REIMR – A Process for Utilizing Liquid Rocket Propulsion-Oriented 'Lessons Learned' to Mitigate Development Risk in Nuclear Thermal Propulsion

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Abstract. This paper is a summary overview of a study conducted at the NASA Marshall Space Flight Center (NASA-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). One of the primary 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 propulsion system development efforts, such as that which is currently envisioned in the field of nuclear thermal propulsion (NTP). 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 in the development of an NTP system.

Keywords: nuclear thermal propulsion, NTP, lessons learned, fundamental root cause, risk mitigation.
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INTRODUCTION

The REIMR study was initiated immediately preceding the Space Launch Initiative (SLI) program to prepare for the clean sheet development of a new generation of booster engines. The genesis of the REIMR study is documented in a previous paper oriented toward liquid rocket engine development (Ballard and Brown, 2005). It was recognized that historical rocket engine programs were not lacking in examples of development approaches and practices to be avoided. The focus of the REIMR study was to not only collect and document these events, but also develop a process to effectively apply them to future development efforts. In terms of NTP system development, many of the results and conclusions of REIMR are very relevant and should be applied to any prototypic propulsion system development effort. In addition to applying specific examples derived from liquid rocket engine programs (e.g., SSME, H-1, F-1, J-2, MC-1), additional examples can also be captured from previous NTP development efforts as they are identified.

NASA-MSFC has recently been moving forward on NTP development through a number of in-house activities. The focus of these efforts has been to develop prerequisite technologies, mitigate technical risk and build relevant experience in the supporting personnel. It is apparent that for NTP to be realized, NASA will be embarking on a program to develop a revolutionary propulsion architecture with limited previous practical experience. It is also understood that the prerequisite experience for development of the complex nuclear rocket engine systems had significantly atrophied since NASA had last been involved in a NTP development program, namely, the Nuclear Engine for Rocket Vehicle Applications (NERVA) program conducted over a quarter century previously. Any modern NTP development effort will have the disadvantage of having very limited institutional experience outside of scattered documents that could be leveraged to bridge the NERVA program with the existing program. Technical consultants that had actual relevant NTP hardware development experience (respectfully known as "greybeards") are diminishing in number and represent a critical source of insight to the potential obstacles to be encountered in the area of NTP development. By comparison, the available information and experience that can be leveraged for liquid rocket engine development is several orders of magnitude greater than that available for NTP development.

Looking ahead at the magnitude of technology development and design-development-test-&-evaluation (DDT&E) effort anticipated for NTP, it is necessary to anticipate the obstacles that could be encountered in the development of a prototypical NTP engine system, and the means by which to avoid them. Previous conventional liquid propellant 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. This approach is not an option for development of nuclear systems due to the expense involved and political consequences. Attention to detail with regard to nuclear component testing will have to be rigorous and thorough. Understanding the problems encountered in previous propulsion system development programs (liquid propellant and nuclear) will serve to avoid similar events in the current NTP development effort. The problems resolved in the development of the SSME have 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 NTP system. 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 NASA-MSFC to develop 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 initial basis for the study was "A History of Aerospace Problems, Their Solutions, Their Lessons" (Ryan, 1996) which contained a comprehensive selection of issues encountered during the development of a number of propulsion systems, especially the SSME. As more issues were identified and studied, the process for understanding and utilizing them collectively was developed. 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.

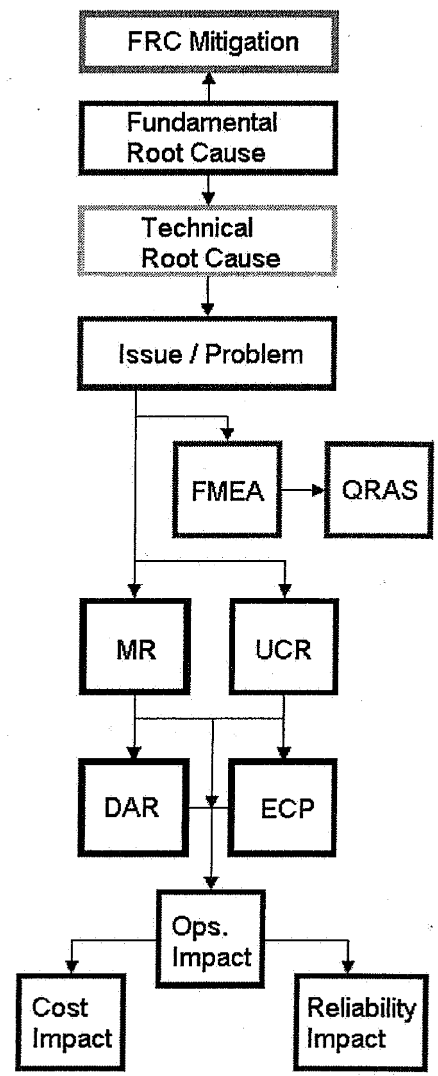

FIGURE 1. Issue Cause and Effect.

The flow of cause-and-effect for a specific issue relevant to SSME and how the FRC integrates into the flow was mapped out (see Figure 1). This shows how the likelihood and consequence of the issue is evaluated using the Qualitative Reliability Assessment System (QRAS) and Failure Modes Effects Analysis (FMEA), respectively, the methods used to document the individual issues and their mitigation using Unsatisfactory Condition Reports (UCRs), Material Reviews (MRs), Deviation Authorization Requests (DARs) and Engineering Change Proposals (ECPs). To mitigate the reliability impact of the issue, maintenance and/or inspection operations are defined. However, this results in a cost impact to system operation.

The goal for the REIMR development effort was to have a database at a sufficient level of maturity to develop a preliminary checklist which would be used during NASA technical insight of the prototype engine projects; comparing 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 are beyond the scope of this paper or the study.

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 provided in the following sections in no specific order:

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 Test-Bed (TTB) program conducted at NASA-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.

For NTP, a full understanding of the natural and induced environments is critical to avoid development failures. This means the individual and collective synergistic effects of the thermal, radiation, stress, dynamic, and chemical environments.

This FRC was demonstrated in problems associated with flow-induced vibration encountered in several of the Kiwi reactor tests (i.e., Kiwi-B1B, -B4A, -B4D), which resulted in fractured fuel elements that were ejected out the nozzle. It took several subsequent full-power tests and several cold-flow tests to discover and confirm the mechanism of the core damage and to demonstrate, after design modifications were applied, that a stable design had been achieved (Koenig, 1986).

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 foreign object digestion (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.

In the anticipated NTP development effort, it is unlikely that the same level of resources will be made available as were provided to the Rover/NERVA program. However, numerous cost analyses show a wide range of total DDT&E costs, but they collectively agree that it will not be cheap if it is to be done with a conservative approach to system development and risk management. Much of this anticipated cost is in the areas of fuel development and required infrastructure for system development, manufacturing and test. How this problem is overcome remains to be seen, but the FRC can be mitigated by careful development planning that is phased to utilize available resources, showing steady success typified by progressive achievement of hardware milestones. It is probable that resources will be more forthcoming once confidence is gained that it will be used effectively.

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). Engine development programs have been guilty of promising high system reliabilities with the expectation that semi-miraculous yet-to-be-developed IEHMS will provide it en lieu of a robust engine design. Experience has repeatedly shown that the complexity involved in developing an effective IEHMS is hard to *over*-estimate.

In NTP development, rigorous technology evaluation must be conducted and minimum readiness levels enforced to prevent integration of any technology into the engine design unless it can be done with minimal technical risk. High-risk, high-payoff technologies should be avoided in the development of the prototypic NTP system. For the prototypic system, it is important to "keep it simple" and avoid the lure of adding enhancements that promise high payoffs on the investment. Unfortunately, this often results in the enhancement consuming ever-increasing levels of resources to bring it to fruition, which can doom an otherwise successful program. As understanding and experience grows through development and operation of the nuclear thermal rocket (NTR), block upgrades to the engine design can be considered that can augment targeted operational regimes (e.g., performance, reliability, safety).

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 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 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 high-pressure oxidizer turbopump 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.

Insufficient design margin can also lead to problems that must be mitigated through scheduled maintenance and inspections, such as fracture control. The likelihood of problems of this nature can be reduced through early attention to non-performance requirements such as safety, reliability, manufacturability, and maintainability. It is understood in conventional liquid rocket engine development that consideration to safety, reliability, manufacturability, maintainability and all the other "ilities" must be incorporated in the system DDT&E process. Studies have shown that incorporating design attributes that pay heed to the non-physical disciplines (e.g., the "ilities") as well as the physical disciplines (e.g., thermal, stress, dynamics, etc.) are well worth the effort expended and go far in assuring the success of the system design. It is important to design out or mitigate hazards and failure modes as they are identified in the design process. An example of this process is shown in Table 1:

TABLE 1. Hazard and Failure Mode Elimination and Mitigation Strategy.

Identify Hazards & Failure Modes	Eliminate by Design	Mitigate by Design	Mitigate by Safety Devices	Mitigate by Special Procedures & Process Controls
• Failure Modes Effects Analysis (FMEA) development • Subsystem Hazard Analysis (SSHA) • System Fault Tree Analysis • Maximum Design Condition (MDC) analysis	• Robust engine cycle • Simplified design • Reduce part count • Weld elimination • Failure/fault tolerant • Redundancy design • Tolerant of process escapes/variability • Material change	• Increased safety factors / design & analysis margin • Incorporate engine health monitors to accommodate malfunctions & operability • Redundancy designs • Advanced design tools to reduce uncertainty • Variability tolerant • Design-to-capability	• Implement redline monitors • Incorporate engine health monitors to detect and mitigate system failure • Thorough pre-flight checkout • Post-flight data analysis	• Rigorous manufacturing / assembly process control • Vigorous material and fabrication process qualification • Stringent acceptance procedures • Robust engine operations and flight safety oversight

The need for a maintenance-free propulsion system is especially important for an NTP because 1) conducting maintenance operations on any in-space engine system during a mission is to be avoided, and 2) conducting hand-on maintenance operations on a hot NTR is not likely to be allowed. The NTP system will need to be designed to be an operational "black box" during the entire mission, requiring zero maintenance and a high level of reliability. The systems engineering function responsible for realizing the "ility" requirements to accomplish this *must* be fully empowered stakeholders in the engine development team.

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.

The numerous problems documented on the varying coefficients of thermal expansion between the different elements of the fuel are examples of this FRC.

The *back-reaction* phenomenon encountered during the early Rover/NERVA reactor tests is a specific example of the interaction of this FRC with that of another FRC – inadequate understanding of the engine environment. The fuel used in the initial Kiwi reactors was graphitic UO_2-loaded fuel that progressively degraded when it was exposed to operational cycles of intense heat of operation and then ambient air. During operation, the UO_2 reacted with the graphite carbon surrounding it and was converted to UC_2 while producing CO. This caused progressive degradation of the fuel element as carbon was leached from the element. Micron-size UC_2 particles are extremely reactive and revert to oxide in the presence of air, particularly humid air. Thus, oxide-carbide-oxide reactions occurred during each heating and storage cycle, including graphitizing, coating, and reactor operation, and each cycle caused loss of carbon by CO gas evolution and degraded the element. Dimensional changes also were noted in stored elements, requiring a change from plastic to metal storage tubes. Oxidation of the UC_2 loading material caused the element to swell as much as 4% so that the final dimensions could not be controlled. This problem was corrected through the introduction of pyrocarbon coated UC_2 particles in subsequent fuel designs (Taub, 1975).

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 (e.g., I_{sp}, T/W) Driving 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 the area of NTP development, analyses show the majority of the engine weight resides in the reactor subsystem. Caution should be taken to prevent an aggressive requirement for T/W that would cause possible problems in the reactor design. It is possible that evolved experience in NTP system development will permit reactor weight reductions through engine block upgrades, but initial performance requirements should be subordinate to reliability and safety. However, because the reactor represents 60-80% of the system weight, this allows pressure to be removed from driving down turbopump and valve weight, which can be optimized to enhance component reliability.

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, including nuclear thermal propulsion. The atrophy of the technical and experience bases matured during the Rover/NERVA program requires a more careful consideration of the development process that will be used to realize a flight-qualified human-ratable NTP system. Exploitation of all available tools requires that the results of the REIMR study be prudently applied to the NTP effort.

CONCLUSION

The primary conclusion of the REIMR study was to illuminate the Fundamental Root Causes that generate technical risk in the development and operation of an advanced propulsion system. Numerous examples can be cited in previous rocket engine programs to support the FRC definitions and their effects. It is also important to note that once their existence is known and understood, the ability to detect and mitigate them can also be understood. The REIMR study has benefited all who worked on it by raising their understanding of synergistic and cascade effects on a complex system, as well as providing a critical calibration to their technical insight and sensitivity to potential risk.

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. 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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