JANNAF "Test and Evaluation Guidelines for Liquid Rocket Engines": Status and Application

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For many decades, the U.S. rocket propulsion industrial base has performed remarkably in developing complex liquid rocket engines that can propel critical payloads into service for the nation, as well as transport people and hardware for missions that open the frontiers of space exploration for humanity. This has been possible only at considerable expense given the lack of detailed guidance that captures the essence of successful practices and knowledge accumulated over five decades of liquid rocket engine development. In an effort to provide benchmarks and guidance for the next generation of rocket engineers, the Joint Army Navy NASA Air Force (JANNAF) Interagency Propulsion Committee published a liquid rocket engine (LRE) test and evaluation (T&E) guideline document in 2012 focusing on the development challenges and test verification considerations for liquid rocket engine systems. This document has been well received and applied by many current LRE developers as a benchmark and guidance tool, both for government-driven applications as well as for fully commercial ventures. The USAF Space and Missile Systems Center (SMC) has taken an additional near-term step and is directing activity to adapt and augment the content from the JANNAF LRE T&E guideline into a standard for potential application to future USAF requests for proposals for LRE development initiatives and launch vehicles for national security missions. A draft of this standard was already sent out for review and comment, and is intended to be formally approved and released towards the end of 2017. The acceptance and use of the LRE T&E guideline is possible through broad government and industry participation in the JANNAF liquid propulsion committee and associated panels. The sponsoring JANNAF community is expanding upon this initial baseline version and delving into further critical development aspects of liquid rocket propulsion testing at the integrated stage level as well as engine component level, in order to advance the state of the practice. The full participation of the entire U.S. rocket propulsion industrial base is invited and expected at this opportune moment in the continuing advancement of spaceflight technology.

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Nomenclature

BEO	=	Beyond Earth Orbit
CPIA	=	Chemical Propulsion Information Agency
CPIAC	=	Chemical Propulsion Information and Analysis Center
DOD	=	Department of Defense
DSIAC	=	Defense Systems Information Analysis Center
ERG	=	Energetics Research Group, of JHU Whiting School of Engineering
FFRDC	=	Federally Funded Research and Development Center
JHU	=	The Johns Hopkins University
JANNAF	=	Joint Army Navy NASA Air Force (…Interagency Propulsion Committee)
LPS	=	Liquid Propulsion Subcommittee
LRE	=	Liquid Rocket Engine
MPCV	=	Multi-Purpose Crew Vehicle
MSFC	=	Marshall Space Flight Center
NSS	=	National Security Space
SLS	=	Space Launch System
SMC	=	Space and Missile Systems Center (of USAF)
TPSP	=	Test Practices and Standards Panel
USAF	=	United States Air Force

I. Background

NASA and the United States Air Force (USAF) Space and Missile Systems Center (SMC) collaborate closely with industry in development and operation of chemical rocket propulsion. The space-related rocket industry is continuing to develop new or upgraded rocket engine systems to meet USAF, National Security Space (NSS), NASA, and commercial mission needs. A few examples include the RS-25 and the RL10 evolved engines for the core and upper stages of the NASA Space Launch System, and several kerosene and methane fueled engines for both commercial industry and NSS launch system needs. A robust development and qualification propulsion hot fire test program is necessary to ensure successful and reliable operation of the liquid-fueled stages in flight. However, defining the appropriate test program for liquid rocket engines (LRE) is a challenging task. On one hand there is a need to avoid overtesting that will cause unnecessary risk, excessive cost, and a prolonged schedule; on the other hand there is a need to prevent undertesting that will allow an unreliable and poorly understood system to be fielded. In the long term, either overtesting or undertesting will cause cost overruns and schedule delays compared to an optimally designed test campaign. Until recently, there was a glaring lack of established test guidelines and/or standards to help determine the appropriate test program. Development and test activity were driven by program and project unique constraints and priorities, and sometimes without appreciation for broader lessons learned, which caused great variability in outcomes.

As discussed previously in detail by VanLerberghe[1] (2007), the situation that existed for several decades was difficult to sustain by the government, and certainly not enticing to industry investors. One review of the historical record (e.g., 1957 to 1998) by Chang showed that propulsion systems account for over 50% of launch vehicle failures[2]. The extremely high power densities of liquid propulsion systems push technology and may always account for a large portion of the vehicle failure modes due to complexity. However, its dominant portion of the total suggested that rocket propulsion test efforts should be re-examined for adequacy, with the desire to improve test approaches for initial qualification to increase system design robustness, and recurring acceptance of each flight unit to improve production quality assurance.

Recognizing that the industry would benefit greatly from the establishment and communication of good practices and guidelines for LRE testing that could certify high reliability at lower cost, the Joint Army Navy NASA Air Force (JANNAF) Interagency Propulsion Committee, via its Liquid Propulsion Subcommittee (LPS), made a concerted effort to improve this situation by establishing in 2003 the Test Practices and Standards Panel (TPSP), a collaborative team consisting of both government and industry representatives. One key pursuit of the TPSP was to steward appropriate test guidelines, practices, and standards for liquid rocket engines - addressing aspects such as general test philosophy, the tailoring of guidelines, the role of modeling and simulation, test planning, test implementation, test data uncertainty and tolerances, and, most importantly, establishing a set of more detailed test guidelines better aligned to design verification. Considerations included the number of hardware samples, number of tests, and detailed recommendations for an extensive list of specific test objectives, and addressed several different phases, such as development, qualification, acceptance, and prelaunch/operational phases. The outcome was the 1st Edition (2012) of the "Test and Evaluation Guideline for Liquid Rocket Engines[3]" (hereafter for brevity referred to as the "LRE T&E guideline"). A great deal of credit for this is also due to the auspices of the Chemical Propulsion Information Analysis Center (CPIAC), which provided an excellent forum to integrate the expertise and perspectives of a wide group of liquid rocket specialty stakeholders towards a credible and consensus outcome. In 2015 CPIAC was renamed the Johns Hopkins University (JHU) Energetics Research Group (ERG) and continues to serve as a trusted and independent member of the aerospace and defense community.

In order to provide an update from prior reported discussions[4] of the CPIAC (and JANNAF), this paper seeks to inform the current chemical rocket propulsion community of practice of the application of this LRE T&E guideline primarily *since* its release in 2012. In particular, the authors provide examples and information of its influence upon both government and industry users and their perspectives on it where possible. Furthermore, the authors wish to share the current plans, interests, and anticipated benefits of expanding and evolving this LRE T&E guideline in the coming years (cf. Parkinson[5], 2016), as the U.S. advances into another era of both government funded and commercially viable spaceflight. As a preamble, an introductory description of the sponsoring JANNAF organization is provided so that the effort can be understood in the context of this primary stakeholder base.

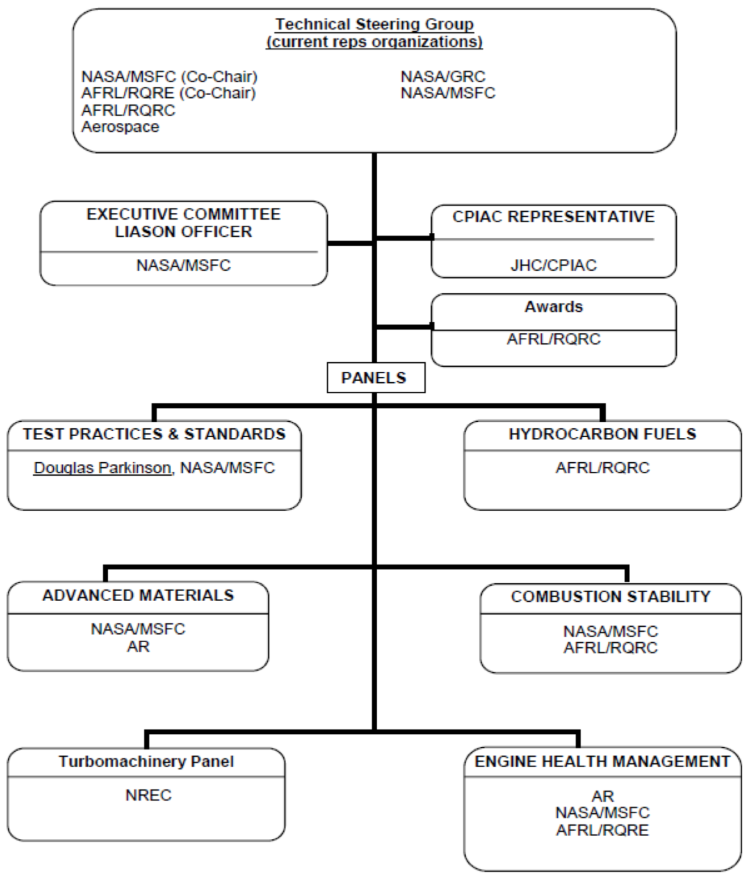

Figure 1. JANNAF LPS Organizational Structure and Leadership.

A. JANNAF Liquid Propulsion Subcommittee (LPS) Organization

The JANNAF liquid rocket propulsion community is represented in the committee structure of the LPS, as illustrated in Figure 1. Today's TPSP operates within the JANNAF LPS structure, as one of several panels within the purview of the Technical Steering Group for the LPS, which is itself comprised of representatives of both USAF and NASA. The USAF steering group representative from Air Force Research Laboratory (AFRL) and from NASA's Marshall Space Flight Center (MSFC) co-chair the steering group and ensure appropriate coordination across these two major governmental stewards of the state of the practice in chemical rocket propulsion. Whereas the other panels are focused on specific disciplines that support LRE propulsion, the TPSP is strictly focused on testing and evaluation aspects in the propulsion development and qualification cycle.

B. LPS TPSP Overview and Activities

The charter of the LPS is to address technical problems and issues of greatest national needs associated with liquid engine systems, where the topics will include technology, components and engines of main propulsion, divert and attitude control, reaction control and post-boost systems applied to tactical, ballistic missile defense and strategic, in-space, and access to space propulsion.

Within the LPS, the TPSP focuses upon the following aspects: (1) Practices and standards for the test and evaluation of liquid rocket engines, its components, and associated propulsion/vehicle interaction/systems; (2) liquid propulsion systems including main propulsion, divert and attitude control, reaction control, and post-boost systems; and (3) application areas including access-to-space, in-space, tactical and strategic, expendable and reusable. Areas of work for the TPSP are to include best practices and standards for acceptance and qualification testing (including life testing and margin testing approaches), failure investigations and lessons learned, safety, process control, and test infrastructure requirements (including data acquisition).

C. Driving Factors for LRE T&E Guidelines

A significant amount of effort and resources have been expended to enable and document this activity, and it is anticipated that further work will continue to evolve the document and enhance its relevance. Thus, it is prudent to periodically consider the benefits and value, and to inform all potential stakeholders. These key benefits are the essential driving factors to further improve upon the current release version document. Key benefits can be categorized into four areas (Ref. 1).

1. Technical Knowledge Preservation

The rocket propulsion community as a whole represents an immense collection of experience, lessons learned, and recommended good practices. It includes experts from many different development and test programs, and with a significant base of different experiences, perspectives, and opinions on various testing aspects. Unfortunately, as occurs far too often, many prior test programs did not include funding to sufficiently document the rationale and logic behind the creation of the test requirements or otherwise have not made such documentation readily available to the community. Emdee[6] performed a survey of available literature on test programs of operational rocket engines and was unable to find comprehensive information to guide future rocket engine developers.

Thus the overall community (both current and future) did not have full access to knowledge of engine testing that led to successful operational systems, and has even less access to knowledge about insufficient engine testing that likely led to *unsuccessful* operational systems (particularly since many organizations are less willing to openly share their failures). Furthermore, such an experience base and requisite knowledge resides with retired or retiring experts. The LRE T&E guideline and its updates will systematically collect and preserve this wealth of accumulated knowledge and experience in an organized and coherent way, with a focus on establishing and presenting proven test guidelines. The ultimate value would be realized with a guideline that is suitable for use as a "handbook" reference, with detailed rationale, both analytical and empirical, supporting the test recommendations presented therein.

2. Standardization of Testing

Currently LRE test programs and test requirements often are to a large degree *negotiated* between the designer/developer/tester and the customer, with each party relying significantly on their own experience base and expertise, as well as their resource constraints. A properly developed LRE T&E guideline would define the recommended development, qualification, and acceptance testing necessary to achieve a low risk system based on the opinion of the entire propulsion community; or alternatively, it would provide more consistent and realistic expectations for the risk level associated with a given level of testing as afforded by the user. Also, bidders on future rocket engine programs would then compete on a more level playing field, since their proposals could be judged against a common and community endorsed set of guidelines (or "best" practices).

3. Program Guidance

A suitable LRE T&E guideline should assist every Program or Project Manager in efficiently formulating a cost-effective, yet adequate, set of test campaigns to validate the engine system design of interest. It should readily indicate the necessary resources and schedule required to achieve the desired technical risk level; or alternatively it should readily indicate the expected technical risk level given the available resources and schedule. In any event, the test program might gain quicker acceptance by the funding agency, prime contractor, or other customer, since its basis would be sound and well-founded. Furthermore, the "handbook" guideline would provide the data and information needed to help *tailor* test programs, as well as to perform effective impact studies and programmatic trades on cost, schedule, and technical risks.

The current guideline document has already been utilized for development of new and evolved propulsion systems. Relevant programs include the NASA Commercial Crew Program[7], the USAF/DOD engine upgrade programs, and USAF/DOD operationally responsive spacelift programs.

4. Reliability Improvement

As noted earlier, the historical record shows that propulsion systems have caused most launch vehicle failures (Ref. 2). Thus, an improvement in propulsion system reliability would certainly lead to a significant increase in launch vehicle reliability. One of the primary objectives of an engine test program is to validate high system reliability at the lowest possible cost. It is also recognized that requiring a demonstrated reliability with sufficient "statistical confidence" is not cost effective when developing and qualifying an LRE for initial use. A LRE T&E guideline derived from the collective knowledge, experience base, and lessons learned of the entire propulsion community should, when utilized properly, yield a much more thorough, robust, dependable, and cost-effective test program, placing an LRE development program on higher reliability path - similar to those, for example, of the SSME (RS-25), Shuttle OMS, and RL10 programs - which each have demonstrated high reliabilities over decades of use. Ideally, this would then in practice effectively identify engine systems developments that have potentially lower reliability paths (via gaps in testing), where additional design or operational improvements can be made before they enter a launch vehicle program.

The authors and the JANNAF TPSP believe these benefits motivate ongoing efforts to further mature and augment the LRE T&E guideline. Subsequent sections outline the current evolution plan as deliberated within JANNAF's LPS TPSP.

II. LRE Test Guide Publication

A. Summary

As referenced earlier, the 1st Edition of the JANNAF "Test and Evaluation Guideline for Liquid Rocket Engines" (JANNAF-GL-2012-01-R0) (Ref. 3) was published for public release in 2012. This followed over a decade of thorough development and refinement of detailed test recommendations. The resulting design verification guidelines were primarily based on heritage test practices, detailed knowledge of a wide variety of test programs with associated successes and failures, and the combined expertise and lessons learned of the panel membership and occasional invited consultants. Panel members and other contributors represented a broad spectrum of industry and government stakeholders associated with liquid rocket engines and related propulsion systems. Whereas the product was primarily the result of volunteer efforts, progress was facilitated greatly by the fairly widespread sponsorship of members' time and resources by their host organizations, as well as by short periods of additional funding to help accelerate the process, particularly by NASA and The Aerospace Corporation on various occasions.

The JANNAF-GL-2012-01-R0 guidelines document is currently available through CPIAC (now ERG). The abridged Table of Contents is shown in Figure 2.

***Abridged* Table of Contents**

3. General Test Guidelines
- Test Philosophy & Tailoring
- Engine Samples & Numbers of Tests

4. Development and Qualification Test
- Performance
- Life
- Functional Characteristics
- Controls
- Operations
- Environments
- Design and Construction
- Physical

5. Acceptance Tests
- Similar categories as 4 (not identical)

6. Pre-Launch Validation and Operational Tests
- Launch-site activities

♦ **Appendices**
- Definitions and Descriptions
- Relevant Discussion
- Test Rates
- Human-Rating Considerations
- Acronyms

Figure 2. Outline of content within the LRE T & E guideline document.

B. Current and Past Applications

1. NASA

The content of the LRE T&E guideline is largely consistent with the (then planned) Ares Upper Stage Engine (J-2X) Program, a NASA liquid rocket engine development for use in the former Constellation Program vehicle architecture, where key J-2X test planners also were key contributors on the JANNAF TPSP. That was also clearly appropriate, as it was a major modern engine development program that would meet a full set of NASA requirements, taking advantage of modern design tools, modern test and evaluation approaches, and modern programmatic constraints (cost, schedule, risk tolerance). It served as a good reference point in which to establish an initial set of guidelines, even though the J-2X engine was considered by many as a significant evolution beyond its Apollo heritage J-2 engine predecessor. It is not the first application of the guidelines, but does anchor them appropriately in the 2010 to 2012 timeframe in the NASA context. Nevertheless, the tie to the J-2X should not overshadow the relevant and considerable experience associated with other endeavors provided by the balance of the JANNAF TPSP membership (industry and other government representatives).

With the inception of the NASA Commercial Crew Program (CCP), there came an opportunity for the JANNAF TPSP to fulfill its mission. The guidelines were of sufficient maturity and deserving a final review leading to a formal publication. The CCP was then standing up and preparing plans and criteria to levy on potential commercial providers[8]. It was clear that the U.S. government was interested in a consolidated set of criteria to establish expectations for liquid rocket engine developments. The guidelines were provided in NASA CCP specification as part of the reference documents (Ref. 8). This meant that the guidelines were not binding (i.e., did not require contractual response), but did communicate a level of expectations from the government to industry. After the initial baseline version release through the JANNAF process in 2012, the guideline document reference was updated, and was distributed for use to NASA's potential commercial partners. This marks the first application for the LRE T&E guideline from a NASA perspective.

2. Industry

The JANNAF TPSP consists of both government and industry participants, who came together with the goal of documenting the best practices and lessons learned in liquid rocket engine testing. This is a remarkable collaboration effort that would both have some historical relevance, and "bootstrap" current and future liquid rocket engine developments.

Even in draft form prior to the 2012 formal publication, the LRE T&E guideline has helped shape the test planning efforts in multiple new engine developments. At a minimum, the guidelines provided an organized forum in which to have technical conversations amongst peers. The drafts contained significant content discussion, documenting experiences and rationale, although much of that was largely consolidated or reduced to provide a more concise set of guidelines in the published version. The evolution of the guidelines within the TPSP indicates that the heart of the guidelines has been utilized by stakeholder peers in the rocket industry.

The rocket industrial base has also evolved since 2012. New industry partners have emerged, while former industry (legacy) giants have merged, evolved, reduced in size, or completely dissolved. These new industry partners ventured into liquid rocket engine developments with a mix of experienced experts and novice engineers; the guidelines have the most potential to benefit these companies. Simultaneously, the more established companies still use it as a reference and tool to help inform and train their more novice test planners.

One example of an industry user is a company that currently flies International Space Station resupply missions and is part of CCP. Recent conversations with their test planners indicate they used the draft versions initially (dating back to early engine development in mid-2000's), and transitioned to using the published version as a reference for test planning during later engine development and qualification programs. The LRE T&E guideline is considered to be fairly complete with regards to topical areas, and provides good guidance, while providing sufficient flexibility. It has been used as a training tool for less experienced test planners/engineers, but still requires more senior test engineers to provide thoughtful and well-considered insights and interpretation. Thus, the guideline document does strike a good balance for content, depth, and customization.

3. USAF Certification of Engines for New Entrants

Numerous new entrants and legacy companies have recently been developing new or upgraded rocket engine systems, and new or evolved space launch vehicles, both for anticipated commercial needs as well as for expected national security space needs. The Aerospace Corporation (aka Aerospace) has traditionally supported the USAF as the USAF certified launch systems (and specific launches) for current and future use with respect to NSS missions, and Aerospace has continued in this role with many of the recent new systems and vehicles. As they assisted certification activities, Aerospace technical staff used the LRE T&E guideline as an additional tool and systematic checklist to complement company expertise and experience in the propulsion discipline. The guidelines were also shared with suppliers and used to help describe and tailor requirements and expectations during technical discussions with various teams involved in design, development, manufacturing, test, and operations.

During these activities, Aerospace technical staff accumulated significant lessons learned with respect to the published LRE T&E guideline (mainly regarding needed clarifications and useful additions; examples will be described later). Since Aerospace is a longstanding member on the TPSP, these lessons learned are shared within the broader panel and considered for future updates of the JANNAF LRE test guideline, as well as for the JANNAF Stages and Engine Components test guidelines which are now a high priority of the TPSP.

III. USAF SMC LRE Test Standard

A. Motivation

Present and future NSS needs require the USAF to pursue acquisition of new propulsion systems and new launch vehicles. Also, Congress has mandated that the USAF ensure the domestic propulsion industry produces new propulsion systems that will eliminate reliance on foreign rocket engines for national security missions. Although the published LRE T&E guideline has been extremely valuable to the USAF and its Aerospace technical support as they have evaluated certification plans and activities for these systems, the USAF needs to establish a means to impose test and evaluation requirements that: a) is suitable as a contract compliance document; b) specifically describes USAF expectations; and, c) facilitates satisfaction of NSS mission needs.

Thus, the USAF has tasked Aerospace to lead an activity to create and recommend a new proposed SMC standard entitled "Evaluation and Test Requirements for Liquid Rocket Engines" (hereafter for brevity referred to as the "SMC LRE test standard") to define and establish the appropriate requirements for liquid rocket engine evaluation and testing associated with design verification (including development and qualification) and flight unit acceptance. A primary goal is to provide a clear and specific description of USAF expectations and recommended requirements related to achieving low risk levels for initial flight operations, and allowing transition to baseline risk level upon adequate accumulation of successful flight history. Furthermore, whereas the SMC LRE test standard is not intended as design specification, some of the verification test requirements will drive various design aspects and capabilities which must be considered and accommodated in the early engine design and development phases. Overall the new SMC LRE test standard is intended to achieve greater satisfaction of USAF needs, provide a consistent set of expectations for the current highly competitive launch provider environment, incorporate additional lessons learned, and establish a rigorous starting point for expected tailoring as USAF objectives are traded against programmatic cost and schedule constraints. It is expected that the SMC LRE test standard will join a wider set of USAF mission assurance compliance documents (the USAF will finalize the list), as illustrated notionally in Figure 3.

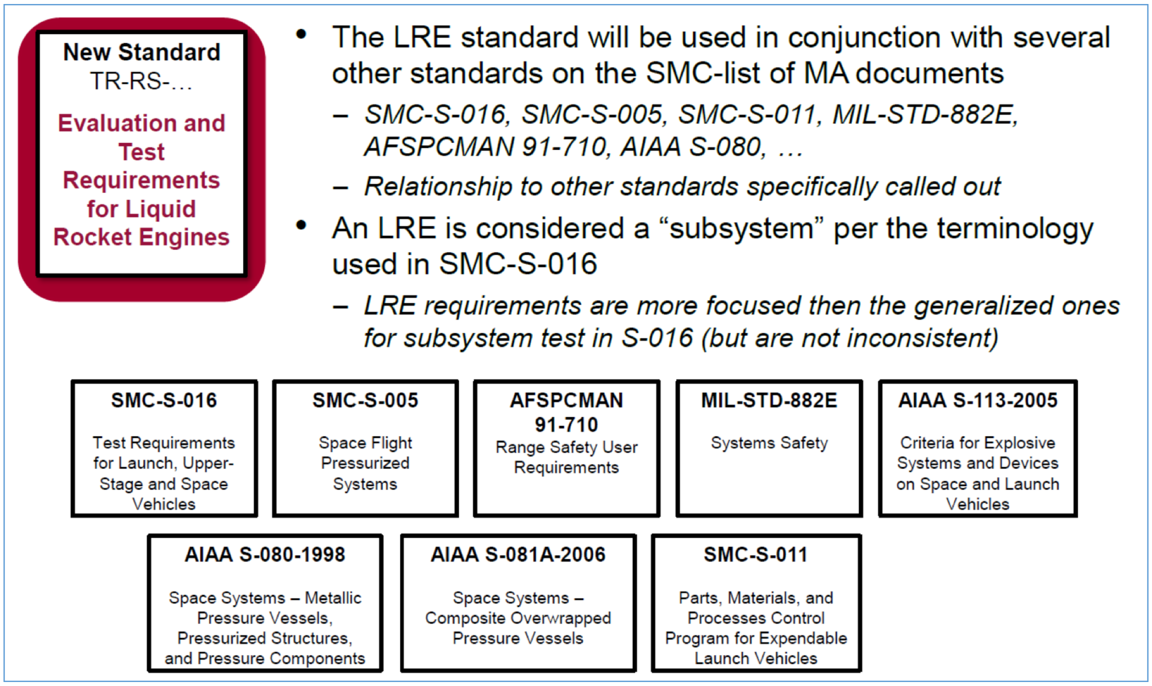

Figure 3. Notional relationship of proposed USAF SMC LRE Test Standard with a wider set of potential USAF mission assurance compliance documents (the USAF will finalize the list).

B. Basis

The SMC LRE test standard content draws heavily from two key documents, as illustrated in Figure 4 and described in the following two sections.

1. *JANNAF-GL-2012-01-R0 "Test and Evaluation Guidelines for Liquid Rocket Engines" [Ref. 3]*

This JANNAF guideline indeed served as the primary basis for the proposed SMC LRE test standard, largely because it is recognized and accepted as a valuable and comprehensive summary of related propulsion community conclusions and recommendations. However, several significant modifications were made as it was incorporated into the new SMC LRE test standard. First, the content was reorganized in the SMC LRE test standard to better reflect the hierarchy of many existing USAF standards and other compliance documents (see again Figure 3) which are already familiar to the space systems community, particularly SMC-S-016 "Test Requirements for Launch, Upper-Stage and Space Vehicles"[9]. Second, each individual requirement in the SMC LRE test standard was parsed into a separate discrete line item to facilitate understanding, compliance, and the potential for tailoring. Third, all intended mandatory requirements in the SMC LRE test standard were written in the more definitive requirements language (i.e., "it *shall* be done") as opposed to guideline language (i.e., "it is *recommended*" or "it *should* be

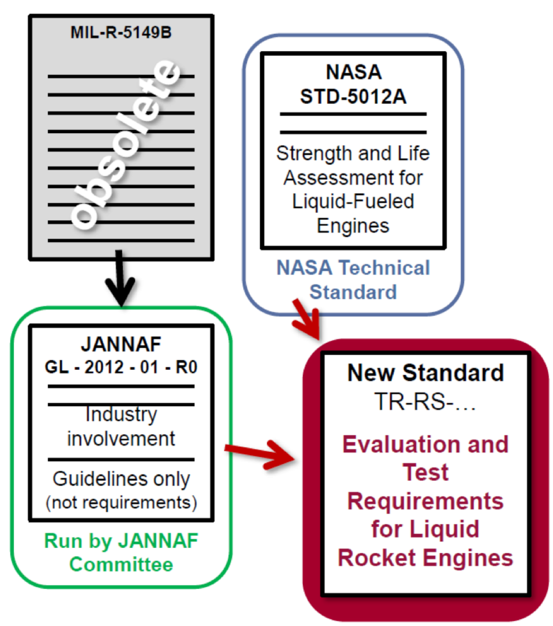

Figure 4. Key source material for the new USAF SMC LRE test standard.

done"). Finally, other significant modifications and additions were incorporated based upon lessons learned during application of the published JANNAF LRE T&E guideline (see earlier Section II, subsection B-3). Specific examples include:

- Modification of various guidelines to make them compatible with certain specific engine characteristics, such as an engine with a capability for continuous throttling versus a few discrete power levels.
- Clarification of the USAF intent regarding test durations needed to adequately characterize and demonstrate successful operation across the intended operating range for thrust and mixture ratio excursions.
- Additional adjustments to better reflect USAF and NSS mission needs (e.g., life demonstration factors).

2. NASA-STD-5012 "Strength and Life Assessment Requirements[10] for Liquid-Fueled Space Propulsion System Engines"

This NASA standard served as another key basis for the proposed SMC LRE test standard. The published JANNAF LRE T&E guideline was intended to be consistent with and complementary to the NASA standard. However, because the intent for the SMC LRE test standard is that it be a standalone document addressing both sets of requirements, a new chapter was generated for the SMC LRE test standard to specifically address structural analysis and test requirements. Furthermore, significant modifications were made in the proposed SMC LRE test standard with respect to NASA-STD-5012 to adjust requirements, where necessary, to better reflect NSS needs (e.g., certain critical structural safety factors).

C. Process and Status

The USAF tasked The Aerospace Corporation to lead efforts related to the creation of a new proposed SMC LRE test standard. This activity is in progress and is following the same typical process as used for other SMC standards. Key elements are described below.

1. The Aerospace Corporation Role

The Aerospace Corporation operates a federally funded research and development center (FFRDC) for the USAF. In this role, Aerospace provides engineering and acquisition management support as well as objective technical analyses and assessments to the Air Force, other Department of Defense organizations, and select civilian agencies supporting the nation's NSS enterprise. Aerospace's end-to-end involvement in space and space-based systems typically focuses on reducing development risks and costs, and enabling a high probability of mission success. Furthermore, Aerospace has served a role as data repository and national memory for NSS launch and satellite systems, supporting both long-term planning and the immediate needs related to NSS. Directly related to this, Aerospace has commonly been requested by the USAF to lead activities related to the generation of acquisition and design standards. One notable past example is the SMC "Test Requirements for Launch, Upper-Stage, and Space Vehicles", historically known as MIL-STD-1540 and now designated as SMC-S-016 (Ref. 9). Leading activities to create the proposed SMC LRE test standard fits well within the traditional Aerospace role.

2. First Draft Submitted to Industry/Gov't for Comment

Aerospace generated the first draft, drawing largely from the JANNAF LRE T&E guideline and NASA-STD-5012, as previously discussed Section III-B. This first draft was submitted on 7 February 2017 to a broad range of industry and government stakeholders within the propulsion and launch vehicle communities for detailed review and feedback as coordinated by Behring[11]. Comments were received and accepted over the following couple months. Several hundred individual comments were received; they were quite varied, including general observations, specific recommendations, and even perspectives on the philosophy and contextual considerations. Certain organizations declined to give detailed feedback or specific suggestions, but instead protested development of a *standard* and alternatively advocated their preference for focused activity on further development of industry *guidelines*. This was not surprising since similar organizational resistance occurred when the JANNAF TPSP previously attempted to develop a standard rather than a guideline. However, although Aerospace and the USAF understand these positions and the driving factors, the USAF needs for the new standard persist nonetheless, and thus the activity continues. Meanwhile, although space vehicle suppliers and insurance providers were not included in the original stakeholders distribution list, Aerospace is considering to solicit feedback from these organizations, as these stakeholders are key "users" of the space launch systems.

3. Process for Vetting, Resolution of Feedback, Comments, Suggestions

At the time this paper was completed, vetting and resolution of individual comments were still in progress. Upon completion, the intent is that all comments received prior to the stated deadline will have been considered and formally dispositioned. Comments received after the stated deadline will be accepted and considered, but may not receive formal disposition during the current revision period. Formal dispositions include a detailed review by an adjudication board comprised of LRE subject matter experts within Aerospace, followed by an additional review by an executive board (including Aerospace and USAF leadership) which may approve each disposition or return it for further consideration. Disposition categories include "Accept", "Reject", "Modify", "Accept in Principle", and "Clarification Only". Formal dispositions will include documentation of appropriate justification for the actions taken. In general, only "Accept" and "Modify" dispositions will result in significant changes and/or updates to the proposed SMC LRE test standard. Timely comments and their associated final dispositions will be documented. The final results will be shared with the stakeholder community at the end of the revision period (albeit without attribution to the specific originators for comments). USAF is requesting completion of the review process and final draft by early summer to support application to near term future USAF requests for proposals.

4. Process for Formal Approval of SMC Standards

Once the stakeholder review process is over and the final draft is complete, the draft will be submitted into the formal USAF approval process for SMC standards for final government vetting, acceptance, and approval. It is anticipated that final version of the standard will be approved later this year.

D. Intended Application to Future USAF Contracts

The new SMC LRE test standard is expected to join a wider set of USAF mission assurance compliance documents (see again Figure 3). It is anticipated that the final draft version of the SMC LRE test standard may be included as a compliance document for USAF requests for proposals released in FY17 (and later) related to new launch vehicles and new rocket propulsion systems, with the draft version to eventually be replaced by the formally approved document. Further details cannot be shared in this forum due to procurement sensitivity.

Tailoring will be allowed, and in fact is expected, to provide limited flexibility to suppliers if they so choose to adjust program requirements to available budget and risk tolerance. In any event the new standard will provide a common baseline for departures.

IV. TPSP Plans for Future Volumes

The JANNAF TPSP remains active in its mission to document LRE test and evaluation best practices and lessons learned. The primary areas that the TPSP concentrates in are potential companion test guideline volumes and compilation of lessons and experiences.

This TPSP focus continues to be motivated by the national need to rapidly provide chemical propulsive capabilities for beyond earth exploration and near-earth commercial space systems, as outlined and directed by US national space policy and plans, and particularly the Space Transportation Policy[12] set forth in 2013 that calls out launch propulsion within Sec. IV Cross-Sector Guidelines. NASA future plans are directed by the US government though the NASA Transition Authorization Act of 2017[13], and outlines the specific work that the Agency is funded to perform.

A. Engines, Stages, Components, and More

Since the engine-level guidelines have been published, attention of the TPSP has been steered towards potential companion volumes. The intent is to provide additional key subsystem and/or component test guidelines, as well as guidelines for liquid rocket engine testing as part of an integrated stage. As shown in Figure 5, the primary candidates

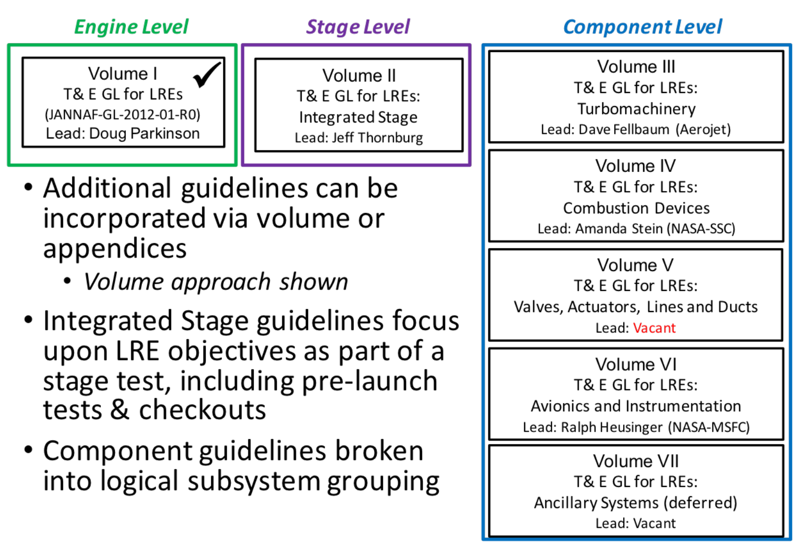

Figure 5. Proposed multi-volume architecture for the ongoing evolution of the LRE T&E Guideline series of documents.

for companion volumes are: turbomachinery, combustion devices, avionics and instrumentation, valve/actuators/lines/ducts, and integrated stage.

Within the last 6 months, the LPS Turbomachinery Panel and the TPSP have begun collaboration on the turbomachinery volume. The Turbomachinery Panel has been provided a copy of the TPSP draft Turbomachinery volume to initiate a more detailed collaboration.

A TPSP member at NASA/MSFC has initiated efforts on a volume addressing testing for integrated stages. This is likely to be the next volume to be published, as industry stakeholders also are eager for the content. If completed expeditiously, it can influence current government and industry development endeavors.

TPSP contact was also initiated with the LPS Combustion Panel. The focus of that team has largely been combustion physics and modeling, whereas the TPSP combustion devices volume would be oriented towards testing of major components such as main injectors, pre-burners or gas generators, nozzles, and main combustion chambers. Furthermore, the TPSP will maintain awareness of and engage with another current JANNAF activity related to updating the existing CPIAC Publication 655 combustion stability verification guidelines[14].

Other volumes have been drafted, but have not had significant content related activity in the past year. These will be developed as necessary, upon perceived priorities of TPSP membership.

B. Compendium Rationale/Lessons Learned Handbooks

In order to facilitate publication of the LRE T&E guideline document in 2012, much background and rationale-oriented content was reduced to provide a more concise set of guidelines. The content removed was still valid and provided important lessons learned and experiential information, but was deemed inappropriate for inclusion in the formal LRE T&E guideline. Recent TPSP meetings indicated that NASA has a lessons learned database that may provide a good architecture to capture TPSP experiences and lessons data. This capability is under review for possible future use.

C. Potential future applications

As new liquid rocket engine developments arise, and currently there are many in progress, it is hopeful that the guidelines provide insightful context from TPSP members - much in the way that we have seen some emerging companies benefit from them. It may be that the companion volume efforts really become more relevant given the state of various industry endeavors, especially when considering CCP or other commercial ventures. The primary motivation for the JANNAF TPSP, as passed through the LRE T&E guideline and the intended additional volumes, remains relevant as the evolution of the propulsion community continues to venture into private industry-led LRE developments. With these new developments brings new experiences and opportunities to mature and maintain the guidelines with proper industry collaboration and benefit to all.

V. Conclusion and Summary

The JANNAF TPSP published an LRE T&E guideline focusing on liquid rocket engine systems and their development challenges and test verification considerations. This document has provided significant value to current and recent engine developers as a benchmark and guidance tool, and is influencing LRE developers for both government applications and fully commercial ventures. Meanwhile, the USAF is creating a new SMC LRE test standard, largely based on the JANNAF LRE T&E guideline; a proposed first draft of the SMC LRE test standard was recently released for review and comment, and is intended to be formally approved and released by SMC later in 2017. The JANNAF TPSP continues efforts to expand upon its initial publication and delve into further critical development and qualification aspects of liquid rocket propulsion testing at the integrated stage level, as well as engine component level. The full participation of the entire U.S. rocket propulsion community is invited and expected at this opportune moment in the continuing advancement of spaceflight technology.

Acknowledgments

This paper is posthumously dedicated to Dr. Kendall Brown (NASA-MSFC; deceased 2016), past chair of the JANNAF LPS Test Practices Standard Panel, for his many contributions to the state of the practice in liquid rocket propulsion and valuable leadership toward the publication of the JANNAF LRE T&E guideline, and also to Mr. Roberto Garcia (NASA-NESC Technical Fellow; deceased 2013), who strongly encouraged and endorsed this JANNAF activity to advance the state of the practice in rocket propulsion.

The authors would like to extend a special thanks to reviewers of this manuscript at our respective organizations, specifically Dr. Thomas Brown (NASA-NESC) and Mr. James Cannon (NASA-MSFC), as well as to Mr. Ken Behring, Mr. Geoff Reber, and Mr. Joe Adams of The Aerospace Corporation.

The efforts of the CPIAC via the JHU Energetics Research Group is instrumental in conducting JANNAF TPSP activities as a community of practice within JANNAF. CPIAC has provided guidance, logistical support, collaboration tools/resources (e.g., information server), and publication services.

Although the LRE T&E guideline has been in circulation for almost five years, it is still appropriate to mention that it may have still been in draft form if not for some seed funding in years prior to 2012 that ensured its development as a grass roots effort by practitioners. This early funding was made possible by the NASA Chief Engineer (via NASA Stennis, MS) and The Aerospace Corporation (El Segundo, CA).

It is impossible to adequately recognize over a decade of contributions from the TPSP panel membership and their host organizations. We appreciate their time and resources devoted to creating and publishing the 1st Edition in 2012, promoting its use, and advising and participating in the evolution of it and compendium volumes. We hope that the LRE T&E guideline itself acknowledges all of the direct participants, and we again give our deep thanks for their invaluable contributions.

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