Orbital ATK

# SLS Booster Development

## QM-1 Demonstration of New Technology

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# Overview

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2.0 – Design Description

3.0 – Insulation Development

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# 1.0 Introduction

- NASA and four prime contractors are developing the mammoth Space Launch System (SLS) and Orion crew capsule for pioneering deep space
  - Destinations such as asteroids, Lagrange points and the moon
  - Culminating with manned missions to Mars in the 2030s
  - SLS may also allow larger science payloads to reach their targeted destination faster than ever before
- SLS is a two-booster system
  - SLS boosters combine proven technology of the past with cutting edge technology
  - Booster Qualification Motor #1 (QM-1) static test demonstrated this technology on March 11, 2015
    - First of two motor qualification tests of the five-segment reusable solid rocket motor (RSRMV)

**Most importantly, SLS will provide the inspiration for young students 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**

# 1.0 Introduction

- RSRMV is closely related to the four-segment version (RSRM) that successfully flew as part of the NASA Shuttle program
  - Key design and process changes include:
    - Accommodations for SLS mission-specific performance requirements
    - Enhanced safety, reliability, and producability
    - Reduced overall costs
  - Produces peak vacuum thrust of 3.6 million pounds
  - Largest solid rocket booster ever built for flight
  - Key motor performance parameters at 60°F propellant mean bulk temperature (PMBT) are:
    - Action time 126.2 sec
    - Action time vacuum total impulse 368.1 Mlbf-sec
    - Max sea level thrust 3.28 Mlbf
    - Web time average vacuum thrust 3.13 Mlbf
    - Propellant mass 1.385 Mlbm

# 1.0 Introduction

- Three full-scale RSRMV development tests and many component-level tests have led up to QM-1
  - QM-1 was a hot-condition test at a PMBT of 93°F
  - More than 530 instrumentation channels
  - 75 qualification test objectives that focused on:
    - Overall motor performance
    - Thrust vector control (TVC) system performance
    - Internal insulation performance
    - Ballistic performance
    - Joint sealing
    - Structural performance
    - Erosion of the ablative nozzle
  - Due to asbestos-based material obsolescence and the desire for a more environmentally friendly material, RSRMV internal insulation has been redesigned
    - Last two years spent in an intense effort to optimize this new insulation system
    - Resulting in the most defect-free motor aft segment ever produced

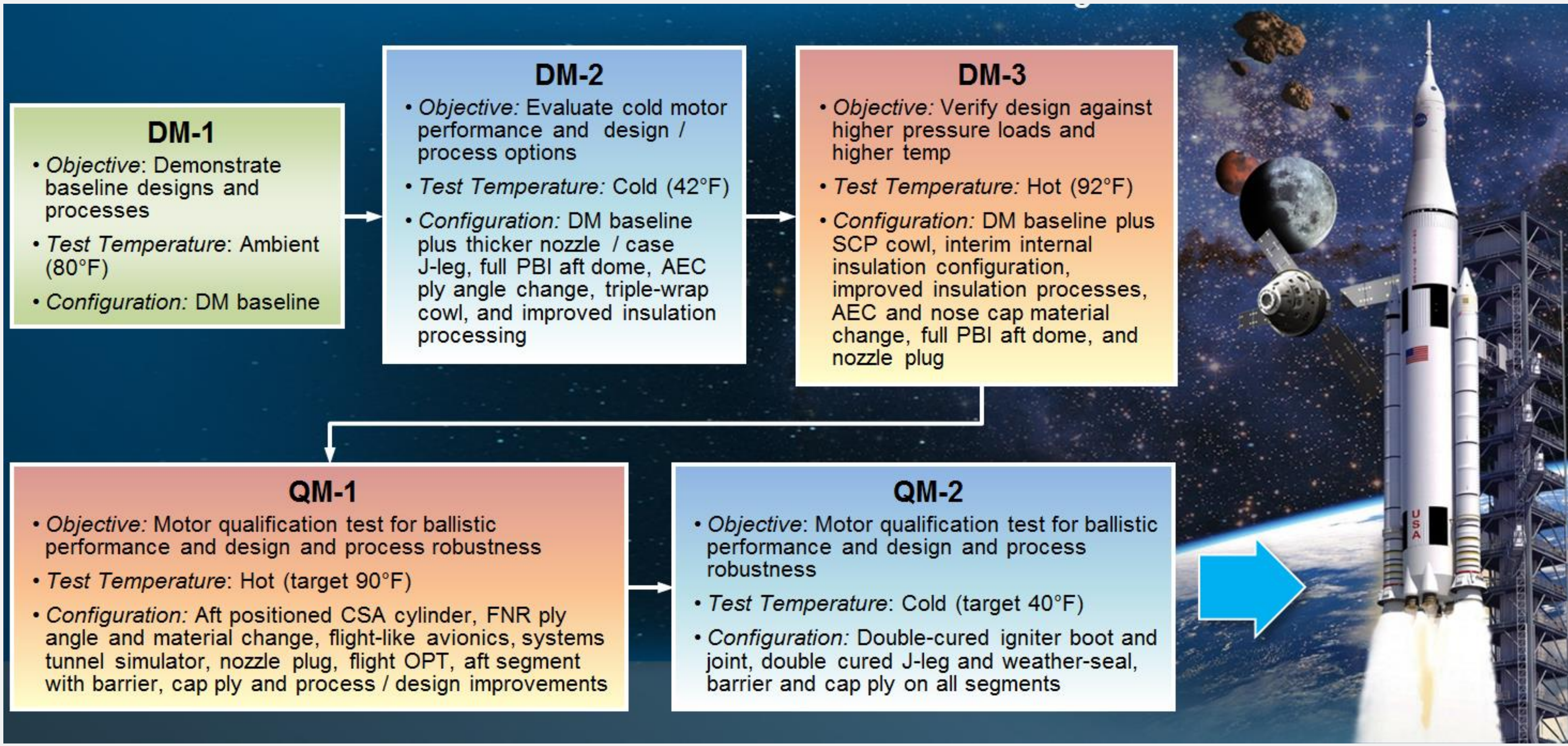
# 1.0 Introduction

- 9 demonstration test objectives including:
  - A nozzle environmental plug
    - Redesigned due to increased loading from the core stage RS-25 additional engine and proximity relative to the Space Shuttle configuration

# 1.0 Introduction

- 9 demonstration test objectives (cont.):
  - Upgraded RSRMV test stand
    - ‘Test like you fly’ avionics system  command and control of motor ignition and TVC
    - Redesigned main pivot flexure to carry tremendous RSRMV thrust while accurately measuring motor-produced loads
    - Additional mid-span support to reduce sag to maximum expected bowing during flight
- 18 development test objectives including:
  - Data gathering for TVC analytical model correlation
  - Loads

# 1.0 Introduction



# 2.0 Design Description

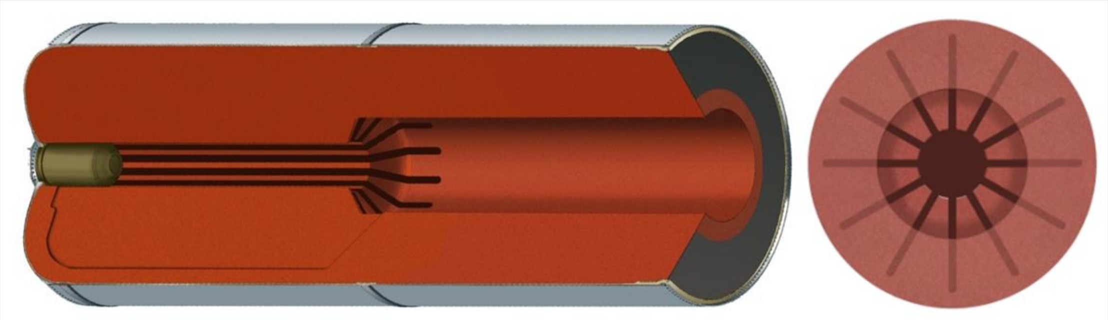
- SLS boosters leverage hardware that has a long and successful heritage on NASA's Space Shuttle program
  - Some hardware used directly from Shuttle inventory
  - Some hardware has been slightly modified
  - Other hardware has been significantly modified or replaced
- Shuttle inventory hardware
  - Motor safe and arm (S&A)
  - Motor segment cases
  - Forward assembly primary structure
    - Nose cone, frustum, and forward skirt
  - Motor igniter metal structure and propellant
  - Aft skirt structure and TVC system

# 2.0 Design Description

- Modified Shuttle hardware
  - Igniter insulation structural improvements
    - Silica-filled acrylonitrile butadiene rubber (SF-NBR) shear ply added in critical regions
  - Motor propellant
    - Composite solid propellant formulation of:
      - Polybutadiene acrylonitrile acrylic terpolymer binder (PBAN)
      - Epoxy curing agent
      - Ammonium perchlorate (AP) oxidizer
      - Aluminum powder fuel
      - Iron oxide burn rate catalyst
    - Burn rate has been reduced to optimize the five-segment configuration

# 2.0 Design Description

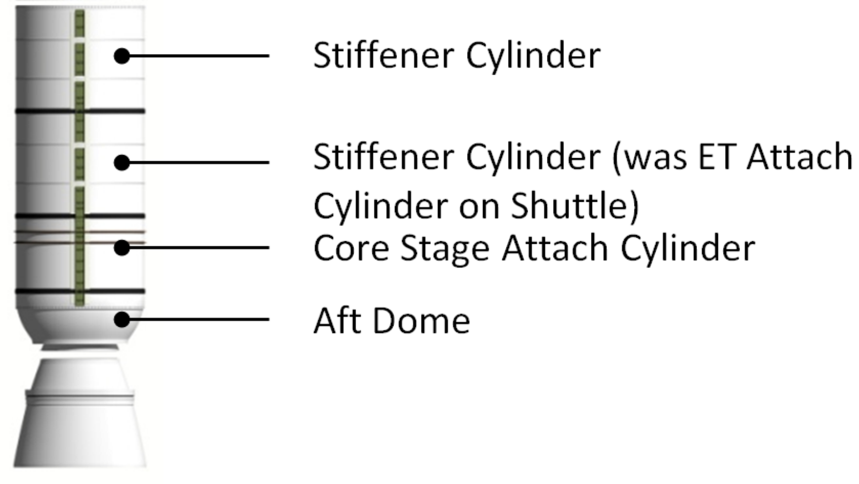
- Modified Shuttle hardware
  - Forward motor segment propellant grain
    - RSRMV 12-fin star design vs 11-fin Shuttle design
    - RSRMV fins dimensionally lengthened from RSRM



  - Center segment inhibitors
    - Aft-end castable inhibitors increased in height from RSRM
      - Aft faces nearly fully inhibited
    - Polybenzimidazole nitrile butadiene rubber (PBI-NBR) inhibitors on the forward faces decreased in height compared to RSRM due to the propellant chamfers
      - Both RSRM and RSRMV are nearly fully inhibited on the forward faces

# 2.0 Design Description

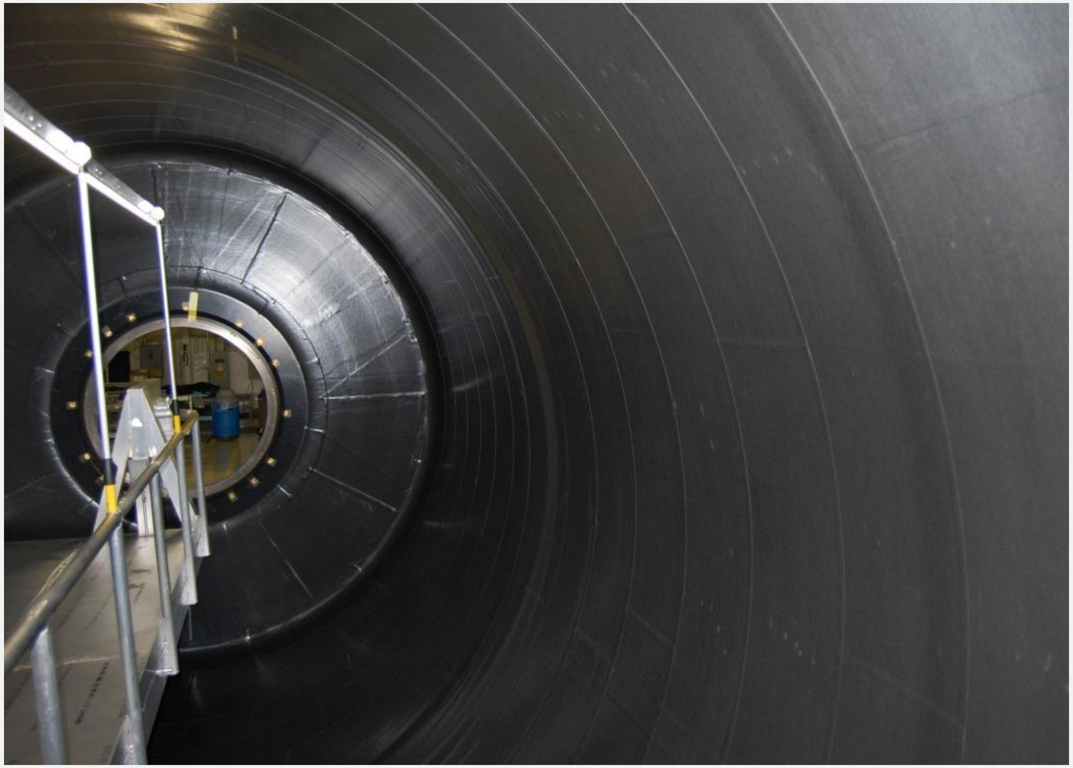
- Modified Shuttle hardware
  - Aft segment cylinder configuration
    - Shuttle external tank attach ring cylinder moved aft to support attachment of the SLS core stage attach ring
    - Achieved by changing cylinder positions with the stiffener cylinder




  - Field joint protection system (FJPS)
    - Simplified version of RSRM design
      - No joint heaters at field joints, nozzle-to-case joint, and igniter joints
        - Low-temperature O-rings demonstrated late in the Shuttle program are being used
        - Field joint primary and secondary O-rings incorporate a larger nominal cross-section diameter for improved low temperature performance

# 2.0 Design Description

- New or redesigned hardware
  - Case insulation
  - Nozzle
  - Head-end pressure transducers
    - QM-1 supports a down select of two candidate pressure transducers



**Aft Segment Insulation**

# 2.0 Design Description

- New or redesigned hardware
  - Avionics system
    - Provides state-of-the-art command and control of the heritage TVC system
    - QM-1 housed avionics boxes in off motor bunkers as a forward skirt is not included in the static test
      - Ignition separation control (ISC) units provide the ignition pulse to the motor igniter
      - Booster control and power distribution units (BCPDU), actuator control unit (ACU), and hydraulic power unit controllers (HPUC) provided actuator servo commands and auxiliary power unit (APU) valve commands
        - Actuators control nozzle position
        - APU supplies hydraulic pressure to move the actuators

# 2.0 Design Description

- New or redesigned hardware
  - Avionics system (cont.)
    - An additional layer of hardware protection is provided by nonflight emergency systems at the test stand
      - Servo commands routed through a TVC null box
        - Allows the nozzle to be nulled in the event of loss of control
      - APU valve drive commands pass through the next generation ground test controller (GTX)
        - Independently monitors turbine speeds and can shut down a system that is exceeding limits
        - Also reacts to commands from the red line monitor (RLM), which provides the capability for additional system parameter monitoring and test abort, if required
    - QM-1 was the first static test to implement this avionics system
      - A significant pre-test effort was performed that included checkouts of all related avionics scripts on various hardware configurations including TVC hot hydrazine tests

# 2.0 Design Description

- New or redesigned hardware
  - Systems tunnel crew safety improvements
    - Pyrotechnic delay implemented that allows 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 than RSRM onto the aft motor segment to more completely disable the motor pressure vessel
    - Floor plate cutouts allow greater case penetration of the LSC plasma jet
  - QM-1 included a section of the systems tunnel to validate the structural dynamic system response
    - Included:
      - Inert pyrotechnic delay
      - Inert LSC
      - Harness bundles
      - Tunnel covers
      - RSRMV EPDM formulation
      - Slotted floor plates

# 3.0 Insulation Development

- During the Shuttle program, booster motor case insulation was 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
- 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
  - 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

# 3.0 Insulation Development

- 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
  - The addition of a barrier to stop gas transfer during propellant cast / cure process

**New Vacuum Bag System**

# 3.0 Insulation Development

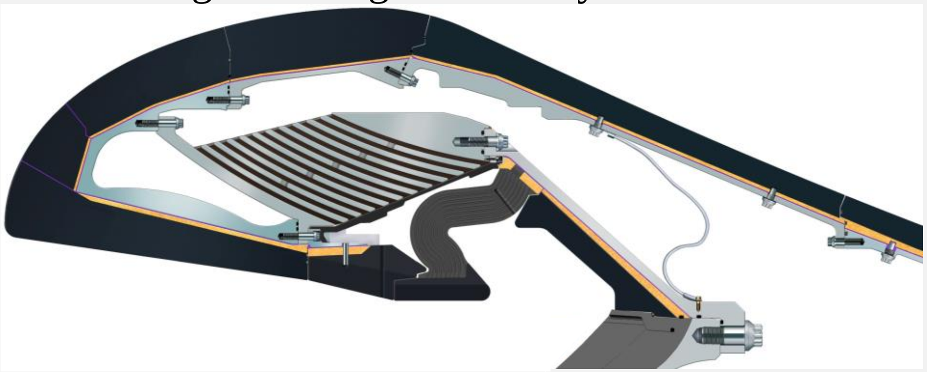
- The insulation lay-up changes are critical to minimize the volume of air available for transfer during propellant cast and cure
- The barrier addition is key to stopping gas transfer of any remaining air or volatiles into the propellant during the cast / cure process
- The addition of the barrier and process improvements 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

# 4.0 Nozzle Development

- The larger RSRMV required a modified nozzle design
  - RSRM nozzle utilized a 7.72 expansion ratio, while a 7.2 expansion ratio is used for RSRMV
  - 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

# 4.0 Nozzle Development

- The RSRMV nozzle has evolved during the SLS booster path to qualification
  - 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
    - Flex bearing attachment was moved to the nose inlet housing
  - Aft exit cone (AEC) ply angle was changed in order to minimize potential for ply lifting
  - 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

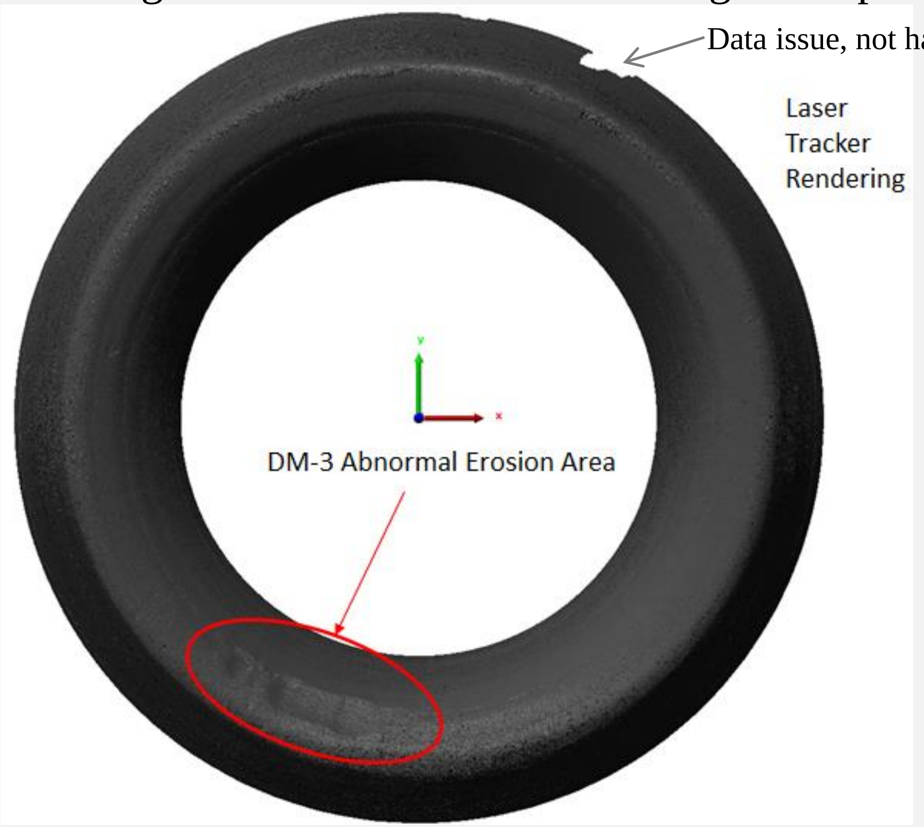


# 4.0 Nozzle Development

- After the DM-2 static test, abnormal erosion on the FNR was observed
  - Although the design requirements were met, an investigation team was formed
  - The DM-3 nozzle was built 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
  - With the ultrasonic gage data, it was determined 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
    - Events include localized delamination of the forward end of the FNR and / or nose cap in the short ply regions (wedgeout)
    - This exposed the ply faces / lifts / 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

# 4.0 Nozzle Development

- 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 to minimize non-flight like particle impingement



# 5.0 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 being disassembled
- All indications to date point towards a very successful QM-1 test
  - There are 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
  - There are no indications of motor insulation issues
- 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 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 some unexpected results; however, no anomalous performance was seen in the TVC duty cycle
  - The avionics and TVC teams are investigating the cause of this unexpected condition and / or measurements

Overall, QM-1 was a very successful test

# 6.0 Conclusion

- QM-1 is a critical milestone in NASA's 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)

# Acknowledgments

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