SLS Booster Development

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The SLS booster combines proven technology from the past with cutting edge technology demonstrated by Qualification Motor #1 to support NASA's Space Launch System.

I. Introduction

QM-1 is the first of two qualification tests of the redesigned solid rocket motor V (RSRMV) motor component in the two-booster system that will propel NASA's mammoth Space Launch System (SLS) off the launch pad and to destinations far beyond low earth orbit. With assistance of the RSRMV motors, SLS enables deep space missions to destinations such as asteroids, Lagrange points and the moon, all culminating with manned missions to Mars in the 2030s. In addition to crewed missions, SLS may allow larger science payloads to reach their targeted destinations faster than ever before. Most importantly, SLS provides inspiration for young students from this nation and around the world to pursue education and careers in Science, Technology, Engineering and Math (STEM) by captivating the mind and unifying the world community in this grand journey of pioneering Mars.

The SLS RSRMV is closely related to the four-segment booster (RSRM) that successfully flew as part NASA's Shuttle program incorporating key design and process changes to:

1) Accommodate SLS mission-specific performance requirements
2) Enhance safety, reliability, and producability
3) Reduce overall costs

As the largest solid rocket booster ever built for flight, the SLS booster produces a peak 3.6 million pounds of vacuum thrust and burns for approximately 126 seconds. Key motor performance parameters are shown below at a 60°F propellant mean bulk temperature (PMBT) reference:

- Action time 126.2 sec
- Action time vacuum total impulse 368.1 Mlbf-sec
- Maximum sea level thrust 3.28 Mlbf
- Web time average vacuum thrust 3.13 Mlbf
- Propellant mass 1.385 Mlbm

Three full-scale RSRMV development tests and many component-level tests led to QM-1 (Figure 1). The QM-1 motor was tested on March 11, 2015, by Orbital ATK in Promontory, Utah. QM-1 had 75 qualification test objectives, 9 demonstration test objectives and 18 development test objectives and was tested in a hot-condition test environment (PMBT 93° F). More than 530 instrumentation channels and rigorous post-test evaluations were used to assess the performance against these objectives to support qualification of the motor system.

Qualification objectives focused on SLS program requirements of overall motor performance, thrust vector control (TVC) system performance, internal insulation performance, ballistic performance, joint sealing, structural performance, and erosion of the ablative nozzle. Due to asbestos-based material obsolescence and the desire for a more environmentally friendly material, the RSRMV internal insulation system has been redesigned since the Shuttle program. The last two years have been spent in an intense effort to optimize this new insulation system, which resulted in QM-1 testing the most defect-free aft segment ever produced.

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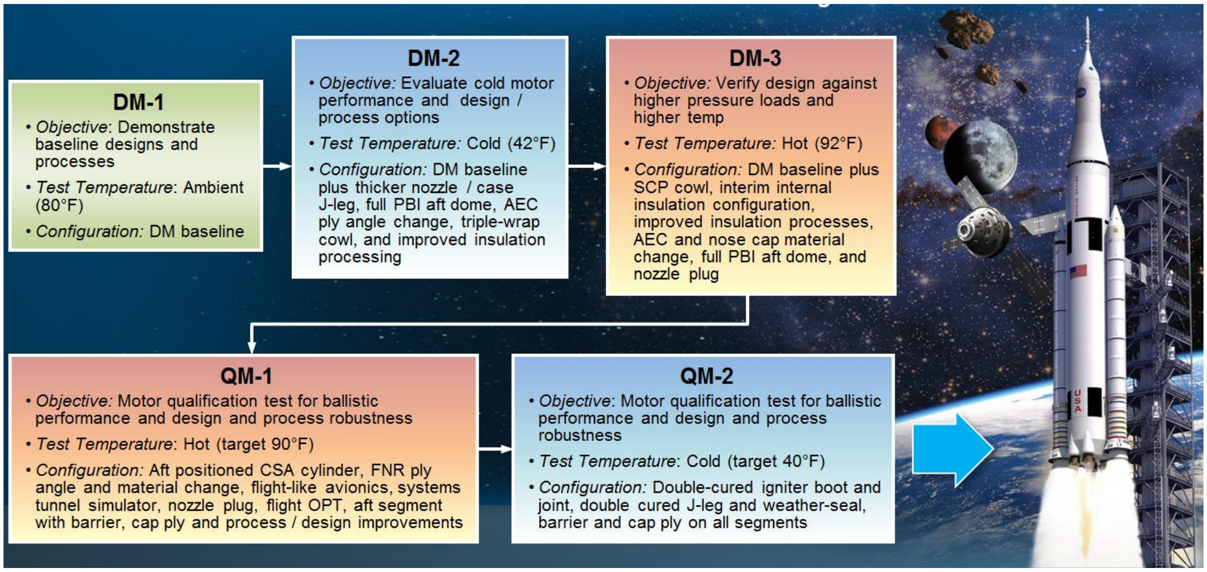

DM-1

- *Objective*: Demonstrate baseline designs and processes
- *Test Temperature*: Ambient (80°F)
- *Configuration:* DM baseline

DM-2

- *Objective:* Evaluate cold motor performance and design / process options
- *Test Temperature:* Cold (42°F)
- *Configuration:* DM baseline plus thicker nozzle / case J-leg, full PBI aft dome, AEC ply angle change, triple-wrap cowl, and improved insulation processing

DM-3

- *Objective:* Verify design against higher pressure loads and higher temp
- *Test Temperature:* Hot (92°F)
- *Configuration:* DM baseline plus SCP cowl, interim internal insulation configuration, improved insulation processes, AEC and nose cap material change, full PBI aft dome, and nozzle plug

QM-1

- *Objective:* Motor qualification test for ballistic performance and design and process robustness
- *Test Temperature*: Hot (target 90°F)
- *Configuration:* Aft positioned CSA cylinder, FNR ply angle and material change, flight-like avionics, systems tunnel simulator, nozzle plug, flight OPT, aft segment with barrier, cap ply and process / design improvements

QM-2

- *Objective*: Motor qualification test for ballistic performance and design and process robustness
- *Test Temperature*: Cold (target 40°F)
- *Configuration:* Double-cured igniter boot and joint, double cured J-leg and weather-seal, barrier and cap ply on all segments

Figure 1. SLS booster development / qualification program summary (colors consistent with test temperature).

Demonstration objectives for QM-1 included performance of the nozzle plug, which has been redesigned due to increased loading from the core stage RS-25 additional engine and proximity relative to the Space Shuttle configuration. High-speed video captured plug debris break-up patterns for debris mass and velocity calculations. Demonstration objectives included the upgraded RSRMV test stand. The test stand command and control system for motor firing and TVC control has been upgraded with a test-like-you fly approach, using many components of the flight system. The test stand main pivot flexure was redesigned to carry the tremendous RSRMV thrust while accurately measuring motor-produced loads, and an additional mid-span support (Figure 2) was added in order to reduce mid-span sag to the maximum expected bowing during flight.

Development objectives focused on data gathering activities for analytical models for the TVC system performance and loads and environments development. The correlated TVC models feed directly into vehicle-level flight control and trajectory predictions.

Figure 2. QM-1 post-test side view

II. Design Description

The SLS boosters leverage hardware that has a long and successful heritage on NASA's Space Shuttle program. Some hardware is used directly from Shuttle inventory, some hardware has been slightly modified, and other hardware has been significantly modified or replaced. This report does not contain an exhaustive list of all hardware changes, but does identify the primary differences.

A. Shuttle Inventory Hardware

Many unmodified heritage components have been taken directly from Shuttle inventory. The motor safe and arm (S&A) is one such component. The motor segment cases are also being used directly without modifications except for stiffener stubs being machined off of the aft segment. The primary structure of the booster forward assembly remains essentially unchanged, which includes the nose cone, frustum and forward skirt. The motor igniter metal structure and propellant have remained the same as was used on the Shuttle program. The booster aft skirt structure and TVC system also remain true to their Shuttle design.

B. Modified Shuttle Hardware

Some components from the Shuttle program have been modified for the SLS program. While the motor igniter has not changed fundamentally, insulation structural improvements have been made by adding a silica-filled acrylonitrile butadiene rubber (SF-NBR) shear ply at the case wall in critical regions.

QM-1 was cast with RSRMV propellant, which is a composite solid propellant formulation consisting of polybutadiene acrylonitrile acrylic acid terpolymer binder (PBAN), epoxy curing agent, ammonium perchlorate (AP) oxidizer, aluminum powder fuel, and a small amount of iron oxide burn rate catalyst, which is used to target a specific burn rate. Motor burn rate has been reduced to optimize the five-segment configuration.

The aft segment cylinder configuration was modified for SLS where the cylinder that supported the Shuttle external tank attach ring was moved aft to support attachment of the SLS core stage attach ring. This was achieved by changing positions with the stiffener cylinder as is shown in Figure 3.

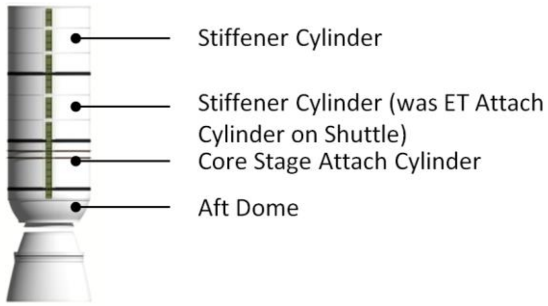

Figure 3. Aft segment configuration

The SLS RSRMV forward motor segment utilizes a 12-fin star design, whereas an 11-fin design was used on the Shuttle program. The forward segment grain geometry shown in Figure 4 has the 12-fin star region at the forward portion with a tapered transition to a center perforated (CP) region at the aft portion of the segment. Additionally, the 12 fins are dimensionally lengthened from the RSRM baseline.

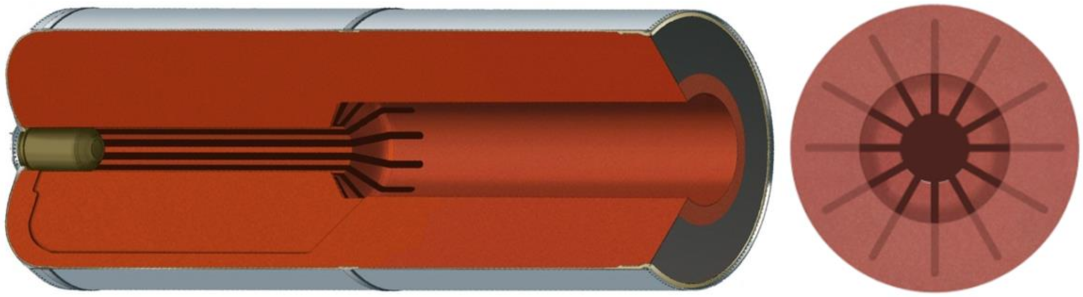

Figure 4. Forward segment grain geometry

The inhibitor design has also been modified from the RSRM baseline. The castable inhibitors on the aft-end of the center segments have been significantly increased in height such that the aft faces are nearly fully inhibited. The polybenzimidazole nitrile butadiene rubber (PBI-NBR) inhibitors on the forward faces of the center segments are decreased in height compared to RSRM due to the propellant chamfers. Both RSRM and RSRMV are nearly fully inhibited on the forward faces of the center segments.

The RSRMV field joint protection system (FJPS) is a simplified version of the RSRM design. RSRMV does not use the RSRM joint heaters at the field joints, nozzle-to-case (N/C) joint and igniter joints as low-temperature O-rings have been utilized for the RSRMV design. These low-temperature O-rings were demonstrated on boosters late in the Shuttle program. The primary and secondary O-rings in the field joints also incorporate a larger nominal cross-section diameter compared to the RSRM baseline for improved performance at low temperatures.

C. New or Redesigned Hardware

Some components of the SLS booster are new or dramatically redesigned from the Shuttle booster design. The RSRMV nozzle and case insulation were both dramatically redesigned for SLS. These components are discussed in more detail in Sections IV and V.

QM-1 head-end pressure data will be used to down select a flight pressure transducer from two candidate designs tested on QM-1 to replace the Shuttle operational pressure transducer (OPT). The results from the candidate designs will be compared to the control data set.

The SLS systems tunnel is based on the heritage Shuttle design with significant modifications. The avionics system has been completely redesigned for the SLS booster. Both of these items are discussed in more detail in Section III.

III. New Technology / Design Improvements

The SLS booster design has incorporated new technology and design improvements that were tested as part of the QM-1 motor firing. One of the key SLS objectives is vehicle safety. The flight termination system (FTS) is part of this safety net and multiple design improvements were implemented on SLS. A pyrotechnic delay was implemented that allows the crew capsule to be jettisoned a safe distance prior to terminating the booster thrust should an anomaly occur. The linear shape charge (LSC) used to terminate thrust was extended further aft onto the aft motor segment to more completely disable the motor pressure vessel. In addition, the systems tunnel in which the LSC is housed was modified by providing floor plate cutouts, allowing greater case penetration of the LSC plasma jet.

The QM-1 test included a section of the systems tunnel (Figure 5) populated with a pyrotechnic delay, LSC, harness bundles, and tunnel covers. All pyrotechnic hardware was inert with the intent to verify dynamic similarity between the SLS and Shuttle designs due to differences in the ethylene propylene diene monomer (EPDM) formulation, component mass changes, slotted floor plates, and removal of the thermal protection system (TPS) closeout along the tunnel-to-case interface.

Figure 5. QM-1 systems tunnel simulator (black pad is process aid)

The new SLS avionics hardware provides state-of-the-art command and control of the heritage TVC system. The test-like-you-fly approach was taken on the QM-1 static test by implementation of the flight-like avionics system. As a forward skirt is not included in a static test, the avionics boxes were housed in off motor bunkers. The ignition separation control (ISC) units provide the ignition pulse to the motor igniter. The booster control and power distribution units (BCPDU), actuator control unit (ACU), and hydraulic power unit controllers (HPUC) provide actuator servo commands for nozzle position and auxiliary power unit (APU) valve drive commands to turbomachinery that supply hydraulic pressure to move the actuators. An additional layer of hardware protection is provided by nonflight emergency systems at the test stand. By routing the servo commands through a TVC null box, the nozzle can be nulled in the event of loss of control. APU valve drive commands pass through the next generation ground test controller (GTX), which independently monitors turbine speeds and can shut down a system that is exceeding limits. The GTX will also react to commands from the red line monitor (RLM), which provides capability for additional system parameter monitoring and test abort, if required. QM-1 was the first static test to implement this avionics system, so a significant pre-test effort was performed that included checkouts of all related avionics scripts on various hardware configurations including TVC hot hydrazine tests.

Motor case insulation and nozzle are both newly designed components for the SLS booster. Significant effort has been devoted to each of these two subsystems, which are addressed in Section IV and V.

IV. Insulation Development

During the Shuttle program, booster motor case insulation used asbestos silica-filled nitrile butadiene rubber (AS-NBR). Due to material obsolescence and a desire for a more environmentally friendly material, the SLS program has chosen to use a PBI-NBR insulator. This PBI-NBR insulation was used successfully on Demonstration Motor (DM)-1, -2, and -3 static tests; however, unacceptable conditions were discovered via X-ray of the original

QM-1 aft segment. Two propellant voids and two propellant-liner-insulation (PLI) separations were detected. An investigation was initiated due to these findings. During the QM-1 investigation, it was determined that the motor PBI-NBR insulation enables off-gassing of sufficient magnitude to create thin-film propellant separations near the propellant-liner interface during the propellant cure process. Rubber materials such as AS-NBR and SF-NBR also trap and retain large amounts of air; however, how the air and volatiles are released during the cure process is unique to PBI-NBR relative to previous experience.

In order to resolve the PBI-NBR related concerns, a set of improvements were implemented on the QM-1 aft segment that included:

- Extended devolatization and dry-cycles to drive air and volatiles out of the insulation
- Improved vacuum system during insulation cure
- Insulation lay-up changes to minimize entrapped air
- Improved insulation blister repairs
- Enhanced environmental controls in the work center
- Addition of a barrier to stop gas transfer during propellant cast / cure process

The insulation lay-up changes are critical to minimize the volume of air available for transfer during propellant cast and cure. The barrier addition is key to stopping gas transfer of any remaining air or volatiles into the propellant during the cast / cure process. These process improvements were implemented for the QM-1 aft segment, which resulted in the most defect-free aft segment ever produced. These improved processing techniques and barrier implementation will be part of the entire motor build for the second qualification motor of the redesigned RSRMV (QM-2) and following SLS flight motors.

Due to the insulation investigation activities, the motor was partially assembled (up to the center aft segment) and then demated. This resulted in the longest cumulative assembly time for the forward field joint (over 18 months). The primary concern with long assembly time is reduced joint resiliency leading to a decrease in joint engagement.

V. Nozzle Development

The larger RSRMV motor required a modified nozzle design. The RSRM nozzle utilized a 7.72 expansion ratio, while a 7.2 expansion ratio is used for RSRMV. The throat diameter, exit diameter, and length all increased in order to control the volume and velocity of the gases that are generated in the RSRMV design.

The RSRMV nozzle has evolved during the SLS booster path to qualification as was partially addressed in Figure 1. The flex boot is now fabricated with PBI-NBR versus AS-NBR on RSRM. Significant changes were made to the nozzle joints. Room temperature vulcanized silicon-based sealant (RTV) filled joints have been replaced with carbon fiber rope and thermal barrier O-rings in two joints. In one joint, the RTV was removed and a barrier O-ring added. A new forward end ring (FER) has been incorporated. The flex bearing attachment was moved to the nose inlet housing. The aft exit cone (AEC) ply angle was changed in order to minimize potential for ply lifting. The forward nose ring (FNR) ply angle was also changed to address abnormal erosion. A triple wrap cowl (glass-cloth-phenolic / carbon-cloth-phenolic / carbon-cloth-phenolic) replaced the heritage silica-cloth-phenolic / carbon-cloth-phenolic cowl to avoid structural design challenges of widely variable silica-cloth-phenolic material properties. Many material changes in the nozzle were also implemented.

After the DM-2 static test, abnormal erosion on the FNR was observed. Although the design requirements were met, an investigation team was formed to work the issue. The DM-3 nozzle was built exactly the same as DM-2, but was instrumented with ultrasonic gages to monitor erosion during burn in order to capture timing and magnitude of the abnormal erosion.

On DM-3, abnormal FNR erosion was once again observed, very similar to the observed DM-2 erosion. The investigation team determined, from the ultrasonic gage data, that the erosion was due to a series of events and environments that individually would not or could not explain the post-test observations but together provided the post-test erosion signature. These events include localized delamination of the forward end of the forward nose ring and / or nose cap in the short ply regions (wedgeout) exposing the ply faces, ply lifts, or ply separations that were then removed by the particle impingement environment. The sloughing of the plies would arrest due to improved venting or development of a char cap. With this condition occurring early in burn, the particle impingement erosion during the remainder of the motor burn would erode the phenolics to the final observed profile having washed out the initial trigger indications.

Due to this abnormal erosion, design changes were implemented for QM-1. In addition, it was felt that nonflight like motor sag exacerbated the erosion due to higher particle impingement early in burn on the inlet regions at the bottom of the nozzle. QM-1 implemented an additional mid-span support in order to produce flight-like motor deflection during static test (Figure 2).

VI. Test Data

Over 530 channels of instrumentation were gathered on the QM-1 static test. Post-test analysis of these data in combination with post-test hardware evaluation is used to determine the successful completion of test objectives. The instrumentation data processing is currently in work, and the motor is in the early stages of disassembly. All indications to date point towards having had a very successful QM-1 test. Figure 2 shows QM-1 post-test while Figure 6 shows QM-1 during the test.

Diving board visual assessments saw no indications of abnormal erosion on the nozzle FNR as was seen on DM-2 and DM-3. All phenolic components inspected have been in excellent shape with no signs of abnormal erosion, pocketing or ply lifting. After nozzle removal, laser tracker and structured light will be used to quantitatively map the nozzle contours. There are no indications of motor insulation issues; however, more information will be known after the aft segment has been demated.

Ballistics performance parameters were within allowable requirements based on preliminary data and quick look analysis methodology. The measured maximum pressure was greater than predicted early in motor burn. This result is very similar to DM-3 performance, which was also tested at an elevated temperature. The ballistics team is assessing approaches to improve the ballistics predictions for this condition.

The TVC actuator servovalve delta pressure data showed anomalous results; however, no anomalous results were seen in the TVC duty cycle results. The avionics and TVC teams are investigating the cause of this anomalous condition and / or measurements.

VII. Conclusion

QM-1 is a critical milestone in the NASA SLS program, which will enable bold human missions to Mars and invigorate the hopes and ambitions of humanity. This SLS booster qualification test demonstrated both the successes of the past Shuttle program and exciting advances developed for the next generation SLS program, including updated insulation, nozzle, and avionics designs. QM-1 will be followed by QM-2 and then vehicle flights (EM-1, EM-2 and beyond). Post-test analysis and hardware assessments are currently in-work; however, preliminary observations indicate a successful test of QM-1.

Figure 6. QM-1 test view

Acknowledgments

The work described in this paper was funded by NASA. This paper is a high level summary of the SLS Booster development effort, and represents the work of a very talented team of professionals from Orbital ATK and NASA Marshall Space Flight Center.