Operational Issues in the Development of a Cost-Effective Reusable LOX/LH2 Engine

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Abstract

The NASA Space Launch Initiative (SLI) was initiated in early 2001 to conduct technology development and to reduce the business and technical risk associated with developing the next-generation reusable launch system. In the field of main propulsion, two LOX/LH2 rocket engine systems, the Pratt & Whitney / Aerojet Joint Venture (JV) COBRA and the Rocketdyne RS-83, were funded to develop a safe, economical, and reusable propulsion system. Given that a large-thrust reusable rocket engine program had not been started in the U.S. since 1971, with the Space Shuttle Main Engine (SSME), this provided an opportunity to build on the experience developed on the SSME system, while exploiting advances in technology that had occurred in the intervening 30 years. One facet of engine development that was identified as being especially vital in order to produce an optimal system was in the areas of operability and maintainability. In order to achieve the high levels of performance required by the Space Shuttle, the SSME system is highly complex with very tight tolerances and detailed requirements. Over the lifetime of the SSME program, the engine has required a high level of manpower to support the performance of inspections, maintenance (scheduled and unscheduled) and operations (prelaunch and post-flight). As a consequence, the labor-intensive needs of the SSME provide a significant impact to the overall cost efficiency of the Space Transportation System (STS). One of the strategic goals of the SLI is to reduce cost by requiring the engine(s) to be easier (i.e. less expensive) to operate and maintain. The most effective means of accomplishing this goal is to infuse the operability and maintainability features into the engine design from the start. This paper discusses some of the operational issues relevant to a reusable LOX/LH2 main engine, and the means by which their impact is mitigated in the design phase.

1. Introduction

1.1 The Space Launch Initiative

The NASA SLI program was initiated under NASA Research Agreement (NRA) 8-30 to begin development of a space launch system that would be significantly safer and more economical to operate than current launch systems. SLI was identified as part of the Integrated Space Transportation Plan (ISTP) and followed on the NRA8-27 study to define an optimal roadmap that would produce a 2nd Generation Reusable Launch Vehicle (2GRLV). The objective of the NRA8-27 study was to identify risk reduction areas and was applicable to several 2GRLV architectures by performing cycle analyses and trade studies on applicable propulsion systems. Risk reduction activities were then identified to mature the technologies and engine cycles to production status. Other elements of the ISTP identified at that time included upgrades for safety of NASA's first generation RLV, the space shuttle, and technologies for third and fourth generation transportation systems.

The 2GRLV program was to build on NASA's then-current programs (e.g., X-33, X-34 and X-37) — testing new materials, structures, propulsion, software, and other technologies needed to meet the program's goals of significantly increasing safety to a 1 in 10,000 chance of loss of life and reducing payload launch costs from $10,000 per pound today to $1,000 per pound.

The scope of NRA8-30 covered more than just the propulsion facet of space transportation. The ten technology areas (TAs) worked on all elements of the next manned space launch infrastructure. In addition, NRA8-30 was separated into multiple cycles and phases to permit management flexibility. Cycle-1 would focus on initial prototype development and risk reduction, with Cycle-2 culminating in the demonstration by test of the prototype engine. Phase-2 of the SLI program would build on the foundation laid by the prototype engine project by proceeding with the design, development, test, and deployment of the human-rated full-scale development (FSD) flight engine.

Under Cycle-1 of the 2GRLV program, two prototype LOX/LH2 main engines were selected for development to reduce technical risks: the COBRA engine by the Joint Venture (JV) of Pratt & Whitney (P&W) and Aerojet, and the RS-83 by Rocketdyne.

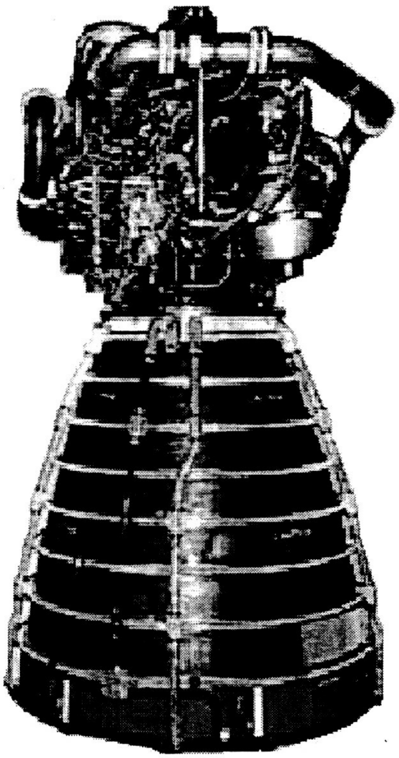

Figure 1: SSME

1.2 The SSME

Rocketdyne initiated the development of the SSME in 1971 under contract to NASA to provide the main propulsion for the Space Shuttle. Engine testing started in May 1975 and was first flown on 12 April 1981 (STS-1). Thirty years, a few thousand tests, over a hundred flights, and one million seconds of operation later, the SSME is still being safely operated as the STS main propulsion system. [1]

The SSME (Figure 1) is a high-performance 490 Klbf LOX/LH2 rocket engine and is the first large-thrust engine ever developed to be reusable beyond that typically associated with an expendable engine life cycle (e.g. a few acceptance or calibration tests followed by the mission operation). It was designed to be reusable with the intent of making access to space more economical than that experienced in previous manned space programs. While the engine has succeeded in being capable of multiple uses, the cost benefit was less than envisioned. This was in part due to the increasing operational costs required to maintain the engine in order for it to operate safely and reliably.

Before and after each flight, the SSME is subjected to extensive external and internal inspections, as well as an exhaustive battery of maintenance procedures. In addition, any nonconformances, irregularities, or discrepancies in the engine or its constituent components are meticulously documented and tracked. These operational constraints require a significant level of skilled manpower to support continued operation of the engine. By comparison, the non-recurring cost of manufacturing the engine is of less concern than the recurring operational cost.

SLI is oriented to utilize the operational expertise gained from the SSME to identify areas of focus to optimize the engine design to operate safely and reliably, while requiring labor to maintain and operate it.

1.3 The COBRA Engine

The Co-Optimized Booster for Reusable Application (COBRA) engine (Figure 2) is a reusable, LOX/LH2 600 Klbf class engine system utilizing the Single Burner Fuel-Rich Staged Combustion (SBFRSC) power cycle set up around the upgraded SSME ATD high-pressure turbomachinery. The SBFRSC cycle reduces the potential for oxygen-rich failure modes inherent in the dual-burner cycle, thus increasing engine reliability and safety. The hot combustion gases from the prebumer drive both the hydrogen and LOX turbines in parallel before entering main chamber. This design reduces the turbine temperature, increasing engine life. In addition, the use of a single "liquid-liquid" preburner means that the high transient turbine temperatures seen during engine start in the dual-burner staged combustion cycle are eliminated. Additionally, the fuel and LOX turbine temperatures are essentially "averaged" in the single preburner system, allowing the peak temperature in the system to stay at a more benign level. The Russian RD-0120 engine also uses this cycle, though with an integrated single-shaft LOX and fuel turbopump.

The COBRA engine system was selected for development under the Cycle-1 of the NRA8-30

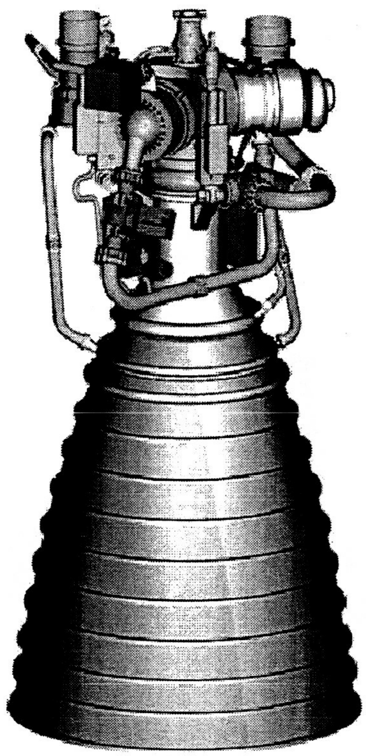

Figure 2: COBRA

SLI program under contract NAS8-01108. The genesis of the COBRA engine system originated during the development of the P&W XLR129 engine for the USAF in the early 1970's. The system utilized a highly integrated "powerduct" arrangement, with the separate turbopumps mounted in a close-coupled configuration with the single fuel-rich preburner to a double-walled hot gas duct.

1.4 The RS-83 Engine

The RS-83 engine (Figure 3) is a reusable, LOX/LH2 750 Klbf class engine system utilizing the SBFRSC power cycle with the main turbopumps arranged in series as compared to the parallel configuration used by the COBRA system. The RS-83 is a clean sheet design built on experience gained from the lengthy history of producing the SSME. Its development relies on advanced integration design tools and more rigorous design optimization in a quicker design cycle. Risk reduction activities have included the development of advanced fabrication processes that result in more consistent material properties and shorter production times. The RS-83 is

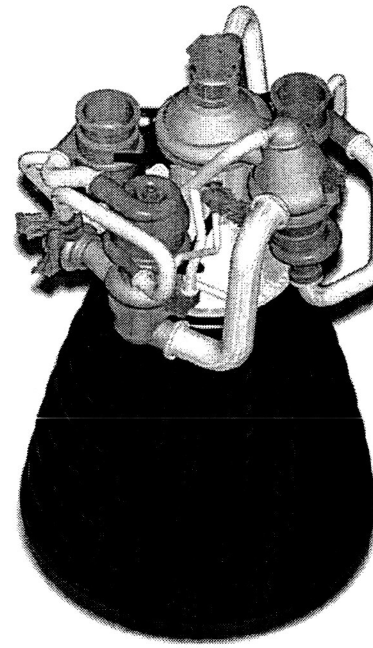

Figure 3: RS-83

similar to the COBRA system in that it decouples the fuel flow to the preburner from the coolant flow to the nozzle and main combustion chamber, promising a smoother start transient over that of the SSME.

The RS-83 engine system was selected for development under the Cycle-1 of the NRA8-30 SLI program.

2. Operational Issues

The following is a discussion of some of the operational issues associated with a LOX/LH2 engine and some of the means to be considered on how they may be mitigated by pre-emptive design.

2.1 Post-flight Turnaround

The economic viability of a reusable launch system is partially dependent on the ability to support a high launch rate. Like commercial aircraft, time on the ground represents lost revenue. From the time when the vehicle rolls to a stop and support personnel are allowed access to it, the vehicle and its subsystems are in a maintenance pipeline to prepare it for the next launch. Minimizing the post-flight turnaround maintenance requirements is a key objective of the SLI program in its pursuit of developing a safe and reliable propulsion system that is less operations intensive than previous systems.

One focus is to identify what maintenance operations are the most time/labor intensive and then either design out the need for doing the operation or develop a means of using existing or modified data (instrumentation) to eliminate the need. One example is the use of a high-fidelity turbopump speed sensor to evaluate the pump speed decay at engine shutdown to eliminate rotor torque checks.

2.1.1 Engine Drying

During engine operation, the combustion of LOX and LH2 produces steam, which is invasive throughout the hot gas system of the engine. The steam also permeates into the turbomachinery, where it condenses and collects as water. It has been described that "about a cup" of water is drained from the SSME HPOTP following a nominal duration (hotfire) operation.

Regardless of the volume, the presence of water or humidity in the engine is unacceptable and must be thoroughly removed prior to its next operation. Engine drying is generally a lengthy process requiring a heated gaseous nitrogen (GN2) purge through the engine. On the SSME, a drying purge is connected to the engines shortly after the orbiter lands.

While the need to dry the engine after operation cannot be eliminated, the amount of time required to complete it may be reduced. This can be accomplished by minimizing the volumes where the water is known to collect, making it more difficult for steam to invade into areas where it could condense, or designing the volumes to permit them to be easily drained. Another means of saving time would more efficient positioning and routing of purge and drains, and to have quick disconnects (QDs) in key locations to permit purges or drains to be easily connected/reconnected.

2.1.2 Inspections

In a perfect world, the engine should never require inspections. Inspections are generally conducted to verify the physical integrity of risk areas on the engine and can be separated into external and internal types. With few exceptions, inspections are usually visual, using the "Eyeball, Mark-1" as the primary instrument. External inspections are less problematic than internal ones, because they do not require the engine to be breeched. Performing an internal inspection on the engine requires the opening of flanges or other component interfaces, or the opening of ports. An internal inspection may be regarded in the same sense as "exploratory surgery" would be regarded on a medical patient – there is always a risk of a "post-operative infection" manifesting itself afterwards. This is generally in the form of FOD (Foreign Object Debris) contamination being introduced into the engine (i.e. LOX tape, cotton swabs, rags, safety wire, nuts, bolts, etc.), which has been known to occur. The following are some means by which inspections can be reduced: [2]

- Do concurrent engineering, i.e., design and manufacturing engineers work to together to have parts and assemblies that are simple, easy to make, low cost and do not require post flight inspection.

  The use of concurrent engineering can be further utilized on a number of other crosscutting development applications. The expertise provided by the engine maintenance technicians should not go unexploited. They should be recruited into the engine and component design teams to provide valuable maintainability insight.

- Eliminate welds by using castings (welds often require inspection to identify crack initiation / propagation). If they cannot be eliminated, locate them where they can be easily inspected, on both sides if possible.

- Eliminate as many inspection points as is possible make those required easy to do by placing inspection ports in locations that are easy to access.

- Eliminate fracture critical areas by using generous radius in all applications (i.e., HPF ducts, turbine housings, internal ties on LPF ducts, etc.).
- Develop techniques for performing non-intrusive inspections.
- Eliminate the need for protective coating materials.
- Characterize the internal environment of the engine as fully as possible and as early as possible during development. Do this by actual test of a highly instrumented engine to develop and verify internal models. This is useful in identifying problem areas and correcting them by pre-emptive design early in the design cycle, rather than later mitigating the flight risk by the implementation of a more-expensive maintenance "band-aid" that has to be added on to the post-flight turnaround procedures. The lack of thorough environment characterization is often mitigated later by limiting engine life to compensate for the lack of design margin.

2.1.3 Engine vs. LRU Replacement

A Line Replaceable Unit (LRU) philosophy should be established early in the engine development that identifies components to be replaced on the engine while it is on the vehicle. Any other components not identified as LRUs would necessitate engine removal if replacement became necessary. In order to reduce the impact to post-flight turnaround time, the engine and all identified LRUs would require design and development to be easily and quickly replaced. One way to optimally develop this philosophy would be to identify those components that have a high incidence of replacement for cause, and for life related. An inventory was conducted by Rocketdyne on the SSME to catalog all the

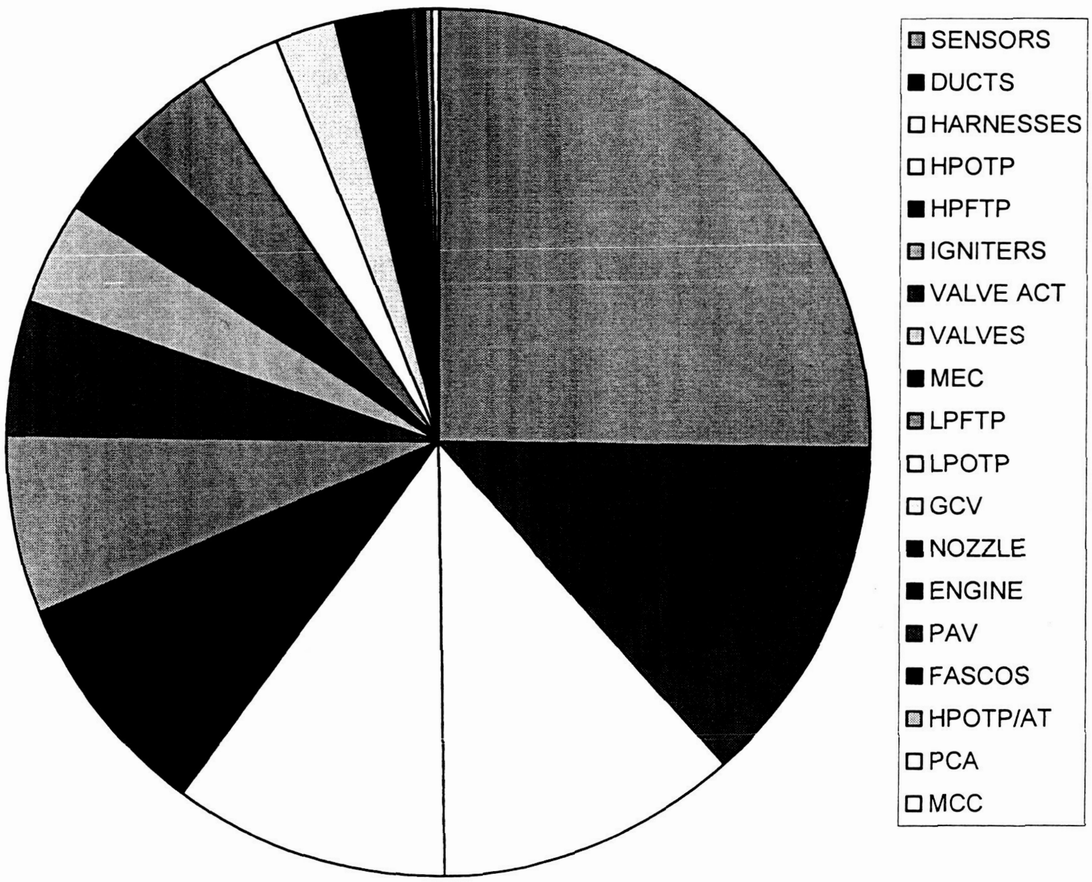

Figure 4: SSME Hardware Replacements for Life & Cause

hardware replacements that had occurred on the SSME during post-flight operations [3]. This replacement inventory was evaluated to show those components that had the highest rate of replacement (Figure 4). The causes of replacement included:

- Latent defects.
- Flight, checkout, or suspect anomalies (includes NASA- or Rocketdyne-directed removals).
- Damage incurred during turnaround operations.
- Operational/life limits

2.2 Engine or LRU Replacement

If it becomes necessary to remove and replace the engine or a LRU part, the ability to do this quickly is important in order to reduce its impact on the post-flight turnaround schedule. The engine and all identified LRUs should utilize design attributes that permit this to be realized.

2.2.1 Fasteners

Simplification of fasteners and latching devices would be useful in designing expeditious removal features into the engine and LRU component interfaces. Timesaving anti-rotation alternatives to the use of lock-wire should be considered whenever possible and can include self-locking nuts, washers with locking tabs, and torque-stripe compound. One example that would save many hours of turnaround time on the Space Shuttle orbiter is the simplification of the fasteners used on the heat shields enclosing the SSMEs, which consist of several hundred bolts and require approximately eight hours each to remove in order to permit access to the engines.

2.2.2 Common Tools

In the same context as the simplification of fasteners and latching mechanisms, the additional simplification and standardization of tools required to perform maintenance operations can also result in a benefit to the time required to perform post-flight turnaround. The requirements for complex or a large number of tools should be avoided.

2.2.3 Shallow Engine Layout

One guideline in the development of the LRU philosophy is to encourage "one-deep" or a "shallow" engine layout that would permit the removal of the LRU without having to previously remove any other component. By design, parts identified for high instances of maintenance or removal are located at easily accessible locations in the engine layout. If a component is identified as needing to be replaced and can only be done so by the prior removal of one or more other components, then the cost (in turnaournd time) of on-site removal and replacement (R&R) may be excessive and the engine should be removed for depot-level maintenance activities.

2.2.4 Advanced Interface Design

Whenever an interface is disturbed, it must undergo a series of leak-checks and inspections to verify the interface seal integrity is acceptable. Another liability to be considered when a component interface is restored following an LRU replacement is the small misalignment tolerance allowed to prevent seal leakage or the formation of stress concentrations. The development of advanced interfaces (e.g., spherical flanges) that reduce the potential for seal leaks and permits a larger range of misalignment would provide a benefit in LRU replacement times. Development of an operationally efficient vehicle-to-engine interface can decrease maintenance operations and engine R&R time. Design considerations may include: location, number and grouping of interfaces, as well as possible use of automation and innovative use of tooling, ground support equipment (GSE), and infrastructure.

3. Useful Engine Development Tools & Techniques

In response to some of the operational issues identified during the SLI program, tools and techniques have been developed to mitigate the technical risk presented by them. In order to develop the best solutions the design process must consider all phases of handling and operations of the engine, from "cradle-to-grave" (including assembly, test and flight cycles, to final disassembly and deactivation).

3.1 REIMR Study

At the initiation of SLI, MSFC conducted a detailed study of development and operational issues associated with liquid propellant rocket engines. This included many of the "lessons learned" that had been documented for most of the large-thrust rocket engines developed in the United States (i.e. F-1, J-2, and SSME). Emphasis was placed on determining common themes in issues or problem areas in all phases of engine design, development, manufacture and operation. The intent was to provide the results of this study to the different engine development teams (i.e. COBRA and RS-83) to assist them in avoid the development "speed-bumps" that had been encountered previously.

The key difference that separated this study, known as REIMR (Rocket Engine Issue Mitigation Resource), from many previous "lessons learned" studies was that it not only focused on the problem/event and the immediate primary cause of it, but also the "fundamental root cause" that had allowed it to occur and how it could be avoided/mitigated in future engine programs. The Fundamental Root Causes (FRCs) identified were:

- Inadequate understanding of the engine environment.
- Inadequate systems engineering and integration design trades.
- Inadequate resources.
- Overestimation of technology base.
- Immature mission/vehicle design requirements imposed unnecessary engine requirements.
- Inadequate understanding of manufacturing environments and process variability.
- Inadequate understanding of material properties.
- Inadequate design margins.
- Inadequate quality processes.
- Inadequate or loosely worded requirements or specifications.
- High performance requirements (I_{SP}, thrust-to-weight, etc.) drove design to be very sensitive to all design and operations parameters.

3.2 Process FMEA

The function of process FMEA (P-FMEA) is to evaluate critical manufacturing and maintenance processes and procedures to identify the likelihood and consequences of an escape. The P-FMEA is useful for mitigating manufacturing and maintenance risks during the preliminary and design phases. It also is useful in mitigating one of the FRCs identified in the REIMR study (e.g. "Inadequate understanding of manufacturing environments and process variability.").

3.3 Periodic Maintenance Schedule Evaluation

In the development of the post-flight maintenance schedule, it is obviously important to document the rationale for conducting each maintenance operation. This permits periodic evaluation of the schedule to eliminate those activities that no longer have a valid rationale for performing.

3.4 Minimization of Flight Sensors

Like inspections, a rocket engine in a perfect world is one that doesn't need sensors. Emphasis should be made to minimize the number of intrusive sensors required by the flight engine. A high number of sensor ports can result in a degradation of reliability by a higher number of potential leak locations, sources of FOD, and sensors that can fail. Sufficient instrumentation should be utilized during engine development to fully characterize the internal environment and model the relationships between the flight sensors and the engine operating condition. This should further reduce the suite of flight instrumentation.

Another means of reducing the number of intrusive instrumentation ports penetrating the engine is through the use of multiplexed sensors that can sense multiple measurands (i.e., temperature, pressure, vibration) through one port.

3.5 Improved Instrumentation

In addition to minimization of sensor quantities, increased performance and robustness of existing intrusive sensors and associated connectors and wiring/cables can be enhanced. Instruments, connectors, and wiring that can withstand long durations of extreme conditions in all phases of operation are absolutely necessary for increased safety and reliability, quicker turn time, and lower operational costs.

High accuracy, non-intrusive instrumentation is another area that can be developed to enhance full engine environment characterization while minimizing risks and operational concerns.

3.6 EHMS-Supported Maintenance Scheduling

The SLI program is supporting the development of engine health management systems (EHMS) to be part of the integrated vehicle health management (IVHM) system. In addition to providing a reliability benefit provided by failure mode mitigation, the EHMS can be also used to support post-flight maintenance scheduling. The data recorded by the EHMS during the engine flight operation can be downlinked to the ground for analysis. This allows unscheduled maintenance to be identified and prepared for implementation before the vehicle returns to earth.

4. Summary

In the summer of 2002, NASA announced that it would not exercise the contract options to continue development of the COBRA or RS-83 engines. The suspension of development efforts was not due to technical or programmatic deficiencies in either project, but was due to reorientation of SLI priorities to focus on LOX/kerosene booster engine development. With the limited program budget (and manpower), the LOX/LH2 development effort could not be continued in parallel and was suspended.

Although the LOX/LH2 engine programs were discontinued, they were useful in developing and demonstrating the process of infusing the strategic engine attributes (e.g., safety, reliability, operability, maintainability) into the engine design at an early stage. This practice should be further refined and implemented in the design process of future engine development efforts.

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[1] Biggs, R.E., "SSME – The First Ten Years," *History of Liquid Rocket Engine Development in the United States*, AAS History Series, Vol. 13, 1992

[2] Interview with NASA personnel, REIMR Study, 2001

[3] RI/RD89-109, "Flight Readiness Firing and Space Transportation System Launch History Data," Rocketdyne Propulsion & Power, 9 June 1998