Multiple Changes to Reusable Solid Rocket Motors, Identifying Hidden Risks

Phillip O. Greenhalgh, CSP; Principal Engineer, ATK Thiokol Propulsion
And
Bradley Q. McCann, Principal System Safety Engineer, ATK Thiokol Propulsion

Keywords: Space Shuttle, Risk Assessment, Assessing Change, Interaction Matrix, Reusable Solid Rocket Motor, RSRM

Abstract

The Space Shuttle Reusable Solid Rocket Motor (RSRM) baseline is subject to various changes. Changes are necessary due to safety and quality improvements, environmental considerations, vendor changes, obsolescence issues, etc. The RSRM program has a goal to test changes on full-scale static test motors prior to flight due to the unique RSRM operating environment. Each static test motor incorporates several significant changes and numerous minor changes. Flight motors often implement multiple changes simultaneously. While each change is individually verified and assessed, the potential for changes to interact constitutes additional hidden risk. Mitigating this risk depends upon identification of potential interactions. Therefore, the ATK Thiokol Propulsion System Safety organization initiated the use of a risk interaction matrix to identify potential interactions that compound risk. Identifying risk interactions supports flight and test motor decisions. Uncovering hidden risks of a full-scale static test motor gives a broader perspective of the changes being tested. This broader perspective compels the program to focus on solutions for implementing RSRM changes with minimal/mitigated risk. This paper discusses use of a change risk interaction matrix to identify test challenges and uncover hidden risks to the RSRM program.

Introduction

ATK Thiokol Propulsion, a division of ATK Aerospace Company Inc., produces the Space Shuttle Reusable Solid Rocket Motor (RSRM). The RSRM is the largest human-rated solid rocket motor ever flown and the only booster capable of recovery and reuse. Developed for NASA by Thiokol in the mid-1970's, the solid rocket motor was successfully static tested on July 18, 1977. During the first 122 seconds of each Space Shuttle flight, the two RSRMs provide 80 percent of the liftoff thrust needed to accelerate the Shuttle to a speed of 3,094 miles per hour before separating from the orbiter and external tank at an altitude of 24 nautical miles. Nearly seven minutes after separation, the spent boosters parachute into the Atlantic Ocean approximately 140 nautical miles downrange from Kennedy Space Center. The recovered boosters are disassembled in Florida and returned to ATK Thiokol Propulsion's Component Refurbishment Work Center in Utah, where the metal components are refurbished for future Space Shuttle flights.

Following the Space Shuttle Challenger accident in 1986 the solid rocket motor underwent a major redesign effort. For the two plus years following the Challenger accident, one of the most extensive efforts for any system was undertaken to identify, understand and control risk associated with the solid rocket motor. System Safety risk assessments for the redesigned rocket motor began at the initial design inception stage and matured as the best design was selected, analyzed and tested in preparation for flight. The established baseline motor design with the respective subsystems, components, parts and materials were analyzed extensively. System Safety analyses and tools were implemented to assure that hazards and associated risks were identified, understood, mitigated to the extent possible, controlled to an acceptable level and communicated within Thiokol and to NASA. The RSRM Fault Tree Analysis, Hazard Analyses, Failure Modes and Effects Analysis/Critical Items List (FMEA/CIL) and the Certificate of Qualification (COQ) were the foundation for risk identification, mitigation, control and the establishment of baseline risk. The baseline risk was communicated by "... the documentation of System Safety and reliability analyses, [which] were reviewed, critiqued and approved by all levels of technical management at Thiokol and at NASA assuring an understanding and appropriate mitigation of risk." (ref. 1) Verification of the RSRM baseline was accomplished by extensive testing to verify design and analytical work. "With all of the testing and analyses completed previous to the first flight of the new RSRM in the fall of 1988, confidence was high that the optimum design had been achieved." (ref. 1) Continued "[safe] and reliable hardware performance is of supreme importance. This includes safety issues affecting the general public, flight crews, ground crews, manufacturing personnel, flight assets, and ground assets." (ref. 2) Therefore, identifying and appropriately addressing changes in risk to the RSRM is an ongoing endeavor.

Only the metal components of the "reusable" solid rocket motor are refurbished and reused. Each flight is a verification of the design, materials and processes. Any change from the baseline (flight proven) design, materials or processes equates to some change in flight risk due to no flight history. Nearly 15 years have passed since the initial establishment of the baseline design of the redesigned Space Shuttle RSRM and subsequent first flight. During these 15 years, numerous processing, material and design changes have been implemented. Changes were, and continue to be necessary due to safety and quality improvements, environmental considerations, vendor changes, material obsolescence issues, post-flight observations, etc. In order to minimize the risks associated with changes from the successful baseline, the RSRM program has established a goal to "test before fly", that is, to test any RSRM change on at least one full-scale static test motor prior to flight implementation. Full-scale static tests are conducted approximately once a year. Therefore, each static test motor typically incorporates several significant changes and numerous minor changes.

In connection with the "test before fly" goal, it is essential for the program to fully evaluate the relative change in risk associated with each RSRM change. The system safety discipline has the responsibility to identify, assess and communicate the relative risk associated with each change made to the RSRM. Relative change in risk for a specific test or flight motor becomes more difficult to identify and assess when multiple changes from the baseline materials, processes or design are simultaneously implemented. Each individual change necessitates a risk assessment specific to that change. However, the change specific risk assessment could miss hidden risks due to concurrent implementation of multiple changes. Changes to materials, processes or design have the potential to negatively interact. In order to fulfill the responsibility to fully assess and identify risk associated with RSRM static test and flight motors, a risk interaction matrix is used to assure all changes from baseline are assessed for potential change interactions. A regimented review of the potential risk, from interacting changes, assures that any change in risk or any new risk is understood and that appropriate controls have been or can be employed to mitigate risk to an acceptable level prior to approving the change.

Changes to the RSRM Baseline

Changes to the RSRM baseline may be in the form of intentional or unintentional changes. Intentional changes are those requested through Engineering Change Proposals (ECP), manufacturing process Operation Change Requests (OCR), or Supplier Operations Change

Requests (SOCR). Changes to the baseline design or process are often proposed as continuous improvement or risk reduction efforts. Even so, they must begin with carefully weighing the potential effects of each change. In the baseline RSRM Flight Systems Hazard Reports, eleven of the "accepted risk" hazard causes have been identified as potential candidates for changes to reduce risk. (ref. 3). Implementing changes on a tried and proven system necessitates careful consideration. "While there has been a desire to implement changes for performance improvements and a need to replace materials that have become obsolete, the robust design, completion of rigorous testing and flight success of the RSRM has resulted in a wise reluctance to make changes. Improvement initiatives and overcoming obsolescence roadblocks are weighed against the reluctance to change with careful comparison and evaluation." (ref. 1)

Prior to the approval of any planned change affecting flight hardware or change to baseline hardware or processes through a discrepant condition, a thorough risk assessment is completed. Changes to processing equipment, tooling, facilities or support materials that are considered to be associated with flight hardware and/or materials are regard as significant and require a risk assessment prior to approval of each change. In accordance with NASA requirements, "Changes in any RSRM equipment design or Thiokol applicable procedures receive the same review and assessment as that conducted for the original equipment and where applicable updates the hazards analysis." (ref. 4). To provide this "same review and assessment" as required, system safety tools are utilized to evaluate each proposed change. This evaluation weighs the effects of the change(s) and assures that implementation will not create a negative impact on the applicable component or associated system. The review and assessment of individual changes includes a comparison to the applicable baseline hazard analysis and accompanying risk matrix and Fault Tree Analysis, the COQ and the FMEA/CIL. The required system safety risk assessments accompany each proposed change to communicate the level of risk involved to the various Thiokol and NASA review boards.

System Safety Assessment Sheets are required to accompany each change to RSRM design or manufacturing processes whether they are a new design/process or a modification to an existing one. Each change is evaluated against the following risk criteria for baseline Hazard Reports and FMEA/CILs.

Does the change:

a) Introduce any new hazards/failure modes or hazard causes/failure causes?
b) Eliminate, adversely affect, or invalidate any hazard controls, verification data, or CIL retention rationale?
c) Reduce a margin of safety for any RSRM component?
d) Change the criticality category assignment?
e) Require an adverse (increase in severity or in probability) change to the NSTS 22254, risk matrix classification of a hazard cause?

If any of these questions are answered "yes" a risk change document Change Notice (CN) to the baseline Hazard Report and/or FMEA/CIL may be required. Such a change also requires review and approval by Thiokol and NASA Level III (Marshall Space Flight Center, Project), Configuration Control Boards and presentation to the NASA Level II System Safety Review Panel (SSRP), along with a Change Request (CR) to the NASA Program Requirements Control Board (PRCB). The thoroughness with which Thiokol and NASA review changes ensures all RSRM related issues are properly "screened" against program risk criteria and that there is an awareness and understanding of any significant change in risk. (ref. 5)

Unintentional changes are those that result from discrepant hardware conditions or process deviations as addressed on Discrepancy Reports (DRs). Discrepancies, by definition, are a change from the baseline that must be assessed. A determination of criticality for each discrepancy is made as an initial risk assessment. Those that are determined to be an insignificant increase in risk may be approved and closed out in a Material Review Board (MRB) meeting. Discrepancies that are determined to constitute an increase in risk are provided with a formal System Safety Risk Assessment and sent on for further review by the Senior Material Review Board (SrMRB). Issues addressed by SrMRB are discussed again as a topic in the Certification of Flight Readiness (CoFR) process.

Testing of Changes to Baseline

Testing all changes made to the RSRM is a goal of the RSRM Program. Changes to configuration and changes to processes are to be tested on full-scale static test motors. Occasionally there are changes that need to be made without the opportunity to complete full-scale static testing. Those changes that will be implemented and will not be tested on a full-scale static test motor prior to first flight must be approved by a NASA Level III (Marshall Space Flight Center, RSRM Project) Configuration Control Board Directive (CCBD) and by a Level II (Johnson Space Center, Space Shuttle Program) Program Requirements Control Board Directive (PRCBD). For those changes that are scheduled for flight without a previous static test, sufficient rationale must be provided showing the testing and analyses that justify an acceptable level of risk.

Most changes are tested on full-scale static test motors prior to their first flight. In many respects, a full-scale RSRM static test motor is treated in the same way as flight motors. "System Safety performs hazard analyses for the major tests to be performed on the RSRM development and qualification program. The applicable major tests include all full-scale static test motors (both test evaluation motor (TEM) and flight support motor (FSM))." (ref. 4) System Safety assesses engineering changes (ECSs/ECPs), process changes (OCRs), discrepancy reports (DRs), and other unique issues applicable to each static test configuration and test objectives. Every new configuration, process and material has inherent risk due to the lack of history. However, Design and Manufacturing Engineering have minimized risk based on design features, test data, analyses, and inspections. The focus of a system safety assessment is on aspects unique to the particular test when compared to the flight configuration or test motors previously fired. (ref. 6)

Due to the nature and cost of full-scale RSRM static tests, it is necessary to test a number of changes on each test motor. Because of the high number of change items/test objectives on many test motors, some form of assessing the potential interaction of changes is needed.

Identifying the Hidden Risks of Change Interactions

As previously mentioned, System Safety personnel assess the qualitative risk of all individual motor changes, discrepancies and technical issues per NASA requirements documented in NSTS 22254 (ref. 5), NSTS 22206 (ref. 7) and ATK Thiokol Propulsion requirements documented in TWR-15902 (ref. 4) and department Organization Operating Instructions (ref. 8). The potential for the negative interaction of multiple changes being tested on RSRM static test motors necessitates an effort to identify possible increases in risk. The result of an interaction between changes can range from benign to compounding risk requiring mitigating action. To reduce the likelihood of an unacceptable or high-risk interaction, ATK Thiokol Propulsion developed and uses a System Safety Risk Interaction Matrix (SSRIM). The methodology is similar to that used by other projects and disciplines that typically use an interaction matrix to assess design or technical interaction potential. The SSRIM is a tool that systematically crosschecks all unique features or issues associated with a flight/test motor to identify items that could interact with other new motor features. The identification of two or more items interacting with each other initiates the process to assess the potential of compounding risk. This matrix is a non-contractual tool used by the System Safety organization, providing a "second-look" at changes/features associated with a particular motor. It is used as part of the test article hazard analysis and supports the requirement to report overall risk to ATK Thiokol Propulsion and NASA management. Flight motors are assessed in a like manner.

Items assessed for test motors and flight motors include:

Test Motors

- Test objectives - engineering and process changes
- Test readiness review technical issues
- SrMRB nonconformance's
- Pre-existing issues, i.e., active problem assessment system items, Contract End Item waivers/deviations, significant "closed by explanation" issues, and wide spread minor waivers
- Significant test facility changes

Flight Motors

- Engineering and process changes
- Certification of Flight Readiness (CoFR) review technical issues
- SrMRB nonconformance's, including Kennedy Space Center (KSC) problem reports
- Pre-existing issues, i.e., active problem assessment system items, Contract End Item waivers/deviations, significant "closed by explanation" issues, and wide spread minor waivers
- Significant KSC motor processing and facility changes

A change is not carried on subsequent SSRIM once the change is approved and baselined for RSRM flight or test motors. Issues closed by corrective action(s) are not carried on subsequent SSRIM. Issues closed by explanation, and that have applicability to the flight or test motors, will continue to be assessed using the SSRIM.

Timing for conducting the SSRIM coincides with the Configuration Control Board baselining of test motors with a preliminary SSRIM. The final SSRIM assessments are completed for the Test Readiness Reviews (TRR). Flight motor assessments support the CoFR review process. Final motor processing flow, following the above-mentioned reviews, may require a matrix update pending any applicable issues.

System Safety Risk Interaction Matrix Methodology: System Safety uses a matrix, such as seen in Figure 1, to systematically crosscheck each applicable item that changes the motor baseline, against one another for compounding risk consideration. All items/issues are listed for assessment in the matrix. The assessment results are recorded in the space at the intersection of two items. The assessment of risk is made with results noted using an alpha character as defined:

O: No issue
I: Inter-related, no significant or no change in risk
J: Justification in place for potential compounding risk
R: Potential compounding risk, additional rationale required

System Safety judgment is used to determine assessment results. This judgment takes into account criticality, change verification data, test usage rationale, performance history and technical experience. The likelihood of occurrence and severity of interaction are judged qualitatively when assigning interaction results. Any items marked with an "R" and determined to have a potential of compounding risk are communicated immediately with applicable component teams including design engineering, manufacturing, quality engineering, etc., in order to mitigate the risk or eliminate the proposed change.

<u>Motor SSRIM Results:</u> Results from the potential compounding risk assessment of change interactions are noted in the Risk Interaction Matrix. The overall assessment and conclusions are presented to the ATK Thiokol Propulsion and NASA RSRM TRR and/or CoFR Boards per appropriate review schedules. The test motor SSRIM results are documented in each test motor System Safety Review Report. (ref. 8) Flight motor SSRIM results are documented in the CoFR presentation packages.

Change number 1									
O	Change number 2								
I	O	Change number 3							
O	O	O	Discrepancy number 1						
O	O	O	O	Discrepancy number 2					
O	O	J	O	O	Discrepancy number 3				
I	O	I	O	O	O	Issue 1			
O	O	O	O	O	O	O	Issue 2		
O	O	O	O	R	O	O	O	Pre-existing issue 1	
O	O	O	O	O	O	O	O	O	Pre-existing issue 2

Figure 1. Risk Interaction Matrix Shell/Example

The RSRM program has realized benefits from utilization of the risk interaction matrix. For example, an upcoming test motor will incorporate a larger nozzle throat diameter by reducing the thickness of the nozzle ablative throat ring. Another proposed objective for the test motor will gather thermal data by implanting thermocouples in the nozzle exit cone liner in four axial locations. Each change carried its own level of risk that could be justified. However, the risk interaction matrix identified the potential of changing the erosion characteristics of the nozzle ablative liners downstream of the throat ring to interact with the method used to implant the thermocouples. This interaction drove an in-depth evaluation, which resulted in the elimination of the higher risk thermocouples.

Conclusion

The effort to put man into space using rocket motors has, and always will have, significant inherent risks. Knowing, understanding and controlling those risks are of the utmost importance to ATK Thiokol Propulsion and to NASA. RSRM risks have been analyzed providing current baseline documentation of what the risks have been and what they presently are. While the intent is to stay as close to the current baseline as possible, changes to the RSRM are accomplished to provide performance improvements as well as to replace materials that have become obsolete. All changes, including improvement initiatives and the replacements for obsolescent materials, are evaluated carefully through the perspective of various disciplines. The system safety discipline assesses each change individually to identify any change in risk. The individual change review is not complete without the additional risk interaction matrix review. The risk interaction matrix provides the finishing touch for assessing potential risk issues for each flight or test motor. A complete risk assessment assures that any change in risk or any new risk is understood and that appropriate mitigation efforts have been employed to control risk to an acceptable level.

References

1. Phillip O. Greenhalgh, "Use of System Safety Risk Assessments for the Space Shuttle Reusable Solid Rocket Motor." *Journal of System Safety* 38, No. 1 First Quarter 2002, pages 12-17.

2. Kerry G. Sanofsky, "Risk Management Plan for the Reusable Solid Rocket Motor (RSRM) Project, TWR-77231". Thiokol Propulsion, Brigham City, Utah, October 15, 2000.

3. Bradley Q. McCann, "RSRM Accepted Risk Status Report, TWR-77350 Rev. A", ATK Thiokol Propulsion, Brigham City, Utah, May 30, 2002.

4. "Safety Plan for the Space Shuttle Reusable Solid Rocket Motor, TWR-15902." Thiokol Propulsion, Brigham City, Utah, January 7, 1998.

5. NSTS 22254, "Methodology for Conduct of Space Shuttle Program Hazard Analyses." National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas, February, 2000.

6. Bradley Q. McCann, "ETM-2 System Safety Review, TWR-77152." Thiokol Propulsion, Brigham City, Utah, September 25, 2001

7. NSTS 22206, "Instructions for Preparation of Failure Modes Effects Analysis (FMEA and Critical Items List (CIL)." National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas, December 10 1993.

8. "RSRM System Safety Risk Interaction Matrix, OOI QA-8410-017." Thiokol Propulsion, Brigham City, Utah, May 30, 2002.

Biographies

Phillip O. Greenhalgh, 437 West 200 South / Brigham City UT 84302, USA, telephone – 1.435.863.5438, fax – 1.435.863.2884, email - Phillip.Greenhalgh@ATK.com

Phillip O. Greenhalgh is a Principal Engineer/Scientist in System Safety and Reliability working on the Space Shuttle Reusable Solid Rocket Motor program for ATK Thiokol Propulsion. After completing a Masters Degree in Safety at Central Missouri State University he began his career at ATK Thiokol Propulsion in 1985. In his eighteen years at Thiokol, he has been involved in the Space Shuttle Challenger Accident Investigation, the subsequent redesign of the Solid Rocket Motor and maintenance of flight system safety and reliability. Phil has also served as a contractor member of the NASA System Safety Review Panel. Phil joined the System Safety Society in 1987. In 1996 he became a Certified Safety Professional (CSP).

Bradley Q. McCann, 1075 East 2925 North / North Ogden UT 84414, USA, telephone – 1.435.863.6838, fax – 1.435.863.3232, email - Bradley.McCann@ATK.com

Bradley Q. McCann earned his B.S. from Brigham Young University and his M. S. from Central Missouri State University. During his fifteen years at Thiokol, Brad has successfully completed assignments in Nozzle Design Engineering and as the Program Manager for full-scale static test motors. His principal work has been in System Safety working on the Space Shuttle Reusable Solid Rocket Motor (RSRM) program at ATK Thiokol Propulsion. He is currently a Lead System Safety Engineer, with responsibility over RSRM flight hazard reports and full-scale static test motors and has performed fault tree analyses for numerous multifunctional investigation teams.