REUSABLE SOLID ROCKET MOTOR—ACCOMPLISHMENTS, LESSONS, AND A CULTURE OF SUCCESS

D.R. Moore and W.J. Phelps
NASA Marshall Space Flight Center
Huntsville, Alabama

ABSTRACT

The Reusable Solid Rocket Motor (RSRM) represents the largest solid rocket motor (SRM) ever flown and the only human-rated solid motor. High reliability of the RSRM has been the result of challenges addressed and lessons learned. Advancements have resulted by applying attention to process control, testing, and postflight through timely and thorough communication in dealing with all issues. A structured and disciplined approach was taken to identify and disposition all concerns. Careful consideration and application of alternate opinions was embraced. Focus was placed on process control, ground test programs, and postflight assessment. Process control is mandatory for an SRM, because an acceptance test of the delivered product is not feasible. The RSRM maintained both full-scale and subscale test articles, which enabled continuous improvement of design and evaluation of process control and material behavior. Additionally RSRM reliability was achieved through attention to detail in post flight assessment to observe any shift in performance. The postflight analysis and inspections provided invaluable reliability data as it enables observation of actual flight performance, most of which would not be available if the motors were not recovered. RSRM reusability offered unique opportunities to learn about the hardware. NASA is moving forward with the Space Launch System that incorporates propulsion systems that takes advantage of the heritage Shuttle and Ares solid motor programs. These unique challenges, features of the RSRM, materials and manufacturing issues, and design improvements will be discussed in the paper.

INTRODUCTION

As of this date, the Space Shuttle Reusable Solid Rocket Motor (RSRM) was the largest diameter solid propellant motor used for space flight and the only large solid rocket motor (SRM) certified to launch humans into space. The RSRM basically consisted of four propellant-loaded steel case segments (forward, forward-center, aft-center, and aft) with a binding liner and thermal protecting insulation, a head end igniter system with a safe and arm device, and a multicomponent metal nozzle structure with thermal protecting carbon phenolic liners. The propellant mixture consisted of aluminum powder (fuel), ammonium perchlorate (oxidizer), iron oxide (burn rate catalyst), epoxy curing agent, and a polymer binder that held the mixture together. An assembled motor was 126 ft long, 12 ft in diameter, and contained approximately 1.1-million lbs_m of propellant. At lift-off of the Space Shuttle (Figs. 1 and 2), the two RSRMs provided 6.6-million lb_f thrust—the RSRMs provided 80% of the Space Shuttle lift-off thrust. Figure 3 is a graphical depiction of the SRB/RSRM detail.

The RSRMs burned for 2 minutes completing the Space Shuttle first stage, which ended at Solid Rocket Booster (SRB) separation. After separations the SRBs parachuted into the Atlantic and were recovered by the two SRB recovery ships. The ships returned the SRBs to the Kennedy Space Center (KSC) for disassembly and postflight inspections. All recoverable hardware was then shipped back to Alliant Techsystems Inc. (ATK) facilities in Utah to undergo further disassembly, postflight inspection, and start the refurbishment process to make other sets of RSRMs.

The RSRM was designed to make the most use of recoverable hardware. The majority of metal hardware was recycled through ATK's Clearfield refurbishment plant in Utah and returned to a flight-qualified conditioned. There were innumerable accomplishments, lessons learned, and cultural changes during the Space Shuttle SRM Program; for brevity only a few have been selected to be discussed here.

Figure 1. STS-1 First Space Shuttle Launch—April 12, 1981.

Figure 2. STS-135 Last Space Shuttle Launch—July 8. 2011.

RESULTS AND DISCUSSION

RSRM EVOLUTION

The contract to develop the Space Shuttle SRM was awarded to Thiokol Corporation in 1974. As shown in Figure 4, the company evolved throughout the history of the Shuttle Program as various mergers, acquisitions, and other name changes occurred between 1982 and 2011.

Figure 5 is a chronological roadmap showing some of the major qualification tests, design changes, process improvements, and operational methodology changes that were incorporated for the SRM as it evolved and matured throughout the life of the Shuttle Program.[2] Between July 1977 with the firing of Demonstration Motor No. 1 (DM-1), and February 2010 with the firing of Flight Support Motor No. 17 (FSM-17), 52 static motor tests were successfully conducted at the ATK facilities in Promontory, Utah to support the Shuttle Program. A total of seven successful tests (four demonstration and three qualification tests) were completed prior to the first Shuttle flight in April 1981. The baseline motor, known as the SRM, was flown on the first seven Space Shuttle missions between 1981 and 1983.[1]

Early evolution of the Space Shuttle vehicle involved a number of performance upgrades, including development of the high-performance motor (HPM). In October 1982 and March 1983, static test firings (DM-5 and QM-4) were conducted to qualify several enhancements to the baseline motor. These enhancements involved increasing the motor chamber pressure, reducing the nozzle throat, increasing the nozzle expansion ratio, and modifying the propellant grain-inhibiting pattern to reshape the thrust-time history. These enhancements resulted in a 3-s increase in specific impulse and an additional 3,000 lb (1,360 kg) of payload. The first HPM motors were flown on STS-8 in August 1983. The SRM/HPM program included a total of 50 flight motors and 11 static test motors between 1977 and 1986.

During the early 1980s, the long-range performance improvement plans involved development of a graphite/epoxy Filament Wound Case (FWC) to replace the steel case in the HPM design. This composite motor case (see Fig. 6) design (developed by Hercules Inc.) reduced the case weight from

98,000–69,000 lb (44,500–31,300 kg) resulting in an additional 6,000 lb (2,700 kg) of Space Shuttle payload capability.
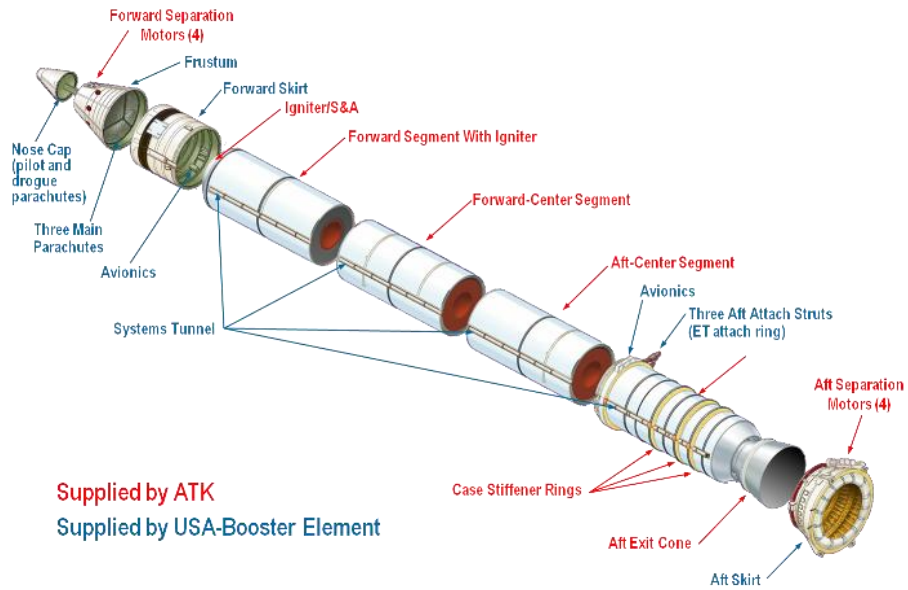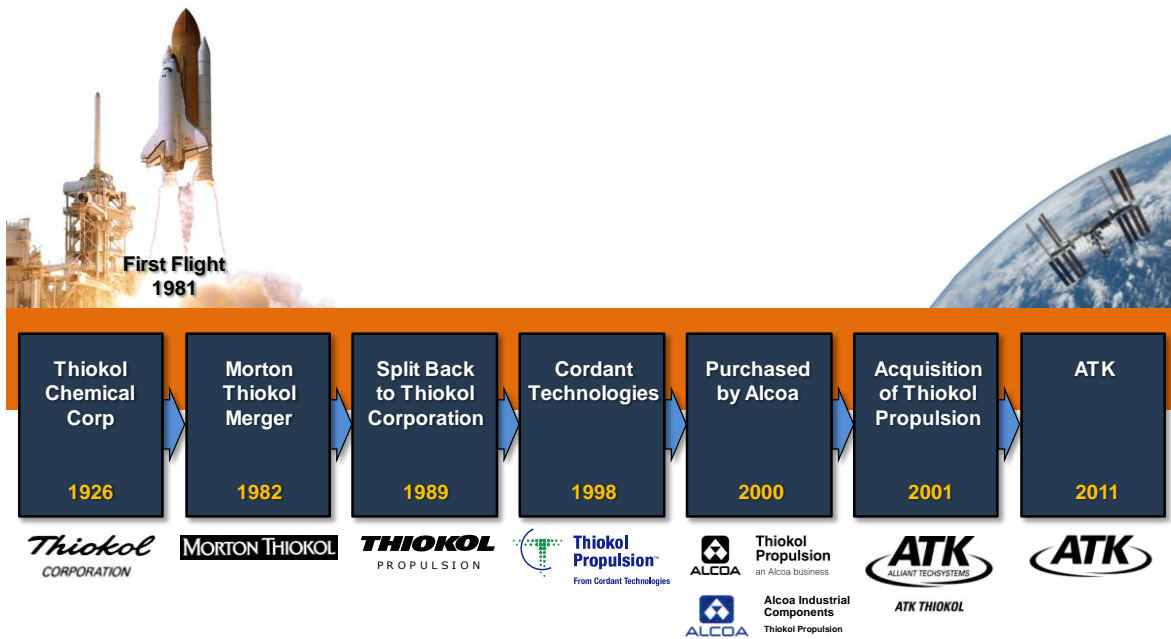

Figure 3. SRB/SRM Detail.
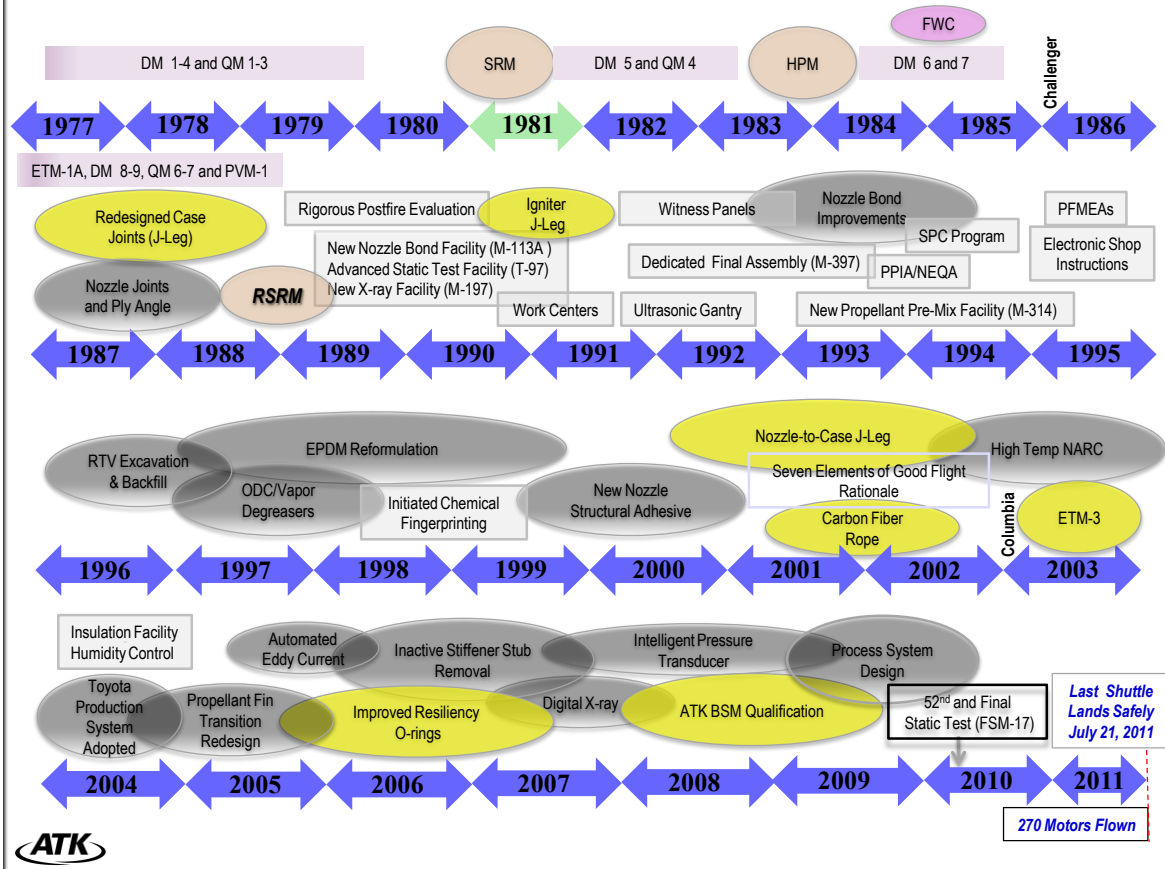

Figure 4. ATK Evolution.

Figure 5. RSRM Evolution.

Figure 6. DM-7.

Two full-scale static tests, DM-6 and DM-7, were conducted in October 1984 and May 1985. A full-scale FWC Qualification Motor (QM-5) was assembled and ready to fire when the Challenger accident occurred. At that time, the first FWC flight motors were stacked and ready to support a July 1986 launch at the Vandenburg launch site in California. The FWC development and the plans to launch the Space Shuttle out of Vandenburg were subsequently abandoned.

Following the Challenger accident, a redesigned SRM (the RSRM, first known as the "redesigned" SRM, but later as the "reusable" SRM) was developed and qualified between the spring of 1986 and the summer of 1988 in one of the most intense engineering efforts ever. During this period, extensive subscale and full-scale tests were conducted to verify the cause of the Challenger accident and qualify the necessary design changes. Six static tests were conducted (Engineering Test Motor No. 1A, Demonstration Motors Nos. 8 and 9, Qualification Motors Nos. 6 and 7, and Production Verification Motor No. 1 (PVM-1)) including tests at hot and cold specification bounds with side loads applied to simulate those induced by the external tank attachments. PVM-1, the final static test prior to return to flight, was a full-scale flaw test motor to verify the redundant features of critical seals. The first flight of the redesigned booster occurred on STS-26 in September 1988 (Fig. 7). The key changes between the HPM and RSRM designs (Figs. 8–10) include (1) improved case metal hardware with a capture feature and third o-ring, (2) improved field joint thermal protection with a rubber J-leg replacing the putty, (3) added field joint heaters to ensure o-rings can track dynamic motions even under cold ambient conditions, (4) improved ply angles in nozzle phenolic rings to preclude anomalous pocketing erosion, (5) more robust metal housings in the nozzle to increase structural margins and accommodate dual and redundant o-ring seals, and (6) an improved nozzle-to-case joint that added 100 radial bolts to reduce the dynamic joint motion plus the addition of a bonded insulation flap with a wiper o-ring in place of the putty thermal barrier (years later the adhesive was removed and replaced with an insulation j-leg with pressure sensitive adhesive (PSA) and a carbon fiber rope thermal barrier).

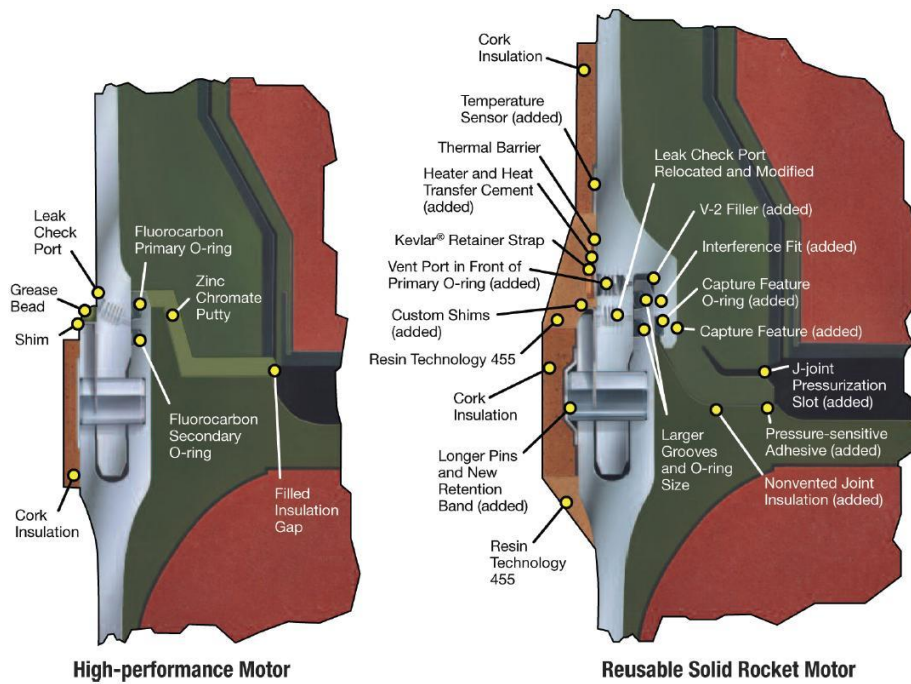Figure 7. STS-26 Post-Challenger.

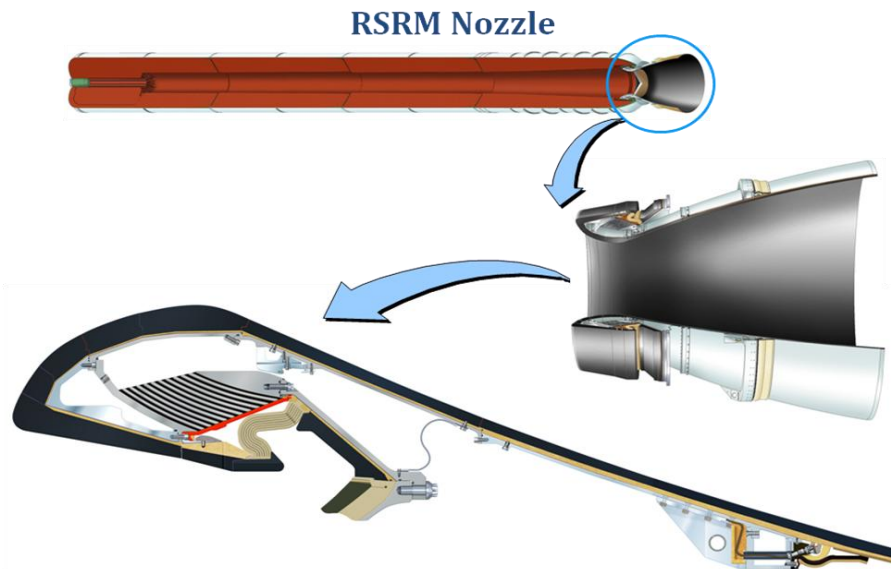Figure 8. Field Joint Comparison.
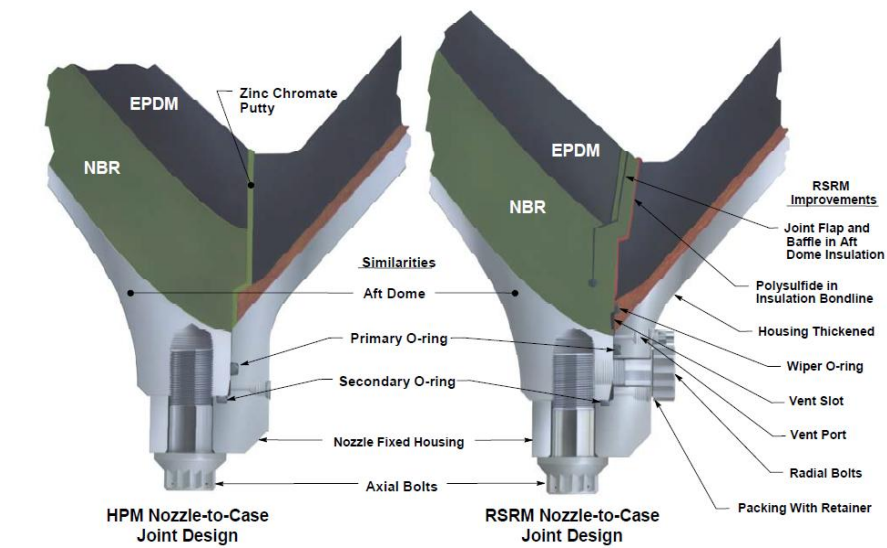
Figure 9. RSRM Nozzle.

Figure 10. HPM and RSRM Return-to-Flight Joint Design.

Shortly after return-to-flight, an insulation J-leg thermal barrier was developed for the igniter inner and outer joints (Fig. 10).
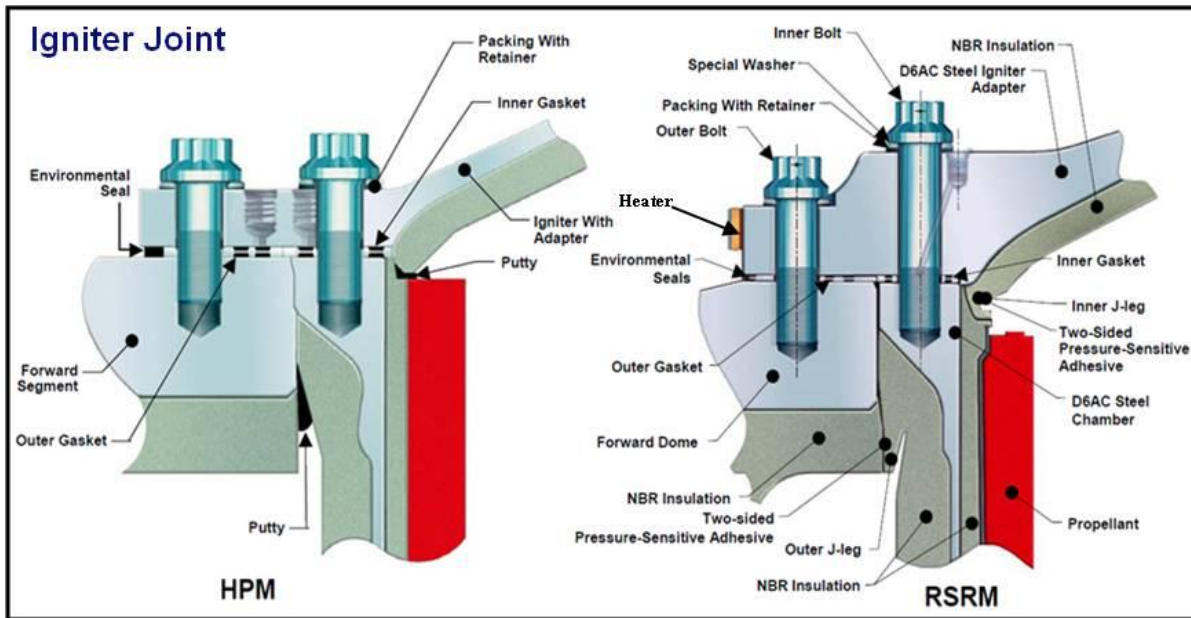
Figure 11. HPM and RSRM Igniter Comparison.

After the Challenger accident, NASA and ATK worked on improving their relationship and the way they were doing business together. The focus became working as a team with emphasis on communication, safety and technical excellence. As a result, NASA and ATK continued to make many RSRM improvements throughout the remainder of the Shuttle Program. Notable improvements to RSRM manufacturing processes, plant operating methodology, and risk management systems include (1) a rigorous postfire evaluation of flown and tested hardware, (2) continuous facility improvements including: a new nozzle bond facility, an advanced static test facility, a new x-ray facility, a new propellant pre-mix facility, a new ultrasonic gantry system, a new automated eddy current inspection system for metal hardware, the switch from x-ray film to digital x-ray, the incorporation of humidity control in the insulation facility, the elimination of trichloroethane (TCA), also known as methyl chloroform, vapor degreasers due to the incorporation of greaseless case segment shipping containers, and a dedicated final assembly building, (3) the use of witness panels for critical manufacturing processes, (4) the use of trending and statistical process control, (5) the use of Process/Product Integrity Audits and NASA Engineering and Quality Audits, (6) the use of Process Failure Modes and Affects Analysis (7) the transition from paper manufacturing planning instructions to paperless Electronic Shop Floor Instructions, (8) the incorporation of chemical fingerprinting to identify constituent anomalies of critical RSRM materials before their use on RSRM hardware, (9) the adoption of the Toyota Production System, known at ATK as the Performance Enterprise System, as a way of operating the ATK manufacturing facilities, and (10) the use of Process System Design.

Many changes to the RSRM design were made after the Challenger accident to improve the safety and reliability of the motors. These changes were mainly driven by anomalous postfire observations, material obsolescence issues, and desired margin enhancements, In addition to those design changes identified above that were made as a result of the Challenger accident, some of the most notable design changes include: (1) the addition of silane primer, enhanced bond surface preparations, and improved assembly processes on nozzle liner bonds, (2) an improved room temperature vulcanized (RTV) thermal barrier excavation and backfill process in nozzle joints, (3) the replacement of the nozzle liner-to-housing adhesive with a new and improved adhesive, (4) the use of carbon fiber rope as a thermal barrier in nozzle joints No. 2 and 5, and the nozzle-to-case joint, (5) the use of North American Rayon Corporation (NARC) material carbonized at higher furnace temperatures to mitigate pocketing erosion in the nozzle throat (6) the redesign of the propellant fin transition region, (7) the removal of the inactive stiffener stub, (8) the use of intelligent pressure transducers (IPTs) to more accurately measure the motor ignition transient and pressure oscillations during motor operation, (9) the redesign of the field

joint protection system to improve processing timelines at KSC, (10) the switch from United Technologies Corporation, Chemical Systems Division (CSD) manufactured booster separation motors (BSMs) to ATK manufactured BSMs, (11) the change to improved resiliency o-rings in the field joints, nozzle joints, the BSM, and the igniter and Safe and Arm (S&A) gaskets, and (12) the use of reformulated ethylene propylene diene monomer rubber (EPDM) in the factory joint weather seal and the carbon fiber EPDM of the aft dome.

The majority of changes made to the RSRM were due to material obsolescence. For example, during a 10-year period beginning in the mid-1990s, more than 100 RSRM materials became obsolete. The largest contributing factor for why suppliers changed their materials stemmed from economics and the desire to reduce costs and can be captured in three main scenarios. First, suppliers changed their own materials and processes. Second, suppliers consolidated operations and either discontinued or otherwise modified their materials. Third, the product constituent materials were simply no longer available from subtier vendors.

The need for compliance with US environmental regulations was another reason why some changes were made to the RSRM. For example, Environmental Protection Agency (EPA) regulations require the phase-out of ozone depleting compounds. NASA and ATK worked closely with the EPA to develop a strategy and timeline for eliminating the use of methyl chloroform as hardware cleaning method in the RSRM manufacturing process. Through extensive full-scale and sub-scale testing, new replacement materials were selected for hand cleaning and Conoco HD2 grease was eliminated as the acreage corrosion preventer for steel case segment hardware. By the time the Shuttle Program ended, most methyl chloroform usage had been eliminated except for that used for rubber activation during case insulation layup, flex bearing manufacture, field joint cleaning and pressure sensitive adhesive production. The yearly usage of methyl chloroform had dropped from the 635 metric tons (1.4-million lb) used in 1989 to approximately 4 metric tons (8800 lb) at the end of the program.

The following brief summaries are examples of five significant and technically challenging projects that occurred during the life of the RSRM program.

INSULATION J-LEG

The Presidential Commission on the Space Shuttle Challenger Accident concluded that the cause of the Challenger accident was the failure of the pressure seal in the aft field joint of the right SRB. The failure was due to a faulty design unacceptably sensitive to a number of factors. These factors were the effects of temperature, physical dimensions; character of materials; effects of reusability; processing; and the reaction of the joint to dynamic loading. One poor design characteristic leading to the cause of the accident was that the zinc chromate putty used between the mating tang and clevis field joint insulation was susceptible to the creation of gas paths and blow holes during segment stacking at KSC. During motor operation, these gas paths allowed hot gas and pressure to penetrate the joint setting up a condition for continuous high temperature gas flow which in turn eroded through the o-rings and allowed the gas to escape through the joint. The redesign team was faced with the challenge of coming up with a new design that solved this issue. The team considered several options, including an option that would allow the rapid pressurization of an open joint at motor ignition that would prevent the continuous gas flow through the putty experienced by the failed motor on Challenger. The team decided on a design solution that would attempt to totally stop the flow of gas into the joint. The selected design (Fig.8) added a J-leg to the tang-side insulation with matching clevis side insulation and included pressure sensitive adhesive to act as a sealing and bonding agent for the mating surface.[3] Figure 12 shows how the pressure-assisted insulation J-leg works.

At ignition, motor gas enters the J-leg slot and with the aid of the pressure sensitive adhesive the J-leg tracks the clevis insulation keeping hot gas away from the downstream o-rings. This design was first used on RSRM-1 (STS-26R). Although it was considered a thermal barrier and not a seal, this design proved to be very successful, and except for the RSRM-55 (STS-78) special cause, never allowed gas into the joint. RSRM-55 used a new water-based PSA whose properties were adversely affected by the high humidity conditions during application at KSC; the fix was to switch back to the previously used

methyl chloroform based PSA. The successful performance of the J-leg in the field joint eventually led to the incorporation of this design feature into the igniter inner and outer joints, and the nozzle-to-case joint.

How it Works

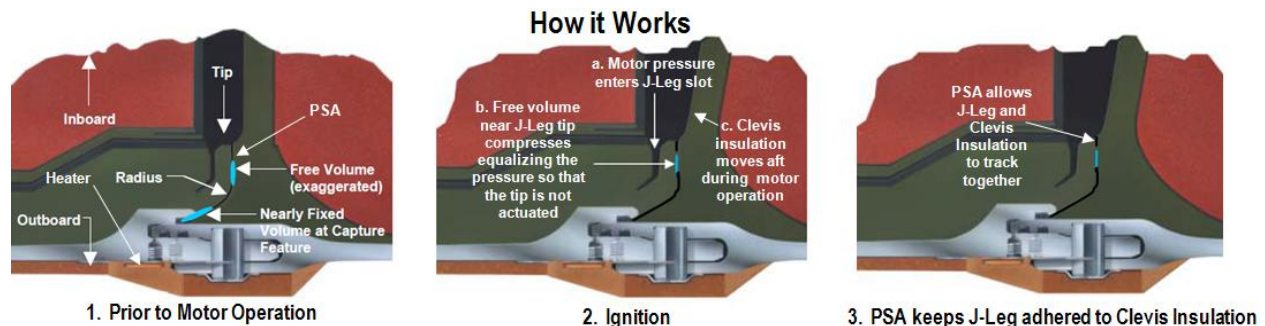1. **Prior to Motor Operation**   2. **Ignition**   3. **PSA keeps J-Leg adhered to Clevis Insulation**

Figure 12. Pressure-Assisted Insulation J-leg.

IMPROVED RESILIENCY O-RINGS AND GASKETS

Brought to the forefront of major HPM design deficiencies by the findings from the Challenger accident investigation, an important aspect of proper field joint fluorocarbon o-ring performance is the ability to track the joint movement, or gap opening, experienced at motor ignition while still preventing leakage past the o-ring. This ability of a compressed o-ring to track joint motion is known as o-ring resiliency. Warm o-rings have better resiliency performance than cold o-rings. Thus, cold o-rings do not track joint motion as well as warm o-rings. Because of this fact, field joint heaters were added to the RSRM. Also added to the joint redesign were structural features intended to minimize the gap opening or maximum expected deflection (MED). Although the reduction in MED and incorporation of joint heaters did mitigate the known deficiency in tracking capability of the o-rings, the search for a better seal material continued throughout the RSRM program. After the Challenger accident and subsequent HPM redesign, a report issued by the National Research Council reviewed the RSRM and concluded that the joint heater power cables were a potential safety hazard and that ways should be pursued to remove them if possible. Thus, various test programs were undertaken over the years to evaluate potential replacement seal materials with the goal of better performance to enable the removal of the joint heaters.

An improved GLT (good low temperature) fluorocarbon material known as Compound 17A had been developed for the Advanced Solid Rocket Motor (ASRM) program and evaluation testing was performed for the RSRM application. Although the material was shown to have good performance, it was found that there were significant problems in the material fabrication. Issues with splicing and grinding meant that fabricating o-rings would be extremely difficult so the effort was abandoned.

Later, ATK internal R&D developed an improved fluorocarbon compound designated RDL5503. Development testing of this material was pursued, along with an improved GLT compound (LV1183). The RDL5503 was shown to be superior to the LV1183 material and was selected to be demonstrated on ETM-2. Full-scale assembly tests were performed in preparation for the static test demonstration. Although the RDL5503 material performed extremely well with significantly improved low-temperature capability, it was found that some of the constituent ingredients were corrosive and the o-ring manufacturer, Parker, declined to fabricate o-rings on a production basis due to the environmental and operator safety concerns, so this effort was also abandoned.

Late in the RSRM program, another effort was begun with a comprehensive industry search for a replacement seal material. Five likely candidate materials were evaluated, with three showing promise for further consideration. Parker made an attempt at slightly modifying the formulas of these three compounds to find an optimized balance of desired resiliency performance and material toughness and strength. When the results did not meet the goals of the program, a design of experiment matrix was developed by ATK to understand the effects of varying some of the key constituent ingredients on the final performance and properties of one of the materials, LV1248. Based on the results of this study of 20

mini-mixes, the ratios for optimum performance were specified and resulted in the creation of the V1288 compound. Verification testing was performed to demonstrate that the final V1288 material performed as advertized and as designed, which it did. Physical properties, damage resistance, ablation resistance, resiliency, and dynamic pressure testing were performed and the material met all of the physical properties and thermal/ablation resistance characteristics of the RSRM baseline V1247 o-rings, but demonstrated equal tracking performance at temperatures approximately 40 °F lower than V1247. Splicing of V1288 o-rings required adhesive made from the old V1247 compound since the new material did not solvate very well, but testing showed that the new splice system (V1247 adhesive on V1288 o-rings) produced sufficient tensile strength and did not adversely impact the resiliency performance at the location of the splice. Testing of repairs was also performed. Full-size o-rings were fabricated from V1288 compound and were demonstrated on full-scale static test motors, FSM-12 and FSM-13, with flaws in the forward field joint to allow hot gas impingement on the V1288 capture feature o-ring for an assessment of its ablation resistance. A comprehensive qualification test program was followed to fully certify the new o-rings. The lab-scale batches of rubber used for the majority of the development and certification program were scaled up to a production-size mix process and demonstrated to be equivalent to the previous lab batches. V1288 o-rings were implemented in the RSRM field joints beginning with RSRM-105, and continued with the nozzle-to-case joint for RSRM-107. Nozzle internal joint implementation was staggered over several flights as remaining inventories of V1247 o-rings allowed. Although the elimination of joint heaters was now possible, a decision was made to keep the heater system. A reduction in the contingency LCC temperature was approved and significantly higher operating margins were achieved for all of the dynamic joints. Late in the program, V1288 material was also incorporated into the igniter inner and outer gaskets, the S&A gaskets, and the ATK BSM.

ETM-3 FIVE SEGMENT MARGIN TEST

In the late 1990s, ATK approached NASA with a Five Segment Booster concept that offered several benefits over the RSRM. The new motor used standard, "off-the-shelf" technology and was the same as the RSRM with the following changes: (1) added center segment, (2) new nozzle with larger nozzle throat, (3) thrust attach point in forward segment instead of forward skirt, (4) shorter, simpler forward skirt, (5) reduced burn rate propellant.

The added performance of a five-segment motor would enable a number of significant safety improvements. For example, the return to launch site and transatlantic landing abort modes could be eliminated. Abort to orbit could be achieved with a five-segment booster even if one of the Space Shuttle main engines had to be shut down on the launch pad. The Space Shuttle could increase payload delivered to Space Station Alpha to 40,000 lb (18,000 kg). Or, this added performance could be used to enable orbiter upgrades that add inert weight, e.g., a crew escape module.

ATK proposed that a full-scale static test be performed to help the understanding of internal gas dynamics in support of a future Five Segment Booster design. The results of the Five-Segment Booster Phase A study were presented to the managers of the Space Shuttle Program in December of 2000. Based on projected program needs and the costs of implementing a Five Segment Booster, NASA chose to not pursue the Five Segment Booster for the Shuttle Program. However, the Shuttle managers recognized there were potential benefits to the Shuttle Program by testing an Engineering Test Motor (ETM-3). Because the five- segment motor produced a harsher environment than the four-segment RSRM, the test would provide important insight into performance margins of the RSRM. Conditions more severe than RSRM included: the thermal environment, structural loads, potential for detrimental erosive burning, enhanced acoustic activity, more slag generation, longer burn time, higher mass flow and Mach number, higher operating pressure and pressure drop down the motor, higher buckling and joint loading, and a higher fill volume and longer length propellant surface for ignition. The test also offered a unique challenge to the NASA and ATK engineers. From scratch, the team would have the design, build and test a new motor in roughly two years. Since it had been over two decades since the original Shuttle SRM had been designed and tested, it was an opportunity for the NASA and ATK engineers to be involved in a new design where they could sharpen their analytical skills and learn from the experience, which would be a benefit to the ongoing Shuttle Program and to future programs using SRMs. The go-ahead for execution of the ETM-3 test was given in February 2001.

Figure 13. ETM-3 Static Test, October 23, 2003.

ETM-3 (Fig. 14) included the following changes from the RSRM four-segment motor design: 1) added center segment (added 273,000 lb of propellant over the RSRM), 2) bored out nozzle throat, 3) reduced burn rate propellant, 4) extended aft exit cone, 5) added chamfer to propellant leading edges, 6) modified center segment rubber inhibitor heights, and 7) modified center and aft segment insulation design. ETM-3 was instrumented with 620 gauges and a total of 635 channels.
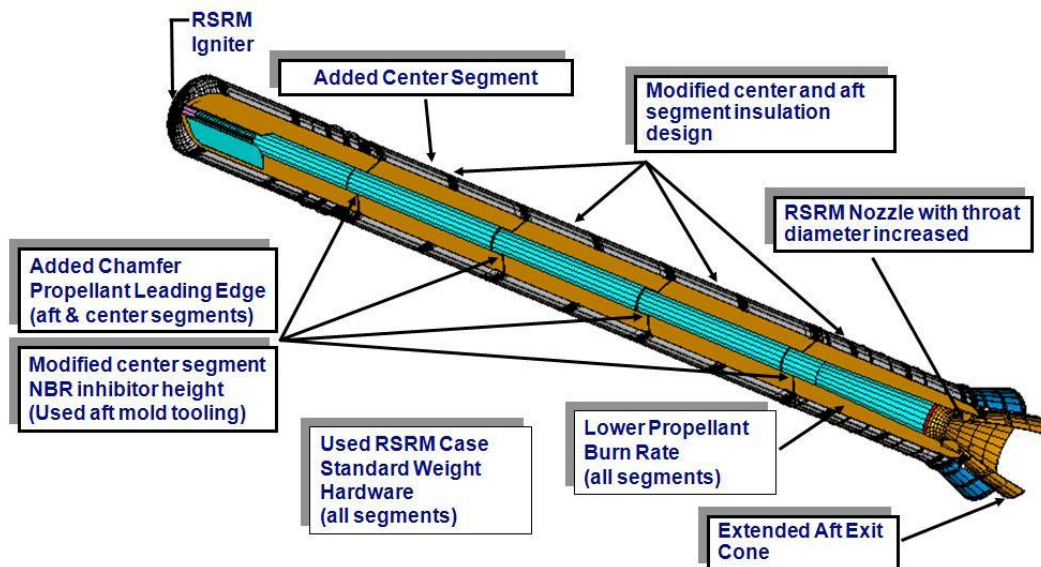

Figure 14. ETM-3 Modifications from RSRM.

ETM-3 was successfully tested in test stand T-97 of the ATK plant in Promontory, Utah on October 23, 2003. Examples of innovations developed specifically for, or as a result of ETM-3, include: advanced coupled fluid structural interaction analysis that shortens run time from weeks or months to overnight, nozzle in-depth thermocouples, aft dome insulation in-depth thermocouples, field joint j-leg slot pressure transducers, erosive burning subscale test simulator and associated improved modeling techniques, and direct measurement of pressure and heat flux inside a motor chamber.

ETM-3 demonstrated that the RSRM had robust margins. It was a great learning experience for the NASA/ATK workforce. And, it was a great step toward development of a future five-segment motor.

CARBON FIBER ROPE

Early RSRM nozzle joints 1-5 were designed with a room temperature vulcanized (RTV) thermal barrier to protect o-ring seals during motor operation. The nozzle-to-case joint used polysulfide adhesive as a thermal barrier to protect the seals. As the RSRM flight history grew, frequent and undesirable gas paths, blow holes, voids, and tail voids through the thermal barriers were seen during postflight inspection. When o-ring erosion was seen on joint 3 of the RSRM-44 (STS-70) and RSRM-45 (STS-71) nozzles, an RTV excavation and backfill process was developed for joints 3 and 4 as a corrective action. This fix proved to be very successful for those particular joints, and no further o-ring anomalies occurred throughout the remainder of the RSRM program. A joint 1 carbon fiber rope design was created and some development work was performed, but since it had a less severe operating environment than other joints, the condition was not a challenge to flight safety and a design change was never incorporated for RSRM. Although no significant o-ring erosion occurred on the other joints as the program progressed, flow paths through the thermal barriers persisted and the subject continued to be a frequent topic of discussion at Shuttle pre-launch flight readiness reviews.
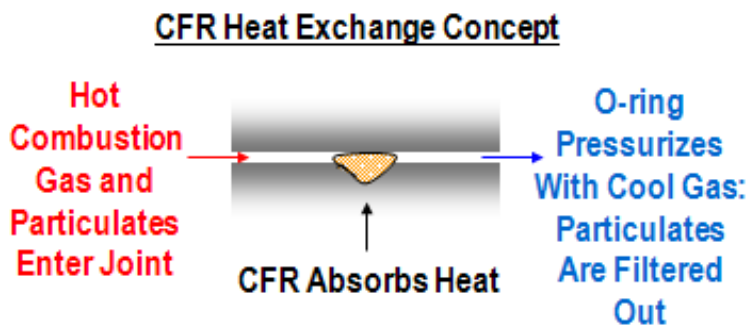

Figure 15. Carbon Fiber Rope Function.

In the late 1990s researchers at the NASA Glenn Research Center (GRC) were experimenting with braided carbon fiber rope and discovered that it had the ability to remove most of the thermal energy from a high temperature gas that passed through it without much noticeable damage after several minutes of exposure. The rope is very permeable and the high heat capacity of the carbon fibers allows for the efficient removal of heat (Fig.15).

ATK, seeking a design solution that would eliminate gas paths through thermal barriers, collaborated with GRC on the development of a carbon fiber rope configuration that could be used in RSRM applications. The final rope design consisted of a carbon fiber center core surrounded by ten sheaths of braided carbon fiber (Fig. 16).
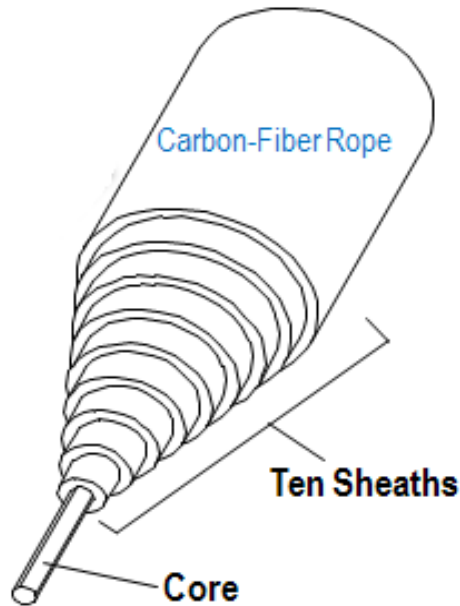
Figure 16. Carbon Fiber Rope.

ATK and NASA developed nozzle design solutions for these thermal barrier gas paths that utilized the heat dissipating qualities of the carbon fiber rope (Figs. 17, 18, and 19).

The nozzle joint 2 and 5 designs eliminated the RTV thermal barriers (open volume allowed gas to fully pressurize the joint at ignition) and placed carbon fiber ropes upstream of the o-ring seals, cooling the hot combustion gases that passed through them to temperatures close to ambient. As an example of how well the new designs performed, photos of the typical joint 2 condition before and after incorporation of the carbon fiber rope design is shown in Figure 20. The nozzle-to-case joint design incorporated an insulation j-leg thermal barrier and downstream carbon fiber rope ahead of the o-ring seals that protected them from high temperature exposure in case the J-leg leaked. All incorporated carbon fiber rope designs eliminated thermal barrier gas paths and performed flawlessly after their incorporation on flight hardware.

ATK BOOSTER SEPARATION MOTOR (BSM)

The original shuttle BSM was designed by United Technologies Corporation, Chemical Systems Division (CSD). This design flew on the first 120 Shuttle missions. In October 2003, ATK received an alternate source contract to develop BSMs with selected design and processing upgrades to further enhance motor reliability. The ATK design was heavily based on the CSD design with specific enhancements based on RSRM design practices and modern analytical approaches. The ignition system was completely redesigned to address lessons learned from an investigation of erratic ignition pressures conducted by CSD, ATK, and NASA. Other components of the motor remained essentially unchanged from the CSD design with minor adjustments made to address obsolescence concerns and lessons learned during the baseline flight program. Improvements introduced with the ATK BSM (Fig. 22) included: (1) ATK manufactured only one motor configuration (at KSC, United Space Alliance performed the necessary BSM closeout depending on whether the BSM was mounted in the forward or aft position), (2) sling lined chamber (CSD was hand applied), (3) ATK BSMs were cast in batches of four motors rather than the 64 by CSD, (4) the design used a new stronger adhesive (TIGA), (5) redesigned graphite throat with improved margins, (6) interchangeable case and aft closures eliminated matched sets (7) incorporated new better resiliency low temperature o-rings, (8) increased o-ring squeeze, (9) added an igniter-to-case leak check port, and (10) redesigned igniter. During the development program for the ATK designed BSMs, CSD announced closure of the San Jose, CA facility that produced BSMs. This revelation led NASA to a sole source contract with ATK to manufacture the BSMs and eventually to the

first flight of ATK BSMs in the forward position on STS-122 and in all positions on STS-126. All ATK BSMs exhibited excellent performance through the end of the Shuttle Program.
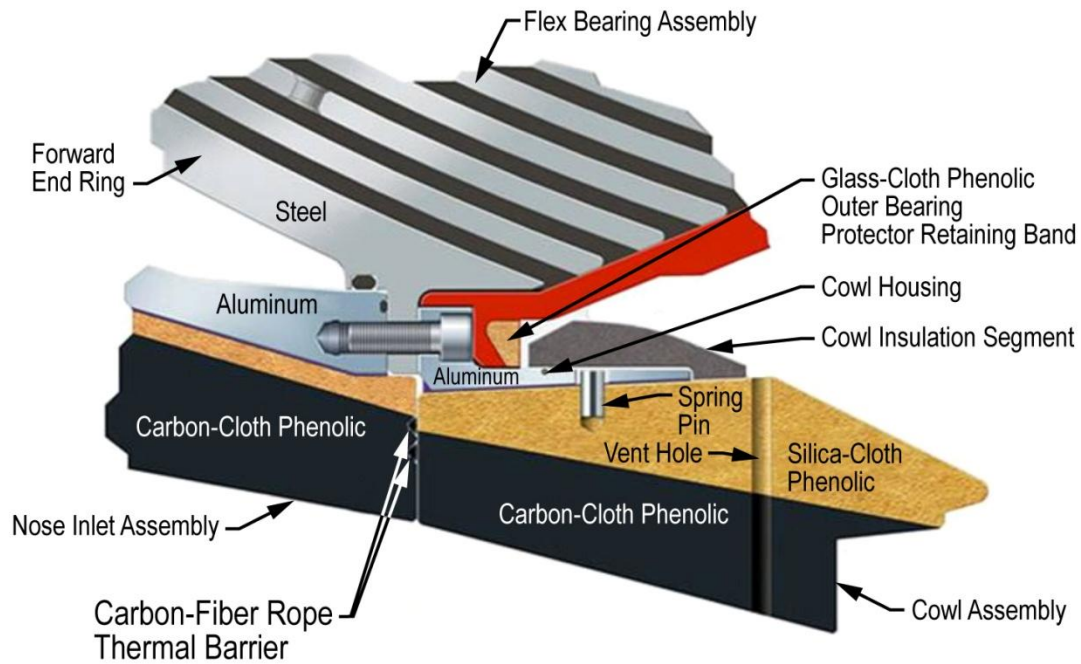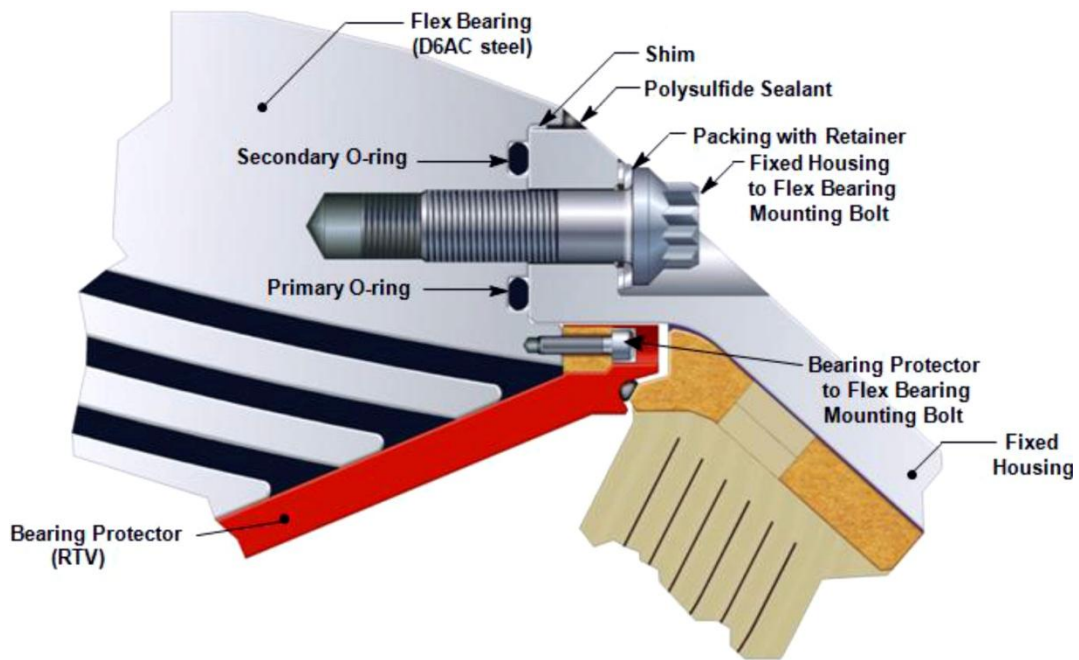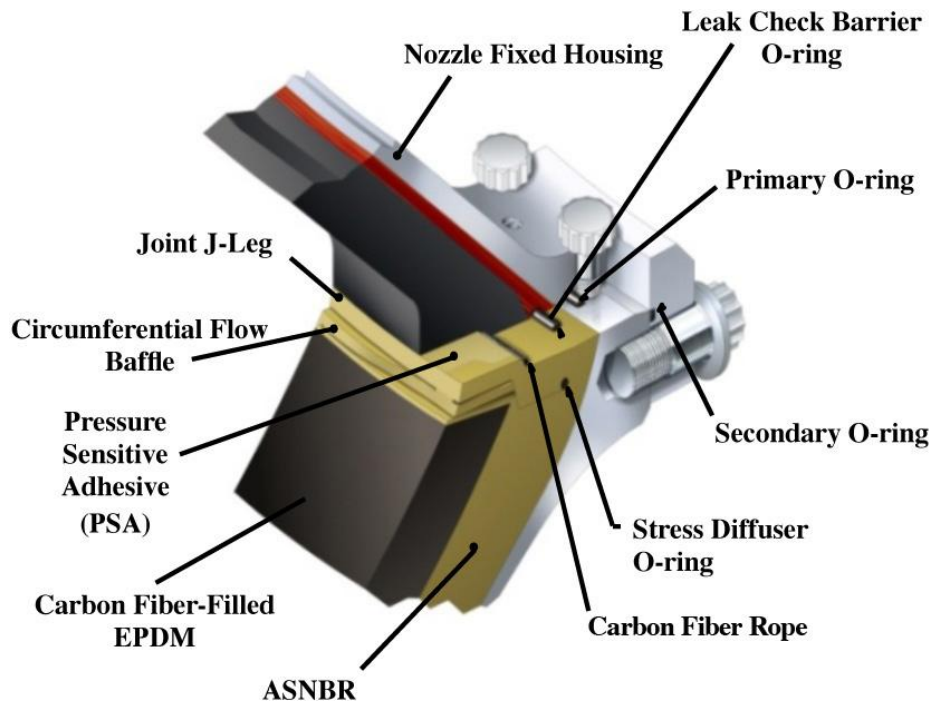
Figure 17. Nozzle Joint 2.

Figure 18. Nozzle Joint 5.

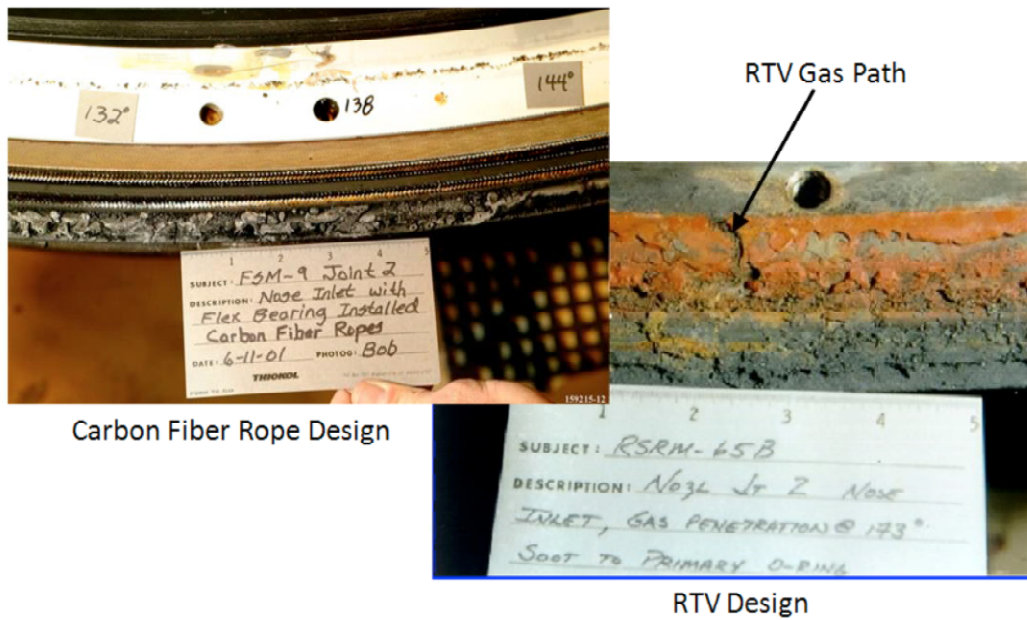Figure 19. Nozzle-to-Case joint.

Figure 20. Joint 2 RTV and Carbon Fiber Rope Design Comparison.

Figure 21. The ATK BSM.

RSRM—HIGHLIGHTED LESSONS LEARNED

NOZZLE POCKETING

During the eighth Space Shuttle flight (STS-8), the carbon cloth phenolic (CCP) ablative rings on the forward nose of one of the nozzles (Fig. 22) exhibited a severe rate of material loss referred to as "Pocketing."[4] The ablative rings form the contour of the nozzle and protect the underlying metal structure from the super-hot exhaust gases. At the end of a nominal motor burn (123 s), there is usually enough material remaining to fire the nozzle a second time. However, the erosion rate on STS-8 was so great that only 8 s of ablative material remained. When carbon/phenolic plies are incorrectly oriented to the flow surface, stresses can exceed the hot charred material strength resulting in anomalous erosion.

Figure 22. Nozzle Pocketing.

Before the Challenger accident, in both flights and static firings, there had been eight pocketing events in 66 nozzles at the nose inlet and one pocketing event in 66 nozzles at the nozzle throat. The problem of pocketing at the nose inlet was completely eliminated with the ply angle change that occurred with the first RSRM flight. Over the next 9-plus years there were zero pocketing events on 170 nozzles. On the RSRM 56B nozzle (Sep. 96), both the RSRM 49A and RSRM 49B nozzles (Nov. 96), and the RSRM 57B nozzle (Aug. 97) throat ring nozzle pocketing returned with accompanying downstream erosion. Because of this problem, a significant effort to understand the nozzle pocketing began. This effort, which involved a widespread technical community, was referred to as an enhanced sustaining engineering (ESE) effort; fault tree methodology was used to understand the pocketing mechanism. Over a 24-month period there were 6,300 mechanical, thermal, and physical property tests conducted. There were 1,650 PTTB tests, 1660 LHMEL (Laser Hardened Material Evaluation Lab) tests, 43 subscale tests, dissections of eight full-scale motor nozzles, seven scrapped nozzles and wrap, and cure and dissection of 11 full-scale instrumented tests.

Though that extensive effort it was determined that:

• Pocketing occurs at high char layer temperature >2,500 °F

• Pocketing requires fiber reinforcement failure

• Pocketing is sensitive to surface ply angle

• Ply distortion occurs in throat billets that can result in a higher angle ply region at the flame surface

• Some CCP has a higher propensity to pocket

• Production CCP material varies greatly in pocketing propensity at 90 °F

It was also determined that the pocket propensity variables were:

• Fabric carbonization temperature

• Fabric carbonization rate

• Scouring of white fabric

Because of these studies, changes were made and the following ten flights and two static motors had zero pocketing issues. In May 2001, FSM-9 experienced multiple pockets (with a maximum depth of 0.38 inch) and downstream wash erosion. A review of all relative variables identified in the ESE effort showed everything within family. However, the carbonization temperature may have been on the lower end of family. A change to target a higher (but in family) carbonization temperature was made. After this change, there were no occurrences of pocketing at the throat.

RSRM INSULATION J-LEG DESIGN

Several instances of o-ring erosion and blow-by occurred in the primary seal locations of the field joints and nozzle-to-case joint on pre-RSRM motors between 1977 and 1986. The design used putty between the motor segments as a thermal barrier to protect the o-rings. Occasional voids in the putty would channel hot gas jets that would vaporize the surface of the rubber o-ring material. During case pressurization at ignition, the joints would move such that the o-ring would lose contact with the metal parts, and hot gas would leak or "blow by" the seal. The ability of the o-ring to track this dynamic motion is significantly degraded at low temperatures. Engineers understood that the primary seal could fail, but were convinced that the secondary seal would hold. Both the primary and secondary seals failed when Challenger was launched on a cold day in January 1986.

PRIMARY SEAL AND THERMAL BARRIER ENHANCEMENT (1986)

Pressure-sensitive adhesive bonded rubber insulation "J-leg" and a "capture feature o-ring" were developed to provide field joint thermal protection. A polysulfide bonded flap and "wiper o-ring" were developed as the thermal protection system for the nozzle-to-case joint. A "capture feature," radial bolts,

and joint heaters were added to the respective joints to ensure the ability of the o-ring to track any dynamic motion with a 2× margin. See Fig. 11 for a comparison of the HPM and RSRM designs and a description of the items listed above. Since these features were added, not one of the primary o-rings on the RSRM field joints or nozzle-to-case joints has been pressurized (over 700 total joints flown or tested).

Thermal barriers made from putty can focus hot gas jets that will damage the elastomeric seal. The seals must be able to track dynamic motion of metal components at operational temperatures.

STS-78 FIELD JOINT GAS PENETRATION EVENT

The space shuttle RSRM uses an internal insulation "J-joint" design for the mated insulation interface between two assembled RSRM segments. In this assembled (mated) segment configuration, this J-joint design serves as a thermal barrier to prevent hot gases from affecting the case field joint metal surfaces and o-rings. A Pressure Sensitive Adhesive (PSA) provides some adhesion between the two mated insulation surfaces. In 1995, after extensive testing, including a successful test on Flight Support Motor (FSM)-5 (full scale RSRM static test), new Ozone Depleting Chemicals (ODC)-free PSA was selected for flight on STS-78, which was launched on June 20, 1996. Postflight evaluation of the case field joints at KSC on July 1, 1996 revealed hot gas penetration into all the field joints on both motors past the J-leg insulation tip. Although not a flight safety threat, the J-joint hot gas intrusion on STS-78 was puzzling to the investigators since the PSA had previously worked well on the FSM-5 full-scale static test.

A team was assembled to thoroughly study the J-joint and PSA further. All J-joint design parameters, measured data, and historical performance data were re-reviewed and evaluated by subscale testing and analysis. Although both the ODC-free and baseline PSA were weakened by humidity, the initial ODC-free PSA strength was significantly lower. The gas penetration event was intentionally duplicated in subscale tests and on FSM-7 and FSM-8 full-scale static tests. Because the next Space Shuttle (STS-79) hardware was also stacked with the same new PSA, the decision was made to destack and replace the PSA.

The root cause of the RSRM-55 J-joint insulation gas penetration leakage was the ODC-free PSA. This change, in conjunction with the significant joint deflection at ignition (highest occurrence in center and aft field joints) and extended high humidity conditions at the launch site in Florida (not present in Utah on FSM-5), resulted in a PSA strength reduction significant enough to allow the J-leg to separate from the clevis insulation a few seconds into motor operation. A significant amount of testing confirms that all three of the following conditions must exist simultaneous to cause the J-joint leakage:

1. New ODC-free PSA in the joint

2. Joint exposed to a history of high humidity (KSC levels)

3. A joint that experiences significant but normal joint motion

Post-test FSM-8 inspections revealed very similar charring characteristics as observed on RSRM-55.

Internal instrumentation capable of obtaining real-time internal motor data was developed on several static tests. This static test instrumentation was used on the FSM-8 joint simulating RSRM-55 environments and proved that key parts of this theory are correct:

1. ODC-free PSA degraded by humidity undergoing normal joint rotation caused the RSRM-55 joint leakage

2. Leakage occurred early in motor operation

RSRM TEST PROGRAM

One major advantage liquid engines have as compared to any SRM is the ability to test the flight unit, the liquid systems people refer to this as a "Green-Run." If an SRM flight unit was tested, the propellant and insulators would be spent and require complete refurbishment including replacement of the

insulators and propellant, it would in effect no longer be the original flight unit, but rather a different unit with some less known reliability—SRMs cannot be green-run. The required high reliability of the Space Shuttle RSRM had to be attained by other methods. This included the constant vigilance and focus on all the necessary elements of RSRM flight safety (Fig. 23).[5] One of these key elements was an intensive test program that included multiple levels of subscale and full-scale testing.

Subscale testing covers the entire spectrum of tests that range from the dog-bone type tensile tests of propellant batches, witness panel peel and tensile testing of insulator materials that follow all flight hardware processes to small scale motor tests that include a 5-inch diameter Center Bore (5-in. CP) used to get propellant burn rate, and larger motor tests like the 70-lb char motor to evaluate insulation performance, the 24-inch diameter Solid Rocket Test Motor (SRTM) used to screen design or material change concepts and the 48-inch diameter MNASA Modified NASA Motor (MNASA) used for further screening and to check expected performance on a motor that closely resembles the RSRM (Fig. 24). The highest level test is the full-scale Flight Support Motor (FSM), a true replicate of the RSRM flight motor, but very highly instrumented to collect as much data as possible. As you might expect, these full-scale motors are very expensive and time consuming tests, we were only able to tests about one FSM per year on the RSRM program. The main purpose of the FSM changed somewhat from its original concept. Originally an FSM was going to be a flight unit taken off the line and tested to totally represent the other units being manufactured during the same time period. The FSM necessarily evolved to being the "Change Precursor"—many of the required changes on the RSRM Program (mostly obsolescence driven) required tests on full-scale static motors prior to flight. Our desire was to test all changes on static tests before flight. Part of the NASA culture to "test what you fly, fly what you test" was a derivative of the RSRM Program. It is this attention to testing coupled with an intensive post-fire inspection and intensive postflight inspection of all flight hardware and particular attention to process control makes up for the inability to green-run the RSRM.
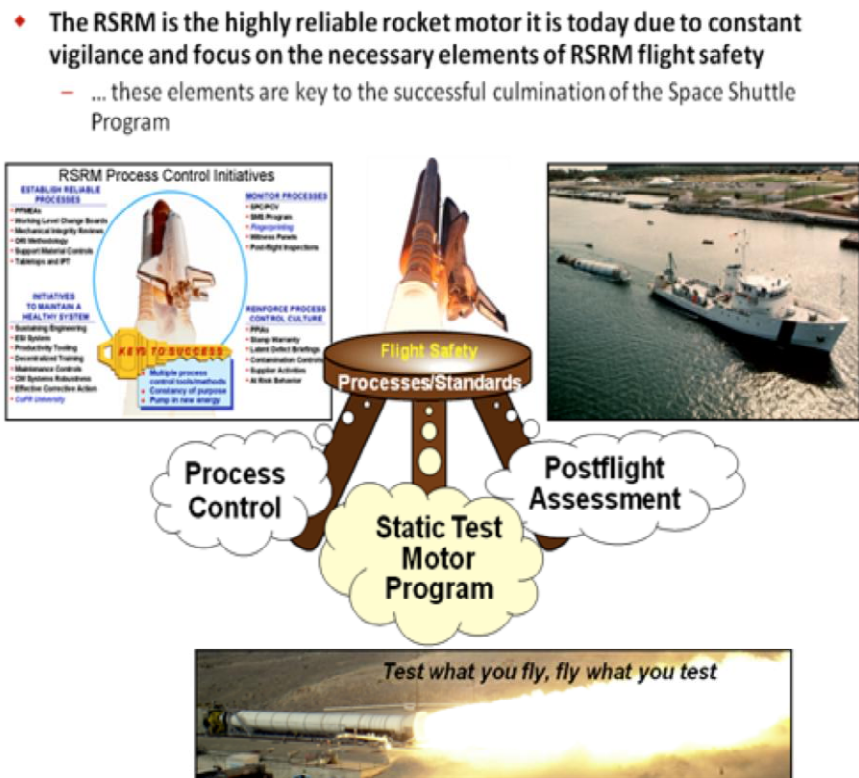

Figure 23. RSRM Overview.

Figure 24. RSRM Testing.

RSRM POSTFLIGHT INSPECTIONS

Another key element of maintaining RSRM flight safety was the amount of emphasis placed on postflight/postfire inspections.[6] The rigor and detail applied to RSRM inspections is unique to the SRM industry. It was rather fortunate on the Space Shuttle Program for the decision to recover the SRBs after each Space Shuttle launch and refurbish the hardware to maximize reusability. The decision to recover the hardware permitted a detailed assessment of the hardware during the disassembly process. At the completion of first stage of a Space Shuttle Launch, the SRB separate from the vehicle and parachute down and land in the Atlantic Ocean about 100 miles off-shore from the launch site. The SRBs are retrieved by the Booster Recovery Ships, Liberty Star and Freedom Star. The ships' crews recover the SRBs and return them to KSC for safing, disassembly, and to undergo postflight inspection. For each Space Shuttle launch we send a crew of RSRM Design Engineers, Manufacturing Engineers, and Quality Engineers responsible for the hardware both from ATK Utah and from Marshall Space Flight Center to inspect and evaluate the performance of the hardware during hardware disassembly and document hardware condition (Fig. 25). Any unusual or unexpected conditions are given special attention and all require disposition prior to the next Space Shuttle Launch. There was a disciplined approach for identifying, evaluating, and dispositioning any In-Flight Anomalies (IFAs) or any reportable conditions. Even small performance differences are noted and require disposition. The same types of inspections are performed after an RSRM Flight Support Motor (FSM) static test fire with the same rigor applied. Any first flight or first test engineering changes are noted in a special issues document for the postflight/post-fire inspectors' review prior to performing inspections. The performance of the hardware relative to any engineering change made was always thoroughly evaluated and documented. At the time of this print, no other SRMs, current or previous, had this degree of detailed postflight inspection.
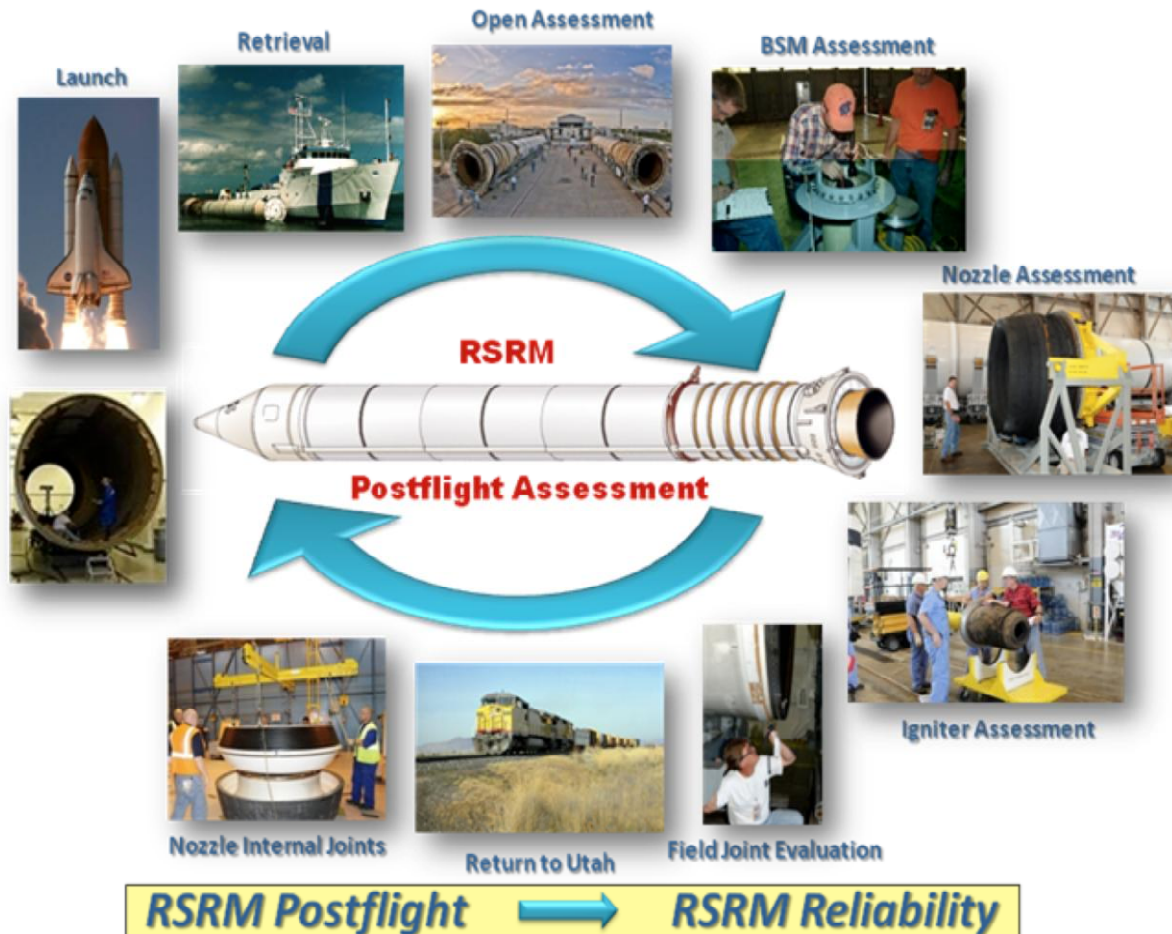
Figure 25. RSRM Postflight.

SEVEN ELEMENTS OF GOOD FLIGHT RATIONALE

After the Challenger accident the RSRM Program developed an improved approach for the thorough evaluation of all significant issues and developed an improved way to communicate how these issues were dispositioned. From STS-26 (return-to-flight post-Challenger) through STS-135 (last flight of the Shuttle Program) the RSRM Program was known throughout the NASA and the contractor team as the Program that '"pounded the issues flat." After Columbia accident we formally documented the approach we used to evaluate issues and shared this approach with all elements of the Space Shuttle and later to other areas of NASA and many of the support contractors and then to others throughout the aerospace industry. We termed this approach the "Seven Elements of Good Flight Rationale." The purpose of the approach was to create a consistent methodical process to discuss the basis of flight safety of significant issues being worked. The approach helped indentify strengths and weaknesses in flight rationale and provided a good tool for communicating all of the risk. Historically, flight rationale highlighted only the strong points; weaknesses were not thoroughly communicated and may not have been totally understood by managers responsible for accepting risk. Once weaknesses are identified, mitigating actions can be assigned to improve the posture, if improvement is required to get to acceptable or improved flight rationale—this approach can be used as a tool to identify was needs to be done to improve flight rationale. The objective of the approach is to understand the risks, mitigate risk as much as possible, communicate all around about the risks remaining, and then decide if we can accept the risk.

The initial part of this is identifying significant issues that affect system risk. Once the issue is identified and understood, decide how this issue can possibly keep you from meeting your objectives, e.g., part can break, component or system can fail to perform as desired, program goal may not be met. The next step is to define the risks that need to be assessed, e.g., risk of an event or consequence of an event, does the risk affect flight safety, mission success, cost, schedule, supportability. A Failure Modes and Effects Analysis (FMEA) approach is a good way to define the risk by defining what can prevent objectives from being met. For each issue, a well-defined risk problem statement should be developed to keep the focus on what you are trying to mitigate. Then the issue should be evaluated against the Seven Elements. The Seven Elements of Good Flight Rationale are as follows:

(1) Solid technical understanding – Do we know how/why this condition occurred? Was it impact, expired shelf life, moisture loss, residual stress, etc.? Did we use a fault tree? Do we understand the extent of the crack, high density indication (HDI), damage, foreign object debris (FOD), etc.? Do we know what the foreign material is? What are the plausible contaminants and how could they be harmful? Do we understand how/why components with similar indications performed the way they did? Is there a fix/repair for this unit/article? Do we understand the repair process/condition? Are the generic design and process robust and in control?

(2) Condition relative to experience base – Have we dealt with this problem before? How is this the same? How is it different? Do we have flight or test history with this defect? With this repair? Other programs? How are we the same? Are we different? Was the similar feature actually exercised in a test? What was the outcome?

(3) Bounding case established – What bounding scenarios (test, analysis, etc.) have been evaluated in the attempt to bound or envelope the issue? e.g., upper 3-sigma loads, lower A basis allowables, a specific worse hardware condition? What assumptions were made? Where are they conservative? Where are they not conservative? Were all the failure modes addressed? Have we assessed the "what if we're wrong" scenarios?

(4) Self limiting aspects –Physical reasons why the defect or condition will not get worse than current state or degrade. How can the condition exceed the bounding case? Is the system failsafe or fault/failure tolerant? Are there built in redundancies if the feature does fail?

(5) Margins understood - What are the predicted margins for the discrepant or repaired part? Have they changed from baseline? What are the margins for the bounding case? Is the component/feature in an area of high or low thermal or structural margin? How far are we from a cliff?

(6) Assessment based on data, testing and analysis – Is the final assessment based on test data and analysis or on expert opinion and gut feel? Where do we actually have data? Are we using too much engineering judgment? Was the test/measurement/analysis technique standard and proven or new? Do we understand all the assumptions that went into the assessment? Does the analysis/assessment rely on a series of dependent or independent assumptions?

(7) Interactions with other elements/conditions addressed – Are there any known, compounding interactions with other issues, components, changes, etc.? How have the potential interactions been identified? How/when will they be addressed?

Figure 26 is an example of how the Seven Elements tool can be used to guide the process of improving flight rationale posture.

The Seven Element Process is an effective tool in understanding, characterizing and communicating the risk to the risk decision makers. It creates a consistent, methodical process to discuss the basis for flight safety that helps communicate risk and identify strengths and weaknesses in the flight/acceptance rationale. It is a robust technical assessment that focuses on the facts and removes emotion from characterizing risk. When implemented early in the process, it provides a "roadmap" in the development of the safety of flight rationale. Seven Elements is an excellent communication tool for risk decision makers. Focuses on the holes—unknowns and uncertainties are key information for informed decision making. It tells the whole story – not just the positive or negative items. This tool probably has widespread applicability throughout the Aerospace Industry and possibly throughout any industry dealing with risk.

Current State	Strong	Mod	Weak	Mitigating Actions
Solid Technical Understanding Unbond results from operator variability and tool differences Maximum extent possible unbond not known	←	X		• Complete statistical analysis of measured void distribution • Complete corner-of-box unbond testing
Condition Relative to Experience Base No known unbonds in previous flight article but assumed since process relatively unchanged			X	• None
Bounding Case Bounding case structural analysis TBD	←		X	• Complete statistical analysis of measured void distribution • Complete high rate capability button testing • Complete loads survey • Complete stress analysis
Self-limiting Concern that non-bond size bounding case has not been captured Impact of stress risers due large non-bond regions not quantified	←		X	• Complete statistical analysis of measured void distribution • Complete high rate capability button testing • Complete loads survey • Complete stress analysis
Margins Current margins unknown	←		X	• Complete statistical analysis of measured void distribution • Complete high rate capability button testing • Complete loads survey • Complete stress analysis
Assessment based on Testing, Data, Analysis Based on analyses and test data Extensive capability database New analysis methodologies Reduced conservatism	←		X	• Complete analyses • Complete measurement and mapping of available bonded tunnels
Interactions with other Conditions/Components No known interactions except age – no age effects identified	X			• None

Figure 26. Seven Elements Tool.

THOUGHTS ON MINORITY/ALTERNATE OPINIONS

The people who worked RSRM over the life of the Space Shuttle Program had to deal with many significant issues that came up from time to time. We always had a large diverse group of folks working the issues at both the contractor and NASA level. A diverse group will always bring the most ideas to the table which provides the best chance of getting to the best path. Although we prefer to have a consensus, and we always work hard to get as much agreement as possible, occasionally there were times when we did not get full agreement, but reached a point in time when decisions needed to be made to get past the disagreements so work could continue. In these circumstances we had what some refer to as "Minority Opinions," also referred to as "Dissenting Opinions," or the words that we prefer which were "Alternate Opinions." RSRM had a few alternate opinions over the life of the RSRM program; there were a few things we learned from dealing with these minority opinions that we would like to share here.

SEEK OUT MINORITY OPINIONS

We have found that sometimes you need to seek out minority opinions. They are not always obvious. Silence doesn't always mean agreement – if you have a lot of thinkers supporting you as we normally did, sometimes you need to give them time to think about it. We found it wise to not allow any fence sitters, there are usually people who well tell you that is doesn't matter to them, or that they have no preference, but after more thorough evaluation, or just more time, we have found this to not be the case— almost always there is a preferred decision if the issue is studied enough.

HAVE A TEAM OF FOLKS LISTEN CAREFULLY – HEAR THEM OUT

We have found it wise to pull in a team of three of so people that would be considered experts or knowledgeable on the subject and knowledgeable on what is being recommended by the alternate opinion. We suggest that you try to avoid arguing or making counterpoints until they've been thoroughly heard out. Always keep in mind that the alternate opinion could be right.

MAKE A DECISION AND TELL THEM HOW YOU GOT THERE

Eventually decisions will need to be made for continued progress. Evaluate all the information you have and make a decision. If you go counter to what is being recommended by the alternate opinion, explain to them how you got to your decision.

BE AN ADVOCATE FOR THE MINORITY OPINION

Even though your decision may be counter to the alternate opinion, you should become an advocate for the opinion and encourage and offer to take it forward—remember as stated above, they still could be right. If they want to take the alternate opinion forward, use the management chain to hear the alternate opinion and use your decision as your recommendation to management.

ALLOW FOLKS TO CHANGE THEIR MINDS

When the "Thinkers" are given more time to think about the issue and positions, sometimes they change their minds on things. Just because someone had previously taken a position that is in agreement with your current direction, there can be new data or a new way of thinking that causes them to take another position. The reverse can also be true, people with alternate opinions sometimes hear from the experts or just think about the issue some more and change their positions. We would recommend that you freely allow either of these.

RSRM LEARNING FROM REUSABILITY

As previously stated, reusability of the RSRM led to postflight inspections that caught many issues in its infancy before they could become major issues. There were however some unique things encountered just from reusing the hardware. Sometimes splashdown damage to metal hardware prevented reuse, we found that hardware had to be re-measured carefully to assure all engineering dimensional requirements were still met. Early on in the program we discovered that the initial three pressure cycles (counting both proof tests and motor pressurizations) would incrementally stretch the RSRM D6AC steel case hardware in highly stressed areas by factions of a percent, but that it could affect critical dimensions including areas near seal surfaces. When this was discovered we added three proof cycles to all new case hardware prior to each use to prevent dimensional changes from subsequent pressure cycles. We also discovered that hardware had to be clean and protected as quickly as possible after recovery to prevent corrosion. Motor combustion products mixed with salt water at splashdown was found to be highly corrosive. When hardware was disassembled and exposed to this mixture, assessments had to be made quickly and the hardware cleaned and greased to prevent further corrosion. Several metal segments were lost early in the program from seal surface degradation from corrosion that occurred from disassembly and exposure. Also, occasionally we experienced extensive splashdown damage to nozzle and/or case hardware that required unique methods to be developed just to disassemble the hardware. Special tools or methods had to be developed many times real time during the disassembly process.

MOTOR EVOLUTION FROM THE FOUR SEGMENT TO FIVE SEGMENT FOR SLS

In the mid-2000's, NASA initiated the Constellation Program which included an objective of developing a spacecraft/launch system that could carry astronauts/payloads to Low Earth Orbit which could support future NASA program needs in this space regime. Known as Ares, the rocket system that was conceived included a five segment first stage solid rocket motor known as the RSRMV. This motor was based off of the Shuttle RSRMs and took advantage of the knowledge gained from the ETM-3 five segment motor test performed in 2003 to assess RSRM margins. Performance drivers for Ares were a

56,200 lb_m payload to orbit, a maximum dynamic pressure of 800 psf, a maximum acceleration of 3.8 g, and a goal to maximize the use of heritage hardware from the Shuttle.[7] Modifications to the RSRM design were made to improve performance (thrust), eliminate hazardous materials and replace obsolete materials. Changes from the RSRM are shown in Figure 27 and included: (1) increasing the number of center segments from two to three, (2) increasing the number of propellant fins in the forward segment from 11 to 12, (3) the addition of forward chamfers on center and aft segments, (4) lowering the propellant burn rate (5) modification of the propellant inhibitor heights and thicknesses, (6) increasing the nozzle throat diameter, (7) extending the nozzle exit cone, (8) modifying insulation and liner formulations to eliminate Chrysotile fibers, and (9) modifying the insulation lay-up to increase thermal protection. Three development motors were successfully static tested at the ATK test facility in Promontory, Utah before the program was ended in October 2011 (see Figure 28). A comparison of the design characteristics for the RSRM, ETM-3, and RSRMV is shown in Table 1. NASA is now moving forward with the next human space exploration program. The U.S. Space Launch System (SLS) will provide an entirely new capability for human exploration beyond Earth orbit. It also will back up commercial and international partner transportation services to the International Space Station. Designed to be flexible for crew or cargo missions, the SLS will be safe, affordable, and sustainable, to continue America's journey of discovery from the unique vantage point of space. The SLS will take astronauts farther into space than ever before. Marshall Space Flight Center is leading the design and development of the rocket system that can take humans, cargo, equipment, and science experiments to the Moon, asteroids, LaGrange points, and eventually to Mars. The initial lift capability is 70 tonnes (154,323 lb_m) which is more than double the value of any current lift vehicle today. Future plans will evolve the lift capability to 130 tonnes (286,601 lb_m), the most of any vehicle ever. RSRMV motors will be used on the first two development flights (one unmanned, one manned). After that, an advanced booster system will be competed for the evolved launch vehicle. Figure 29 shows how the SLS configuration will evolve.
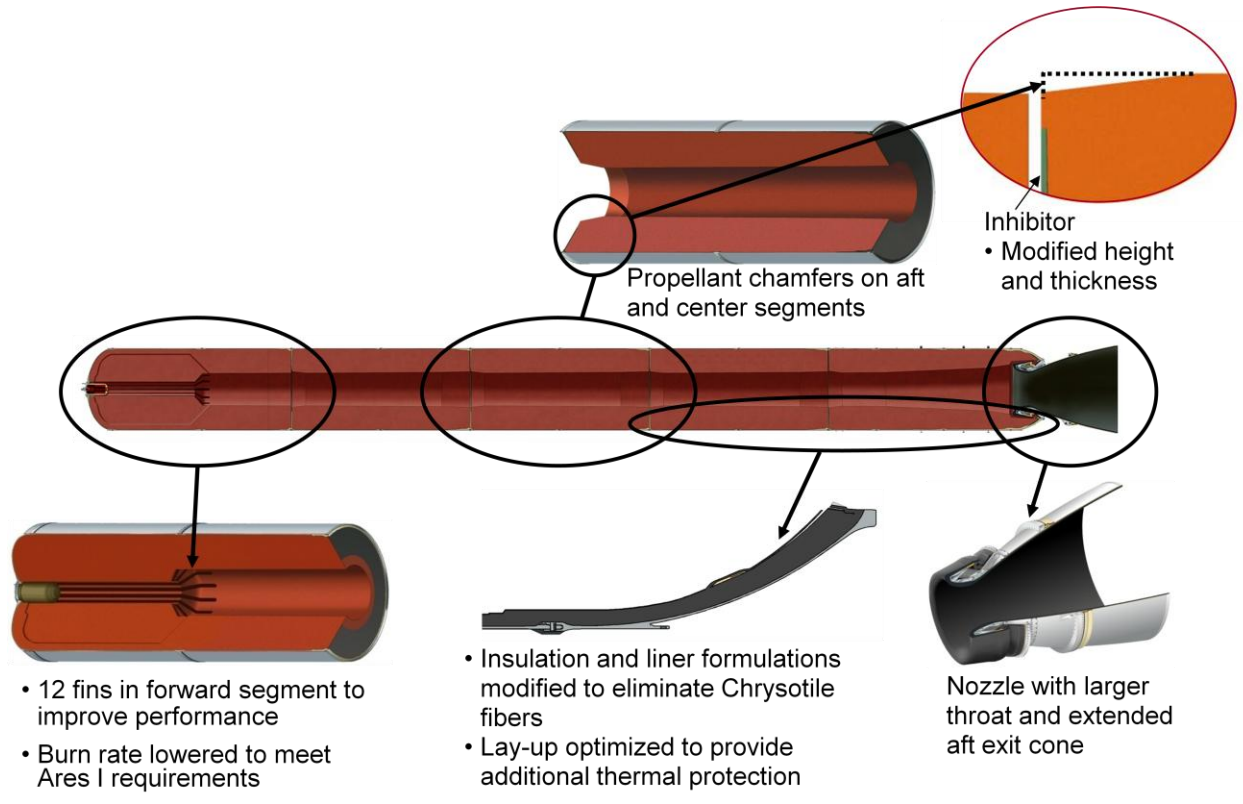
Inhibitor
• Modified height and thickness

Propellant chamfers on aft and center segments

• 12 fins in forward segment to improve performance
• Burn rate lowered to meet Ares I requirements

• Insulation and liner formulations modified to eliminate Chrysotile fibers
• Lay-up optimized to provide additional thermal protection

Nozzle with larger throat and extended aft exit cone

Figure 27. Changes from RSRM to RSRMV.

Figure 28. Ares First Stage DM-3 September 8, 2011.

|	RSRM	ETM-3	RSRMV
Motor			
Overall Length (in.)	1,513.49	1,868.25	1,868.25
Case Diameter (in.)	146.08	146.08	146.08
Nozzle			
Throat Diameter (in.)	53.86	56.11	56.86
Exit Diameter (in.)	149.64	152.75	152.75
Expansion Ratio	7.72	7.41	7.22
TVC Vector Clearance at Throat (deg)	11.64	11.64	5.22
Ballistics			
Total Propellant Weight	1,106,000	1,366,000	1,383,000
Maximum Thrust	3,326,000	3,690,000	3,566,000

Table 1. Motor Design Comparison
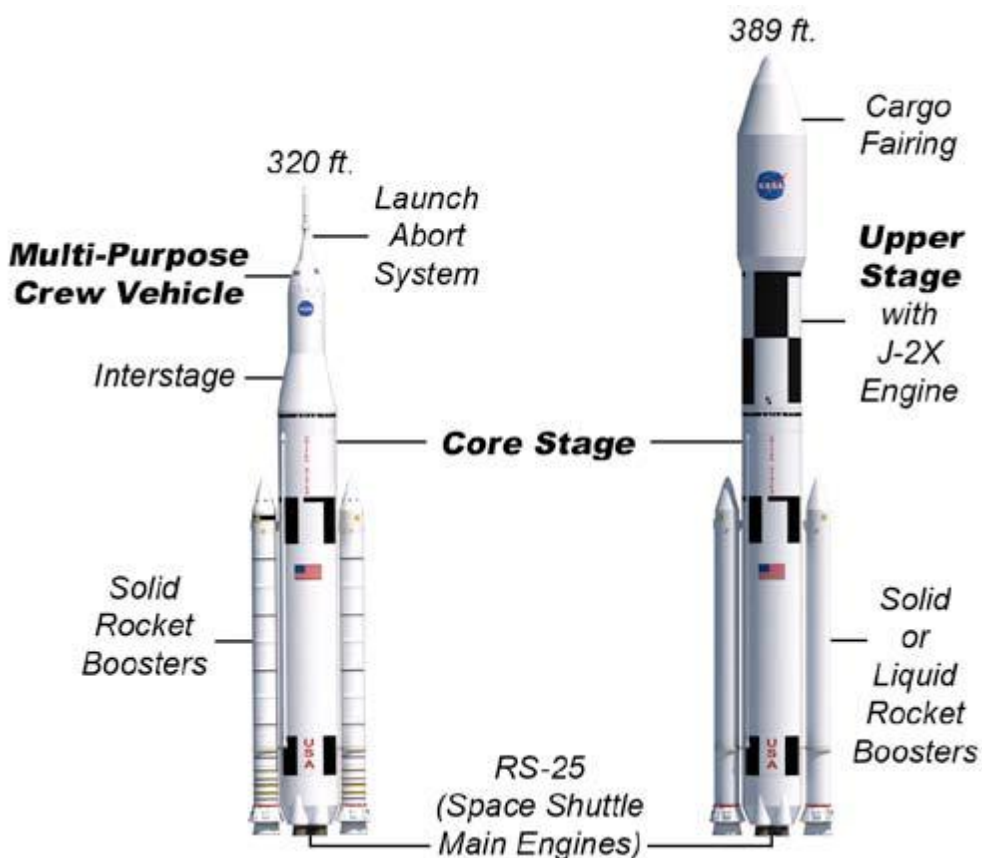
Figure 29. Evolution of the SLS Configuration

SUMMARY

The Space Shuttle Reusable SRM was a highly reliable human-rated SRM. At the time of this print, the RSRM was the largest diameter SRM to achieve flight status and the only large-scale SRM to be human-rated. The RSRM was instrumental in the development of the SLS launch system. The RSRM achieved this high reliability by applying special attention to Process Control, Testing, and Postflight, and

by thoroughly and timely communicating and dealing with all issues encountered. We followed a structured and disciplined approach for identifying and dispositioning all issues and all "out-of-family" conditions. We learned to carefully consider and disposition alternate opinions. We tried to learn as much as we could from our lessons.

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