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This current draft guideline is a work in progress written by members of the Joint Army Navy NASA Air Force (JANNAF) Liquid Propulsion Subcommittee (LPS) Test Practices and Standards Panel (TPSP). The Acknowledgements page lists the current and past members of the TPSP, as well as other contributors. The content herein does not represent the official or approved position of any of the organizations involved in its preparation. It is intended as an initial starting point for further discussion within the propulsion community regarding the appropriate specific test requirements for liquid rocket engines (LREs). This draft is intended for submittal to the JANNAF TPSP and the greater United States propulsion community for detailed review, comment, and revision. Further review, comment, and revision over multiple review periods are anticipated. Furthermore, the focus and content of this current draft edition relates primarily to engine testing and integrated vehicle propulsion system level testing. Although testing at the component level is not discussed in detail, this is recognized as also being important and valuable, and therefore it is anticipated that detailed treatment of component testing will be incorporated into subsequent editions of the guideline. Similarly, although reaction control systems (RCS) and satellite propulsion are not addressed in the current draft edition, it is anticipated that these areas will also be incorporated into subsequent editions of the guideline.

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Joint Army Navy NASA Air Force (JANNAF)

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Foreword (with Status and Disclaimer)

This current draft guideline is a work in progress written by members of the Joint Army Navy NASA Air Force (JANNAF) Liquid Propulsion Subcommittee (LPS) Test Practices and Standards Panel (TPSP). The Acknowledgements page lists the current and past members of the TPSP, as well as other contributors. The content herein does not represent the official or approved position of any of the organizations involved in its preparation. It is intended as an initial starting point for further discussion within the propulsion community regarding the appropriate specific test requirements for liquid rocket engines (LREs). This draft is intended for submittal to the JANNAF TPSP and the greater United States propulsion community for detailed review, comment, and revision. Further review, comment, and revision over multiple review periods are anticipated.

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Contributors

This draft guideline is the result of contributions received from many individuals representing different organizations associated with the design, test, and operation of LREs. The names and organizations of principal contributors and JANNAF LPS TPSP panel members, as well as those acting as the focal point of contact for their organizations, are listed below:

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1 SCOPE

1.1 PURPOSE

This document is intended as a test and evaluation guideline that establishes the recommended nature and extent of testing to successfully develop, qualify, accept, and ready liquid propellant rocket engines and propulsion systems for launch and space vehicles. The goal is to define a test program that will verify the design, eliminate latent defects, and help ensure a high level of confidence in achieving successful space missions.

1.2 APPLICATION

This guideline applies to liquid rocket engines (LREs) and LRE propulsion systems for expendable and re-usable applications, including non-human rated and human-rated systems including pump-fed and pressure-fed, utilizing various propellant combinations including hydrogen/oxygen, hydrocarbon/oxygen, storable, and mono-propellants. This guideline addresses development, qualification, acceptance and pre-launch testing for main propulsion systems (i.e., thrust > 1000 pounds force[lbf]) for space launch vehicles (including booster and upper stage propulsion). This current edition does not address launch vehicle reaction/roll control systems (RoCS/ReCS), satellite, air-breathing or combined cycle propulsion. This guideline focuses on testing of an LRE at the individual engine and integrated vehicle propulsion system levels. It does not address development and qualification of any system outside of these bounds, although it is recognized that an LRE is a part of a larger system (a.k.a. stage). Furthermore, this current edition does not discuss testing at the component level in detail.

1.3 MOTIVATION

The members of the JANNAF TPSP concluded there was a lack of established test guidelines to help determine the appropriate level and types of testing for LREs. Although certain existing documents provide guidance for certain related areas, thorough and specific guidance are noticeably lacking in many areas. The most recent U.S. government specification intended for LRE qualification was MIL-R-5149B. This specification, last updated in 1969, was used as a guide for formal qual of military rocket engines. It was canceled in 1993. A standard published in 1996 by the Society of Automotive Engineers (SAE) primarily concentrates on reliability certification requirements [SAE ARP4900 (1995)]. No programs have applied this standard in practice. MIL-STD-1540 and the associated MIL-HDBK-340 describe qualification and acceptance test guidelines for space systems, but do not adequately represent the nuances of rocket engine testing, mainly because of the difficulty of reproducing engine environments at the engine subsystem or component level. Existing surveys of past test programs for liquid oxygen (LOX)/kerosene engines and LOX/hydrogen engines [Emdee (2001) A, Emdee (2001) B, Pempie (2001)] provide valuable insight into typical test histories, but they are not sufficient by themselves to define the appropriate requirements for a new engine test program.

Program Managers want a set of guidelines to help scope the engine test program because testing is one of the largest expenses in a new launch vehicle system. The major costs are associated with the purchase of engine hardware, test time on test facilities, and failure resolution. Unfortunately, the recent historical record shows that propulsion systems account for over 50% of launch vehicle failures [Chang (2000)]. Such a poor flight record suggests that test efforts should be re-examined for adequacy or at least that a larger proportion of resources be devoted to engine testing. The industry would benefit greatly from establishment of practices and guidelines for engine testing that certify high reliability at the lowest possible cost. This document attempts to fill that need.

LRE development, testing, and verification are an extensive undertaking that can be very expensive, but absolutely critical for mission risk reduction. A benchmark understanding of the Test & Evaluation (T&E) aspects of Design, Development, T&E (DDT&E) for LREs is needed as well as a benchmark approach to reduce the uncertainty and variability in the outcomes of government and future commercial LRE products.

2 REFERENCE DOCUMENTS

2.1 GOVERNMENT APPLICABLE DOCUMENTS

The following documents form a part of this guideline to the extent referenced herein. Unless otherwise noted, the latest revision is preferred.

- Aerospace Report TR-2005(8583)-1, "Electromagnetic Compatibility Requirements for Space Equipment and Systems," 8 Aug 2005.
- CPIA Publication 247, "Combustion Stability Specifications and Verification Procedures for Liquid Propellant Rocket Engines," Oct 1973.
- MIL-A-83577B (USAF), "Assemblies, Moving Mechanical, For Space and Launch Vehicles, General Specification For."
- MIL-STD-461 (DOD), "Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment."
- MIL-STD-464 (DOD), "Electromagnetic Environmental Effects Requirements for Systems."
- MIL-STD-1522 (USAF), "Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems."
- MIL-STD-1541 (USAF), "Electromagnetic Compatibility Requirements for Space Equipment and Systems" [Note: references within this document prefer the proposed MIL-STD-1541B as described by Aerospace Report TR-2005(8583)-1, "Electromagnetic Compatibility Requirements for Space Equipment and Systems," 8 Aug 2005].
- MIL-STD-1546A (USAF), "Parts, Materials, and Processes Control Program for Space and Launch Vehicles."
- MSFC-HDBK-2221, "Verification Handbook Volume I: Verification Process" DCN 001 Change 1, Sep 1994.
- MSFC-HDBK-2221, "Verification Handbook Volume II: Verification Documentation Examples," Aug 1994.
- MSFC-SPEC-164, "Cleanliness of Components for Use in Oxygen Fuel and Pneumatic Systems Specification," Nov 1996.
- NASA-STD-5012, "Strength And Life Assessment Requirements For Liquid Fueled Space Propulsion System Engines."
- SMC-S-016, "Test Requirements for Launch, Upper-Stage, and Space Vehicles," Space and Missile Systems Center, Air Force Space Command, 13 June 2008.

2.2 NON-GOVERNMENT APPLICABLE DOCUMENTS

- ANSI/IEEE C63.14, Standard Dictionary for Technologies of Electromagnetic Compatibility (EMC), Electromagnetic Pulse (EMP), and Electrostatic Discharge (ESD).
- CPIA Publication 655, "Guidelines for Combustion Stability Specifications and Verification Procedures for Liquid Propellant Rocket Engines," Jan 1997.
- IEC 61000-4-2, "Testing and Measurement Techniques - Electrostatic Discharge Immunity Test," International Electrotechnical Commission.

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- Aerospace Report TOR-2003(8583)-2894, "Space Systems-Structures Design and Test Requirements," 2 Aug 2004.
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- Manual Of Regulations & Procedures For Federal Radio Frequency Management, National Telecommunication And Information Agency (NTIA).
- MIL-HDBK-340, Volume I, “Test Requirements for Launch, Upper-Stage, and Space Vehicles: Baselines.”
- MIL-HDBK-340, Volume II, “Test Requirements for Launch, Upper-Stage, and Space Vehicles: Applications Guidelines.”
- MIL-Q-9858, “Quality Program Requirements” [Note: the most recent revision A was cancelled 1 Oct 1996].
- MIL-R-5149, “General Specification for Liquid Propellant Rocket Engine” [Note: the most recent revision B was cancelled 20 Apr 1993].
- MIL-STD-810 (DOD), “Test Method Standard for Environmental Engineering Considerations and Laboratory Tests.”
- MIL-STD-822 (DOD), “Standard Practice for System Safety.”
- MIL-STD-1540 (USAF), “Test Requirements for Launch, Upper-Stage, and Space Vehicles” [Note: references within this document prefer a proposed MIL-STD-1540E as described by SMC-S-016, “Test Requirements for Launch, Upper-Stage, and Space Vehicles,” 31 Jan 2004].
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- RTCA/DO-160 (ISO 7137) (EUROCAE ED-14), “Environmental Conditions and Test Procedures for Airborne Equipment,” Radio Technical Commission for Aeronautics (RTCA), Washington, DC.
- SAE ARP4900, “Liquid Rocket Engine Reliability Certification,” 1995.
- Space Vehicle Design Requirements, The Aerospace Corp., 13 Jan 2005.

2.4 ORDER OF PRECEDENCE

In the event of conflict between the text of this document and the references cited herein, the text of this document takes precedence. However, nothing in this document supersedes applicable laws and regulations unless a specific exemption has been obtained.

3 GENERAL TEST GUIDELINES

3.1 GENERAL TEST PHILOSOPHY

The primary objective of any test program should be to maximize the probability that the tested design will function properly and successfully when used in actual service for the intended application. Flight risks should be mitigated via prudent and effective testing. Certain key tenets of testing have served the liquid propulsion test community well as it has tried to accomplish that objective.

One particular "tried and true" philosophy is the "test-like-you-fly" approach. "Test-like-you-fly" means that testing should demonstrate engine operation with flight representative hardware and under flight representative conditions, including expected worst-case conditions. The overall test program should encompass and explore as much of the operational flight envelope as possible to accomplish the general objective of avoiding operating any flight hardware configuration under any conditions for the first time in flight. Specific tested conditions for expected operating ranges should include, but are not limited to, general performance requirements (such as thrust and mixture ratio), interface conditions (such as propellant inlet conditions, electrical, pneumatic and hydraulic connections), and environmental exposure (such as thermal, acoustic, and vibration conditions). Some flight environments (acceleration for one) cannot be replicated during ground test. 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 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 might be appropriate. Furthermore, testing should consider and account for engine hardware experience throughout all phases of the required life cycle, including manufacturing, acceptance testing, transportation, handling, storage, vehicle integration, checkout testing, launch preparations, liftoff, and flight.

A corollary to the above is the "fly-as-you-test" approach. "Fly-as-you-test" means that flight operation should remain within demonstrated ground-tested and qualified regimes, and that design and process differences between qualified test hardware and flight hardware should be minimized. A successful development and qualification program will anticipate all potential flight conditions and ensure those conditions are validated by a robust test program.

Hot-fire testing to verify that a LRE design is ready for flight typically consists of four phases of major program activity: prototype testing, development testing, qualification, and integrated system testing. The first three test phases can 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 a LRE design has completed the qualification program, each individual flight engine is typically 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. Finally, additional testing can be performed or additional data obtained for the system during the operational phase of a test flight or actual mission launch. Each of these test phases is described below to provide a common set of definitions for the discussion.

3.2 TAILORING OF GUIDELINES

The test guidelines provided herein establish a baseline of test recommendations for consideration as part of an overall verification program. Specific recommendations are based on experience and industry/government best practices, and assume a new engine system with no design heritage.

The Panel anticipates that each program will tailor these general guidelines based upon specific requirements and programmatic constraints. Not every program will utilize all test objectives described herein, nor are the listed objectives all encompassing. The intent of these guidelines is to provide recommendations and possible alternatives.

It is the recommendation of this Panel that rationale for any tailoring be established and documented, especially in cases where a lower equivalent level of verification is being accepted, so a Program Manager, Chief Engineer, and Chief Safety Officer can jointly make knowledgeable decisions regarding any additional risk resulting from deviation from the established best practices.

3.3 ENGINE SAMPLES

Few aspects of a development and qual program have as great an impact on its scope, cost, and schedule as the number of engine samples and number of tests to be incorporated into that test program. Historically, testing and test hardware account for about 75% of the total full-scale development costs [George (1995)]. Thus, program costs scale quite directly with the number of engine and test samples. On the other hand, as will be discussed below, programs typically do not have sufficient engine and test samples to statistically demonstrate the high reliability and high confidence demanded for launch vehicle propulsion systems. Thus, determining the appropriate scope of a test program can be difficult. The following sections describe various aspects and approaches to consider when making these decisions.

3.3.1 Number of Engine Samples

To remain consistent with the NASA-STD-5012, six (6) unique engine samples holding similarity with the flight design are required for verification. Each engine may have different test objectives associated with it, thus introducing some leeway with regards to hardware configuration. The intent is to apply a sample size large enough to begin to establish build-to-build variation with some level of confidence. The total engine count to meet this recommended sample size can include the later development and qualification samples as verification tends to demand a configuration closely related to flight. Alternate paths do exist and have been exercised in the past.

Alternate approaches utilizing fewer samples are implemented to demonstrate the robustness of the system and build the confidence necessary for spaceflight. The intent is to replicate all the major functions of the integrated propulsion system to capture the complex system interactions

3.3.1.1 Number of Engine Samples (Pressure-Fed)

A select set of pressure-fed engine applications fall under the auspices of this guideline. It is recommended for a new engine design, a minimum of three engine samples be included as part of the engine verification activity. These are to include: one development article with a corresponding successfully completed development test activity (addressing all intended usages, propellant condition/interface conditions, representative operating duty cycles, and thermal and combustion stability); and two engine qualification samples (encompassing and formally verifying the aspects of the development thruster program). Size-scaling of existing engine designs should be considered as equivalent to a new engine design. Development or qualification engine activities which result in major failures or anomalies requiring modification of the engine design should not be considered as part of the three engine samples.

For a modification of an existing pressure-fed engine design or a mission application which extends an existing pressure-fed engine design in terms of life or interface conditions, but for which existing analysis shows the design to be capable of meeting all requirements, it is recommended that a minimum of two engine samples, with a minimum of one qualification specification, be included as part of the engine verification activity. Development or qualification engine activities which result in major failures or anomalies requiring modification of the engine design should not be considered as part of the three engine samples.

This approach is different than that of NASA-STD-5012, which was formulated to address pump-fed engine design. The above pressure-fed engine guidelines reflect a historical precedence approach, just as NASA-STD-5012 reflects a historical precedence approach for pump-fed engines. The pressure engine design has a reduced number of design elements which could contribute to variations in life and performance, although mission specific application effects (propellant interface conditions, operating duty cycles) may be much more significant for the engine design and subsequent verification.

3.3.2 Engine Qualification Samples

It is recommended that there be at least two (2) qualification engine samples. Detailed discussion for specific objectives in later sections will note when more or less unique samples are recommended.

3.3.3 Integrated Propulsion System Samples

It is recommended that at least one integrated propulsion system sample be tested. The intent is to replicate all the major functions of the integrated propulsion system to capture integrated propulsion system interactions. This can sometimes be done using a battleship, although flight similarity is encouraged.

Background/Rationale: The complexity of a rocket engine design results in hardware dimensional variances from engine-to-engine. Despite the careful attention paid 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 forcing functions, bearing loading, pump chilldown characteristics, ignition effectiveness, and self-induced vibration. Adverse responses to variations can result in a design with fewer margins than desired. Therefore, part of the function 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 within the given application. Multiple engine samples demonstrating a test objective are required to provide adequate confidence that the engine operation and its variations are well understood. It is acceptable to use some rebuilt engines to reduce costs, but at the disadvantage of reducing the extent of normal variation that will be observed. A significant number of development engines should be included into the program to refine and reduce risk for the final flight design. The optimum number will depend on design complexity, heritage, and risk tolerance. However, for the final verification and qualification of a new engine, experience indicates that four (4) unique engine samples with the flight design are typically the minimum required for most objectives. Qual programs should include at least two of these unique flight design engines samples, with the remainder being incorporated into the development test program. Some verification test objectives can be satisfied by the development effort (e.g., combustion stability bomb tests). Based upon engineering assessment some of the development test effort can also provide additional test samples to support verification and add confidence. Detailed discussion for specific objectives in later sections will note when more or less unique samples are recommended. If an engine includes reused parts, determination of whether that engine sample is "unique" depends on 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, but for a pump chilldown test sample the uniqueness of the turbopump unit would be of interest. One or more engine samples (new or reused from the engine level testing) should undergo additional tests at the integrated systems level.

Fewer than four unique engine samples may be appropriate for a modified engine design with significant design heritage and extensive existing test experience (e.g., an "evolved" engine or a slightly modified new version of an existing engine). However, such reductions must be considered carefully and well justified to ensure that prior design heritage and test experience is directly applicable to the new aspects of the current engine design.

3.4 NUMBER OF TOTAL TESTS

The test program should include enough tests to verify all the specific engine system performance requirements and functional objectives. Planning a sufficient number of tests to verify all the requirements is difficult to determine. There is simply no "cookbook." Experience, analytical capabilities, and deviation from known, highly matured technologies/practices all play a role. The number of tests to satisfy a particular requirement will be visited during the design and verification planning phase, and then revisited during and after the test phase when the verification compliance paperwork is being filled out, telling the story of how the requirement was satisfied and how the actual test program satisfied versus the planned.

Further, there will be programmatic influences that significantly shape the test campaign. Depending upon these influences, there can be a number of paths available to obtain the necessary data to qualify the design. Largely, the development path will have to do with interdependencies of components, sub-systems, and system (a.k.a. system interactions).

Looking back at previous large engine programs, a "learning curve" of sorts has been established (Figure 3.4-1). Even with recent programs like RS-68, the trend was essentially in family. However, with one significant difference, the total numbers of tests for the development program was significantly less than the predecessors whose programs were used to generate the curve. Evidently, some of the key factors which play a role in understanding the physical system and its interactions had evolved. Some of the benefits this program had over the predecessors can be attributed to the increased analytical capability, experience base, and mission (cost-driven, non-manned spaceflight). The complexity of Space Shuttle Main Engine (SSME) and the long lasting ground test programs have allowed modeling of physical systems to evolve significantly as did computing power. The cost-driven aspects kept technology development to an absolute minimum, which would be another significant driver for additional development tests. Technology development areas will definitely add significant amounts of testing at lower levels through system level (depending on technology area) to ensure it is understood sufficiently before flight.

Utilizing this information for test planning, it is recommended that the qualification portion of the test program not be initiated until the latter portion of the total test program. There tends t o be efforts to reduce test program durations by running engines in parallel on multiple facilities. This is viable, but maintaining that a development test program should be through at least 80% of its tests or greater is a good rule. The intent is to minimize any potential for issue, and this would logically be at the latter portion of the program where there has been sufficient time to explore each of the functional requirements and incorporate necessary design changes or operational refinements.

Continuing the focus on test planning, there are two potential approaches which can be used to establish a total numbers of tests: the "statistically relevant based" approach or the "functional objectives based" approach. A successful test program might include a combination of both of these approaches. There are other approaches and, as always, the Program Manager, Chief Engineer, and Chief Safety Officer must carefully weigh programmatic requirements and constraints versus acceptable risk levels when selecting the desired test approach.

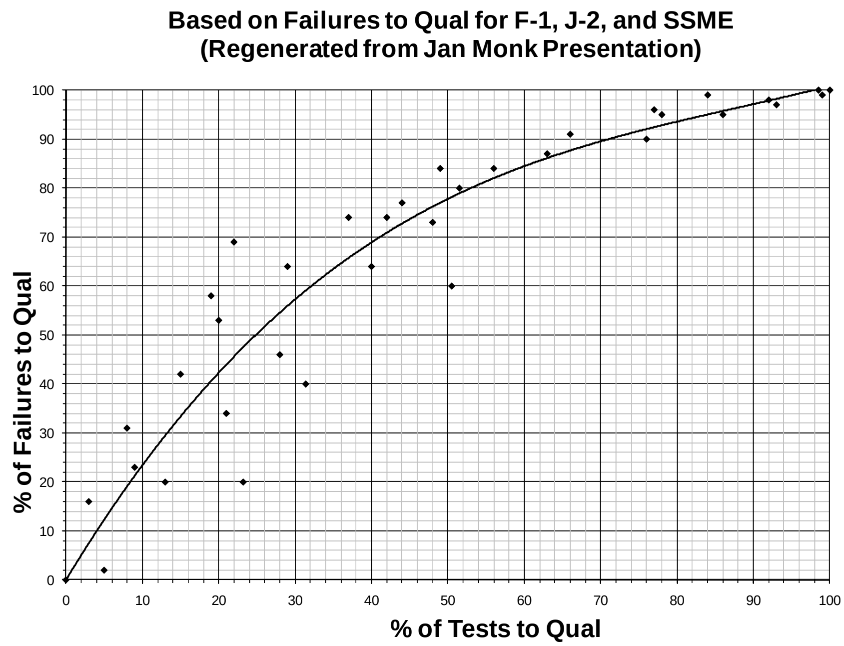

Figure 3.4-1: "Learning Curve" for F-1, J-2, and SSME Programs

3.4.1 Statistically Relevant-Based

This approach relies on standard statistical analysis methods to determine the number of tests that must be performed successfully to statistically demonstrate the specified engine reliability, for a defined confidence level and with an assumed failure distribution. For example, some past programs have used the Weibull statistical methodology as described in AFWAL-TR-83-2079. Based on this methodology, demonstrating 99% engine reliability at 90% confidence versus random failure modes (Weibull statistical distribution with Beta = 1) requires, for example, testing of about 20 times the required engine operational life on each of ten engine samples with zero failures (Figure 3.4-2). Based on the same methodology, demonstrating 99% engine reliability at 90% confidence versus wearout failure modes (Weibull statistical distribution with Beta = 3 to 6) requires, for example, testing of about 2 to 4 times the required engine operational life on each of four engine samples with zero failures (Figure 3.4-3). The plots show that demonstrated reliability increases fastest for random failure modes by testing additional units, and for wearout failure modes by testing additional duration, as would be expected. Unfortunately, the testing required to statistically demonstrate the high reliability and high confidence demanded for launch vehicle propulsion systems against random failure modes is typically cost prohibitive and impractical. On the other hand, demonstrating high reliability and high confidence against common wearout failure modes is much more reasonable and achievable.

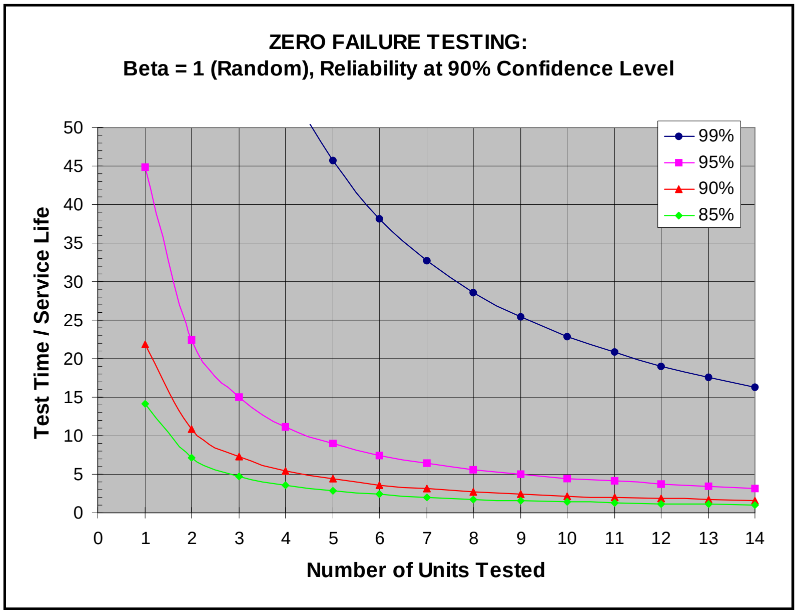

Figure 3.4-2: Demonstrated reliability test requirements versus random failure modes based on Weibull statistical analysis methodology.

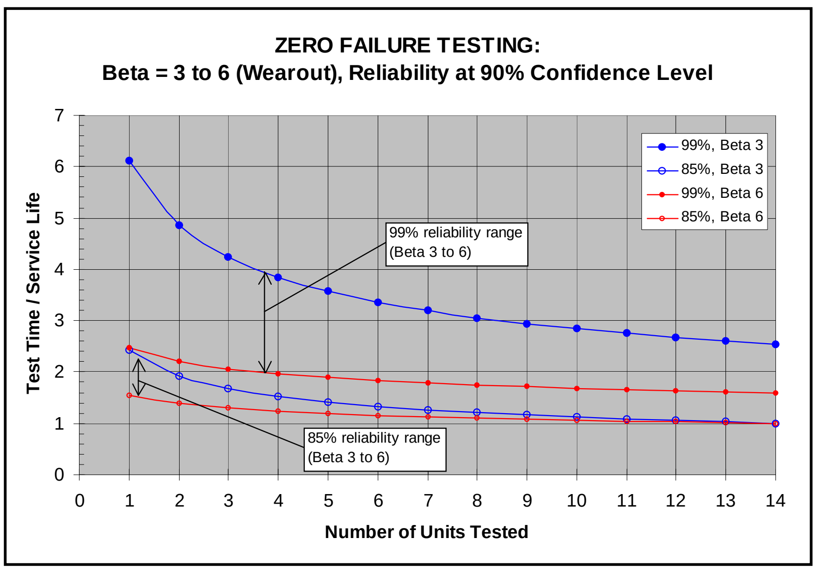

Figure 3.4-3: Demonstrated reliability test requirements versus wearout failure modes based on Weibull statistical analysis methodology.

3.4.2 Functional Objectives-Based

This approach is preferred. The goal of the functional objectives based approach is to verify all the specific engine system performance requirements and functional objectives of Table 4.1-1: Development and Qualification Test Matrix as efficiently as possible in the minimum number of tests. However, it is recommended that enough tests be performed 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. Since this approach generally will not include sufficient test samples to statistically demonstrate reliability requirements against random failure modes and perhaps not against 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 by identifying any design flaws and failure modes that might exist. If sufficient margin is demonstrated, the functional objectives approach provides protection against unknowns not addressed by the demonstrated reliability based approach.

Margin is relative to the maximum expected operating conditions. It may include an increase in level or range, an increase in duration or cycles of exposure, or any other appropriate increase in severity. Other technical disciplines have incorporated robust margin test requirements for their systems to reduce historical failure rates. For example, standard practice for structural static load test qualification requires a design ultimate load test of 1.4 times the limit load (LL) for human-rated flight, and 1.25 times the LL for non-human rated flight (MIL-STD-1540, MIL-HDBK-340A). A global margin requirement is impractical to apply for a LRE, since 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, without over testing other parts. Recommended margin requirements for specific objectives and design aspects of LREs are discussed within the respective sections that follow.

3.4.2.1 Functional Objectives-Based (Pressure-Fed)

In addition to the approach identified for section 3.4.2 (Functional Objectives-Based), it is recommended that pressure-fed engines under the auspices of this guideline also address the application specific combinations of propellant interface conditions, propellant quality and conditions, and operational duty cycles of the mission. Particular consideration should also be given to thermal soak-back conditions possible for the engine for any restartable application or mission duty cycle, as well as any potential environmentally-induced thermal conditions imposed on the engine. It is recommended that verified engine life meet or exceed a minimum life margin of 100% of the mission application (twice the required mission application), in all appropriate potentially life-limiting characteristics such as propellant through-put, thermal cycles, pressure cycles, etc.

3.4.3 Testing to Failure

Historically, testing to failure was originally employed since analytical tools were immature and experience was limited. After multiple test-fail-fix cycles, the hardware demonstrated the necessary margin and reliability for spaceflight. It can be a very effective technique as it produces quantifiable results, especially for smaller or newer organizations entering the rocket business. However, it can become costly as the samples necessary to perform these demonstrations is significant, driving program cost and schedule.

3.4.4 Modeling and Simulation

Although details of this effort are excluded from this document, it is recognized that modeling and simulation complement testing. Therefore, acquisition of data to validate and calibrate analytical models for the ‘by analysis’ element of development and qualification verification of requirements of compliance 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 past experience and applying it to new or evolved propulsions system designs. Analysis efforts that are inherently lower risk can be initiated earlier in the 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 substitution for test.

There are test objectives tied to validating and anchoring models, which can then be extrapolated or interpolated with confidence to verify functionality and performance. The goal is to reduce the numbers of tests necessary to provide the confidence necessary for flight.

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 start of more powerful computing capabilities, advanced simulation tools, and improved manufacturing processes, recent engine development and qualification programs have successfully utilized more extensive and accurate upfront robust design, sensitivity studies, and optimization to reduce the traditional and costly “test-fail-fix” design cycle 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 since any design result is subject to the validity of assumptions and proper consideration of all potential failure modes. Improved analyses coupled with customary design 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 DEVELOPMENT AND QUALIFICATION TESTS

The objective of the overall development and qualification test program is to yield a flight design, manufacturing processes, and acceptance program that produces flight hardware/software that meet specification and performance requirements with adequate margin to accommodate normal engine hardware variations. Development testing is required to achieve design maturity, demonstrate capability, and to reduce risk to the qualification program. Qualification testing is required to formally verify compliance of the flight design with requirements. The guidelines below apply to both development and qualification testing, except as noted. It is suitable to satisfy multiple objectives on any given single test if it can be accomplished safely and effectively.

4.1 TEST TYPES AND RECOMMENDATIONS

Even though requirements levied upon a propulsion system can vary from system to system, the body of types of tests is relatively well known. These establish the basic functionality and overall robustness of an engine or integrated propulsion system. The tables in this section provide the different test types and recommendations; the following section provides context for the recommendation.

4.1.1 Component Tests

Specific component test guidelines will be addressed in future editions. The focus of this current edition is engine level testing, so no detailed discussion of component level testing will be provided. Readers should refer to SMC-S-016, MIL-HDBK-340, MIL-A-83577B, and AIAA S-114-2005 for component level test guidelines.

Many major engine components are subjected to component level development and qualification testing to reduce risk for subsequent engine level testing and to verify flight readiness. SMC-S-016 and MIL-HDBK-340 describe test guidelines for components such as valves and engine control units (ECUs). AIAA S-114-2005, NASA-STD-5017, and MIL-A-83577B specify general requirements for the testing of moving mechanical assemblies (MMAs). Test standards for more complex components, such as turbopump assemblies (TPAs) and combustion devices, are not generally available. These more complex components mainly undergo development testing to reduce risk for engine level testing. The significant level of engine system interaction with these types of components makes it impractical to qualify these parts on an individual basis, since the component-level test conditions are not representative of engine conditions. Often a robust sub-scale test program is used to significantly reduce full-scale component risk. Furthermore, since the actual engine operating environments for various components may not be well characterized prior to the engine level testing, it is prudent to include significant margin in the component level design and testing.

The specific test plan and objectives for different types of components will vary. For example, testing of the TPA and its components might emphasize piece part development, performance mapping, efficiency characterization, and TPA health checkout, with a gradual buildup of the system from turbopump to powerpack. In contrast, testing of combustion devices such as the thrust chamber assembly (TCA), gas generator (GG), or preburner (PB) might emphasize c-star performance evaluation and verification. The intent would be to characterize these components, then push to systems test to truly verify the requirements. The component stand will not provide FULL verification – the requirements will be verified at the system level. Therefore, even after their respective component test programs, componentry will be assembled into an engine to validate component qualification levels (where possible), and expose the component to the interactive, or combined, system environments.

Some components, such as line replaceable units (LRUs), may undergo sufficient component acceptance testing to preclude the need for engine hot-fire testing. If this is the desired approach, it has to be verified at the system level that the engine is insensitive to the manufacturing variability, or the variability is predictable enough to not require engine level hot-fire characterization prior to flight.

Following component testing, it often is valuable to include some additional sub-system testing. This provides further risk reduction prior to full-up engine level tests. One common example is testing of the powerhead (or powerpack) sub-system, which includes the turbopump, GG or pre-burner, injector, and chamber. Depending upon cycle, the system may not allow you to test the main injector or chamber. Typical powerhead test objectives include verifying pump performance and efficiencies, verifying turbine efficiencies, developing purge and bleed requirements, and characterizing injector and chamber performance. This test would be performed with propellant flow and would utilize flight representative spin start system, if applicable, and could include various throttle conditions as required. Another common example is testing of the engine control system, which might include valves, ECU, sensors, and flow orifices. Typical engine control system objectives include validating control system logic, verifying response times, exercising fault detection and accommodation, and characterizing control system accuracy. This test could be performed with simulated fluid flow and resistances, or as a combination of hardware and system response performance simulation.

4.1.2 Engine

The single engine test program (together with appropriate analysis) accomplishes most of the demonstration and qualification necessary to verify requirements compliance. It is necessary because of the significant component-to-component interactions, unknown environments, and non-linearities that cannot be adequately predicted nor replicated at lower levels. The engine unit includes an assembly of all of the 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 since 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. In several instances, the component development and qualification testing addresses individual environmental stresses and the impact to the functional capability, whereas the engine level introduces systems interactions and combined environments (engine self induced). Most of the test recommendations will be pertinent to this level of testing.

Table 4.1-1 types of tests which are expected to be included in a DDT&E engine test program for a single engine. These are to be utilized in conjunction test recommendations, and should not be treated as mutually exclusive.

Table 4.1-1: Development and Qualification Test Matrix

			Component		Engine	
Section		Objective	Dev	Qual	Dev	Qual
4.2 Performance	4.2.1	Steady State Performance Characterization			x	x
	4.2.2	Repeatability			x	x
	4.2.3	Run-time Trends			x	x
	4.2.4	Engine Influence Coefficients			x	x
	4.2.5	Mixture Ratio Excursions			x	x
	4.2.6	Thrust/Mixture Ratio Margin Demonstration			x	x
	4.2.7	Ignition System	x	x	x	x
	4.2.8	Turbomachinery	x		x	x
	4.2.9	Combustion Devices	x		x	x
4.3 Life	4.3.1	Operational Life/Durability	x	x	x	x
	4.3.2	Single Burn Endurance Test			x	x
	4.3.3	Service Life (SL), Number of Starts			x	x
	4.3.4	Acceptance Test Validation			x	x
4.4 Functional Characteristics	4.4.1	Cold Shock Tests			x	
	4.4.2	Cold Flow Tests	x	x	x	
	4.4.3	Propellant Conditions				
		– Pre-start Chilldown			x	x
		– Start Propellant Conditions			x	x
		– Steady State			x	x
		– Shutdown Propellant Conditions			x	x
	4.4.4	Transient Characterization				
		– Start Transient			x	x

Section		Objective	Component Dev	Component Qual	Engine Dev	Engine Qual
		– Restart			x	x
		– Throttle Transient			x	x
		– Shutdown Transient			x	x
		– Abort Shutdown			x	x
	4.4.5	NPSP Margin and Cavitation	x		x	x
	4.4.6	Pogo and Compliance Characterization	x		x	x
	4.4.7	Ancillary Subsystems				
		– Autogenous Pressurization			x	x
		– Valve Actuation	x	x	x	x
		– Purges	x	x	x	x
		– Electrical Power and Ignition	x	x	x	x
	4.4.8	Thrust Vector and Gimballing				
		– Gimbal Limits	x	x	x	x
		– Roll Control Limits			x	x
		– Ambient Environment			x	x
		– Inspections	x	x	x	x
		– Heat Flux			x	x
		– Clearance			x	x
		– Interface Compatibility			x	x
		– Thrust Vector Alignment			x	x
4.5 Controls	4.5.1	Functional Tests	x	x	x	x
	4.5.2	Eng Control System Malfunction Logic Check	x	x	x	x
	4.5.3	Engine Health Management	x	x	x	x
4.6 Operations	4.6.1	Pre-Test Inspections and Checkouts	x	x	x	x
	4.6.2	Leakage	x	x	x	x
	4.6.3	Post-Test Inspections	x	x	x	x
	4.6.4	Drying Purges			x	x
	4.6.5	Line Replaceable Unit (LRU) Demonstrations			x	x
	4.6.6	Reusability	x	x	x	x
	4.6.7	Operability			x	x
	4.6.8	Preflight Procedures and Flight Sequences			x	x
4.7 Environments	4.7.1	Thermal Environment	x	x	x	x
	4.7.2	Climactic Tests	x	x	x	
	4.7.3	Vibration/Shock/Acoustics				
		– External Vibration	x	x	x	
		– Self-induced Vibration	x	x	x	
	4.7.4	Modal Surveys/Testing			x	x
	4.7.5	Vehicle Interface Loads			x	x
	4.7.6	Electromagnetic Interference/Compatibility Tests	x	x	x	
4.8 Design & Construction	4.8.1	Proof Pressure	x	x		
	4.8.2	FOD/DOD Tolerance	x		x	
	4.8.3	Structural Model Validation			x	x
	4.8.4	Margin Testing			x	x
	4.8.5	Human Rating	x	x	x	x
	4.8.6	Hardware Discrepancy Tracking	x	x	x	x
4.9 Physical	4.9.1	Gas Liquefaction Control	x		x	x
	4.9.2	External Icing Control	x		x	
	4.9.3	Mass Properties				
		– Mass	x	x	x	x
		– Center of Gravity	x	x	x	x
		– Moments of Inertia	x	x	x	x
4.10 Unique Requirements						

4.2 PERFORMANCE

4.2.1 Steady State Performance Characterization

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 anchor analysis models over a range of input variations to minimize any interpolation of flight data from the family of ground test data. Accurate measurement and characterization is necessary as vehicle requires characterization of engine performance over time to properly calculate propellant load and reserves, calculate vehicle guidance, navigation and control parameters, etc.

4.2.1.1 Component

RESERVED

4.2.1.2 Engine

Steady state performance should be thoroughly characterized by varying various parameters to anchor analytical models to minimize uncertainties and minimize flight risks. The engine physics-based steady state model should be anchored to test data such that 3-sigma conditions can be evaluated and show that build-to-build and run-to-run variations still falls within requirement limits. Establishing and validating engine gains are inherently a part of this model anchoring activity. To accomplish this, multiple engine tests on each of a family of engines are expected. Measuring performance tends to occur during “steady state” time slices during a test where no commanded changes occur. Measurements should be taken at all power levels with emphasis at power levels where the engine spends a significant portion of the mission.

4.2.2 Repeatability

Run-to-run and engine-to-engine variations in thrust, mixture ratio (MR), Isp, and other key engine operating parameters.

4.2.2.1 Component

RESERVED

4.2.2.2 Engine

Run-to-run and engine-to-engine variation characterization should be performed during a repeatability test campaign. Tests program should be sufficient to have the steady state analytical model anchored to enough data so that the predictions fall at or below 0.1% of measured values (once calibrated). Three tests repeating the same profile should be run each of 3 engines minimum. For engines with multiple power levels required, this must be taken into account as part of the profile (thrust, mixture ratio, etc.).

4.2.3 Run-Time Trends

These are uncommanded and/or unintentional time varying operating conditions in pressures, temperatures, or component efficiencies.

4.2.3.1 Component

RESERVED

4.2.3.2 Engine

Conduct characterization of time dependent parameters. If significant unexpected trends or trends exceed specification limits, corrective action or specification changes are required.

4.2.4 Steady State Analytical Models

Steady state analytical models predict engine internal operational conditions (pressures, temperatures, flowrates) based upon specified input conditions and expected hardware characteristics. Because the model is physically-based, exercising the model varying the input parameters results in influence coefficients that represent changes in various engine performance parameters given the change in input.

4.2.4.1 Component

RESERVED

4.2.4.2 Engine

Determine (development testing) and verify influence coefficients based on inlet conditions, valve positions if applicable, and other interface conditions for steady state engine performance (e.g., thrust, Isp, MR) and key operating conditions (e.g., pump speed, chamber pressures and temperatures, pump discharge pressures). Exact parameters will vary depending upon the engine design. Characterize influence coefficient for other allowable propellants (like ancillary systems), if applicable.

4.2.5 MR Excursion Tests

The intent is to vary mixture ratio to disperse the family of data which will help characterize engine behaviors and hardware durability. Depending on engine configuration, MR variation may be a desired functionality for a number of reasons. However, start and run box variations that may exist on a stage can also introduce variations which the engine has to contend with. Some systems may have control features to minimize variation in combustion zones and/or turbomachinery (closed-loop control), but others may elect to tolerate these potential external variations (open-loop control).

4.2.5.1 Component

RESERVED

4.2.5.2 Engine

The mixture ratio excursion test campaign should characterize the engine hardware sensitivity to mixture ratio variations. Verify MR control and dispersion requirements are met. Test duration at each MR condition should be equal to at least one times the maximum expected operational life exposure. Develop MR and inlet condition relationships. Test minimum and maximum MR at nominal, off-nominal and worst-case propellant inlets, including margin. Include demonstrations at throttle points and repeatability tests.

4.2.6 Thrust/MR Margin Demonstration

The intent is to envelop extreme operating conditions and verify engine robustness via margin testing on thrust and MR conditions beyond expected worst-case ground-test and flight conditions. Worst-case conditions should account for all possible dispersions and biases, including run-to-run variations, acceptance test measurement uncertainty, ground-to-flight dispersions, operating biases (e.g., off-standard inlet conditions), run-time trends, and post-test engine hardware replacements. Minimum MR and thrust margin should be 2% beyond the worst-case MR and Thrust envelope. The test duration at various margin conditions should be at least one times the maximum expected SL exposure time at the respective worst-case condition. Testing of greater margin during development testing is recommended to increase the likelihood of successful qualification testing unless development data indicates otherwise. To the extent possible, testing should also encompass the worst-case expected flight operating range of critical engine parameters (e.g., speeds, pressures, temperatures).

4.2.6.1 Component

RESERVED

4.2.6.2 Engine

The Panel recommends that engine thrust and mixture specification margins be demonstrated at the engine system test level. Testing outside of the specification limits is desired to help understand the engine's off-design perormance, significant testing outside the specification limits is unrealistic due to the cost associated with damaging engine hardware and the test facility.

4.2.7 Ignition System

Verify reliable ignition of all combustion devices under nominal, off-nominal, and worst-case conditions for propellant conditions (including mixture ratio, temperature, and pressure), chilldown conditions, input voltage (if electronic excitation is utilized), and hardware temperatures. Ignition testing should take place at sea level for ground start engines and at vacuum for altitude start engines. Tests for worst-case conditions should include ignition system variables with margin on top of the engine operational limits. Electronic ignition must address spark production variables and delays. Hypergolic ignition systems must address quantities and timing of fluid introduction. Pyrotechnic ignitions must address the pyrotechnic device's loading and timing.

4.2.7.1 Component

Significant component or subsystem type testing should be conducted on ignition systems to minimize risk to engine level testing. The testing should be conducted within a environment that simulates the engine operation.

4.2.7.2 Engine

Characterizing start transient timing and sensitivities will capture the ignition system performance as a part of the engine test program. The engine hot-fire program should vary parameters for propellants, conditions, etc., sufficiently to capture ignition performance relative to start transient variation. Altitude-start engines should conduct altitude simulation to characterize ignition system performance in the simulated environment, even though the individual ignition system should have been tested in these conditions at the component level.

Background/Rationale: 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 conditions for 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 when a minimum amount of oxidizer (low mixture ratio) is present at the igniter (typically minimum oxidizer net positive suction pressure (NPSP) for cryogenic propellants). Very low pressure and cold propellants generally require more available energy to ignite, so vacuum testing under conditioned environments are recommended for upper stage engines. Extreme hardware environments may exist, particularly for upper stage engines with multiple restarts required. Cold propellants at high pressure may also be difficult to ignite since more exciter power is required to produce a spark (i.e., Paschens Law). Other factors that may affect the amount, density, quality, or mixture ratio of propellants in the vicinity of the ignition location (e.g., purges, known potential leaks) must be considered and tested appropriately. For hypergolic ignition systems, the quantity of the hypergol delivered, its associated timing (e.g., characteristic fill times, valve actuation times), and potential impacts on propellant delivery in the vicinity of the ignition location (e.g., purges, known potential leaks) must be considered and tested appropriately. Tests for worst-case conditions should include margin and a minimum of four unique engine hardware samples.

4.2.8 Turbomachinery Performance

Analytical models for steady state performance utilize turbomachinery maps to predict engine performance. These maps are predicted analytically and need validation with testing. Ideally, the testing would span the ranges of expected 3-sigma 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. Tendency is for the engine to be concerned with turbine and pump efficiencies and net positive suction head (NPSH) performance. Efficiencies will drive the need for turbine drive power, which can translate into system performance losses (inefficiencies). Turbine flow area can be a parameter which carries uncertainty that can affect engine performance and prediction capability. Vehicle systems like to drive tank weight down by minimizing tank operating pressures, but a lower limit must be established as turbomachinery will require a minimum NPSH to avoid pump cavitation, which can damage and fail hardware. The secondary flows (bearing coolant, fluid film bearing flow) also need validation as can affect performance, functionality, and margins in the system.

4.2.8.1 Component

Depending upon engine configuration, which drives complexity for the test facility, a full-scale turbomachinery test may be conducted to obtain much of the mapping information. This facility will have some method to drive the turbine and control speed that may not match the turbine drive on the engine. The pump may or may not pump same propellant as engine. However, it is preferred to match drive gas and pumping fluid to engine as much a possible.

The full-scale testing would be on top of the typical characterization of turbine and pump performance at a subscale in an airflow test and water flow test, respectively. These types of lower level tests occur to validate turbine flowpath and pump inducer performance.

4.2.8.2 Engine

Verify acceptable pump and turbine performance for all operating conditions. Any evidence of significant pump cavitation must be assessed and appropriately tested to verify robustness against the conditions. Map pump and turbine efficiencies for use in validation of analytical models. Loss of efficiency may be related to bearing and/or seal wear, and seal leakage.

4.2.9 Combustion Device Performance

Verify combustion device performance under nominal, off-nominal, and worst-case conditions for propellant conditions (including mixture ratio, temperature, and pressure), chilldown conditions, input voltage (if electronic excitation is utilized), and hardware temperatures.

4.2.9.1 Component

At the component level, subscale testing is typical to characterize combustion efficiency and injector delta pressure. If possible, there tends to be workhorse calorimeter spool pieces to simulate a combustion chamber to also estimate heat loads/fluxes for MCC designs. All of this is to reduce risk to the engine test program.

Combustion Stability: Either here, on a full-scale component test or engine test, verify combustion stability in combustion devices per the requirements of CPIA Publication 655.

Nozzle Sideloads: Subscale nozzle sideload testing should be consider for high area ratio designs, particularly if those nozzles will be tested in an over-expanded condition during ground testing. Further validation should occur on full-scale component and/or engine test.

Turbine Drive: These systems tend to manifest itself in a PB or GG. The purpose is the same, but engine cycles and operating conditions tend to separate them. In addition to the conditions mentioned above, the turbines tend to be sensitive to temperature distribution at the inlet, which can drive design features into both PB and GG. These are added requirements to be validated and tested at a component level prior to engine test.

4.2.9.2 Engine

Most of the performance characterization will occur on the engine as it couples the self-induced environments to combustion devices. Transient priming and purging characteristics should be explored thoroughly (include nozzle sideloads). Gas-ingestion testing falls in this category as it has historically affected combustion stability and performance (both steady state and transient), particularly in pressure-fed systems. Depending upon component test program, bomb testing may have to occur on the engine program. Coolant flow heat loads/fluxes verified here primarily. All operational power levels including expected maximum variations should be explored and characterized. To name a few characteristics that are analytically-modeled and need validation/anchoring to match steady state performance predictions to test and flight results include combustion efficiency, injector delta pressure, and coolant channel heat load characterization.

Ablative Nozzle: Develop correlations for predictions and corrections to flight thrust and Isp for engines that are not acceptance tested with the flight nozzle. Ablative chamber char and throat area erosion characteristics should be included.

Background/Rationale: If the engine is not ground tested with the flight nozzle, then the measured thrust and Isp must be adjusted for the absence of the nozzle or for the presence of a slave nozzle. Slave nozzles include any attachments to the exit area of the MCC that provide additional performance, such as water spray rings or witness rings (WRs), attached or not attached. Engine thrust and Isp with a slave nozzle will differ from that which would be achieved with the flight nozzle.

4.3 LIFE

4.3.1 Operational Life/Durability

As a part of qualification of an engine for flight, it is recommended to show margin to maximum expected operational life. This is one aspect of demonstrating hardware robustness. The intension is to show this on multiple engines throughout the DDT&E program to build confidence in manufacturing processes and build-to-build variation. Some programs have used a fleet leader program to ensure the part that flies is well within the bounds of the experience base. Life limited parts are expected and can drive engine maintenance intervals and total life.

4.3.1.1 Component

Component testing is expected to qualify several of the components for use on the engine. One of the tests in the component qualification programs tends to be life (ref. MIL-STD-1540).

4.3.1.2 Engine

Testing should demonstrate margin on maximum specified operating life. Multiple engines are required to verify manufacturing process stability and compliance with specified engine-to-engine performance and operability variability limits. The margin should be between 2x and 4x (4x more properly accounts for scatter in high cycle fatigue related failure modes); test conditions should include specific thrust, mixture ratio, inlet box, and other flight conditions. Development of test margins may be larger to provide confidence in qualification success.

Ablative Nozzle Life: Show 20% life margin (i.e., 1.2x) via test and/or analysis for all nozzle locations. Verify acceptable erosion rates and uniformity. Verify acceptable structural interface and liner interface temperature margins at the end of the extended duration, including during the soak-back heating at shutdown. If a WR or slave nozzle is to be used during acceptance testing to characterize the injector environment for flight units, establish correlations of erosion characteristics between the WR and/or slave 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. Verification of nozzle erosion acceptability should include post-test dissection inspections.

Background/Rationale: For ablative nozzles, the primary concern is erosion and char depth margin and not fatigue. Experience with ablatives has shown that a life demonstration factor (LDF) of 1.2x is adequate to cover variations in erosion characteristics.

4.3.2 Single Burn Endurance Test

Intent is to qualify hardware to maximum expected mission single burn duration with margin. Other than being able to repeatably show tolerance to several successive firings as expressed in the operational life/durability tests, this type of test shows that the engine does not have issues meeting maximum burn durations. Issues relating to HCF or self-induced environments can be exposed and life limiting components can result.

4.3.2.1 Component

Component testing can be used as part of component qualification testing.

4.3.2.2 Engine

Test the greater of a 10% burn time duration margin beyond the maximum expected mission duration on a single continuous test or the design specification stated value. Include flight representative profiles in thrust and mixture ratio. For multi-burn applications, tests must demonstrate margin on cumulative mission duration in a series of single burn continuous tests.

4.3.3 Life, Engine 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 to the limits. Rocket engine life is typically quoted in starts and seconds (run time). Engine testing will push the limits on number of starts because the cost of hardware drives to use it as many times as possible before refurbishment.

4.3.3.1 Component

RESERVED

Note: Component qualifications should stress the hardware cycles.

4.3.3.2 Engine

Conduct testing to demonstrate margin relative to the specified service life requirement, including multi-burn applications. Fleet leader tends to be at least 2x the operational life. Qualification demonstrations are out to 4x. Pressure-fed engines are qualified to 2x operational life.

4.3.4 Acceptance Test Procedure Validation

Intent is to establish the ATPs to be used for acceptance test of flight units. Verify the performance data slice provides stable and consistent engine operation at that time in the test sequence. Verify performance meets the requirement for integration into the flight vehicle. Include vacuum testing if needed. Mission profiles should be performed if specified by program requirements.

4.3.4.1 Component

Component level ATPs are derived for a manufacturing screen and to assure product readiness for an engine build.

4.3.4.2 Engine

These tests should validate the processes and procedures that will be used during production level acceptance of engines. Burn times should be sufficient enough to screen for infant mortality issues and flex the engine enough to ensure that it is within qualification family with sufficient life remaining for possible stage ground test and flight with margin.

4.4 FUNCTIONAL CHARACTERISTICS

4.4.1 Cold Shock Tests

Facility propellant systems and test article hardware should be exposed to propellants during intial activation of the test facility and the test article, especially if the propellants are cryogenic. The facility and test article will be examined for leaks and thermal distortion, and inspected for material compatibility issues in test article hardware following the tests.

Background/Rationale: Cold shock is normally performed upon initial integration of the test facility and first test article or two, as risk reduction prior to cold flow tests and hot-fire testing. Most if not all, new cryogenic propellant rocket engines should go through a cold shock test.

4.4.2 Cold Flow Tests

Flow test the facility prior to test article integration for validation of facility capability. This also characterizes pressure drops, resistances, temperatures, and flow rates through the feed system. Turbomachinery places restrictions on this test as spinning the turbomachinery may not be desirable. Often these tests are performed only on the initial activation of a test facility or on the first test unit.

Background/Rationale: Cold flow tests should be performed early in the development test program to characterize flow rates and feed system pressure drops, and to verify model results and predictions as risk reduction prior to hot-fire. This is especially important on the first test unit for which uncertainty in system flow resistances may otherwise pose unreasonable risk to proceed to hot-fire testing. Cold flow tests may also be performed prior to the first test on each subsequent test series to verify system integrity and readiness. Combustion devices may be removed and replaced by equivalent simulated resistance if beneficial to the test implementation. Test results should be compared to predictions to verify resistances, pressure drops, temperatures and flow rates are within expectations and design requirements. Safety precautions, such as flowing only a single propellant at a time and abort system modifications, should be employed to avoid unwanted mixing and combustion of propellants. Also, the use of simulated propellants, such as the use of liquid nitrogen (LN_2) for LOX, may be employed for safety and/or cost reasons. Cold flow with an integrated engine including turbomachinery and regenerative-cooled combustion devices may be difficult to test and results may not match intended performance; in these cases it may be acceptable to cold flow the large components (valves, injectors) rather than the integrated rocket engine.

4.4.3 Engine Propellant Inlet Conditions

Through each phase of operation, it is important to characterize the propellant conditions expected. Pre-start, it is important to thermally condition the engine hardware to minimize thermal shock that could be detrimental to hardware durability. Start transient is sensitive to propellant conditions due to NPSH sensitivity of the turbomachinery, where severe enough cavitation can cause a failure to start and damage hardware. 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 can vary from the dominant part of the burn due to tank heat loads, ullage temperature, and pressure control bands.

Testing must verify that any engine system will have proper and reliable operation for all propellant conditions that might be supplied by the vehicle at the engine inlet. 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 a region within prescribed temperature and total pressure boundaries. Generally there is one set of inlet boxes for engine start conditions and another set for steady state engine operation. If the engine to be used on the vehicle will run at multiple power levels, then there may be different steady state inlet boxes for the various power levels. As an example, Figure 4.4-1 shows propellant inlet boxes for a LOX and liquid hydrogen (LH_2) engine. Vehicle feed systems should be replicated as closely as possible during propellant inlet condition testing.

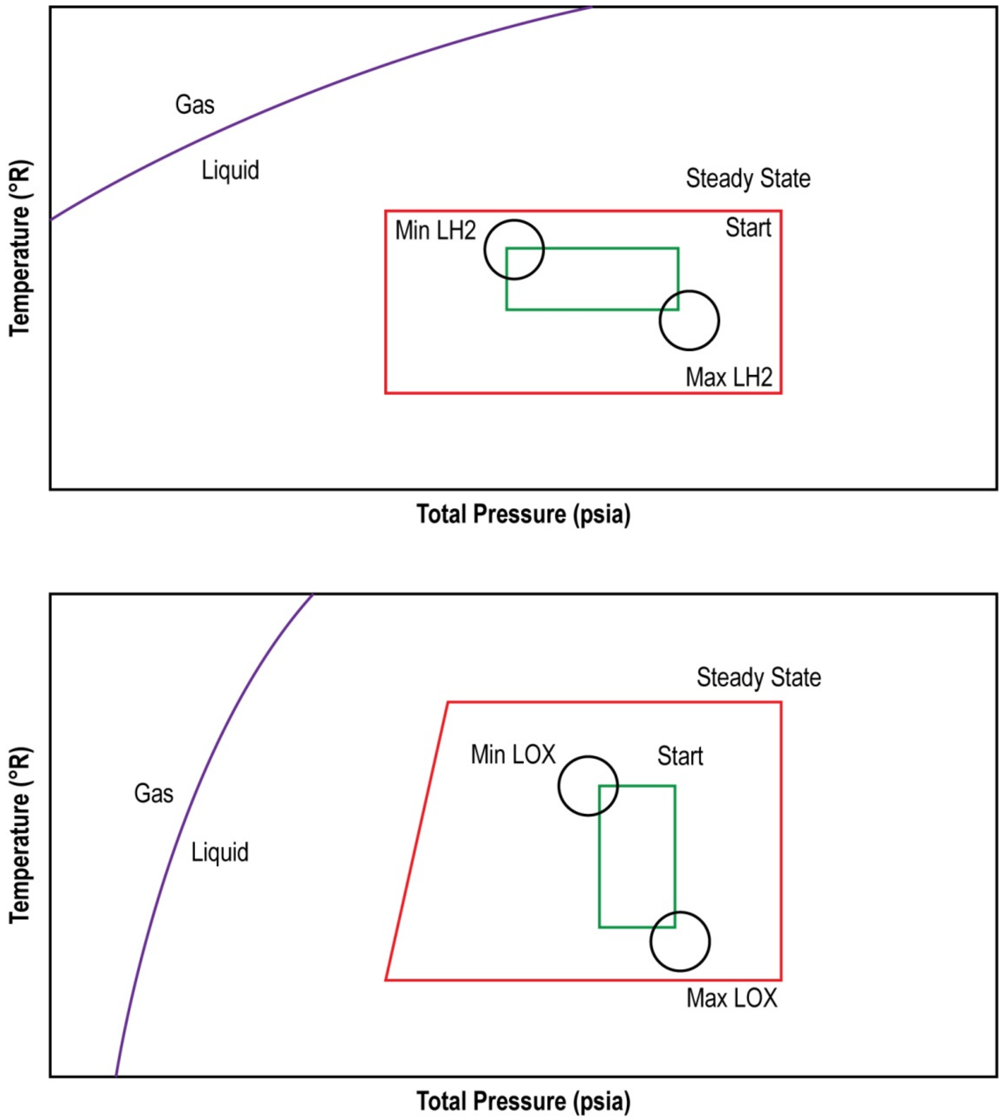

Figure 4.4-1: Notional inlet boxes for a liquid oxygen/liquid hydrogen engine.

4.4.3.1 Prestart Chilldown

Prior to start, 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. Cryogenics cause significant thermal loads that could be detrimental to hardware if not properly thermally conditioned before operation.

4.4.3.1.1 Component

RESERVED

4.4.3.1.2 Engine

Verify the chilldown or conditioning procedure to be used during the launch preparation or mission. Characterize chilldown system operation (flow rates, temperatures, valve operations) and hardware thermal condition variability (temperature versus flow rate versus time). The minimum, nominal, and maximum chilldown pressures, temperatures, and flow rates should be tested. Minimum and maximum chilldown should be tested in combination with hardware at the maximum and minimum predicted temperatures, respectively. Verify hardware temperatures meet requirements prior to engine start. Demonstrate chilldown margin, especially for upper stage engines started in flight. Include vacuum testing as appropriate to simulate the flight environment. Verify requirements are met for fluid consumption rates. Verify hold durations and allowable chilldown duration, if applicable.

4.4.3.2 Start Propellant Inlet Conditions

These conditions exist immediately prior to start command. Chilldown covers the conditions when the hardware is thermally conditioned; however, there is a small window that holds conditions in the “start box” where the tanks are pressurized to run pressures. The start box tends to reside within the “run box,” which is related to steady state propellant conditions. These conditions take into consideration any propellant feed pressure “slump” (from feed system inertance and resistance) and possible variation in local temperature conditions due to low circulation flow rates and feedline heat loads. Consideration must also be given to the various ancillary systems and their relative operating boxes as these effects are not trivial.

4.4.3.2.1 Component

RESERVED

4.4.3.2.2 Engine

Reference section 4.4.4.1, Start Transient, for testing expectations.

4.4.3.3 Steady State Propellant Inlet Conditions

Run boxes are to be established based on vehicle and engine configuration and documented in the engine/vehicle ICD. Reference section 4.2, Performance.

4.4.3.3.1 Component

RESERVED

4.4.3.3.2 Engine

Reference section 4.2.1, Steady State Performance Characterization, and section 4.2.4 Engine Influence Coefficients, for more details on testing expectations.

4.4.3.4 Shutdown Propellant Inlet Conditions

Engine performance and overall vehicle performance is very sensitive to MR. The durability of engine components can be very sensitive to mixture ratio conditions and the associated environments. The end-of-burn propellant density is more prone to vehicle tank heat loads and ullage temperature. This introduces the MR issue. Further, the end-of-burn ancillary system conditions must be explored as valve timing and purging/inerting of the engine can see variations. Particularly for upper stages, shutdown transients are important for vehicle orbital positioning.

4.4.3.4.1 Component

RESERVED

4.4.3.4.2 Engine

Reference section 4.4.4.4, Shutdown Transient, for testing expectations.

4.4.4 Transient Characterization

Transients are critical to explore during the development of a rocket engine. Transients test hardware durability, analytical modeling, and interactions between components/subsystems (i.e., system interactions). Significant time should be spent characterizing the variations that could occur during any given flight by varying propellant conditions (primary and secondary) and valve command timing.

4.4.4.1 Start Transient

Start transients on rocket engines are typically described as controlled explosions. 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. Like the steady state performance models, the testing in this area must also anchor the start transient model. Because of the complexities with the time-varying conditions of propellants and hardware condition, the models, in general, will not represent the test data to the accuracy and precision that the steady state models will. Specifically in this area, it is not unusual to see two independent models run in parallel. And because they are physically based, model inputs include propellant and secondary/ancillary flow conditions and hardware characteristics (resistances, pump maps, valve control volume (Cv) curves, valve slew rates, etc.), which all need validation in parallel to providing output critical in the decision making process regarding how to alter the commanded sequence to successfully start the engine, repeatably.

4.4.4.1.1 Component

Depending upon the component being tested and the complexity of the facility, the ability to mimic the engine start transient can diminish. Obviously, it is desirable to duplicate where feasible, but not mandatory. Typically, these lower level tests will have to derive a component specific transient, with the tendency to minimize wear on the component. Objectives for this level of testing are not necessarily tied to engine start transient verification.

4.4.4.1.2 Engine

This level of testing would dominate the start transient characterization. Timing is everything. Verify that the final startup sequence produces a start transient that satisfies all requirements. Typical approach is to break the start transient into logical steps, which will flow into a series of tests, prior to obtaining mainstage operation with any substantial steady state duration. The logical steps are dependent upon engine cycle and engine configuration. It is typical to see adjustments in valve slew rates, orifices, and commanded sequence throughout these tests. Variations in propellant conditions (both primary and secondary/ancillary), hardware thermal conditioning, electric power, valve command timing, valve slew rates, orifices, and ambient conditions (if altitude start) must be considered.

Tests for worst-case conditions should include margin and a minimum of four unique engine hardware samples. Margin values vary widely depending upon the actual engine cycle with criticality determined from development testing and specification requirements. Vehicle and mission configurations, single or multiple engines, are drivers for unique limits that must be demonstrated. Critical starting conditions such as those discussed above must be demonstrated.

Characterization tasks include the following: Develop forcing functions for structural dynamics loads analyses; Define/validate control valve timing; Establish purge system schemes, timing, and flow rates (e.g., to mitigate potential reverse flow); Determine ignition overpressure (IOP) and structural loads environment; Establish start commit criteria and launch commit criteria (LCC) (ground start engines only).

Verification tasks include the following: Verify specification limits are met; Verify acceleration rates, flow rates, propellant consumption, and side forces are acceptable; Validate initial spin-up and/or bootstrap method.

4.4.4.2 Restart

Depending upon the role for the engine, it is not out of the realm of possibility to have to restart an engine during flight. J-2 and RL10 are examples. Uncertainty in models is introduced the greater time there is between initial burn cut off and restart. The concept of operations can make a significant difference in the amount of testing required to anchor models.

4.4.4.2.1 Component

RESERVED

4.4.4.2.2 Engine

Restart or multiple restart capability should be validated with conditions as representative of the predicted flight condition as possible. Depending upon the important restart conditions (including but not limited to heat soak back, propellant settling, and propellant slosh), this testing may be more appropriately reserved for higher level testing.

Because of variability that could be introduced by natural/external influences, any testing at this level should include excursions to the worst-case with margin (where possible). Ideally, flight would always remain within test experience, or the extrapolation is minimized.

4.4.4.3 Throttle Transient

Demonstrate throttle rates and control capability to satisfy specification limits. Include all throttle points and worst-case control system response requirements. Simulate relevant external influences in flight (e.g., rapid inlet pressure change due to rapid acceleration change) to the extent possible.

4.4.4.3.1 Component

RESERVED

Note: Can be explored and characterized somewhat on component stands.

4.4.4.3.2 Engine

Engine throttle transients should be characterized during engine system testing. Most of the parameters influencing throttling are expected to be characterized as a part of normal start, steady state, and shutdown characterization testing. Throttle transient characterization testing should be incorparated into tests with other objectives to maximize development engine life.

Demonstrate throttle rates and control capability to satisfy specification limits. Include all throttle points and worst-case control system response requirements. Simulate relevant external influences in flight (e.g., rapid inlet pressure change due to rapid acceleration change) to the extent possible.

4.4.4.4 Shutdown Transient

Shutdown transient must be repeatable as possible to provide guidance, navigation, and control the best knowledge of where the vehicle exists in space relative to the expected/predicted flight trajectory. Shutdown modeling must be physics-based to best represent the predicted hardware characteristics. Like the start transient and steady state performance models, the testing in this area must also anchor the shutdown transient model. Because of the complexities with the time-varying conditions of propellants and hardware condition during burn, it is not expected that the model will represent the test data to the accuracy and precision that the steady state model can provide. As with the start transient model effort, it is not unusual to see two independent models run in parallel. Especially since the start and shutdown transient models stem from the same modeling effort, and because they are physically-based, model inputs include propellant and secondary/ancillary flow conditions and hardware characteristics (resistances, pump maps, valve Cv curves, valve slew rates, etc.), which all need validation in parallel to providing output critical in the decision-making process regarding how to alter the commanded sequence to successfully shutdown the engine, repeatably.

4.4.4.4.1 Component

RESERVED

Note: Can be explored and characterized somewhat on component stands.

4.4.4.4.2 Engine

Establish (development testing) and characterize a baseline shutdown sequence. Demonstrate shutdown from all potential power level conditions at nominal, off-nominal, and worst-case conditions, including those that produce the slowest and fastest shutdown transient. Important engine shutdown parameters to consider include impulse ranges and repeatability, propellant inlet conditions, mixture ratio, repressurization flows, purges, and control system parameters (e.g., voltage, pressure, valve timing). Realistic combinations of shutdown parameters that cannot be test verified must be verified by analytical means. 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 should be tailored to the specific engine system being tested.

Verification tasks include the following: Verify specification limits are met; Verify deceleration rates, flow rates, propellant consumption, shutdown impulses, impulse repeatability, and side forces are acceptable; Validate spin-down rates; Validate dynamic responses (e.g., chugging, “pops”) are within allowable limits.

4.4.4.5 Abort Shutdown

Abort scenarios vary widely from vehicle to vehicle. Which stage the engine is on will also vary the conditions an engine may see during an abort scenario. Complex systems tend to fail in complex ways, therefore modeling all possible abort shutdown scenarios is rather difficult. Hazards and Failure Modes and Effects Analysis (FMEA) documentation should be examined at all levels to best understand the reasonable failure modes to test and evaluate. The test program should incorporate some testing of abort scenarios to better anchor models that can be extrapolated to satisfy safety concerns.

4.4.4.5.1 Component

RESERVED

Note: Can be explored and characterized somewhat on component stands.

4.4.4.5.2 Engine

Verify the ability to safely abort and shutdown while on the pad. Launch site abort logic and shutdown procedures should be used. Launch pad and launch vehicle interfaces should be simulated or represented to the greatest extent possible. Demonstrate the planned post-abort shutdown safing, inspections, and turnaround activities.

4.4.5 NPSP Margin and Cavitation

NPSP is effectively the delta pressure between the total pressure minus the vapor pressure of the propellant. For engines with turbomachinery, this is a key parameter to understand and thoroughly characterize during development. Low inlet pressure to the pump can result in cavitation, and in turn create head fall off and significantly degrade pump life. The tendency is to always maintain a minimum amount of NPSP margin to prevent head fall off and hardware damage. The margin is analytically predicted along with the turbo pump maps, which need to be anchored to test data, feeding into engine steady state performance and transient models. It is possible to obtain much of the necessary information off of component level testing, but this does not eliminate the need to conduct some of these excursions on the full engine to validate the component level findings. Some programs have used “powerpack” type configurations, which tends to include the turbomachinery and parts of the engine to test these items in combination, prior to or in parallel with the full engine development test program.

4.4.5.1 Component

Test throughout the prescribed operating range to map structure, strength, and extent (operating parameter range) of cavitation instabilities. The engine operating range should be parameterized and 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. Propellant inlet temperature, pressure, and flow rate measurements for determination of cavitation number and flow coefficient 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. Quantify the strength and oscillation frequencies associated with cavitation instabilities with pump housing axial and radial accelerometers. If possible, include one or more close-coupled dynamic pressure transducers at the inducer inlet. Accelerometers and pressure transducers should have sufficient frequency response and sample rate to resolve the frequencies associated with the highest frequency cavitation instabilities. If instabilities are observed, a circumferential array of pressure transducers should be employed to provide information on the structure and rotation rate of the cavitation disturbance. Verify robustness and margin against any instability behavior that cannot be eliminated by accumulating 4x duration versus worst-case total SL duration. Worst-case durations should account for the often hysteretic behavior of cavitation instabilities. Test durations should be increased, or an alternate test sample obtained, if cavitation response amplitudes on the intended test sample are well below the maximum expected cavitation response amplitudes for all engines. Flight representative feedline geometries should be employed and propellant cleanliness and dissolved gas content levels should be representative of flight conditions.

<u>Background/Rationale</u>: Development and qualification test programs for LREs with turbomachinery must include testing to demonstrate robustness of the engine design to the cavitation phenomena commonly encountered in turbopumps. The inlet condition testing guidelines associated with cavitation above are intended to primarily address engine performance degradation that prevents the engine from meeting specified performance requirements. However, current turbopump designs typically employ cavitating inducers to maximize cavitation performance. These inducers commonly experience various forms of localized cavitation that are routinely present at operating conditions well inside the intended flight operating range of propellant inlet conditions. Experience shows the localized cavitation regimes can be very sensitive to small changes in propellant inlet conditions, hardware variations (e.g., inducer tip clearances), and engine operating parameters (especially speed). While these localized cavitation phenomena do not significantly impact pumping performance, they can lead to reduced system reliability through the generation of elevated engine and vehicle vibration environments.

Localized turbopump inducer cavitation phenomena can take a variety of forms including partial blade cavitation, tip vortex cavitation, backflow cavitation, surge cavitation, rotating cavitation, and higher order surge and rotating cavitation. These complex cavitation phenomena produce both broadband and discrete frequency excitation that can damage both turbopump and vehicle components. In addition, they can provide the excitation and/or compliance necessary to initiate turbopump rotordynamic or coupled propulsion/structure (pogo) instabilities.

A rigorous test program is absolutely essential for the identification and elimination of the potentially harmful impacts of these phenomena on flight hardware. Initial characterization of inducer cavitation performance and screening for cavitation instability behavior within the intended operating range should be conducted in inducer and pump component tests, which will not be discussed here in detail. However, it is important to consider that such tests are often conducted using subscale hardware at scaled speeds using stimulant 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 impact from unknown engine system effects. For these reasons, the engine development test program should include a thorough mapping of the cavitation behavior of the pumps over an operating range that envelops the intended flight operating range, including low NPSP and high and low speed extremes.

Focused testing to map structure, strength, and extent (operating parameter range) of cavitation instabilities over the prescribed operating range requires specific test procedures and careful selection of instrumentation type, placement, and data acquisition strategy. To ensure that no potentially damaging instability behavior is overlooked, the engine operating range should be parameterized and mapped in terms of the dimensionless pump parameters which govern cavitation behavior, namely cavitation number and flow coefficient. Propellant inlet temperature, pressure, and flow rate measurements for determination of cavitation number and flow coefficient should be located as close as possible to flight measurement locations or carefully corrected to flight measurement locations to ensure test parameters are flight representative. Care must be taken to locate the inlet pressure measurement sufficiently far upstream to prevent erroneous pressure readings that may be caused by local backflow near the inducer inlet. Test ranges should be expanded sufficiently beyond the test range of interest to account for cavitation number and flow coefficient uncertainties derived from measurement uncertainties, hardware variation, and ground-to-flight differences. Particular interest should be paid to temperature measurement uncertainty as cavitation number is acutely sensitive to temperature, especially at low NPSP, due to the slope of propellant vapor pressure curves. In addition to the instrumentation required to accurately establish the pump operating parameters, pump housing axial and radial accelerometers are required, at a minimum, to quantify the strength and oscillation frequencies associated with cavitation instabilities. Where possible, it is highly desirable to also include one or more close-coupled dynamic pressure transducers at the inducer inlet. These accelerometers and pressure transducers should have sufficient frequency response and be sampled at a rate sufficient to resolve the frequencies associated with the highest frequency cavitation instabilities. Higher-order cavitation modes have been observed at frequencies as high as 6 to 10 times shaft synchronous frequency. In problematic hardware where additional information is required, a circumferential array of pressure transducers can be employed to provide information on the structure and rotation rate of the cavitation disturbance, which is useful in identification of the type of instability present. The objective of cavitation instability mapping in development testing is the identification and elimination of cavitation instabilities having frequencies that are coincident with fundamental engine, propulsion system, and vehicle frequencies such as inducer blade resonant frequencies, propellant feedline resonant frequencies, and vehicle mode frequencies.

While the goal of the development test program is to identify and eliminate potentially harmful cavitation instabilities, it is typically not possible to eliminate all instability behavior from the engine operating range. Consequently, qualification testing should verify margin by accumulating 4x duration versus worst-case total mission duration of operation for any remaining cavitation instabilities that occur in the flight operating range of the engine. Worst-case mission durations should be carefully determined to account for the often hysteretic behavior of cavitation instabilities (the pressure at which an instability is suppressed once initiated can be substantially different than that required for initiation). Test durations may also need to be increased, or an alternate test sample obtained, if cavitation response amplitudes on the intended test sample are well below the maximum expected cavitation response amplitudes for all engines. Flight representative feedline geometries should be employed to capture potential interactions between localized inducer cavitation and feedline dynamics. In particular, a surge type of instability involves the dynamic characteristics of the overall feed system and so the upstream facility feed system should be dynamically decoupled from the flight representative feedline by using an isolation accumulator to create a dynamic pressure null at the accumulator position. In addition, care should be taken to ensure that propellant cleanliness and dissolved gas content levels are representative of flight conditions as these factors are known to impact cavitation behavior. Again, proper selection of instrumentation type, placement, and data acquisition strategy is essential to ensure adequate characterization of and qualification to flight cavitation environments.

4.4.5.2 Engine

If not obtained on the component test, the default becomes the engine test program. Powerpack test configurations will fall in this category as a subsystem test program.

Demonstrate adequate steady state pump performance and acceptable head falloff characteristics (i.e., no worse than 2-3% degradation) with decreasing NPSP. Test margin outside of pump inlet box and/or beyond the specified minimum NPSP requirement. A separate NPSP margin demonstration test is recommended for each propellant to avoid risk of 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 impact of potential single point system failures (e.g., failed pressurization branch), but not lower than the 2% head falloff region. Actual margin values should be the result of development test results and specification requirements for the type of engine being tested.

4.4.6 Pogo and 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 suppressor is required. Suppressors can be engine-mounted or stage-mounted. If engine-mounted, the majority of majority of engine development tests and all engine qualification testing should be performed with the Pogo suppressor hardware installed and operating as designed during flight.

4.4.6.1 Component

RESERVED

Note: Turbopump compliance can be explored and characterized on component stands.

4.4.6.2 Engine

Engine testing is the one place in a development program that can offer an environment that generally simulates vehicle provided inlet conditions. Determine pump compliance and pump gain, as a function of cavitation index and flow coefficient at the pump inlet, to facilitate vehicle pogo modeling. Derive parameters using pogo pulse testing and analytical modeling.

Verification of the pogo model of engine oscillatory behavior requires special engine development testing to determine frequency response functions over the full range of engine operating conditions. These frequency response functions express the amplitude and phase of engine inlet, pump discharge, and Pc versus frequency per unit of sinusoidal flow oscillation inserted upstream of the engine inlet. This testing is applied to each propellant circuit that remains liquid up to the MCC, such as LOX or a kerosene-like propellant. Testing for liquid hydrogen is not required because gasification occurs upstream of the MCC.

Ideally, the overall test feed system should include a replication of the flight feed system or, as close thereto 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 the data acquisition ranged to accurately determine small-amplitude oscillations in the frequency range of interest. The pump inlet pressure amplitude is intentionally kept below a few pounds per square inch (psi) to insure 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. The paramount parameters to be verified are pump cavitation compliance and pump gain as a function of cavitation index and flow coefficient at the pump inlet.

4.4.7 Ancillary Systems

Ancillary subsystems are secondary systems (mechanical, hydraulic, pneumatic, and electrical subsystems) that make the engine function as it is intended. All functions are necessary in these systems and are no less significant than the primary flowpath items. These systems tend to make up the majority of the interfaces with the stage. Just as the primary propellants, there are operating boxes defined for each ancillary system. Either coming from or sent to the stage, the ancillary systems influence performance and functionality of the engine. Each ancillary system operational band must be characterized and models are to be anchored through testing.

4.4.7.1 Autogenous Pressurization

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.

4.4.7.1.1 Component

RESERVED

4.4.7.1.2 Engine

Verify specification autogenous pressurization requirements. Determine influence on engine operation. Test with margin on flow rates. Include nominal and worst-case engine operating conditions.

4.4.7.2 Valve Actuation

Variations in conditions for valve actuation directly affect repeatability of start and shutdown transient characteristics. Anchor models to the family of test data gathered over the spread of the operational boxes.

4.4.7.2.1 Component

RESERVED

4.4.7.2.2 Engine

Verify electrical, pneumatic, hydraulic operational box minimums and maximums do not significantly affect engine or stage operation.

4.4.7.3 Purges

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 (purge sequence number or PSN) and flowrates are key to start and shutdown characteristics of the engine.

4.4.7.3.1 Component

RESERVED

4.4.7.3.2 Engine

Establish (development testing) appropriate purge schemes, flow rates, and timing, and validate (qualification testing) purge effectiveness using dew point measurements or other appropriate means.

Verify effectiveness of purges at minimum, nominal, and maximum purge flow rates, temperatures and pressures. Include operational sequences and procedures and abort situations.

4.4.7.4 Electrical Power and Ignition

Electrical power tends to be supplied by the stage/vehicle. These systems have power quality requirements. Engine electrical systems include the engine controller, data systems, valve control, and likely ignition systems. Variations in power quality can have detrimental effects to engine functionality.

4.4.7.4.1 Component

RESERVED

Note: Many times this functionality is checked at the lowest levels and several steps along the way.

4.4.7.4.2 Engine

Test electronics from utilizing end-to-end checkouts, valve sequence checkouts, etc., prior to hot-fire. Systems should run thorough checkouts over the full range of interface power conditions.

Ignition systems should also get timing and sequence checks relative to power variations.

4.4.8 Thrust Vector and Gimballing

Testing should verify capability of the integrated engine system and the thrust vector control (TVC) system. TVC includes engine gimbal and roll control systems, or differential throttling in non-conventional configurations such as aerospike engines. 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. Testing should be performed at engine firing and non-firing conditions.

4.4.8.1 Component

RESERVED

4.4.8.2 Engine

Verify that the TVC functional capability meets system requirements including maximum control range, slew rate, acceleration, loads, and frequency response. Firing tests should be performed at worst-case combination propellant conditions for TVC loading, and at minimum and maximum thrust levels.

Gimbal Limits: Engine or chamber (as appropriate) should be gimbaled to and functionally operated at its limit positions, slew rates, and accelerations during hot-fire testing, where possible. Non-hot-fire testing should include functional and hardware clearance checks; however, maximum slew rates and accelerations tend to be reserved for hot-fire.

Roll Control Limits: Roll control should be functionally operated at its limit positions during non-firing testing and during hot-fire testing.

Ambient Environment: TVC should be demonstrated at sea level and/or vacuum conditions (as appropriate). If vacuum testing is required (lubrication systems and frictional characteristics may be vacuum sensitive), but not practical at the engine level, then this may be verified at the component level.

Inspections: 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.

Heat Flux: Verify that the engine induced heat flux on adjacent surfaces during hot-fire TVC testing is within acceptable limits.

Clearance: Validate the engine envelope clearance analyses at TVC limit positions. The recommended 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.

Interface Compatibility: Verify gimbal block and roll control interface compatibility for mechanical (e.g., bearings), hydraulic and electrical connections. Minimum and maximum control parameters should be demonstrated.

Thrust Vector Alignment: Verify thrust vector alignment characteristics (arc minutes and offset). Tolerance stack-ups of hardware play a significant role in repeatability. Some gimbal bearings have adjustments to reduce offset. All should be verified on the engine stand utilizing thrust measurement systems with lateral measurement capability.

4.5 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.

4.5.1 Functional Tests

These tests tend to be run initially off of the engine. Component and Subsystem labs are set up to integrate software and electronic hardware.

4.5.1.1 Component

RESERVED

Note: Thoroughly test component and subsystem in laboratory environment. Hardware-in-the-loop type labs are common approaches for flight software and electronic hardware integration.

4.5.1.2 Engine

Verify the engine control system can reliably and accurately satisfy specification requirements for startup, steady state operation, throttling, and shutdown. This includes command and control type activities and data transfer activities.

Verify data collection and transfer characteristics.

Verify engine response time characteristics regarding sending and receipt of command to actual physical movement of fluid, mechanical, and electronic driven devices.

Verify vehicle commands through vehicle computer simulator.

4.5.2 Engine Control System Malfunction Logic Check

These tests explore the various ways the control system can fail. Standard flight computer systems contain two channels and in-flight switchover is a standard redundancy feature on engines.

4.5.2.1 Component

RESERVED

Note: Thoroughly test component and subsystem in laboratory environment. Hardware-in-the-loop type labs are common approaches for flight software and electronic hardware integration.

4.5.2.2 Engine

Demonstrate fault detection and accommodation for engine control system faults. Demonstrate channel switchover during the start transient, steady state, throttling, and shutdown for control systems with redundancy. Demonstrate acceptable engine, engine controller, and control hardware responses to malfunctions

4.5.3 Engine Health Management (EHM) System Validation

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; and provides condition monitoring data, and if also so configured, manages engine health.

4.5.3.1 Component

RESERVED

Thoroughly test component and subsystem in laboratory environment. Hardware-in-the-loop type labs are common approaches for flight software and electronic hardware integration.

Demonstrate and validate that the EHM system can correctly detect and identify potentially hazardous conditions, especially selected critical vehicle system scenarios identified by the system FMEA. Demonstrate and validate that the EHM system can inform the appropriate controller in time to acceptable engine corrective action and recovery, without exposing the test hardware and facility to excessive risk. Verify that the EHM can evaluate start commit criteria and LCC and respond accordingly, if separate, and independent ground facility systems do not perform this function. All actions must be completed in time to prevent unacceptable damage or degraded performance.

4.5.3.2 Engine

Demonstrations at the engine level are required prior to active control during flight.

4.6 OPERATIONS

4.6.1 Pre-Test Inspections and Checkouts

Pre-test inspections and checkouts primarily refer to visual inspections and functional checks. Both the facility and test article must perform these checklist items in preparation for test. Items like understanding of hardware configuration going into test, condition of hardware, removal of covers/closures where appropriate, review of hardware changed/altered since previous test, functionality checks like cycling the valves or end-to-end electrical checks all fall into this area.

4.6.1.1 Component

RESERVED

4.6.1.2 Engine

Generate (development testing) and validate basic inspection procedures. Key aspects to incorporate into or consider for the pre-test inspections and checkouts follow.

Perform all specified general checkouts. These may include, but are not limited to, the following: 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.

Engine-to-facility interfaces should be inspected to verify compliance with dimensional and surface finish requirements. If main propellant inlet covers are removed, the internal area should be inspected to verify foreign object debris (FOD)-free conditions. Interfaces associated with internal components sensitive to moisture intrusion should be verified to be dry.

Verify that all test procedures to be implemented are applicable for the intended test objectives and the correct version.

Verify all facility and engine software to be used are the correct versions with the correct inputs. Relevant checksums should be performed.

Perform all specified functional checkouts. These may include, but are not limited to, the following: manual or commanded operation/movement of mechanical systems, electrical integrity verification, control system checks, abort system readiness, data system readiness, and turbopump torque checks.

4.6.2 Leakage

The intent is 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 upon hardware configuration and operating pressures. Some locations may need mass spec; others may only need bubble soap. The SMC-S-016, MIL-STD-1522, and MIL-STD-1540 also address leakage.

4.6.2.1 Component

RESERVED

4.6.2.2 Engine

Integrated enigne fluid leak checks should be performed. Leak tests performed during engine assembly and at any joint that is disturbed (i.e., removal and replacement of a component) during testing or integration to larger assemblies.

Perform leak tests at pressure levels and durations sufficient to identify unacceptable leaks pre- and post- engine hot-fire. Acceptable leakage rates should be based on analysis and test experience. If the engine contains pneumatic and hydraulic systems, which are integrated with the stage, these systems should be tested at an integrated level for full verification. Different methods for quantifying leakage include mass spec, bubble soap, pressure decay (other methods also exist that may be acceptable).

Integrated pneumatic and hydraulic sub-systems should be leak tested per MIL-STD-1522 or MIL-STD-1540 for pressurized systems.

4.6.3 Post-Test Inspections

Inspections after a test is conducted contain valuable data that will help explain or elaborate on any unexpected data, hardware life/durability concerns, etc. Depending upon 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 (acceptance test) 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.

4.6.3.1 Component

RESERVED

4.6.3.2 Engine

Post-test inspection requirements for individual tests are defined below. In general, the 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.

Establish (development testing) and validate procedures to evaluate engine health prior to subsequent processing. Requirements for post-test inspections following individual hot-fire tests generally are fairly similar to pre-test inspections. Differences should be documented and verified during the test program.

Establish (development testing) and validate appropriate periodic inspection schedules and methods (e.g., visual, throat impressions) to evaluate post-test condition of combustion chambers and nozzles and to identify evidence of unacceptable hot spots or erosion. Verify acceptable hardware conditions before and following the engine testing for operational life, MR excursion testing, and thrust/MR margin demonstration. Develop acceptance criteria for allowable chamber cracks and leakage rates, if any.

Establish (development testing) and validate procedures to secure and safe the engine for subsequent processing.

Establish (development testing) and validate (qualification testing) procedures for post-test inspection data review and evaluation.

4.6.3.2.1 Post-Test Series Teardown

Conduct a detailed engine teardown and inspection following each test series. Teardown to the piece-part level. Inspect for any signs of distortion, damage, excessive wear, or any other unexpected discrepancies. Identify design modifications, operating constraints, or other corrective actions required.

Background/Rationale: A detailed engine teardown and inspection is recommended following each test series. The extent of the teardown preferably would be thorough engine disassembly to piece part level. Assemblies and piece parts should be carefully inspected for any signs of distortion, damage, excessive wear, or any other unexpected discrepancies. Such review of both “expended” and reusable hardware is necessary to identify areas with low margin, if any, so design modification, operating constraints, or other corrective action can be taken. If any hardware is found to be in particularly good condition and is shown to have adequate life remaining, it may be appropriate to re-use that hardware for other test engines, provided the reused hardware does not compromise any objectives in the respective test series that need unique hardware samples.

4.6.4 Drying and Heated Purges

These purges are intended to minimize the moisture (water) in the system. It is especially a concern with cryogenics and propellants expecting to operate below the freezing point of water. Icing of sense lines, effectively blocking the pressure from being measured, has been seen in engine hot-fire testing. Some materials need attention to prevent swelling of seals or rusting.

After a cryogenic engine hot-fire, it is typical to see drying and heated purges to warm hardware for inspection and preparation for the next test. Heated purge temperatures have a maximum due to materials, and should be considered for each hardware configuration.

4.6.4.1 Component

RESERVED

4.6.4.2 Engine

Establish (development testing) drying procedures and verify (qualification testing) ability to dry engine per specification limits. Check dew point at purge exit points at designated times to verify requirements are met.

4.6.5 LRU Demonstrations

LRUs are components that are interchangeable and do not pose a threat to the understood performance of the engine. Typically, the line is drawn such that the component can be change after acceptance testing without significantly altering performance. However, there are different stages in the operational flow for engines that could create variations in the LRU list. Prior to acceptance test complete, it is feasible to change a much larger set of componentry if a calibration hot-fire will follow.

SSME tends to be the extreme in this area by allowing almost all the components to be interchangeable. However, most components have to undergo engine level hot-fire acceptance series, which creates a need for “slave” engines to hot-fired for sustainment of this need. The engine hardware and control architecture also enable this capability.

Expendable engines tend to head down the path of minimizing LRUs and accepting full engines. This is not to mean that there are not logical LRUs incorporated into these programs, but it is all to keep engine costs down.

4.6.5.1 Component

RESERVED

4.6.5.2 Engine

Verify LRU replacement procedures. Verify acceptable operation with approved LRUs via LRU replacements.

Demonstrate potential LRUs during development by comparing performance variation for potential LRUs to relevant performance uncertainty requirements.

4.6.6 Reusability

The best example of a system being close to reusable is the SSME. The engine is reused, but tends to carry significant operational cost for inspection and maintenance to ensure the components remain flight worthy for human spaceflight.

4.6.6.1 Component

RESERVED

4.6.6.2 Engine

Demonstrate two sets of two complete flight sequence simulations to the extent possible at the engine level. The first set should demonstrate the nominal turnaround timeline. The second set should demonstrate the minimum required turnaround timeline. Test objectives include the following:

- Demonstrate engine system start, steady state operation, and shutdown. Perform a complete flight sequence during engine operation.
- Verify turnaround capability. Verify engine system turnaround procedures. Operational turnaround and countdown procedures should be used.
- Demonstrate any required between-flights hardware or software modifications.
- Perform post-flight checkout and inspections, required health monitoring data reviews, and pre-flight checkout. Access limitations and restrictions, including vertical and horizontal access as applicable and confined spaces, should be simulated to reflect operational physical constraints.
- Demonstrate engine system re-start, steady state operation, and shutdown. Perform a complete flight sequence during engine operation.
- Perform post-flight checkout and inspections, required health monitoring and data reviews. Engine system should successfully meet all criteria.

4.6.7 Operability

The term is utilized to describe the ability to conduct operational procedures in a timely and effective manner. Minimizing the level of effort required to change LRUs when necessary, conduct pre-and post-test checkouts, electrical and mechanical checkouts, etc. This also manifests itself in operational timeline optimizations. It helps decide the time allowed to perform the multitude of operational tasks on an engine.

4.6.7.1 Component

RESERVED

4.6.7.2 Engine

Establish (development testing) and verify (qualification testing) practical servicing procedures, operational readiness capabilities, maintenance access requirements, 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 similar to those needed for battleship testing, and use available resources, including on-ground maintenance equipment and logistics support infrastructure, as close as possible to actual launch operations.

4.6.8 Preflight Procedures and Flight Sequences

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

4.6.8.1 Component

RESERVED

4.6.8.2 Engine

Because DDT&E tends to have significant time before 1st flight, the procedures known at this point are likely significantly lower fidelity than what will be used on flight day (if in existence). However, notional procedures can be put in place based on known vehicle architecture and concept of operations. To the extent possible, demonstrate/simulate preflight procedures and operational procedures. Interfaces with vehicle simulated command and data systems should be part of the facility configuration.

Demonstrate the flight sequence of events. Thermal conditioning may be simulated if it is impractical to simulate long soak periods under space environments. The sequence of events may be compressed through elimination of steady state operation provided all critical sequences are tested.

4.7 ENVIRONMENTS

Natural and induced environments are key factors in the design of hardware. The analytical estimates for loads and environments essentially design the engine until test data is obtained. To validate the model, the inputs need to be anchored to test data. In this section, various environments to be considered for test are discussed.

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.

4.7.1 Thermal Environment

Thermal environments are initially modeled at various levels. Vehicle analysis flows down natural and vehicle induced environments to its constituents. The engine level model takes these inputs and combines them with the self-induced thermal environments from expected engine operation. All phases of operation are taken into account. Output of the engine model [typically finite element model (FEM) in nature] will flow to component thermal models, where detailed design will take this into account.

Model validation will utilize test data from thermocouples, resistive temperature devices (RTDs), and skin temperatures to convey the thermal profile of the engine.

4.7.1.1 Component

RESERVED

4.7.1.2 Engine

Verify the engine thermal environments. Extrapolate between engine ground test environments and in-flight environmental predictions. The greatest wealth of thermal data is to be gathered during this campaign.

4.7.2 Climatic Tests

Testing must verify that engine is robust against or adequately protected against expected exposure to salt, fog, sand, and dust, per the requirements of SMC-S-016.

Many times these requirements can be verified by similarity to designs in the past. Full climatic test programs are not necessarily needed.

4.7.2.1 Component

RESERVED

4.7.2.2 Engine

Refer to MIL-STD-1540 or Aerospace Report TOR-2004(8583)-1 for more detailed testing requirements for engine hardware.

4.7.3 Vibration/Shock/Acoustics

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

4.7.3.1 Component

RESERVED

4.7.3.2 Engine

External Excitation: Refer to SMC-S-016 and MIL-STD-1540 for test requirements. External excitation is not required if it can be shown that engine self-induced vibration is much more severe. Following external excitation vibration testing, it would be appropriate to functional test and hot-fire the rocket engine in a flight simulation to identify any hidden failure modes.

Background/Rationale: Traditional methods can be used to qualify engine hardware for external environments induced during non-operating phases of flight (e.g., boost phase loads on an upper stage engine). The appropriate test requirements are described in SMC-S-016 and MIL-STD-1540. Qualification of vehicle components or subsystems for external excitation environments is typically achieved by affixing the test article to a shaker table and exposing it to a pre-determined dynamic environment that replicates or exceeds the expected flight environment. Predicted environments usually are derived from flight data. They are simulated by an equivalent base-shake input, generally stationary random or sine dwell excitation, that induces dynamic loads in the component at frequencies and amplitudes consistent with expected operational loads. In this manner, the test article is subjected to fatigue damage potential equivalent to that experienced by the flight hardware. The duration of exposure required to adequately demonstrate durability is determined based on margin requirements and SL (including acceptance testing and flight duration).

Self-Induced Vibration: The engine turbopump and other critical components should be 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.

Background/Rationale: 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. Typical sources of self-induced dynamic excitation include rotating imbalance, pump and turbine blade passage, gear train and bearing dynamics, cavity flows, unsteady cavitation phenomena, fluid-structure interaction, and combustion instabilities. The complexity of engine systems makes the dynamic environments to which engine hardware are exposed impossible to replicate in traditional shaker-type testing. Self-induced dynamic excitations from multiple sources within a running engine, each subject to variations in transmissibility, combine in complex ways to produce frequency and location-dependent loads throughout the engine system. Thus, identification of an equivalent base-shake input to reproduce operational loads in the components is not possible, and even if the appropriate input could be determined, introducing vibration at a single point cannot accurately reproduce the complex dynamic loads imposed on components in a running engine. Furthermore, since qualification for self-induced vibration by analysis typically requires complexity beyond current state-of-the-art capabilities, direct demonstration by engine level testing is left as the only means to qualify engine component durability. Since the nature of the environments in conjunction with the size, cost, and complexity of LREs makes vibration test qualification of engines by traditional methods impractical, an engine-unique methodology is required to qualify and ultimately accept engine hardware for the self-induced vibration environments.

Current engine development and qualification testing practices rarely adequately address the test requirements for the complex self-induced engine dynamic environments. Also, engine specification limits for self-induced environments are rarely defined, largely due to the inability of state-of-the-art analyses to predict these environments. Furthermore, there often is significant engine-to-engine variability in various aspects of the self-induced engine environments. As a result, engines and engine components can be subjected to higher dynamic loads during acceptance testing than during development and qualification testing, thereby introducing the potential to severely degrade life and consequently posing an often-unquantifiable level of risk to mission success. When these higher environments and the resultant higher dynamic loads occur during acceptance testing, an assessment is required to evaluate the health of engine components prior to flight and, if possible, identify potential mission risks.

To facilitate clearance of self-induced vibration encountered during acceptance testing, the durability of engine hardware should be demonstrated via extended duration engine operation under flight representative operating conditions during development and qualification testing. The engine turbopump and other critical components should be well instrumented with accelerometers to characterize the dynamic environment. The engine should be operated over a wide range of conditions to envelope all inlet and mixture ratio excursions that will be encountered by the engine in service. Post-test inspections and functional tests are performed to verify proper component function and to establish that no damage has been sustained during testing. The resulting accelerometer test data then represents the qualified environment for self-induced engine vibration and, as such, serves as a comparison case to establish engine vibratory health for future production engines during acceptance testing.

4.7.4 Modal Surveys/Testing

This is done to characterize the frequency response characteristics of the system by exciting the entire engine system with a low frequency sine sweep. Extract engine modes and identify resonant excitation.

4.7.4.1 Component

RESERVED

4.7.4.2 Engine

A modal testing can be done for engine specific characterization only.

4.7.5 Vehicle Interface Loads

Vehicle-to-engine interfaces have a combined 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 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 for engine models and then flowed to component level designers for detailed design. These models need anchoring from engine testing for engine generated loadings.

4.7.5.1 Component

RESERVED

4.7.5.2 Engine

Verify interface environments are within the Maximum Predicted Environments (MPE). Characterize frequencies and amplitudes at the interfaces and validate engine testing encompasses expected vehicle interface loading and dynamics.

4.7.6 Electromagnetic Interference/Compatibility Tests

Electronics are becoming more critical on flight systems as dependency on these items to control and manage engine functionality increases (engine health and status, valve controls, data, etc.). These systems must meet EMC limits as described in Aerospace Report No. TOR-2005(8583)-1 (proposed MIL-STD-1541B), as well as additional documents referenced therein, subject to the tailoring below.

The above requirements must be tailored for a LRE. For example, only the electrical components are usually subject to EMC requirements. In addition, ordnance, deployment and fuel systems must be protected from, or made impervious to, inadvertent activation, due to high electric field strengths, electrostatic discharge (ESD) and lightning. The following specific initial tailoring of TOR-2005(8583)-1 is recommended for electrical equipment for launches:

(a) Requirement 6.15(RE102): Include any expected receiver notches not already called out in the TOR.
(b) Requirement 6.16(RS103): The levels in bold face type should be adequate for a starting point, but it may be beneficial to identify the possibility that they could go up.
(c) Requirement 6.12(CS06): Increase amplitude to 800V, and apply to all power and signal lines (to address lightning indirect effects).
(d) Requirement 6.43c2(ESD): Contact discharge increased to 16kV, and applied to the pins of all power and signal lines.
(e) 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. Guidance may be obtained in Requirements 6.42 and 7.7.

4.7.6.1 Component

RESERVED

Note: Reference Aerospace Report Number TOR-2005(8583)-1 (proposed MIL-STD-1541B) for EMC testing.

4.7.6.2 Engine

Not Applicable.

4.8 DESIGN AND CONSTRUCTION

4.8.1 Proof Pressure

Proof testing is not performed on engines due to the large pressure gradients throughout the engine during operation. Typically, this is reserved for the component level as a part of manufacturing and assembly. Refer to NASA-STD-5012 for additional detail regarding proof pressure testing and burst factor demonstrations.

4.8.1.1 Component

RESERVED

Note: Pneumatic and Hydraulic Sub-systems - Integrated pneumatic and hydraulic sub-systems should be proof tested per the more stringent of MIL-STD-1522 or MIL-STD-1540 for pressurized systems.

4.8.1.2 Engine

Not Applicable

4.8.2 FOD / DOD Tolerance

Foreign and Domestic Object Debris (FOD/DOD) 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. Prevention of FOD damage is accomplished by design features (clearances, material selections, filters, etc.), or process control (cleaning, white rooms, protective covers, inspections). Analysis should be done to identify the particulate size allowed through tightest clearances in the engine. Filters tend to be incorporated where large sources of particulate or very small clearances are identified. Fluid cleanliness and hardware cleanliness specification should be established for engine design. MSFC-SPEC-164 is a reference typically used as there are MIL-PRF documents, too.

4.8.2.1 Component

RESERVED

Note: Material characterization is used for oxygen compatibility.

4.8.2.2 Engine

Demonstrate tolerance to self-generated particles due to wear (e.g., gear teeth, turbine seals). These will naturally exist within the system during engine operation. Inspections should be performed to find any significant FOD/DOD. Special inspections may be necessary in development to ensure system cleanliness is maintained.

Confidence is gained from running multiple engines well past the expected operational life. Testing and operational procedures verify system maintenance procedures are adequate and manufacturing and assembly processes deliver clean parts. It will also verify that propellant quality and in-place filters are adequate.

However, some testing has been done in the past regarding introduction of contamination (metallic particulate and gases as appropriate).

4.8.3 Structural Model Verification

Extensive hot-fire testing of each individual engine provides data regarding structural integrity and durability of the engine hardware. Engine qualification programs involve life testing that validates structural models which involves low-cycle fatigue (LCF)/HCF estimates. Structural models report margins and are anchored to test data. Refer to NASA-STD-5012 for structural requirements for LREs.

4.8.3.1 Component

RESERVED

4.8.3.2 Engine

Refer to NASA-STD-5012 for structural verification for LREs. Margins should be reported for all major components and interfaces.

Include strain gauge measurements for the purpose of structural model verification.

4.8.4 Margin Testing

Margin testing is utilizing test as a method to demonstrate the robustness of the engine. It tests the engine a percentage beyond the expected maximum and minimum conditions. It is not necessary to demonstrate all conditions outside of the expected operational box, but selected ones where the engine design shows sensitivity or where the actual corner of a box may be a condition where the engine operates for some period of time. This part of the test program should be well supported by analytical models. Since not all model scenarios can be run on a test stand, the test points will anchor the model in each margin area so interpolation between the tested points and the analytical case is minimized.

Margin testing provides confidence in the robustness of the design when significant numbers of tests and significant numbers of samples are not an option. To be effective, the areas to demonstrate margin must be selected carefully. Emphasis should be put on structural model anchoring to show hardware durability to LCF and HCF - the idea being to result in positive margins for flight. Functionality extremes like propellant conditions, NPSP, and ancillary systems like valve actuation method (pneumatics, hydraulics, electronics) should be exercised to characterize any impacts to performance (possibly identify “the cliff”).

4.8.4.1 Component

RESERVED

Component level margin testing can come in lots of flavors since component qualification test programs many times occur prior to engine test. Being sensitive to over-test as expressed in R-8099.

4.8.4.2 Engine

Demonstrate the engine system's margin capability to operate at conditions, which exceeds the worst-case maximum and minimum operation points required by the engine specification. Both a development/verification engine assembly and a qualification engine assembly should be tested during their respective phases of the program.

Development/Verification Phase Margin Tests: A final development/verification engine configuration should be subjected to tests to demonstrate engine robustness beyond the operating limits established by the engine specification. Demonstration should be a series of tests at 2% increments up to failure or 110% of minimum and maximum operating limits whichever comes first**.**

Qualification Phase Margin Tests: One qualification engine configuration should be subjected to tests to demonstrate engine robustness beyond the operating limits established by the engine specification. Demonstration should be a series of tests at 2% increments up to the value established during the development/verification phase.

Background/Rationale: Engine operating margin has historically shown many examples where unplanned flight anomalies have occurred where propulsion system operation outside the specified performance requirements has been able to salvage the mission. Knowing the margins that the engine is capable of provides the flight controllers with expanded options for saving the mission.

Additionally, other applications of the engine may be considered where above nominal operation of the engine is required.

4.8.5 Human Rating (further description in Appendix D)

Without trying to over constrain design solutions, the NPR 8705.2 attempts to impose requirements which continue to "raise the bar," following the "each program builds on the lessons from the last" philosophy. Most, if not all, historical engines would not meet the NPR 8705.2, including SSME. However, even for Constellation Program (CxP) that levied the document, each of the designs were brought forward showing proposed design approaches based on interpretation of these requirements. Although 2-fault tolerance is levied, there is also design for minimum risk (DFMR) or fault avoidance available as a possible path. It is not logical or necessary to impose 2-fault tolerance in its truest form, or the vehicle would not be able to leave the ground. But, it is justifiable to go through the process of rationalizing and justifying the design approach taken.

The design must demonstrate these capabilities and redundancies. Margins, environmental, and life testing all come into play when demonstrating robustness of design. Functional testing should include exposing redundancies to demonstrate that it is, in fact, a redundancy (i.e., little or no loss in capability).

4.8.5.1 Component

RESERVED

4.8.5.2 Engine

Testing should demonstrate redundancy, fault tolerance, increased margins in thrust and mixture ratio, and durability (life and structural). Testing should demonstrate durability and thrust margin for engine-out conditions. Characterize functionality at degraded level of functionality or loss of redundancy.

4.8.6 Hardware Discrepancy Tracking

Although this is not specifically testing, it is good to 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 it is likely to see several manufacturing issues of varying criticality during development due to low production levels.

Identify and resolve hardware or operational discrepancies, anomalies, or deficiencies. These may include, but are not limited to, leakage, cracks, material erosion/ discoloration, part deformation, unexplained elevated vibration, and unusual operating characteristics.

Background/Rationale: During the course of testing and/or operational experience, various hardware or operational discrepancies, anomalies, or deficiencies may be identified. These may include, but are not limited to, cracks, material erosion/ discoloration, part deformation, unexplained elevated vibration, and unusual operating characteristics. It is recommended that such items be eliminated by a proper design modification since, at a minimum, reduced margins are indicated. However, if sufficient testing and/or analysis can show the increased risk is acceptable, then a programmatic decision may be made to accept such items as a normal expectation for flight hardware. In this case, special inspections and/or data review are recommended to ensure that the condition remains within the qualification experience and bounds of analysis/testing.

4.9 PHYSICAL

4.9.1 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 which can cause dripping onto electrical components, cryo-pumping, and insulation damage. The control and mitigation methods need testing to demonstrate durability, repair techniques, etc.

4.9.1.1 Component

RESERVED

4.9.1.2 Engine

Demonstrate on multiple units (at least 2) the life and durability characteristics to prove out application processes and design sensitivities. Demonstrate repair techniques (if foam and tape) and effectiveness.

4.9.2 External Icing

Ice formation on the external surface of the hardware can act like an insulator or vibration dampener. Environmental testing should simulate vehicle environments to mimic the atmospheric moisture conditions, pre-start conditioning, etc. On J-2, ice formed on the augmented spark igniter (ASI) line and acted as a dampener for ground test. When in flight, the ice did not form and the line ruptured due to vibration.

External iceing should be characterized in the normal course of testing.

4.9.3 Mass Properties

Engine weight, center of gravity (CG), and moments of inertia must be understood and translated to vehicle controls and trajectory analysts. Expect some level of testing to characterize unit-to-unit weights and how that translates to CG and moments of inertia (MOI). This is to include an understanding of the associated uncertainties around these values and weight growth allowances.

4.9.3.1 Component

RESERVED

4.9.3.2 Engine

The engine assemblies should be weighed in the as-tested configuration as part of the engine test program; with the CG and MOI calculated.

4.10 UNIQUE REQUIREMENTS

4.10.1 System Unique Requirements

RESERVED

4.10.1.1 Booster

RESERVED

4.10.1.2 Upper Stage

RESERVED

4.10.1.3 Cryogenic

RESERVED

4.10.1.4 Hypergolic

RESERVED

4.10.2 New or Mission Unique Requirements

New requirements or mission unique requirements levied on the engine following completion of qualification must be evaluated carefully to determine whether or not the existing qualification experience adequately addresses and verifies satisfaction of the new requirements. If not, additional testing and/or analyses should be performed to qualify the engine for the new requirements.

4.10.3 Delta-Qualification Requirements

Qualification testing should be performed on the final design, manufacturing processes, procedures, and acceptance program to be used for flight units. Any deviations following completion of qualification must be justified and the system re-qualified (i.e., “delta-qualification”) via suitable testing or analyses, unless it can be verified that change does not affect form, fit, or function. Changes applicable to delta-qualification include design changes, configuration changes, modified processes, new suppliers, and revised procedures.

5 ACCEPTANCE TESTS

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 a LRE includes hot-fire testing to ensure the article is acceptable for delivery. 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 goal of the acceptance hot-fire test since discrepancies are not always detected during the build process. The extreme thermal, pressure, and dynamic environments during engine operation can cause failure if significant 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.

Although there will be an acceptance series of tests conducted on hardware during the DDT&E phase, this section is primarily to address the production phase and acceptance of hardware during the flight operational phase.

Further, this section focuses upon the aspects which need to be acceptance tested and may have significant references back to previous sections.

5.1 TEST TYPES AND RECOMMENDATIONS

Acceptance tests are conducted to demonstrate the acceptability of each deliverable flight item to meet performance specification and demonstrate acceptable workmanship in manufacturing.

5.1.1 Component

Specific component acceptance test guidelines will be addressed in future editions.

Depending upon the component, a mix of functional and performance tests will be conducted prior to delivering a component to the next higher level of assembly. Items like turbopumps and combustion chambers tend to go through manufacturing checks like torque, leakage, and proof pressure checks as a part of manufacture and ATPs. Items like valves and flexible ducts may undergo more thorough series of functional checks.

Since the standard practice is to hot-fire test an engine to calibrate and “green run” it for acceptance, the components will receive a level of testing over and above the component ATP. This reduces the risk of a failure due to manufacture and assembly. Engine test also hones the performance of each particular build as a contributor to the entire engine. Turbomachinery might have differences in efficiencies from build to build, or maybe coolant flows, thrust balancing, etc. Injectors may have some variation in performance and efficiency, or maybe require some tuning for outer row biasing for coolant flow, etc.

Largely, there is an expectation (like on SSME) that flight propulsion system hardware be hot-fire tested prior to flight. However, there are instances where components may be allowed to bypass this expected norm (LRU type situations). Refer to the section on LRUs for more information, but there may be another level of scrutiny required as a part of acceptance to ensure the proper functionality of these components coming directly from the vendor.

Table 5.1-1 shows the recommendations for acceptance testing, which might share the same title as development and qualification testing, but its contents have been altered to be more commensurate with the production/operational phase.

Background/Rationale: Component acceptance testing at the bench level serves to reduce risk for engine testing, but it often cannot adequately simulate the engine environments. Thus, in general, components should at a minimum be hot-fire tested at the engine level to adequately reduce flight risk. If a component is a LRU, then that component may be removed and replaced by a new unit without requiring re-acceptance hot-fire test of the engine with the new unit. However, if that engine is not to be hot-fired again and the replacement unit normally includes an engine hot-fire test as a standard part of its acceptance test, then the replacement unit should be subjected to a hot-fire test on some other engine. Individual components are excluded from engine hot-fire test requirements only when they can undergo equivalent unit-level acceptance testing. Equivalent testing should consider all appropriate environments such as temperature, vibration, pressure, vacuum, and chemical, and such testing should demonstrate functionality and performance of the unit under conditions similar to those achieved in the engine acceptance test firing and flight.

5.1.2 Engine

Acceptance testing should to occur at the integrated engine system level. Because of the combination of complex componentry, significant dependency on functional timing, and strict performance bands, the engine testing tends to be a logical step in acceptance of flight propulsion systems. Single engine acceptance is more “regular” as clusters tend to be seen as part of integrated stage acceptance.

The acceptance series functionally checks critical systems and performance should be “tagged” for flight predictions. The acceptance series test parameters and instrumentation should fall within the development and qualification experience.

New engines should have a minimum of two tests and a minimum total hot-fire duration equal to the full mission burn duration. If full mission duration is not possible on the engine system due to facility limitations, then key life critical components may be green run separately to full duration, followed by shorter duration engine system testing. As an engine system accumulates successful ground and flight history, starts/duration requirements may be reduced provided that performance- and workmanship-verification objectives are not compromised.

Table 5.1-1 shows the recommendations for acceptance testing, which might share the same title as development and qualification testing, but its contents have been altered to be more commensurate with the production/operational phase.

5.1.2.1 Engine (Pressure-Fed)

Pressure-fed engine testing should be in accordance with the above paragraph, with the exception of the requirements for a minimum of two tests and a minimum total hot-fire duration equal to the full mission burn duration. Historical precedent for pressure-fed engine design is to not accumulate a significant portion of the required mission life requirement as part of acceptance test.

Table 5.1-1 shows the recommendations for acceptance testing, which might share the same title as development and qualification testing, but its contents have been altered to be more commensurate with the production/operational phase.

Table 5.1-1: Engine Acceptance Tests Matrix

Section		Objective	Component	Engine		
5.2 Performance	5.2.1	Steady State Performance Characterization		x		
	5.2.2	Repeatability		x		
5.3 Life	5.3.1	Operational Life/Durability		x		
	5.3.2	Single Burn Endurance Test		x		
5.4 Functional Characteristics	5.4.1	Propellant Conditions				
		– Pre-start Chilldown		x		
		– Start Propellant Conditions		x		
		– Steady State Propellant Conditions		x		

		– Shutdown Propellant Conditions		x		
	5.4.2	Transient Characterization – Start Transient – Restart – Throttle Transient – Shutdown Transient – Abort Shutdown		 x x x x x		
	5.4.3	Ancillary Subsystems – Autogenous Pressurization – Valve Actuation – Purges – Electrical Power and Ignition		 x x x x		
	5.4.4	Thrust Vector and Gimballing – Gimbal Limits – Roll Control Limits – Ambient Environment – Inspections – Heat Flux – Clearance – Interface Compatibility – Thrust Vector Alignment		 x x x x x x x x		
5.5 Controls	–	Functional Tests	x	x		
	–	Engine Control System Malfunction Logic Check	x			
	–	Engine Health Management	x	x		
5.6 Operations	5.6.1	Pre-test Inspections and Checkouts		x		
	5.6.2	Leakage	x	x		
	5.6.3	Post-test Inspections		x		
	5.6.4	Drying Purges		x		
5.7 Environments	–	Vibration/Shock/Acoustics – External Vibration – Self-induced Vibration		 x		
5.8 Design & Construction	5.8.1	Proof Pressure	x			
	5.8.2	Human Rating		x		
	5.8.3	Hardware Discrepancy Tracking	x	x		
5.9 Physical	5.9.1	Mass Properties – Mass – Center of Gravity – Moments of Inertia	 x x x	 x x x		
5.10 Unique Requirements						

5.2 PERFORMANCE

5.2.1 Steady State Performance Characterization

The objective is to understand the performance of each build relative to the experience base set in development and qualification. Typically, as a part of this, each engine will require some level of tuning to ensure the performance is within the desired operational parameters. Performance parameters (primarily thrust, Isp, and MR) can vary over the flight regime depending upon propellant and hardware conditions. Flight profile tends to be mimicked to a certain extent, but is not required.

5.2.1.1 Component

RESERVED

5.2.1.2 Engine

Tag performance and calibrate engine to desired thrust and mixture ratio and Heat Exchanger/Tap-Off parameter, if required, based on hardware build performance as demonstrated during acceptance tests. A single hot-fire to mission duration is desired within the series as a minimum. If orifice or valve position changes are required, or some performance-related change/procedure is conducted, then a validation run may be required. "Paper" calibration should be permitted provided adequate history is provided to keep calculated error within calibration limits.

5.2.2 Repeatability

The objective is to characterize the run-to-run performance variation of a particular build, which aids in flight predictions.

5.2.2.1 Component

RESERVED

5.2.2.2 Engine

This requires multiple hot-fire tests to show comparison to DDT&E and production experience.

5.3 LIFE

5.3.1 Operational Life/Durability

Employ life limits (starts and durations) based upon DDT&E experience. This must be balanced with other test objectives that can draw out the numbers and durations of tests. The intent is to fly with the maximum life margin to minimize sensitivity to build-to-build hardware durability variation.

This should not become a reason to eliminate acceptance testing, but rather it will help ensure sufficient margin in the system to handle the proper number of cycles over the expected life of the hardware.

5.3.1.1 Component

RESERVED

5.3.1.2 Engine

Pre- and post-test inspections are expected. The data gathered through these activities in conjunction with hot-fire test data should reinforce that the hardware is not degrading faster than rates experienced and accepted during development and qualification.

5.3.2 Single Burn Endurance Test

Test objective is to demonstrate that each build can endure a mission duration prior to flight.

5.3.2.1 Component

RESERVED

5.3.2.2 Engine

A single mission duration hot-fire should be part of the acceptance series. It is not necessary to explore margins with respect to time unless this is an expected operating condition. Flight profile is not necessarily required but, if not used, the profile should be deemed equivalent with regards to duration and performance output expected in flight.

5.4 FUNCTIONAL CHARACTERISTICS

5.4.1 Propellant Conditions

Since acceptance series includes hot-fires, 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 promote consistency to understand build-to-build variations.

5.4.1.1 Component

RESERVED

5.4.1.2 Engine

Prestart Chilldown: Ensure proper functionality of chilldown systems. Flowrates and time should be tracked as it pertains to knowing systems have been adequately thermally conditioned.

Start: Acceptance series should attempt to replicate vehicle start conditions.

Steady State: Acceptance series should attempt to replicate vehicle start conditions. Vary interface pressure to show any performance variation within run box conditions. Have a portion of the test held as steady as possible for performance tagging.

Shutdown: Production testing should maintain consistent shutdown conditions to enable build-to-build and run-to-run variations to be exposed. Varying interface propellant pressure is reasonable to bound shutdown characteristics expected in flight if vehicle is significantly sensitive.

5.4.2 Transient Characterization

5.4.2.1 Component

RESERVED

5.4.2.2 Engine

Start: Understand where run-to-run variation lands within experience for each build.

Restart: Understand where run-to-run variation lands within experience for each build. Additional parameters may come into play to simulate restart conditions that the engine may be sensitive to during the mission.

Throttling: If required in flight, expect acceptance series to thoroughly exercise the control systems and understand the response of each build relative to “family” of experience.

Shutdown: Understand where run-to-run variation lands within experience for each build.

5.4.3 Ancillary Systems

Acceptance test series should operate these systems under expected nominal range of operation. Some controlled variation on interface conditions are allowed as it pertains to understanding performance and functionality variation from build-to-build.

5.4.3.1 Component

RESERVED

5.4.3.2 Engine

For the most part, expect nominal interface conditions and control profiles. Assure variation lands within experience for each build.

Autogenous Pressurization: Expect engine test stand configuration to vary from flight systems.

Valve Actuation: These systems can be responsible for significant variation of flight performance and need thorough examination, which can drive some additional variation of interface conditions during acceptance test depending upon system sensitivity.

Purges: These systems can be responsible for significant variation of flight performance and need thorough examination, which can drive some additional variation of interface conditions during acceptance test depending upon system sensitivity.

Electrical Power and Ignition: May vary interface conditions slightly, but still within expected nominal operating range

5.4.4 Thrust Vector and Gimballing

5.4.4.1 Component

RESERVED

5.4.4.2 Engine

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.

Gimbal Limits: Flex engine to exercise flexible ducting, lines, cabling, and structure. Expect nominal control profiles to be exercised.

Roll Control Limits: Expect nominal control profiles to be exercised.

Ambient Environment: Measure to understand effects on hardware relative to "family" of experience.

Inspections: Nominal pre- and post-test inspections.

Heat Flux: Verify that the engine-induced heat flux on adjacent surfaces during hot-fire TVC testing is within acceptable limits.

Clearance: Dry, ambient hardware conditions can be used to check fits/clearances.

Interface Compatibility: Expect nominal interface conditions and control profiles to be exercised.

Thrust Vector Alignment: Measure thrust vector during hot-fire and quantify for stage integration and vehicle guidance, navigation, and control.

5.5 CONTROLS

Expect strict adherence to software verification and validation (V&V) procedures that are established during DDT&E. A significant amount of testing is done during the V&V at the component or subsystem level in a laboratory setting. Engine and higher levels of assembly do little during actual hot-fire testing to validate all the software functions since test conditions are typically nominal. However, there are more benign conditions on these assemblies when the system is not in operation to exercise more of the software functionality and response of the physical aspects of the system (i.e., valves).

5.5.1 Component

Thoroughly test component and subsystem in laboratory environment. Hardware-in-the-loop type labs are common approaches for flight software and electronic hardware integration.

Functional Tests: RESERVED

Engine Control System Malfunction Logic Check: RESERVED

EHM System Validation: RESERVED

5.5.2 Engine

Control nominal profiles to be run during hot-fire acceptance series.

Functional Tests: Prior to hot-fire, expect a series of functional readiness tests (FRTs) to be run showing the logic of the software matches expectations. Expect valves and purges to be exercised as a part of the FRTs.

Engine Control System Malfunction Logic Check: FRTs should include checking fault detection and response systems built into the engine control system. This may only be exercising redline type cut off systems.

EHM System Validation: FRTs should also exercise any advanced logic that would be considered part of the fault detection, isolation, and recovery system and the response desired/expected.

5.6 OPERATIONS

5.6.1 Pre-Test Inspection and Checkouts

See Section 4.6.1, Engine Development/Qualification. However, the verification of the procedures is assumed complete and this phase focuses primarily on execution of the established procedures.

5.6.2 Leak Test

See Section 4.6.2, Engine Development/Qualification. However, the verification of the procedures is assumed complete and this phase focuses primarily on execution of the established procedures.

5.6.3 Post-Test Inspection

See Section 4.6.3, Engine Development/Qualification. However, the verification of the procedures is assumed complete and this phase focuses primarily on execution of the established procedures.

5.6.4 Drying Purges

See Section 4.6.4, Engine Development/Qualification. However, the verification of the procedures is assumed complete and this phase focuses primarily on execution of the established procedures.

5.7 ENVIRONMENTS

The 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 build’s response. Engine environments during operation tend to be the most extreme environments on engine hardware.

5.7.1 Component

Acceptance testing for environmental acceptance of components is informed by SMC-S-016 or MIL-STD-1540 type documents.

5.7.2 Engine

Largely, engine operating environments encompass the worst-case environments for the engine hardware. Thus, it tends to act as an adequate screen for hardware acceptance. For upper stage or in-space propulsion, there may be significant environments that exist, which drive design features that need additional testing over and above engine hot-fire. Many times, the engine hot-fire can still serve as an adequate screening environment.

5.8 DESIGN AND CONSTRUCTION

The design and construction standard have mainly been applied during the design phase and verified during DDT&E. This section is the execution of procedures developed during that phase to be continued screening for adequacy of hardware.

5.8.1 Proof Test

Proof testing should occur as part of manufacturing and assembly procedures at the component level. Leakage is measured during engine and higher assembly build processes.

5.8.2 Human Rating

Tests should be incorporated to ensure the functionality of systems and controls pertaining to redundancy, fault avoidance, DFMR, and caution and warning systems over and above what have been discussed already in previous sections.

5.8.3 Hardware Discrepancy Tracking

Processes and procedures defined in DDT&E are expected to be utilized during the production phase.

Refer to Section 4.8.6, Development/Qualification.

5.9 PHYSICAL

5.9.1 Mass Properties

Mass properties characteristics should be provided at major component, and engine levels. Procedures and analysis is accompanied by weighing individual pieces to establish mass and moments of CG inertia at major assembly levels. Each build is expected to track these characteristics.

5.10 UNIQUE REQUIREMENTS

RESERVED

6 PRELAUNCH VALIDATION AND OPERATIONAL TESTS

6.1 *GENERAL GUIDELINES TEST TYPES AND RECOMMENDATIONS*

General prelaunch requirements are defined in SMC-S-016. The scope of these tests covers from receiving a stage at the launch site to launch. This section is focused on augmenting these, where needed.

Table 6.1-1: Prelaunch Validation and Operational Tests Matrix

Section	Objective	Component	Engine
6.2.1	Receiving Inspection – Software – Functional Checkouts – Leak Checks	 x 	 x x x
6.2.2	Purges		x
6.2.3	Vehicle Readiness Test		
6.2.4	Vehicle Tanking Test – Preflight Procedures – Preflight Sequence of Events – Propulsion System Thermal Conditioning – Launch Commit Criteria (LCC) Check – Thrust Vector Control (TVC) Test – Post-test Inspections		 x x x
6.2.5	Prelaunch Countdown		x

6.2 *PRELAUNCH VALIDATION AND OPERATIONAL TEST DESCRIPTIONS*

6.2.1 Receiving Inspection

An external inspection of the condition of hardware is to be conducted. Discrepancies must be noted and dispositioned. Desiccants, covers, closures, acceleration monitors, and support equipment/cradles/etc., that "touch" flight articles should also be included as part of the receiving inspection, with the focus on understanding if the condition of the hardware has changed as a result of transportation and handling. Follow SMC-S-016 recommendations for shock, vibration, temperature and humidity monitoring. Interfaces should be inspected to verify compliance with dimensional and surface finish requirements. If main propellant inlets covers are removed, the internal area should be inspected to verify FOD-free conditions. Follow on inspections and checkouts regarding functionality and more thorough understanding of internal hardware condition are expected per SMC-S-016.

Software: Any engine software should be verified to be the correct version and a checksum performed.

Functional Checkout: Reference SMC-S-016

Leak Checks: Reference SMC-S-016

6.2.2 Purges

Intent is to maintain engine internal environment (desired cleanliness and moisture levels) after any protective covers and closures have been removed. Verify pressures, temperatures, flow rates, and fluid quality (grade, moisture content, etc.) meet requirements.

For vehicle assembly and maintenance: While performing final vehicle assembly, maintenance, etc., in a semi-controlled environment, periods of exposure may be allowed. However, to ensure the propulsion system internal environment remains clean, a sequencing of purges and moisture checks are likely to follow to validate the internal environment.

In preparation for launch: This includes tanking and loading of propellants and pressurants. Purges are necessary to on a more continuous basis to provide the confidence that the hardware internal environment is maintained. Purge sequences are usually programmed in and rules for moving from one sequence to another (forward or backward) are well established and software controlled.

6.2.3 Vehicle Readiness Test

Perform engine control system functional checks through the airborne flight control system with control parameters at nominal values. Operate the control system per the flight sequence. 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. Also refer to SMC-S-016.

Background/Rationale: The vehicle readiness test is intended to verify readiness of the assembled vehicle by performing a simulated flight sequence. If the engine control system is capable of being remotely functioned, it should be functioned accordingly per the flight sequence. Control parameters should be at nominal operating values.

6.2.4 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 as possible in the pre-launch countdown procedures as feasible without igniting the propulsion systems, including loading of propellants.

For pressure-fed 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 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.

Preflight Procedures: Demonstrate preflight procedures and launch timelines. Operational procedures should be used to the extent possible.

Preflight Sequence of Events: Demonstrate preflight sequence including any functional health checks such as TVC and valve slewing and engine controller checkout.

Propulsion System Thermal Conditioning: Exercise thermal conditioning processes and procedures. Verify performance of engine system passive and active thermal control (including chilldown, warming purges, heaters, etc.).

LCC Check: Verify engine LCC can be satisfied prior to commit time.

TVC Functional Check: Demonstrate TVC operational envelope prior to introducing propellants. Demonstrate TVC operational envelope after propellant load and engine thermal conditioning.

Post-Test Inspections: Expect nominal post-test inspections to be performed after vehicle and launch facility is “safed.” Intent is to verify that the hardware resulting condition is satisfactory and ready for flight.

6.2.5 Prelaunch Countdown

Refer to Vehicle Tanking Test for expected checks to be performed during nominal prelaunch countdown (with exception to post-test inspections). Checks for prelaunch countdown are in addition to these as they are intended to verify propulsion system health immediately prior to liftoff. Primarily, this consists of review of the 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: Definitions and Descriptions

Acceptance Hardware: The item subjected to acceptance testing should be flight hardware and can include software as applicable. Manufacture of the acceptance hardware must comply with all quality requirements of the flight hardware.

Acceptance Phase: Phase in which hardware is tested and subsequently accepted for operational use. Consists of a series of tests that screen for workmanship issues, checks functionality, and measures the performance of each particular build.

Acceptance Test: Test conducted to demonstrate that flight hardware is free of workmanship defects, meets specified performance requirements, and is acceptable for delivery. Generally, acceptance test operating conditions should remain well within the operating envelope and, in most cases, are fairly nominal. Margins are not tested except under extraordinary circumstances (e.g., specific technical issue resolution) since the hardware being tested is intended for flight. 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 “clear” prior to flight.

Ambient Environment: The actual external environment surrounding an engine or subsystem. Will vary depending on whether operation is during ground test or flight test.

Assembly: Completed functional subsystem, system, engine, vehicle, or other hardware, which itself is assembled from smaller parts.

Battleship Test: A test configuration in which any one piece is designed with the intention of holding significant margin regarding life, disregarding the thrust-to-weight target of the assembly (a.k.a. workhorse).

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

Breadboard: Representative components are integrated in a laboratory or facility test environment that is representative of the functional relationship of the final system to understand , but is not configured with in the final system configuration or with all of the

Burst Factor: A multiplying factor applied to the maximum expected operating pressure (MEOP) to obtain the design burst pressure.

Burst Pressure: The maximum force per unit area that an object containing a fluid can withstand before the stress created by that force causes the object to fail.

Burst Test: Test to identify the 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).

Component: Major subdivision or elementary part of a system (e.g., injector, chamber, turbopump, etc.).

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, Development, Test and Evaluation (DDT&E): The period during which a new program 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. Also refer to development phase.

Development Hardware: Generally full-scale hardware and very similar to the flight hardware. The hardware in the early development phase should be representative in flow path and function, although it may not necessarily be flight-weight hardware or meet flight quality requirements. This is appropriate since design changes are often required during the development program as new data are collected. However, by the time the development program is completed the test articles should be completely or nearly completely equivalent to the flight hardware in all aspects of flow-path and design.

Development Phase: The development phase usually provides the first true demonstration of the capabilities of a proposed design. Development tests are conducted as required to: (a) Validate new design concepts or the application of proven concepts and techniques to a new configuration; (b) Assist in the evolution of designs from the conceptual phase to the operational phase; (c) Validate design changes; (d) Expand, update, and anchor models; (e) Reduce the risk involved in committing designs to the fabrication of qualification and flight hardware; (f) Develop and validate qualification and ATPs; and (g) Investigate problems or concerns that arise after successful qualification. Requirements for development testing therefore depend upon the maturity of the subsystems and units used and upon the operational requirements of the specific program. An objective of development testing is to identify problems early in their design evolution so that any required corrective actions can be taken prior to starting formal qualification testing. Development tests should be used to confirm structural and performance margins, manufacturability, testability, maintainability, reliability, life expectancy, and compatibility with system safety. Where practical, development tests should be conducted over a range of operating conditions that exceeds the design requirements to identify marginal capabilities and marginal design features.

Development Test: Tests conducted on representative articles to characterize engineering parameters, gather data, and validate the design approach. Development test conditions should encompass worst-case conditions for the intended application. In addition, the development program is used to verify by test margin outside the operating envelopes. 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.

Duty cycle: (1) Ratio of pulse duration time to pulse repetition time. (2) Required operating life.

Engine: See “Liquid Rocket Engine.”

Engine Cycles: A thermodynamic cycle that describes how liquid propellants are fed to the engine combustion chamber. Types 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.

Envelope: (1) Boundary which encompasses all possible variations of a set of parameters (e.g., operating conditions envelope). (2) Dimensional boundary which encompasses the component or system.

Expansion Ratio: Ratio of cross-sectional area of rocket nozzle exit to area of nozzle throat.

Expendable Engine: An engine that is discarded after use on a single mission. The SL of an expendable engine includes all ground testing and mission operation time.

Factor of Safety (FoS): A multiplying factor applied to the maximum expected operating loads in the design analysis to account for uncertainties in actual load conditions, material properties, design procedures and analyses, and manufacturing.

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. Not all new vehicles will include test flights but, when they do occur, they may be performed for a nominal mission or a selected mission of particularly high interest or value. In some cases, special operational tests may be added to a mission flight provided those tests do not adversely impact the mission objectives. Both test flights and mission flights may be flown with special flight instrumentation along with the standard flight instrumentation (SFI) suite to provide additional flight data for further operational characterization and/or verification for aspects that could not be adequately ground tested. Results generated during this phase may include 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. If flight experience is found to be significantly different than expectations and/or specified design requirements, then further development and/or qualification ground testing may be warranted. No further detailed discussion of flight operational testing is contained in this document, since objectives for this phase are often program dependent.

Functional Test: Test that exercises the function of an item.

Guard Band: The magnitude of the offset from the specification limit to the acceptance or rejection zone boundary.

Impulse: Integral of thrust and time over a specified time period.

Line Replaceable Unit (LRU): A unit (e.g., igniter or closed-loop control valve) that may be removed and replaced by a new unit without requiring engine removal and test firing.

Limit Load (LL): The highest load, or combinations of loads, that may be applied to a structure during its SL and, acting in association with the applicable operating environments, produces a design or extreme loading condition for the structure. When a statistical estimate is applicable, the LL is that load not expected to be exceeded on at least 99% of flights, estimated with 90%conficence.

Liquid Rocket Engine (LRE): Launch or space vehicle propulsion subsystem device utilizing a combination of components and liquid phase chemical reactants to provide thrust. These devices also can be grouped or be part of an engine system to satisfy full stage and vehicle propulsion needs.

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

Margin of Safety (MS): MS = 100% x allowable / (FS x actual) - 1.

Maximum Expected Operating Pressure (MEOP): The highest gage pressure that an item in a pressurized subsystem is required to experience during its SL and retain its functionality, in association with its applicable operating environments. The MEOP is synonymous with limit pressure or maximum operating pressure (MOP) or maximum working pressure (MWP). Included are the effects of maximum ullage pressure, fluid head due to vehicle quasi-steady and dynamic accelerations, water hammer, slosh, pressure transients and oscillations, temperature, and operating variability of regulators or relief valves.

Maximum and Minimum Expected Temperatures: The highest and lowest temperatures that an item is expected to experience during SL, including all operational modes.

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

Non-destructive Testing (NDT): Methods of testing for integrity that does not impair serviceability or future life.

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: Extreme boundaries of conditions to which hardware may be subjected during operation (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 operational life of an engine is 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 joined pieces, which are not normally subject to disassembly without destruction or impairment of the design use.

Pogo Effect: Self-excited, sustained vibration due to interaction of structural vibration and engine thrust oscillation.

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 vehicle factory or launch site prior to launch. Used to verify system readiness for integration, to verify system integrity, safety and performance, and to verify successful integration.

Pressure Vessel: A structural component whose primary purpose is to store pressurized fluids.

Proof Factor: A multiplying factor applied to the LL, or MEOP, to obtain the proof load or proof pressure for use in a proof test.

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

Proof Pressure: Synonymous with the term proof load. Value established by taking the calculated maximum design condition, MEOP, etc., and multiplying it by the proof factor.

Proof Test: An acceptance test used to prove the structural integrity of a unit or assembly, or to establish maximum possible flaw sizes for safe-life determination.

Propulsion System: The system required to produce 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.

Prototype: First example build of item intended for production. Intended to be as representative of definitive article as possible, but usually deficient in many respects. Many times the prototype will be focused on replicating only specific parameters since its purpose is to guide future development, permit customer evaluation, and demonstrate key new technologies.

Prototype Phase: Prototype testing (a.k.a. feasibility, risk reduction, or demonstration testing) often precedes development and is intended to assist design definition by providing engineering data to confirm analyses and/or help define expected operating conditions. Often this testing includes Research & Development (R&D) 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. Not all programs will utilize prototype hardware or perform prototype testing. The decision will be based on a number of factors, including the design maturity, technology readiness levels, and the program risk mitigation strategy. No further detailed discussion of prototype testing is contained in this document since objectives for this phase are often technology dependent.

Qualification Hardware: Essentially first production articles that go through a series of qualification tests to demonstrate readiness for flight operation. Qualification hardware should be produced from the same drawings, using the same materials, tooling, manufacturing processes, and level of personnel competency 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. These changes may include adding instrumentation to record functional parameters for engineering evaluation. Feedlines should also be as flight representative as possible, definitely at the integrated propulsion system level testing, but preferably at engine level testing as well. Manufacture of the qualification hardware should be controlled to the same quality requirements as the flight production hardware. Often the qualification engines are the first engines off of the production line.

Qualification Phase: 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 of the development test program to reduce program risk at this phase, and concurrent completion of development objectives and qualification testing is not recommended. 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 Test: Tests conducted to demonstrate satisfaction of design requirements including 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 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) are also verified to demonstrate robustness. However, qualification testing should not create conditions that violate acceptable safety margins or cause unrealistic modes of failure.

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

Reuse: Use of engine after completion of one mission.

Reusable Engine: An engine that is to be used for multiple missions. The SL of a reusable engine includes all ground testing, planned reuses (mission operation times), refurbishment, and retesting.

Reusable Item: An item that is to be used for multiple missions. The SL of reusable hardware includes all testing, planned reuses, refurbishment, and retesting.

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.

Similarity: The process of assessing by review of prior acceptance data or 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 weight flow rate of propellants through the engine inlet. Specified at specific altitude (e.g., sea level and/or vacuum conditions).

Storage Life: The time that a unit can be stored after acceptance tests without replacement of parts and subsequently operate within specification limits.

Subassembly: A unit containing two or more parts which is capable of disassembly or part replacement.

Ultimate Load (Design): A load or combination of loads that the structure must withstand without rupture or collapse in the applicable operating environments. It is equal to the product of the LL and the design ultimate FoS.

Upper-stage Vehicle: An upper-stage vehicle is one or more stages of a flight vehicle capable of injecting a space vehicle or vehicles into orbit from the sub orbital trajectory that resulted from operation of a launch vehicle booster.

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 by inspection, test or analysis.

Yield Load (Design): A load or combination of loads that the structure must withstand without experiencing detrimental deformation in the applicable operating environments. It is equal to the product of the LL and the design yield FoS.

Appendix B: Other Relevant Discussion

B.1 OTHER ASPECTS OF DDT&E RELEVANT TO TEST

Requirements definition specify and describe functional requirements, program requirements, technical requirements document, interface control document, engine and system requirements. Test planning and implementation cannot be completed properly if detailed requirements and necessary engine operating characteristics are not well established. Programs should not over specify requirements or establish unnecessary requirements. Instead it should set goals for aspects that do not have hard requirements to allow for pushback on goals to make an overall more optimal system.

B.1.1 Design Heritage

Previous design heritage is important, but must be appropriate to the specific intended conditions and application. Design heritage includes any past testing and operational use of engine components and sub-systems. Heritage can provide a significant advantage and a “head start” on the path toward thorough understanding of engine operation and ultimate verification of the engine capabilities. Together, modeling and simulation and design heritage help determine whether it is appropriate to qualify certain aspects of the engine by similarity to existing systems, by analysis, or by test. For vehicle structures, well-defined “qualification by similarity” guidelines allow objective use of design heritage to assist with qualification of new designs. In any event, care must be taken that the “similarity” being assumed is indeed there. For example, a component ostensibly built to the same drawings and specifications, but by a different vendor cannot be assumed to be the same without additional verification. Experience has shown this to be increasingly important as the life cycle of the engine progresses.

B.1.2 Risk Management

Risk Management is intended to anticipate potential failures, mitigate the impact of failures, and solve issues early in the program. Program Managers should avoid a “1-strike-and-you’re-out” mentality during the test program (i.e., very adverse to near term political risk) and instead adopt a mission success-oriented mentality (i.e., mitigate long term technical risk). Impacts increase as risks are deferred, and it is far better to perform robust testing and damage test hardware than to perform “safer” testing but lose a mission payload due to a failure mode that should have been identified by a proper test program. It might be possible to actively encourage a focus on mission success and mitigate the impact of political risk by tying stakeholder metrics and rewards to long term mission success. Technology development tends to be a part of every engine development program. Inherently there is risk to realizing all the benefits as promised by the advancement in technology. This undoubtedly has programmatic risk, but also performance and functionality risk. DDT&E programs must be careful in the classification of risk as countermeasures for the two different types (i.e., programmatic versus technical) are totally different.

B.1.3 Programmatic Considerations

Apart from the technical aspects that this document strives to focus upon, there are significant programmatic aspects that must be considered on each program/project. Consider politics, cost, and schedule. Careful planning is necessary to provide the appropriate cost and schedule margins to testing and evaluation activities.

B.2 TEST PLANNING

Test planning includes the process that establishes the test objectives from program and technical requirements, and integrates those objectives with the product configuration, to identify test article configurations, establish detail test data monitoring and analysis plans, and to identify requirements for human resources, the facility, test equipment, safety, pre-/post-test inspections, and reporting. Fundamental elements of the test planning process include identification of test objectives, success criteria, and analyses plan. Supporting elements include instrumentation, facilities & special test equipment (STE), safety, test risk assessment, scheduling, and test procedures. Data deliverables set up the necessary submittal rate and level of detail needed at each submittal. For example, there is a need for validation of the requirements early in the program. Verification matrices need to be set up with verification methods and success criteria (top level) to validate the requirements as early as systems requirements review (SRR). One reference to utilize is MSFC-HDBK-2221, Verification Handbook, which describes the verification process in Volume I, and provides verification documentation examples in Volume II. Other discussion below may be useful in scoping the documentation and planning effort in preparation of the test program. It is not considered all inclusive.

B.2.1 Minimum Elements for Test Plan

The minimum requirements for a test plan include security classification, objectives/success criteria, test matrix, test schedule, test risk assessment, required safety procedures, test article description, facility and STE requirements, instrumentation list, list of all engine and facility abort parameters (by instrumentation header), test conditions/set-up/standard tolerances, detailed run procedures, and post-test requirements.

B.2.2 Requirements Definition

Planning must properly define requirements, including a description of the technical and contractual requirements to be accomplished through testing. In addition, it should provide a link to the Systems Engineering & Integration requirements verification planning activity. It should include data, documents, reviews, propellant conditions, hardware, and data. Planning must consider how flight margins will be accounted for (e.g., during ignition or minimum NPSP start demonstration, “testing of propellant tank inlet conditions should demonstrate a minimum of 0.5 pounds per square inch differential (psid) start box margin”).

Test Team

Planning must specify the roles and responsibilities of test team, as well as define the mechanism for communicating changes to test plan.

Test Resources

Planning must establish resource allocation baselines, as well as providing spare hardware. The plan must account for the likelihood of failures and damage to facility or test article hardware.

B.2.3 Requirements Verification Test Planning Elements

Objectives

Specific objectives should be generated to quantitatively describe what is to be accomplished in the test or test series. All objectives should have measurable outcomes.

General Implementation

The most appropriate test methods should be selected. Candidates include Design of Experiments, direct functional objective based approaches, or statistical methods.

Test Article/Assets

Actual engine hardware with the correct configuration must be defined and tested.

Success Criteria

Specific and well-defined success criteria must be established for the measurable parameters of various test objectives to ascertain whether a given test achieved its respective requirements and goals. There should be success criteria defined for all objectives. Agreed upon definitions for valid tests, premature cut-offs, and aborts must be established.

Analysis Plan and Data Review

Analysis and data review requirements must be identified for each test. Items may include inspection reports, low-speed data analysis, high-speed (hi frequency) data analysis, spectral analyses, video/film, and comparison to system and transient models. Results should include recommendations for subsequent testing, depending upon satisfaction of success criteria for the preceding tests.

Instrumentation

A detailed instrumentation list must be generated that defines what must be measured to evaluate the success of the test and safely operate the facility. The list should include all instruments used in the test program, including those used on the test article and the facility. Detailed specifications should be provided for the following: parameter description, instrument name/callout, instrument type, instrument vendor/serial number, calibration life cycle, critical instrument designation (i.e., required or desired for upcoming test), redline channel assignment (if applicable), installation torque, placement/location, port requirement, cleanliness requirement, timing (i.e., time periods of active recording), range, response, sample rate, power/purge requirements, and designation (e.g., normal flight instrumentation, ground test instrumentation [GTI], SFI).

Test Facilities and Equipment

All equipment needed to support the various tests must be specified and allocated with respect to the schedule. Standard interfaces should be used to the maximum extent possible. Necessary computer control and communication must be determined and established.

Environmental Impact

The potential impact of the test program to the surrounding environment and proposed mitigating actions must be defined. The appropriate processes should be employed well in advance of testing to ensure the required approval is received.

Safety

The safety procedures to be used during test article installation, operation, and removal must be identified. Special precautions should be included as necessary. This should include provisions for handling of hazardous materials and contaminated hardware.

Test Risk Management

Test risk assessment should be performed to identify and provide a summary of the risks associated with the tests required by the test plan. Pre-declared risk statements should be generated for any tests including operating conditions that are either inherently dangerous or do not exist during the mission (e.g., malfunction tests, tests to failure, safety limits testing, operating limit survey), as well as known high risk tests that may not accurately represent true flight conditions but if successful could mitigate mission risk. In addition, a clear plan for incident handling is needed in case of significant test mishap.

Scheduling

The tasks and timing required to complete the test or series of tests must be identified and incorporated into an integrated schedule. The schedule should be used to monitor progress, so that any potential issues can be identified and mitigated in a timely manner.

Test Procedures

Detailed test procedures with instructions for performing each test should be generated. They should provide line-by-line description of the test sequence to be performed. Potential test procedures include facility and test article setup, countdown checklist, post-test securing, and next-test preparations.

Hazards Analysis

An integrated facility and test article hazard analysis should be completed and reviewed prior to first test to confirm that appropriate mitigations are in place.

B.3 TEST OPERATIONS AND IMPLEMENTATION

Processes must be put in place to efficiently and effectively turn tests around. When considering the complexity and cost associated with each engine or higher level of test, it needs to be well orchestrated. The following information is provided as guidance information, helping formulate an effective turn around process.

B.3.1 Test Preparation

Test Readiness Review

Performing a test readiness review just prior to actual start of testing provides many benefits. It brings together the entire test team to review a summary component and engine pedigree, the planned testing, schedule and manpower constraints and open items that must be closed prior to first engine test.

Test Performance Predictions

Performance analysis will provide the basis for understanding the expected operational profile of the test article. Pressure, temperature, flow rates are all modeled to provide a pre-test prediction.

B.3.2 Post-Test Activities

Data Review

A systematic review of the test data should be conducted concurrently within a test series as well as upon the completion. This should include test article as well as test facility data. The basis for the review should include comparison to specifications and interface requirements, identification and disposition of out-of-family conditions and statistical outliers, and comparison to model predictions. The data review should be conducted by the hardware experts and reviewed with the multi-disciplinary test team and other experienced and objective personnel. The latter reviewers' function is to provide a systems review and to identify potential cross-discipline issues. Future test constraints should be identified and resolved. A database of test anomalies should be maintained to capture lessons learned. The individual test data review should be limited to verification that success criteria or test objectives were met, identification of test anomalies, and evaluation of future test safety based upon current test results. Extensive analysis of test results for model validation etc., should be separated from the test turnaround process.

Test Objectives Success Evaluation

Evaluate the gathered data relative to the test objectives, and then relate them back to verification activities. The data should be scrutinized heavily as it is significant to determine whether the success criteria has been met or if another test will have to pick up this objective. Consider the data, calibration of instrumentation, and system uncertainties.

Anomaly Resolution

The anomaly resolution process should include a comprehensive assessment of potential root causes utilizing a fault tree, fishbone analysis, or other similar techniques. The potential impacts of the anomaly on the health of the hardware directly or indirectly impacted by the anomaly should be systematically evaluated. Investigation of the anomaly may require additional instrumentation and/or testing. Recovery from the anomaly may require design or operating changes.

Hardware Functional Checkout and Inspection

Functional checkout of engine components is often valuable following the completion of higher level testing. This testing serves to verify hardware viability and performance. Inspection of hardware following completion of testing should entail disassembly to the extent that wear and/or mechanical integrity can be evaluated. Assemblies that are in the process of life testing can be subjected to an abbreviated inspection sufficient to confirm viability to continue the life testing followed by a complete disassembly inspection at the conclusion of life testing. Inspection and functional checkout may be waived if sufficient prior experience exists for the hardware under similar test conditions. Qualification engines should be completely disassembled, inspected, and displayed after completion of testing.

Test Plan Adjustments

Replanning is crucial to effective use of the test budget (numbers of tests and contingency available for retest/reverify activities).

B.3.3 Quality Assurance (QA)

QA provides an independent check on the workmanship performed in all program phases. In design, they ensure the proper features, criteria, and processes are included into the DDT&E phase, which will set the stage for production and operational phases. In manufacturing and assembly, QA performs the function of ensuring the design and process checks are properly implemented. QA oversees activities during test and evaluation to ensure tasks are performed per instruction. QA also enforces the dispositioning of hardware (and it associated paperwork) when something does not meet specification tolerances. This can occur in any phase from manufacturing through test. QA Plans are written to document nominal and dispositioning processes for a program to follow, and is expected to vary from program to program.

B.3.4 Configuration Control/Management

Discuss general goals, objectives, and value of effective configuration control. Configuration Management Plans are written for each program to document information flow and management for a program to follow, and is expected to vary from program to program. Look for future revisions of this document to be more explicit on scope of configuration management relative to test and evaluation of liquid rocket engines.

Test Article

Discuss general and specific requirements, with guidance on what are minimal acceptable requirements. Describe potential processes to track/control configuration. Identify potential allowable configuration deviations from flight for various phases. Discuss the implications of design changes subsequent to development and qualification testing. Discuss technical value of recording and documenting evolution of design, rationale for design decisions, and the associated testing performed on various evolved designs. Identify classifications. Configuration control must address various phases including design, manufacturing processes, system integration, testing, handling/transport processes, and storage procedures. Development/qualification processes must be consistent with future processes for production and flight.

Test Facility

Discuss general and specific requirements, with guidance on what are minimal acceptable requirements. Describe potential processes to track/control configuration.

Flight Design

Discuss need to provide and document direct traceability between test articles (especially qualification) and flight articles.

Software

Discuss general and specific requirements, including the configuration control levels required during various types and phases of testing. Discuss the configuration control requirement differences between on-vehicle software and test stand control software. Describe potential processes to track/control configuration.

Methods/Procedures

Provide more details for the various activities to understand/track/validate changes through physical configuration audit (PCA), functional configuration audit (FCA), drawings, schematics, procedures, functional/similarity checkouts, end-to-end checks, and configuration control board.

B.3.5 Documentation

List and describe all the required documents for test program, which may include, but not be limited to, the following: design requirements review, preliminary design review, critical design review, system design review, test requirements document, critical experiment review, test plan, process specifications, test procedures, propellant specifications, interface control document, system modeling analyses, test readiness review, data reviews, test results briefings, and test reports. Nomenclature on reviews tends to be facility-specific, so there may be a need to define various types of documents and reviews.

B.4 TEST DATA UNCERTAINTY AND TOLERANCES

B.4.1 Testing and Uncertainty Determination Overview

Analytical engine performance must be verified with test data results, which are not equal to the true performance values. Rather, the test data results approximate the true engine performance values within measurement uncertainty bounds. Estimating those uncertainty bounds in the test-planning phase is recommended to ensure that the test results meet accuracy requirements.

Measurement uncertainty in desired results such as thrust, specific impulse, characteristic velocity (C*), C* efficiency, and mixture ratio must often be estimated from more fundamental measurements, such as temperature, pressure, mass flow rate, each with its own characteristic measurement uncertainty. The composite uncertainty in a result is then determined by combining the uncertainties of more fundamental measurements.

Fundamental measurement errors may be categorized as bias (systematic) errors, and precision (random) errors. Bias errors are fixed and may be quantified and reduced by calibration. Precision errors are variable in nature, may be quantified by statistical methods, and may be reduced by averaging multiple readings. The composite uncertainty in a result is the combination of bias and precision uncertainties that approximate the bias and precision errors of more fundamental measurements. Standard uncertainty analysis methods [Coleman & Steel (1989); NIST Technical Note 1297 (1994)] may be used to calculate composite uncertainty in result variables, which depend on fundamental uncertainties through sensitivity (influence) coefficients. Sensitivity coefficients may be estimated analytically or numerically.

Calibration of fundamental measurement instrumentation against “primary” standards is required. Primary standards include measures of mass, length (volume), and time traceable to the National Institute of Standards and Technology (NIST). For example, a thrust load cell instrument may be calibrated against a primary standard of mass if the local value of gravitational acceleration is known. There are bias uncertainties associated with the mass standard and the gravitational acceleration constant that transfer bias to the load cell instrument via the calibration process. Calibration against “transfer” standards may also be advantageous. For example, pressure transducers may be periodically calibrated against an electronic transfer standard which, in turn, is periodically calibrated against a primary standard traceable to NIST. Maintaining control charts of calibration data is recommended to ensure that bias errors stay within estimated bias uncertainty limits. It is also recommended that sources of bias uncertainty be carefully evaluated to account for dependencies. Such bias dependencies can increase or decrease the actual composite uncertainty of result variables. Bias correlation can be accounted using standards methods [Coleman & Steel (1989); NIST Technical Note 1297 (1994)].

In addition to bias uncertainty in measured variables, additional ground-to-flight engine performance biases may require estimation, including:

- Effects of hardware installed post-test (e.g., nozzle extensions)
- LRUs change-out

- Time/duration effects correction
- Mission unique adjustments
- Post-qualification manufacturing changes

Estimation of such ground-to-flight biases may require additional development tests to quantify the differences within the desired level of uncertainty.

Precision (random) uncertainties are estimated with test data using standard statistical methods [Coleman & Steel (1989); NIST TN 1297 (1994)]. Precision uncertainties may be reduced by averaging multiple readings since the standard deviation of a mean value is a factor of square root(N) lower than the sample standard deviation (where N equals the number of data readings averaged). In many cases, data from previous testing can be included to obtain a larger sample size; however, care must be taken to ensure the previous data is statistically relevant.

There are many potential sources for uncertainties in measurements. Some are caused by human errors such as improperly reading the instrument, chart, or record, and/or improperly interpreting or correcting these data. Some are caused by instrument or system errors that may fall into four classifications: static errors, drift errors, dynamic response errors, and hysteresis errors. Static errors are usually fixed errors due to fabrication and installation variations. Static errors can usually be detected and mitigated by careful calibration and an appropriate correction can be applied to the reading. Drift error is a varying output reading over a period of time for the same input, often caused by changing biases of measurement system or changes in the environmental conditions. Drift errors can also usually be detected and mitigated by careful calibration and an appropriate correction. Dynamic response errors occur when the measured quantity changes its value faster than the measurement system can accurately register. Dynamic response errors can be mitigated by the careful selection of instrumentation with the appropriate response characteristics. Hysteresis error is usually a combination of mechanical hysteresis (output deviation at a certain input condition when that input is approached first with an increasing reading and then with a decreasing reading) and temperature hysteresis (output deviation at a certain input, before and after a temperature cycle). Hysteresis error can be mitigated by careful evaluation and correction for such system characteristics.

Statistical Design of Experiments (DOE) is often used to reduce the number of test conditions and test samples required to characterize the influence of individual variables in a multi-variable system. For small test articles, it may be appropriate and affordable to conduct many tests with many different hardware samples. For the LREs considered in this Guideline, 1000 lbf thrust and greater, it is usually not fiscally viable to test the number of unique hardware samples that a DOE designed test plan would suggest. This should not be used as justification to not perform statistical analysis; rather, the proper application of experimental uncertainty methodologies can yield important insights into the behavior of the engine. In fact, knowledge of the experimental uncertainty can make a test program more efficient. For example, postulating a fictitious rocket engine test campaign that includes tests to characterize a hardware configuration change. However, the potential benefit is expected to be a factor of 4 less than the uncertainty for a single test. In that case, the testers could either perform the test and accept a confounded result, perform a statistically sufficient number of tests in each configuration, test with a sufficient number of unique samples, or not perform the test. By having the experimental uncertainty knowledge, the program can make a well-informed decision.

Regardless of the level of uncertainty, these levels must be well characterized and acknowledged in the test planning and test evaluation. Test planning must account for data uncertainty to ensure that test conditions, objectives, and verification targets will be satisfied beyond the uncertainty range of the data. Test evaluation must account for uncertainty to determine whether a certain test objective is accomplished, a particular design specification requirement is satisfied, or an acceptance test result meets mission requirements.

B.4.2 Specification Decision Making with Consideration of Uncertainties

LRE characterization is one of the most critical aspects of launch vehicle performance. As this section has previously discussed, there are significant contributors to LRE performance uncertainty. The uncertainty associated with the propulsion system uncertainty must be incorporated into the vehicle's flight performance reserve. Therefore, uncertainty contribution from the rocket engine acceptance test tag-value must be properly accounted for to ensure the mission is not subject to unknown risk or excessive propellant margin. The American Society of Mechanical Engineers standard, ASME B89-7.3.1-2001 was developed "to facilitate the development of understanding between suppliers and customers regarding measurement uncertainty in the decision to accept or to reject a product." Liquid propellant rocket engines are provided in a customer-supplier relationship to a launch vehicle or spacecraft. Even in cases where the engines are developed with the same company, that relationship still exists. The engine is provided as a major component and how its performance is integrated into the vehicle system is critical. ASME B89-7.3.1-2001 does not dictate a singular way to consider conformance to specifications; rather, it provides a set of definitions and alternative approaches to interpreting the acceptance of a product and conformance to specifications. Any of the approaches will work if properly propagated through the integrated performance model; however, the benefit of explicitly using one of these methods is the consistency provided through clear communication of the confidence in the engine's performance.

A customary practice today is to acceptance test an engine and to perform analysis during data reduction equations to calculate a performance parameter (for example, calculating specific impulse using measured thrust, measured mass flow rates, and making corrections for known biases, adjustments to nominal inlet conditions, etc.); then compare the result to the contract specification. If it is within the specification, the engine is accepted; if not, it is rejected until changes are made such that it is within the specification zone. By explicitly incorporating the fact that measurement uncertainty exists, a set of decision rules can be created. ASME uses the term *guard band* to represent the uncertainty estimate associated with a specification parameter. The guard bands can either be inside the specification range or outside of it, and then creates regions of stringent acceptance and relaxed acceptance. Figures B.4-1 and B.4-2 represent two possible decision rules. Other decision rules include cases where a specification value is a not to exceed or a greater than, i.e., an asymmetric or one-sided decision rule. The other decision rules can be found in the ASME Guideline.

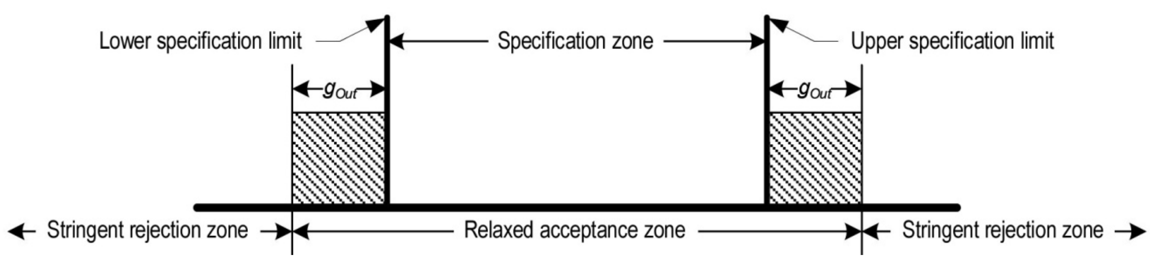

Figure B.4-1: Symmetric two-sided relaxed acceptance and stringent rejection

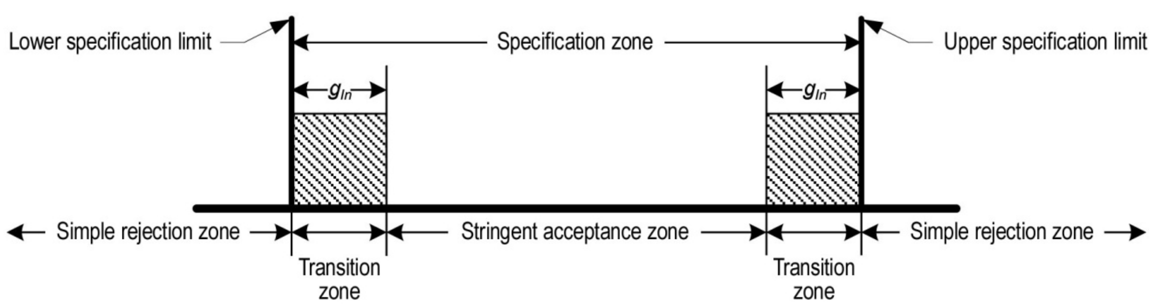

Figure B.4-2: Stringent acceptance, simple rejection, and a transition zone example using symmetric two-sided guard banding

Appendix C: Representative Campaigns and Test Turn-around Rates for a Variety of R&D and Flight LRE Testing

This Appendix is an extracted synopsis of an NASA SSC internal document entitled "SSC Rocket Propulsion Testing Major Statistics," dated 29 April, 2005, and filed as Study #6323-06-007, in NASA SSC Central Engineering File, developed by co-authors Kirchner, Morgan, and Rahman.

The following summarizes testing activities conducted at the John C. Stennis Space Center (SSC). The results include the total number of tests performed, the total number of test seconds accumulated, the test turnaround rate, and the test achievement rate for all test campaigns during the history of SSC (from 1966 until the end of 2004, i.e., four decades).

The primary benefit of collecting this information is to apply it as a planning and forecasting tool for future test projects to indicate the "time it takes" (i.e., test windows) to conduct tests for either research and development (R&D) or flight hardware (components, engines, stages).

Results and Discussion

The results are presented and discussed primarily in terms of the various major statistical outcomes (number of tests, test seconds, test achievement rates or "completion rates," etc.). The outcomes are affected by a variety of factors and these are highlighted in the discussion in terms of how they likely influence the respective outcomes.

For various types of large scale test articles at SSC, it is found that the test project teams can engineer and operate the facilities to accomplish a test on an average of approximately every 11 calendar days, and will generally test with better than 75% probability of completing that test. Further illustration and discussion of these results by test stand, and by test project, is the subject of the following sections.

Details, caveats, and additional data including results categorized by complex, project, and thrust scale can be found in the parent document (NASA SSC Study #6323-06-007).

Total Number of Tests at SSC

The best available information indicates that over 3000 hot-fire tests have been performed at NASA SSC. The data presented is counted up to and including December 31, 2004.

The projects reflected in the graph of Figure C-1, include Apollo rocket propulsion tests, which were all booster stages with multiple engines. The SSME testing in particular for Space Shuttle has occupied multiple stands over the past three decades. Also note that the testing at E Complex is relatively recent, most of it occurring during the past 6 years (1999 – 2005). The quantity of tests there is quite large, numbering over 700, and the statistics represent a remarkable variety of R&D testing involving many types of test articles (PBs, thrust chambers, GGs, pumps, powerheads, and engines), and encompasses a large span of thrust scale (from less than 1000 lbf to as much as 650,000 lbf thrust scale). Testing at E-Complex is shown as the sum of all tests at stands E-1, E-2, and E-3, the large majority of them being conducted at E-3 with relatively smaller test articles.

The well-known heritage testing of the Saturn V booster included: (a) 15 first stage tests at B-2 stand, and, (b) 7 and 23 second stage tests at the A-1 and A-2 stands, respectively. Although few in number, the test articles were quite large and complex since they were actual flight hardware (in most cases) with clusters of engines. Five J-2 engines powered the Apollo second stage and five F-1 engines powered the Apollo first stage. The large test stands were built in large part to ensure that man-rated Apollo booster stages were adequately ground-tested prior to delivery to Cape Canaveral for launch.

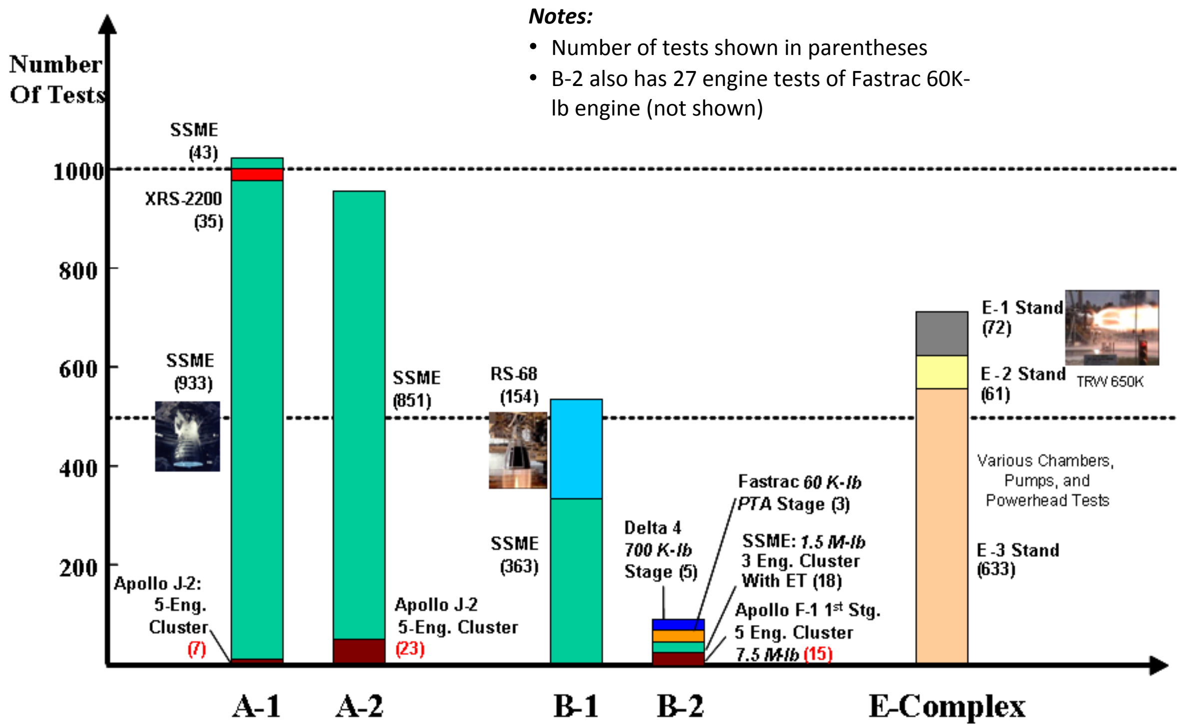

Figure C-1: Total number of tests conducted (as of 12-31-04), by stand.

Total Number of Test Seconds at SSC

Figure C-2 is the complement of Figure C-1, showing the accumulated test seconds from all test projects over the years. It indicates that at least 850,000 hot-fire seconds have been accumulated at NASA SSC across all the test complexes. The majority of test seconds are for the SSME engine, including SSME Main Propulsion Test Article (MPTA) at 765,366 seconds. When SSME flight seconds from launch were included into the SSME total, along with some testing at other test sites (NASA Marshall Space Flight Center [MSFC], Rocketdyne Santa Susana Field Laboratory [SSFL]), the "1 Millionth second test" was completed at SSC in February 2004 and celebrated as a public event.

Testing of integrated engines and stages at A and B stands has been performed with low-pressure propellant feed, and for long durations that are representative of flight profiles (SSME, RS-68, Apollo first and second stages). Testing duration was anywhere from 1.5 seconds to 2017 seconds. An SSME flight profile is approximately 8 minutes, and therefore 500 or greater seconds of test duration is typical. The on-stand propellant run tanks are augmented by ground-based barge-fed propellants to achieve much greater test duration when that is a test requirement.

At the E-Complex, where ultra-high pressures of 8000 psia are needed in the propellant run tanks, the durations are limited by run tank size and pressurant gases (up to 15,000 psi). Typically, 5 seconds to 50 seconds of run duration is likely based upon the test article thrust scale and its development test objectives.

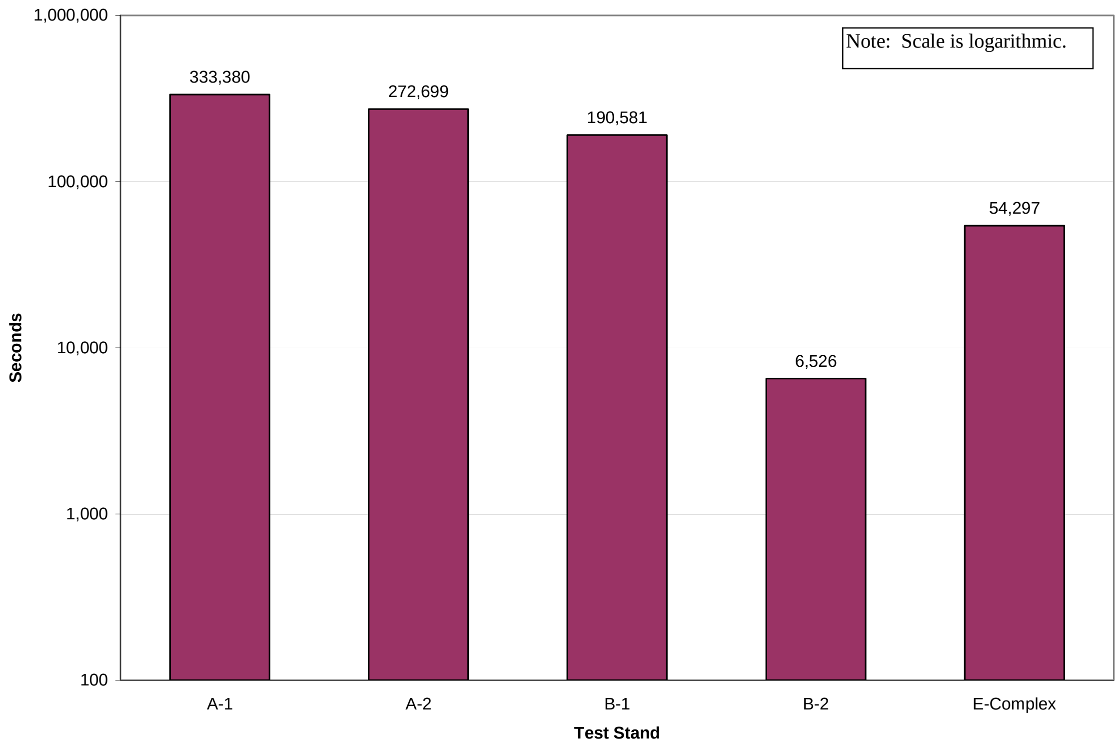

Figure C-2: Total number of hot-fire test seconds (as of 12-31-04), by stand.

Test Turnaround Rates at SSC Major Test Complexes

Figure C-3 illustrates and compares the so-called "test turnaround rate" for different types of testing. Historically, test customers have not specifically planned for a particular optimum test turnaround rate, and have generally accepted the outcome. A current test project at E-1 [Integrated Powerhead Demonstration (IPD) engine system] has systematically addressed its own achievable project test turnaround rate to optimize the use of resources.

It should be noted that this rate is the average *number of days between successive tests* (or mean time between Tests) and is counted only from the first day that a test campaign begins to the last test of the series. The year or more that it may take to prepare the test stand for a new test project or series is not included as it would skew the data. (The preparation time is a separate consideration.) At all stands except E-3 stand, it is rare for multiple tests to be conducted on a single day, and usually a second test is only performed because the first attempt was deemed an unsatisfactory test attempt. At E-3 stand, due to the smaller scale and relatively lesser complexity of test article, the norm is that multiple tests are conducted on a single day. Therefore the "test turnaround" is more correctly interpreted as the *number of days between successive test days* (or mean time between Test Days). Henceforth it is referred to as "Days between Test Days" for convenience.

Interestingly, owing to the large database on SSME testing, a time history trend for this statistic can be shown indicating year-to-year variations in the test turnaround rates. When this trend was examined for a given stand (either A-1 or A-2), it generally highlighted a rapid turnaround rate R&D period in the late 1970s, and a more nominal-turnaround-rate production testing period since the early 1980s. When all SSME single-engine data from all three stands is combined as shown in Figure C-4, it is clear that the test rate can be increased by commissioning multiple test stands. A test every four days was possible when three test stands were active to support SSME engine tests between 1988 and 1997. In contrast, a single test stand is, at best, likely to conduct a test every 10 days on average.

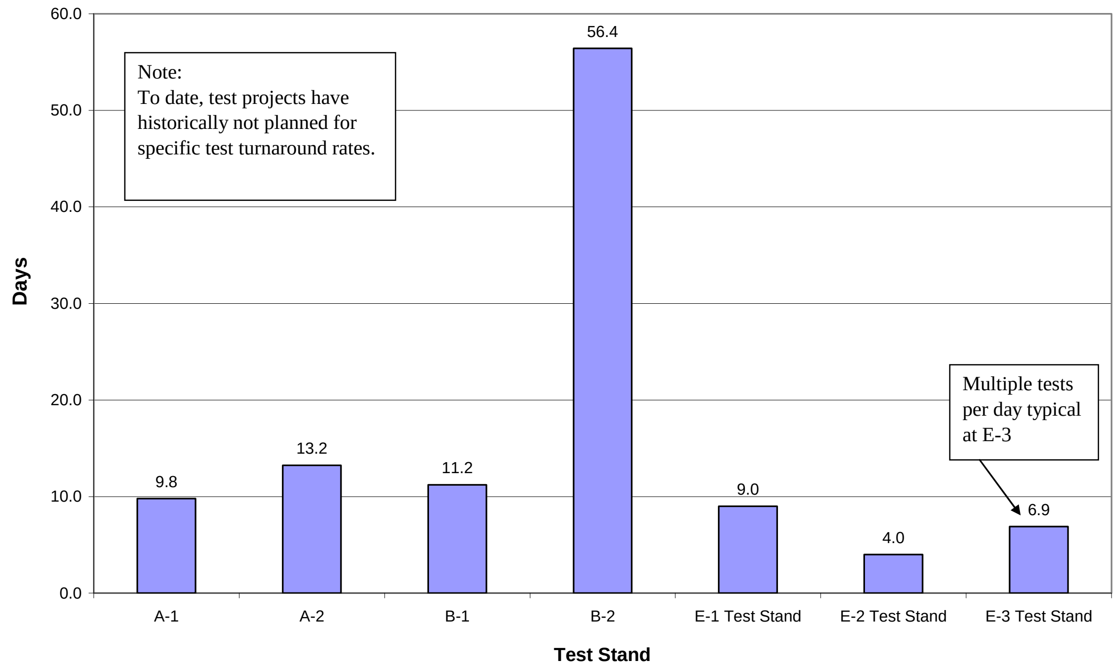

Figure C-3: Average number of Days between Test Days, by stand.

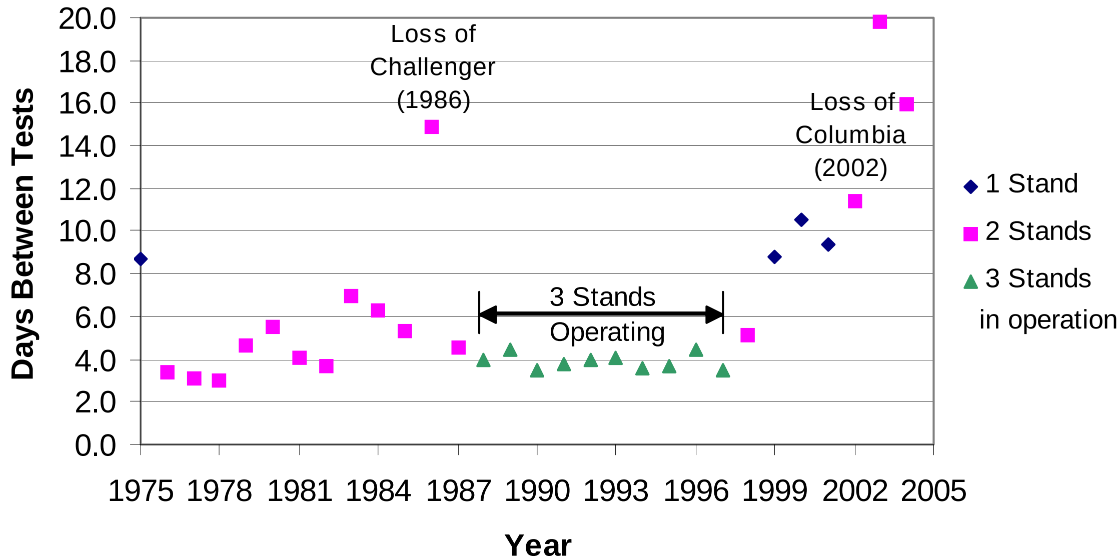

Figure C-4: SSME Days between Test-Days, by number of stands operating.

Test Completion Rates at SSC

Figure C-5 shows two different test achievement metrics. Firstly, the "Actual vs. Planned Seconds Completed" is a percentage measure of planned total test seconds that were actually achieved during hot-fire. Second, the "Tests Reaching Full Duration" is a percentage of the tests that were completed to full (planned) duration without a so-called redline cut (a "redline" provides for a programmed test shutdown based upon a measured instrument parameter). If planned full duration was not achieved, this may have been the result of either a test article anomaly or a test facility anomaly, or other scenario. Therefore, it should not be viewed as either characteristic of the facility, test article, or process, but simply as an attribute of R&D testing. Sometimes, aborts are performed during tests to test systems of the test stands and of the test articles.

From different perspectives, it is possible to measure testing achievement both by the percentage of test seconds successfully completed, or by the completion of the full planned test duration. If achieving steady state hot-fire duration is an important test objective, i.e., for production engines which must demonstrate a specific flight profile and accumulated run duration, then "Tests Reaching Full Duration" is relevant. It might also be assumed that any redline cut represents some anomaly or vulnerability that must be mitigated before testing resumes. However, many tests meet all the objectives of customers and/or stakeholders without reaching full duration – the planned duration may have been somewhat flexible, or just not as important. Also, as an engine component or system reaches maturity, the achievable duration usually increases. In this way, the "Actual vs. Planned Seconds Completed" is a useful metric indicating design maturity.

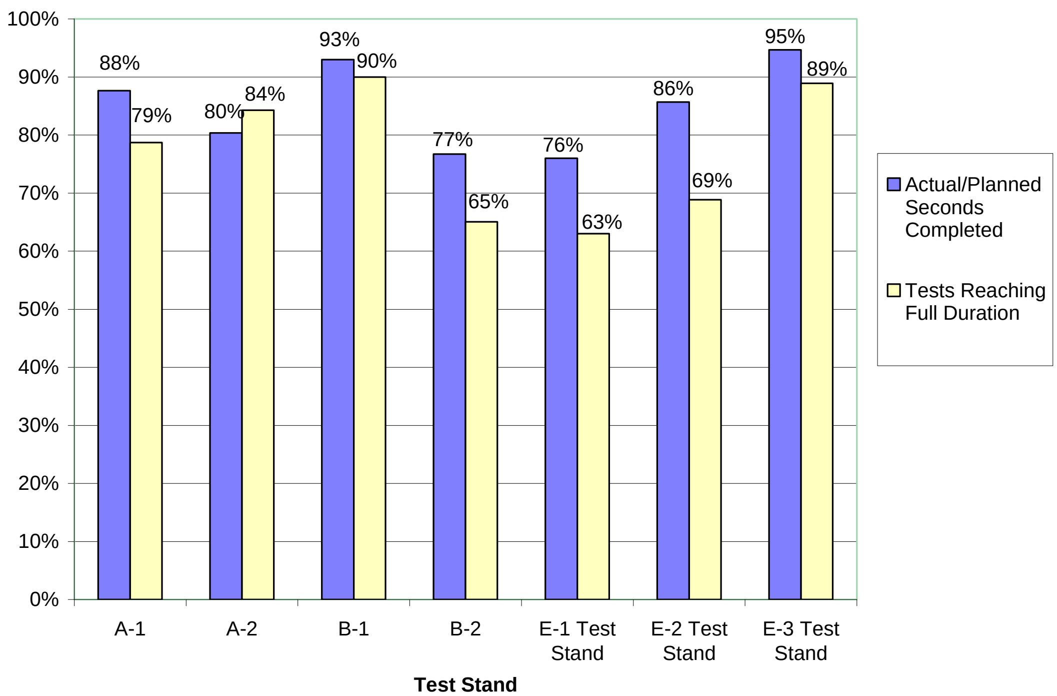

Figure C-5: Test seconds completion metrics, by stand

Note: Rocketdyne has chosen not to release data, which would lead to calculation of completion metrics for the RS-68, out of a desire to keep such performance measures proprietary.

Due to the wealth of SSME testing information, a yearly average was generated for test completion rates for the SSME test campaigns at SSC. The time history trend in Figure C-6 shows a rapid rise in completion rate during the early years of the program in the mid-1970s (at 45 to 75% completion), with an eventual asymptote at 80 to 100% as both the engine itself and the test program matured.

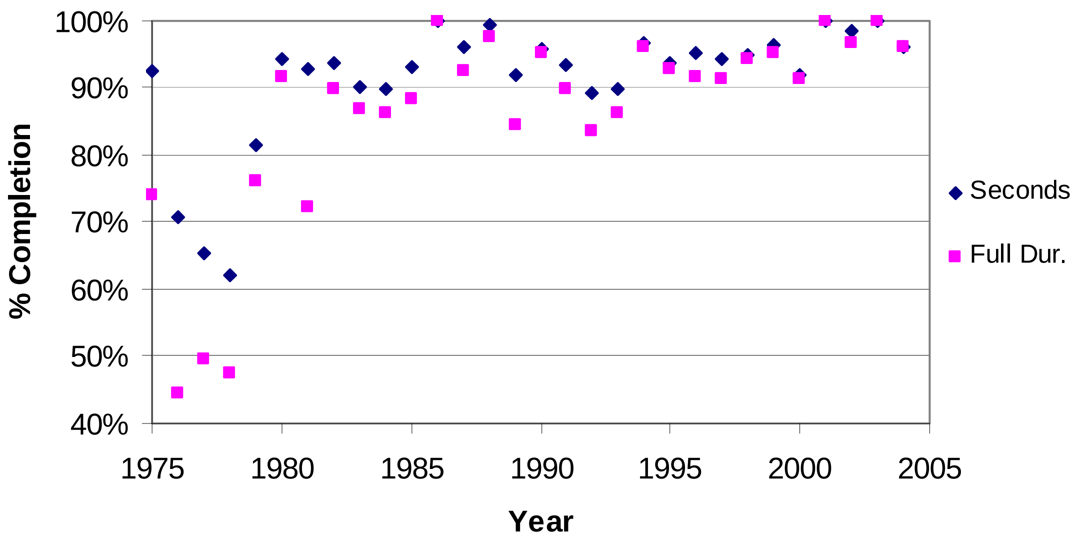

Figure C-6: Historical trend of SSME testing completion rate.

Conclusions

The following notable findings and conclusions are highlighted as a result of this study.

- The test turnaround time, or "days between test days," is significantly greater for the larger scale test articles, either engines or engine components.
- Multiple tests per day have been achieved only at the subscale testing level, or for small size test articles, such as with several test projects at the E-3 test stand. Interestingly, E-2 test stand has also conducted multiple tests per day during a couple of test projects.
- For SSME, it appears that a 10-day turnaround time per stand has been typical over the years for high-completion-rate testing. Quicker turnaround is possible, but is associated with a lower test completion ratio.
- During peak testing periods, turnaround time can be minimized by testing a given engine system on multiple test stands. This was the case when SSME was testing an average of once every four days on any one of three SSC test stands.
- It is clear from the data that flight engine test activity has a higher test completion rate (e.g., > 80%) than the low-to-mid-TRL R&D testing conducted for early development.
- Early in the flight engine program, the test completion rates are relatively low (even less than 50%), for a variety of reasons, and improve over time as the engine development and test experience matures.
- Rocket propulsion test facilities at SSC are adaptable to handling a variety of related, but perhaps not strictly propulsion, testing activities.

The data collected and presented in this study reflects an enormous amount of unique testing experience, especially in long-standing production engine programs such as SSME. As stated earlier, the information indicates a global average test turnaround capability of every 11 calendar days, with significant variation around this mean depending on test article maturity, size, complexity, type, and other such parameters.

Appendix D: Human-Rating Considerations for LRE Testing and Evaluation

The foundation for any approach for human-rating a propulsion system comes from referencing NPR 8705.2B, "*Human Rating Requirements for Space Systems.*" "*Human-rating consists of three fundamental tenets:*

> *1. Human rating is the process of designing, evaluating and assuring that the total system can safely conduct the required human missions.*
> *2. Human rating includes the incorporation of design features and capabilities that accommodate human interaction with the system to enhance overall safety and mission success.*
> *3. Human rating includes the incorporation of design features and capabilities to enable safe recovery of the crew from hazardous situations.*

Human rating must be an integral part of all program activities throughout the life cycle of the system, including design and development; test and verification; program management and control; flight readiness certification; mission operations; sustaining engineering, and maintenance / upgrades; and disposal."

While these tenets guide programmatic approach, interpretation and design implementation of these tenets reside at much lower levels (i.e., propulsion system, LRE, or even component level). Fundamentally, a propulsion system must operate as part of a larger vehicle system. Therefore, it must be understood that human-rating for a given LRE cannot be completely addressed independently from the integrated vehicle architecture. Integration of systems across the interface is a key in understanding how as system could fail, and what mitigations can be incorporated as prevention or avoidance measures. More explicitly, because an engine is considered human-rated on one vehicle, does not automatically imply that it is human-rated on any vehicle.

For LREs, design characteristics fall into four primary categories:

1) Fault avoidance – design out the failure mode
2) Design margins or DFMR – design with increased margin to add sufficient robustness
3) Redundancy – design redundancy capability into the system to be tolerant to failures
4) Caution and Warning Devices – provide detection capability to detect, warn, and provide other systems to activate or respond to avoid loss of crew scenarios

To implement these features appropriately, it is required to have knowledge of how the system can fail, and how those failures can most likely propagate through establishment of hazards, FMEA, and CIL.

Although each engine will have different and distinct characteristics, there is a generally an accepted T&E approach which can be summarized by an excerpt from "Point Paper on Space Propulsion Technology Necessary to Enable Human and Robotic Missions" by Robert Sackhiem:

1) *"Selecting a sufficiently large number of specimens of the new product design to be tested;*
2) *Conducting a sufficient number of tests on each prototype and flight-like specimens to demonstrate adequate operating and performance capabilities under nominal operational and environmental conditions;*
3) *Conducting significant off-nominal and/or overstress conditions for testing to demonstrate adequate new product design margins;*
4) *Design the new product systems with as much redundancy as feasible to minimize single-point failures; and finally*
5) *Use a logical optimized combination of all of the above approaches to establish sufficient confidence in the human-rated capabilities, reliability, and safety of the new products and their associated integrated systems under all anticipated operational conditions."*

Number 5, the use of a logical optimized combination of all the approaches is generally accepted. This brings out the point that the T&E approach of the LRE must be carefully constructed and will be as unique as the design characteristics, which must be logically tied back to the vehicle architecture and program.

It can be stated that the expectation is that the T&E must scrutinize the validity of the design features which add to the reliability of the propulsion system and safety of the crew. Do they really add significant safety to crew return and mission success? Do these features negatively affect the crew safety in any way (foreseen or unforeseen)? Redundancy tests should be done beginning at the component level and follow through to the propulsion system level, as necessary. Margin tests should be conducted as discussed in earlier sections for qualification (expected operating box plus margin). Caution and warning systems should be tested as this is software dependent, which there are established V&V processes that scrutinize each revision. Must work and must not work functions should be tested to avoid inadvertent activation or deactivation.

Thorough test programs that consist of risk reduction activities, component, subsystem, and engine testing are required for human-rating. Significant understanding of the system must be acquired during the T&E stage to provide the confidence that the propulsion system and how it will react in a given situation is very well understood; over and above test-based reliability analysis results (demonstration of reliability is typically too costly). Reliability is not the sole characteristic that determines whether a system is human-rated or not.

Human-rating promotes the “test-as-you-fly” approach discussed earlier, where production and operational phases should fly within experience base of ground test. Further, it is important to have consistency in manufacture and resulting build-to-build performance. Acceptance testing should thoroughly screen the LRE for defects which can affect crew safety or mission success. Significant variations in build-to-build performance (design specific) can indicate a lack of understanding of the characteristics that drive the system, therefore reducing confidence. Statistically relevant numbers of tests are typically not available so an acceptance series must provide an adequate screening function.

Although not explicit, the expectation of human-rating adds rigor to all phases of the DDT&E process and carries through production/operation.

Appendix E: Sample Cases of Using Test Guideline to Plan Test Program

To be considered in future revisions.

Appendix F: Acronyms

AIAA	American Institute of Aeronautics and Astronautics
a.k.a.	also known as
ANSI	American National Standards Institute
ASEE	American Society for Engineering Education
ASI	augmented spark igniter
ASME	American Society of Mechanical Engineers
ATP	acceptance test procedures
C*	characteristic velocity
CG	center of gravity
CIL	critical items list
CPIA	Chemical Propulsion Information Agency
Cv	control volume
CxP	Constellation Program
DAR	deviation approval requests
DDT&E	design, development, test and evaluation
DFMR	design for minimum risk
DoD	Department of Defense
DOD	domestic object debris
DOE	design of experiments
DOP	detailed operating procedure
E&M	electrical and mechanical
ECU	engine control unit
EHM	engine health management
ELV	expendable launch vehicle
EMC	electromagnetic compatibility
EMP	electromagnetic pulse
EOM	end-of-mission
ESD	electrostatic discharge
FCA	functional configuration audit
FEM	finite element model
FID	failure identification
FMEA	failure modes and effects analysis
FOD	foreign object debris
FCA	functional configuration audit
FRT	functional readiness tests
FoS	factor of safety
GG	gas generator
GTI	ground test instrumentation
HCF	high-cycle fatigue
IEEE	Institute of Electrical and Electronics Engineers
IOP	ignition overpressure
IPD	integrated powerhead demonstration
Isp	specific impulse
lbf	pounds force
LCC	launch commit criteria
LCF	low-cycle fatigue
LDF	life demonstration factor
LH_2	liquid hydrogen
LL	limit load
LN_2	liquid nitrogen

LOX	liquid oxygen
LRE	liquid rocket engine
LRU	line replaceable unit
MCC	main combustion chamber
MEOP	maximum expected operating pressure
MIL	military
MMA	moving mechanical assemblies
MOI	moments of inertia
MOP	maximum operating pressure
MPE	maximum predicted environments
MPTA	main propulsion test article
MR	material review
MS	margin of safety
MSFC	Marshall Space Flight Center
MWP	maximum working pressure
N	square root
NASA	National Aeronautics and Space Administration
NCSL	National Conference of Standards Laboratories
NIST	National Institute of Standards and Technology
NPR	NASA procedural requirement
NPSH	net positive suction head
NPSP	net positive suction pressure
PB	preburner
Pc	chamber pressure
PCA	physical configuration audit
psi	pounds per square inch
psia	pounds per square inch absolute
psid	pounds per square inch differential
PSN	purge sequence number
QA	quality assurance
qual	qualification
R&D	research and development
RCS	reaction control systems
RLV	reusable launch vehicles
RTD	resistive temperature device
RTCA	Radio Technical Commission for Aeronautics
SAE	Society of Automotive Engineers
SFI	special flight instrumentation
SL	service life
SRR	systems requirements review
SSC	John C. Stennis Space Center
SSFL	Santa Susana Field Laboratory
SSME	space shuttle main engine
STE	special test equipment
T&E	test & evaluation
TBD	to be determined
TCA	thrust chamber assembly
TOR	Technical Operating Report
TPA	turbopump assembly
TVC	thrust vector control
V&V	verification and validation
WR	witness ring