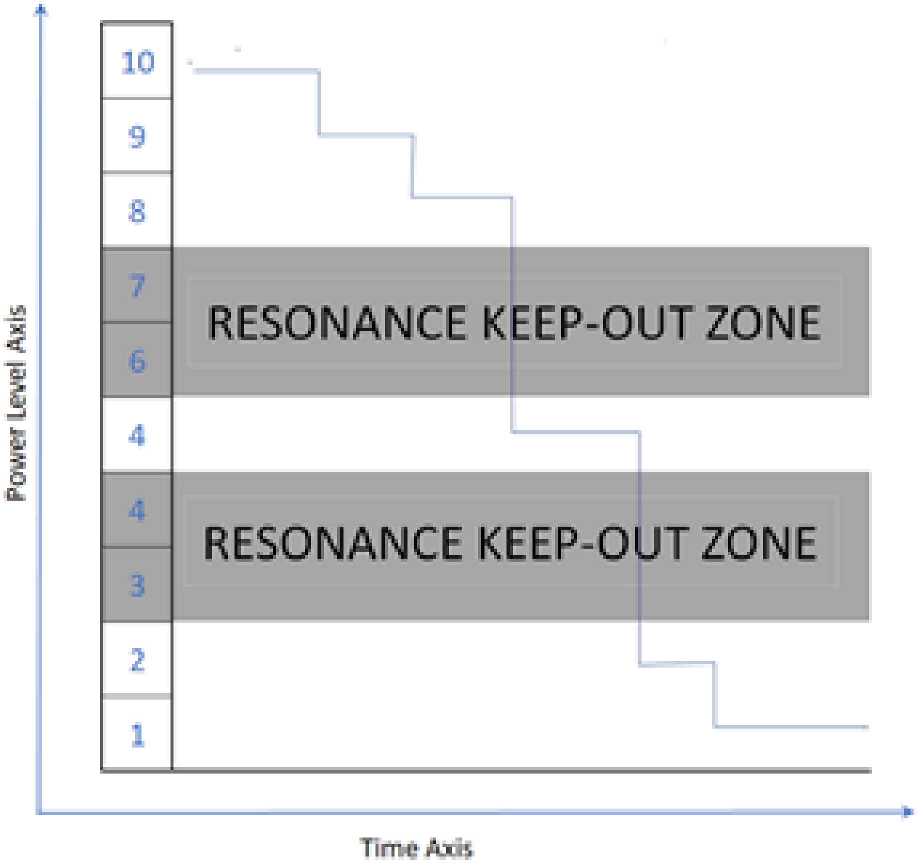

Figure B-2. Notional Flight Profile.

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Alejandro Prieto
SSC SSIO/BZEE
alejandro.prieto.1@spaceforce.mil

Eric Mattessich
SSC SSIO/BZEE
eric.mattessich@spaceforce.mil

Mark Honda
SSC SSIO/BZE
mark.honda.1@spaceforce.mil

Jon D Strizzi
USSF/SSC/AATS
jon.strizzi@spaceforce.mil

John Wong
USSF/SSC/AATS
john.wong.6@spaceforce.mil

APPROVED BY____ DATE______________
(AF OFFICE)

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Evaluation and Test Requirements for Liquid Rocket Engines

Approved Electronically by:

Mark J. Silverman, CHIEF ENGINEER/GENERAL MANAGER
OFFICE OF EVP

Cognizant Program Manager Approval:

Bruce H. Mau, PRINCIPAL DIRECTOR
LAUNCH SYSTEMS DIVISION
LAUNCH & ARCHITECTURE OPERATIONS
SPACE SYSTEMS GROUP

Aerospace Corporate Officer Approval:

Kevin D. Bell, SENIOR VP SPACE SYSTEMS GROUP
OFFICE OF EVP

Content Concurrence Provided Electronically by:

Jeffrey J. Murphy, SENIOR ENGINEER SPECIALIST
PROPULSION DEPT
VEHICLE PERFORMANCE SUBDIVISION
ENGINEERING & TECHNOLOGY GROUP

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Technical Peer Review Performed by:

David A. Reese, DIRECTOR - DEPARTMENT
VEHICLE PERFORMANCE SUBDIVISION
VEHICLE SYSTEMS DIVISION
ENGINEERING & TECHNOLOGY GROUP

John C. Klug, DIRECTOR - DEPARTMENT
STRUCTURAL MECHANICS SUBDIV
VEHICLE SYSTEMS DIVISION
ENGINEERING & TECHNOLOGY GROUP

Wayne M. Van Lerberghe, PRINCIPAL DIRECTOR
VEHICLE SYSTEMS DIVISION
ENGINEERING & TECHNOLOGY GROUP

Alvar M. Kabe, PRINCIPAL DIRECTOR
VEHICLE SYSTEMS DIVISION
ENGINEERING & TECHNOLOGY GROUP

Amy Weir, SENIOR PROJECT LEADER
ENTERPRISE INTEROPERABILITY STANDARDS
SPACE SYSTEMS GROUP

Jeff B. Juranek, SENIOR PROJECT LEADER
ENGAGEMENTS
ENTERPRISE SYSTEMS ENGINEERING
CORPORATE CHIEF ENGINEERS OFFICE

SI0722