AIAA 2005-4522

# REIMR – A Process for Utilizing Propulsion-Oriented 'Lessons Learned' to Mitigate Development Risk

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**41st Joint Propulsion Conference & Exhibit**
10-13 July 2005
Tucson, AZ

# REIMR – A Process for Utilizing Propulsion-Oriented 'Lessons Learned' to Mitigate Development Risk

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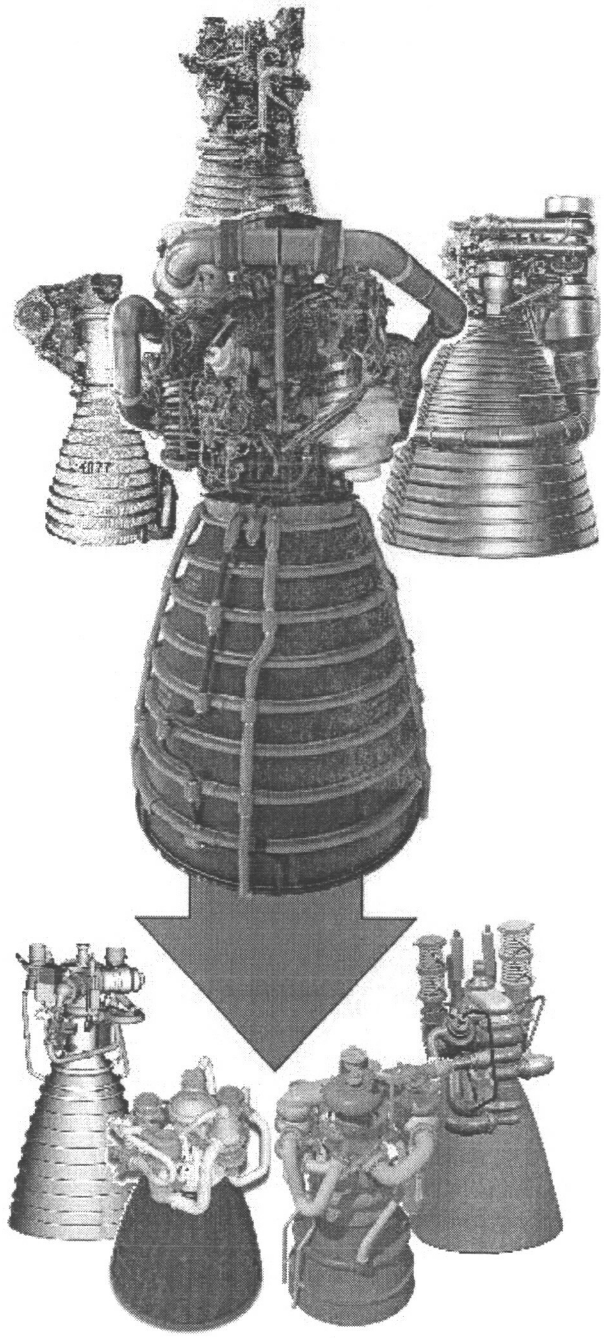
**This paper is a summary overview of a study conducted at the NASA Marshall Space Flight Center (MSFC) during the initial phases of the Space Launch Initiative (SLI) program to evaluate a large number of technical problems associated with the design, development, test, evaluation and operation of several major liquid propellant rocket engine systems (i.e., SSME, Fastrac, J-2, F-1). The results of this study was the identification of the "Fundamental Root Causes" that enabled the technical problems to manifest, and practices that can be implemented to prevent them from recurring in future engine development efforts. This paper will discus the Fundamental Root Causes, cite some examples of how the technical problems arose from them, and provide a discussion of how they can be mitigated or avoided.**



## Introduction

The NASA SLI program was initiated under NRA8-30 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 were 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 cycles to production status. Other elements of the ISTP identified at that time included upgrades for safety of NASA's 1st-generation RLV, the space shuttle, and developing technologies for 3rd- and 4th-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, computers and other technologies needed to meet the program's goal 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

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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 the design, development, test, and deployment of the human-rated full-scale development (FSD) flight engine.

At the beginning of the SLI program, it became apparent that NASA was embarking on a program to fully develop a selection of "clean sheet" rocket engines to power the next generation of reusable launch vehicles. It also became apparent that the prerequisite experience for development of the complex rocket engine systems had significantly thinned since NASA had last been involved in a clean-sheet rocket engine program, namely, the Space Shuttle Main Engine (SSME) development program conducted over a quarter century previously. Even then, the SSME program was able to utilize the relatively fresh experience in rocket engine development resulting from the Apollo program. By comparison, the body of knowledge available for application to the SLI engines was significantly more scarce, effectively either buried in a mountain of historical documents or residing in a diminishing number of technical consultants that had actual hardware development experience (respectfully known as "greybeards").

Looking ahead at the aggressive schedule projected by the SLI program, it was seen as necessary to try and anticipate some of the obstacles that could be encountered in the development of a prototypical engine system, and the means by which to avoid them. Previous rocket engine development programs had relied on the "test-fail-fix" philosophy of using hardware testing to wring out problems at the expense of destroyed test articles and abused test facilities. The expense involved in using this development philosophy was prohibitive in view of the more fiscally conservative environment and the fact that there were several concurrent engine development programs gearing up rather than just one. The problems resolved in the development of the SSME had been exhaustively documented, as well as similar impediments encountered in other rocket engine development programs (i.e., F-1, J-2, H-1, MC-1, etc.). However, the technical issues initially identified appeared highly specific to design elements of the particular engine system, which could be very difficult to effectively apply to a clean-sheet engine design. The realization developed that what was really needed was to look one level higher and try to identify the "fundamental root cause" that enabled the technical problem(s) to manifest in the first place.

## The REIMR Study

A study was initiated at MSFC to begin development of a risk mitigation tool to assist in the development of liquid propellant rocket engines, as well as the process for the continuing enhancement of the tool and its effective use. The tool, known as Rocket Engine Issue Mitigation Resource (REIMR), can also be applied in a broader sense to almost any complex system development effort through the understanding and application of the Fundamental Root Cause (FRC) philosophy that the study identified.

The REIMR study had several primary and secondary objectives:

Primary

- Initially, the study was to document and study possible technical issues that could be encountered in the development of a clean-sheet rocket engine. As more results developed, the objectives of the study were adjusted to include identification of the significant technical and fundamental root causes for the problems that have occurred during rocket engine development, and apply this knowledge to improve future liquid rocket engine programs with emphasis on reusable manned systems.
- Establish process to allow personnel to contribute to and benefit from past applicable engine experience in both broad and narrow focus. This process was oriented toward reducing technical risk of future programs.
- The goal of this effort was not so much to identify the technical issues that can occur, but more to illuminate the fundamental root causes that allowed the technical issue to develop.

Secondary

- Expand the experience base of personnel that will be supporting the 2GRLV program in terms of reusable liquid propellant rocket engines.
- Infuse an understanding of the sensitive trades that go into the engine development process by using examples derived from SSME.

The initial basis for the study was Bob Ryan's "A History of Aerospace Problems, Their Solutions, Their Lessons" which contained a comprehensive selection of issues encountered during the development of a number of propulsion systems, especially the SSME[1]. These issues provided the initial set of subjects that the REIMR study focused on, where additional information regarding the issue was researched to determine a more indepth understanding of the problem, how it developed, and how it was solved. Additional issues and supporting information was also derived from other "Lessons Learned" activities, mishap/failure reports, personal interviews, and other archived information. The primary sources used to support the REIMR study are shown in Figure 1.

As more issues were identified and studied, the process for understanding and utilizing them collectively was developed, which is shown in Figure 2. This process started out with reviewing existing engine development summaries and "Lessons Learned" documentation to identify the specific issue to be researched, followed by "data mining" from validated sources/databases and interviews with personnel with detailed knowledge of the problem. This was initially focused on documenting all the technical causes of the engine issues and look for any similarity in the candidate engines being developed under the 2GRLV program. However, it became apparent that trying to match the operational or design event that had caused the issue to the emerging specifics of any of the 2GRLV engines was a "hit-or-miss" affair, being very difficult to accurately match the "Lesson Learned" to the potential "Lesson-to-be-Learned." Identification of a score of more generic symptoms, referred to as "Fundamental Root Causes," permitted the study group to review the 2GRLV development engines at a system level. The evolved REIMR process took the standard "Lessons Learned" exercise one step further. After an individual or subgroup collected required relevant material on a particular issue, it was reviewed in consensus with the rest of the study group to identify the FRC(s) that precipitated the issue. Identification of the FRC and the issue itself was also recommended. The flow of cause-and-effect for a specific issue and how the FRC integrates into the flow is shown in Figure 3.

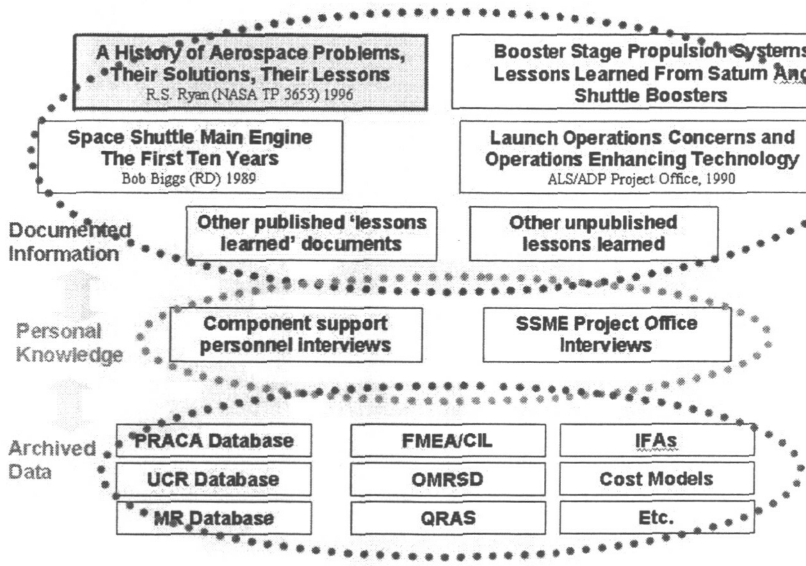


Figure 1: Primary Sources Supporting the REIMR Study

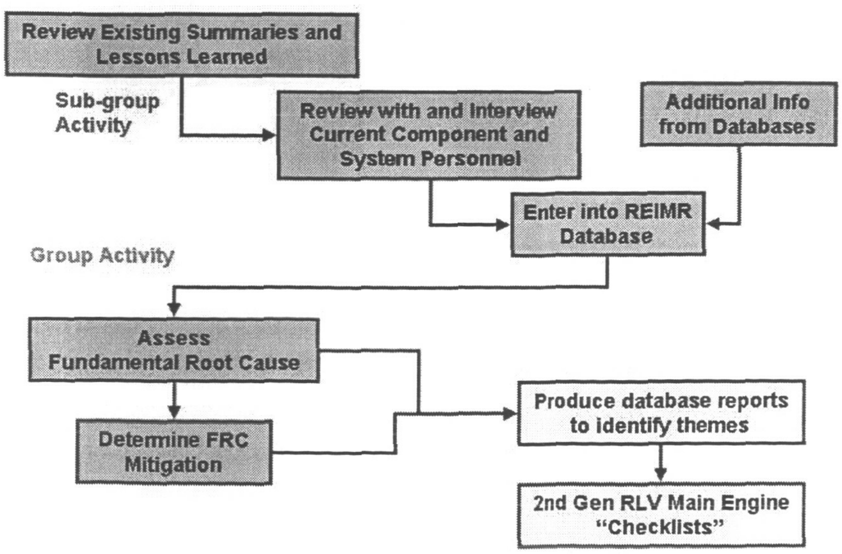


Figure 2: The REIMR Development Process

By the time information was due to be released on the 2GRLV engines, the REIMR database was expected to have achieved a sufficient level of maturity to permit a preliminary checklist to be extracted to compare the engines at the system level against the FRCs and at the component level against specific technical issues. Any relevant issues identified by the REIMR checklist would be tracked for potential mitigation. It was expected that the initial release of information on the 2GRLV engines would probably not be at a high level of detail. For this reason, REIMR was used as a tool to help guide the engine DDT&E process in Cycle-1 of the 2GRLV program.

Effort was made to keep the number of FRCs small. A large number of root causes were initially identified, but many were actually subsets or reflections of the FRCs that REIMR utilized. Many of the FRCs identified in the REIMR study come as no great surprise to an experienced systems engineer and can be largely seen as common sense. The reasons for why these violations of common sense occur is beyond the scope of this paper or the study.

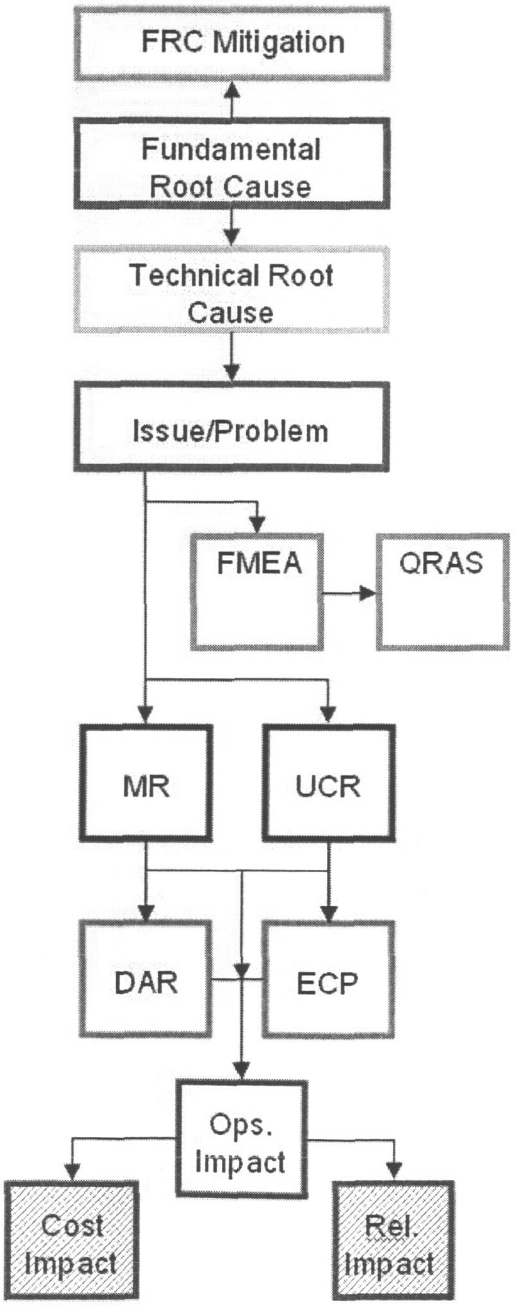


**Figure 3: Issue Cause & Effect**

## Fundamental Root Causes

Identification of the FRCs was not an epiphany that suddenly happened, but was rather a progressive understanding of some of the higher-order predecessors that can spawn a particular problem during the life cycle of a rocket engine, ranging from conceptual development to flight. As more and more issues were collected and studied, one or more FRCs could often be identified that enabled the problem to manifest.

The FRCs currently used in REIMR, as well as descriptions and examples are as follows:

*Inadequate understanding of the engine environment*

This fundamental root cause includes adequacy of analysis tools & techniques used to predict the physical environment in the engine, the ability of the instrumentation system to measure the environment, and all other physical or conceptual reasons the real engine environment is different than the predicted value used during the design process.

The SSME hot gas system provided several examples of this FRC enabling technical problems, specifically, recurring incidences of sheet metal cracking in the turbine turnaround ducts. The lack of understanding of the engine environment did not permit the sheet metal to be designed with sufficient coolant flow, which precipitated the initiation and propagation of the cracks. The corrective action required for this problem was to inspect and track the propagation of the cracks, then perform a weld repair on any crack that got too long. The consequence of this problem was expensive and time-consuming inspection, maintenance and repair operations. Resolution of this issue was accomplished as a result of the Technology TestBed (TTB) program conducted at MSFC in the mid-1990's, where a highly-instrumented SSME was subjected to a test program that permitted a more penetrating characterization of the engine internal environment. As a result, when Pratt & Whitney designed the Advanced Turbopump Development (ATD) turbomachinery for SSME, this expanded data allowed effective elimination of the sheet-metal cracking problem.

*Inadequate systems engineering and integration design trades*

This fundamental root cause captures problems resulting from not adequately addressing all aspects of the systems engineering trade studies, including reusability, reliability, maintainability, manufacturability, and performance.

The design of the SSME heat exchanger has been a source of concern throughout the SSME program history, in that any leakage of the GOX from the heat exchanger into the fuel-rich hot gas system is a Crit-1 failure mode that can cause a loss of vehicle or crew. The original heat exchanger design utilized a dual-tube configuration that had several critical welds that were difficult to accomplish and inspect. The exposed thin-walled tubing extending into the hot gas flowpath also made it susceptible to damage from FOD impacts. The high heat transfer requirement and chosen method of tank pressurization drove the design, but the design trades did not take into account the manufacturing difficulties and FOD intolerance. One mitigation measure implemented was to change the design to a single-tube configuration that had fewer welds.

*Inadequate resources*

This fundamental root cause captures problems resulting from inadequate budget, schedule, personnel, equipment, or facilities being made available when needed.

The MC-1 engine development program had many instances of insufficient resources causing recurring problems in development hardware, especially the engine valves. One of the goals of the MC-1 program was to demonstrate the ability to develop a flight-certified engine for use on the X-34 vehicle at a fraction of the historical recurring and non-recurring costs. In this respect, the program was successful, but the consequences included a dire shortage of development hardware and temperamental engine valves. As a result, budget and schedule were affected by repeated trouble-shooting of valve problems for which there were few replacements available. A shortage of development hardware also required constant cannibalization of off-stand engines to support the ongoing development test program, causing lost schedule and hardware tracking headaches.

The initial SSME development program rushed into system testing, sacrificing the potential benefits of component- and/or subsystem-level testing in order to shorten the development schedule and cost. This made any test failures more costly as the failure occurred at the system level, rather than at the component level.

*Over estimation of technology base*

This fundamental root cause captures issues where overly optimistic design goals established unrealistic design requirements, and were caused by an over estimation of the state-of-the-art of technology at that time. This also addresses an inadequate understanding of the technical risk or current technology readiness level (TRL).

Examples of this fundamental root cause are numerous, both at a programmatic level (i.e., NASP, X-33) and further down at the analytical or component design level. Other examples of this include overestimation of the technical maturity of the materials, manufacturing processes or avionics applied to an engine development program, such as in projects involved in the development of an integrated engine health management system (IEHMS). Experience has repeatedly shown that the complexity involved in developing an effective IEHMS is hard to *over*-estimate.

The complexity of SSME data reduction required numerical methods that were not within the state-of-the-art computational capabilities at the time of initial SSME development, and has only recently been identified as being feasible for use in an engine health monitoring system.

*Inadequate quality processes*

This fundamental root cause captures problems resulting from inadequate quality processes, or conversely problems which would have not occurred if quality process had been followed or if appropriate quality process had been in place. This FRC includes 'mistakes', or human-factor events if the event could have been precluded with a "quality" or management process in place.

Several engine test failures were caused in the SSME by quality process failures allowing the introduction of FOD contamination (e.g., LOX tape) during assembly or maintenance operations. Other process failures include utilization of incorrect weld wire, which caused a catastrophic SSME steerhorn failure at the assembly weld, or failure to install an actuator coupling during a valve change-out, causing a premature cut-off during a test.

*Immature mission/vehicle design requirements imposed unnecessary engine requirements.*

This fundamental root cause captures problems caused by the flow down of immature or unrealistic mission or vehicle requirements. While this is similar to the inadequate SE&I trades FRC, it is differentiated by being higher level requirements that the engine program had no control.

An example of an immature requirement was for the SSME to have independent thrust and mixture ratio control. This was a requirement levied by the vehicle to permit thrust control to achieve the desired flight trajectory, and mixture ratio control to optimize ascent performance and minimize residual propellants at main engine cut-off (MECO). This forced the engine system design to utilize a dual preburner configuration, which significantly increased the complexity of the engine system and subsequently the number of concerns to solve. As it turned out, the requirement for mixture ratio control during flight was eventually eliminated from the vehicle, but too late to be reflected in a more simple SSME design.

Another example of an immature engine requirement was that of the high thrust-to-weight ratio (T/W) levied on the SSME during its initial development. This requirement is generally based on the vehicle being able to carry as much propellant or payload as possible by forcing the vehicle systems to be as light as possible. This forced engine weight to be at a premium, resulting in development of high pressure, high-performance, low-weight components with a corresponding high number of component life and safety concerns. This required extensive inspections and maintenance between operations to mitigate. The high T/W requirement levied by the vehicle also turned out to be largely unnecessary, as the first glide flights of the Shuttle identified a stability concern that was corrected by the installation of ballast in the vehicle boat-tail. As the SSME weight was increased over the years as a consequence of block upgrades to enhance reliability, the vehicle ballast was progressively removed.

*Inadequate understanding of assembly environments and process variability.*

This FRC captures problems resulting from not adequately understanding or considering the manufacturing and assembly environments and process variability. This includes proper concurrent engineering processes to design for manufacturability. Failure to overcome this FRC will result in a high reject rate of fabricating parts or elevated inspection and maintenance needs.

During SSME post-flight inspections, cracking was identified on a turbopump shaft bearing inner race. An investigation showed that the cracking had initiated at a corrosion pit and traces of chlorine were detected on the part. Some changes in the manufacturing process and drying procedures had been instituted in a new manufacturing facility that were different from those used in the original development pump room. The drying procedure to eliminate moisture prior to bearing installation did not work properly at the new facility and permitted the trapping of moisture between the race and shaft. Future mitigation would be to ensure that the component design and assembly process allows for the removal of moisture from the assembly stack and eliminate potential for trapping of moisture.

*Inadequate understanding of material properties.*

This FRC captures problems resulting from inaccurate or incomplete material performance information used during the design and analysis process. This includes proper consideration of allowable variations within specification.

Identification and mitigation of the effects of hydrogen exposure embrittlement (HEE) to engine materials should always be taken into account. For example, the SSME experienced a catastrophic test failure caused by failure of a 2nd-stage turbine blade. The blade failure was caused by internal crack growth of a pre-existing subsurface flaw embrittled by hydrogen exposure. The embrittlement was a result of hydrogen exposure through microshrinkage porosity or by diffusion as a result of long-term exposure.

*Inadequate design margins.*

This FRC captures problems resulting from design requirements with optimistically low margins of safety and is related to the "Over-estimation of technology base," but at a lower level application.

An example of this FRC is the investigation and mitigation of high synchronous rotordynamic vibration in the SSME HPOTP caused by lack of margin in the bearing design to account for unknown hydrodynamic influences. The identification and resolution of this anomaly was conducted during component-level testing. This shows the importance of component-level testing under realistic conditions to work out design and operational problems early.

*Inadequate or loosely-worded requirements or specifications*

The FRC captures problems resulting from requirements or specifications that fail to adequately capture what is required from the system or component. This can be a result of wording the requirement or specification such that there is too much "wiggle-room" allowing unacceptable materials or components to be used. A good requirement provides a balance between ensuring that the system needs are achieved while leaving enough latitude to permit the designers to reach the optimal design solution.

Pre-emptive mitigation for this gremlin is to baseline down the requirements as early and as thoroughly as possible. Some change in the requirements is permitted so long as it is understood that the larger the change, the more impact in budget and schedule it will cause. Further, any requirements changes after the engine Preliminary Design Review (PDR) should be kept to an absolute minimum. Make sure the requirements do not force the designers into using a specific design solution or unnecessarily constrain the design trade space. Immature requirements imposed early can have a lasting impact.

*High performance requirements (Isp, T/W, etc) drove design to be very sensitive to all design and operations parameters*

This fundamental root cause addresses the lack of margin or robustness in the engine system or component caused by the high performance requirements.

For example, the high T/W requirement levied on the SSME during its initial development forced engine weight to be at a premium, causing development of high pressure turbomachinery with very high power densities. This sacrificed system robustness and made the turbomachinery highly sensitive to variances ranging between engine units.

In addition, the high performance requirements (i.e., high Pc, dual preburner, high power density, high energy propellants, etc.) made test data reduction difficult due to the difficult measurement environment and the complex, closed loop nature of the SSME cycle.

Many of the fundamental root causes are inter-related and often one will precipitate another. For example, when high performance requirements for T/W conflict with structural requirements for margin of safety, one will be given priority over the other unless the available materials can answer the needs of both. Then it becomes a question of whether the materials technology is mature enough to answer the needs of the engine, or if there are adequate resources available to develop it.

The goal of the REIMR exercise is to identify which FRC is the primary initiator that gave rise to the others. Additional FRCs were limited to one secondary if needed.

## Application to Future Propulsion System Development

Although the REIMR study was conducted to support the SLI / 2GRLV program, it can be easily extended to support any future propulsion system development program, including the ongoing Lunar/Mars exploration initiative.

It is also important to note that while the technical issues collected in the REIMR database are primarily specific to liquid propellant rocket engines, the FRCs can be applied to almost any complex system.

## Conclusion

It should be emphasized that the objective of this paper was not to provide a "Systems Engineering 101" or "Rocket Science for Dummies" tutorial, or to attack the SSME by parading out every problem it ever had. The REIMR study was useful in highlighting the top-level triggers that generate issues during the life cycle of a rocket engine, and then provide specific examples.

With regard to the SSME, it has the distinction (and liability) of being one of the most long-lived (and extensively documented) rocket engine systems ever used, accumulating over a million seconds of total hotfire time. It has an amazing track record of performance and demonstrated reliability, and most of the rocket propulsion engineers at NASA have gained valuable experience by supporting the SSME program. However, its passage into history has not been without a few potholes, and those have to be understood lest they be repeated.

In retrospect, the REIMR study had a few Lessons Learned of its own, including:

- Potential perception as being another "Lessons Learned" (i.e., "Lessons Learned, Documented, and then Forgotten") activity.
- "Oh my gawd, not another database!"
- A majority of the technical issues identified were primarily specific to SSME, so extrapolation was required to apply to 2GRLV main engines except through application of the Fundamental Root Causes.
- REIMR focuses more on what was done wrong and not enough on what was done right.
- Time to fully develop REIMR was very limited after the SLI/2GRLV propulsion projects began.

Overall, most of the results from the REIMR study come as no great surprise to an experienced systems engineer and can be largely seen as "common sense." However, it has been shown that bringing all these bits of expensive wisdom together under one cover was useful in preparing the engineers tasked with supporting the 2GRLV program by providing a better sensitivity of what conditions to avoid or mitigate. Continued application of the REIMR process and the Fundamental Root Causes can be useful in the development of future propulsion systems and other complex systems.

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[1] Ryan, R.S., "A History of Aerospace Problems, Their Solutions, Their Lessons," NASA-TP-3653, 1996