

# DEVELOPING THE WORLD'S MOST POWERFUL SOLID BOOSTER

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## ABSTRACT:

NASA's Journey to Mars has begun. Indicative of that challenge, this will be a multi-decadal effort requiring the development of technology, operational capability, and experience. The first steps are underway with more than 15 years of continuous human operations aboard the International Space Station (ISS) and development of commercial cargo and crew transportation capabilities. NASA is making progress on the transportation required for deep space exploration – the Orion crew spacecraft and the Space Launch System (SLS) heavy-lift rocket that will launch Orion and large components such as in-space stages, habitat modules, landers, and other hardware necessary for deep-space operations. SLS is a key enabling capability and is designed to evolve with mission requirements. The initial configuration of SLS – Block 1 – will be capable of launching more than 70 metric tons (t) of payload into low Earth orbit, greater mass than any other launch vehicle in existence. By enhancing the propulsion elements and larger payload fairings, future SLS variants will launch 130 t into space, an unprecedented capability that simplifies hardware design and in-space operations, reduces travel times, and enhances the odds of mission success. SLS will be powered by four liquid fuel RS-25 engines and two solid propellant five-segment boosters, both based on space shuttle technologies. This paper will focus on development of the booster, which will provide more than 75 percent of total vehicle thrust at liftoff. Each booster is more than 17 stories tall, 3.6 meters (m) in diameter and weighs 725,000 kilograms (kg). While the SLS booster appears similar to the shuttle booster, it incorporates several changes. The additional propellant segment provides additional booster performance. Parachutes and other hardware associated with recovery

operations have been deleted and the booster designated as expendable for affordability reasons. The new motor incorporates new avionics, new propellant grain, asbestos-free case insulation, a redesigned nozzle, streamlined manufacturing processes, and new inspection techniques. New materials and processes provide improved performance, safety, and affordability but also have led to challenges for the government/industry development team. The team completed its first full-size qualification motor test firing in early 2015. The second is scheduled for mid-2016. This paper will discuss booster accomplishments to date, as well as challenges and milestones ahead.

## 1. INTRODUCTION

NASA's Space Launch System (SLS), a heavy lift, human-rated vehicle, is designed to lift the Orion Multi-Purpose Crew Vehicle and other payloads beyond Earth orbit to the Moon, asteroids, and eventually Mars. SLS has leveraged the successes of the Space Shuttle Program (SSP) into an evolvable design with an initial payload capability of 70 metric tons (t) to Low Earth Orbit (LEO). SLS's first flight, deemed Exploration Mission-1 (EM-1), will be unmanned and is scheduled for 2018 with an Exploration Mission-2 (EM-2) manned flight scheduled for 2021.



Figure 1: Rendering of SLS Block 1 lifting off for its first mission, EM-1.

The initial SLS vehicle configuration, Block 1, is comprised of a core stage, an upper stage, and two solid rocket boosters. The core stage is powered by four RS-25 liquid hydrogen/liquid oxygen (LH2/LOX) engines. The upper stage, also called the Interim Cryogenic Propulsion Stage (ICPS), uses one RL-10 LH2/LOX engine. The two solid boosters are attached to the core stage and provide more than 75 percent of thrust during the first two minutes of flight.

## 2. BOOSTER OVERVIEW

The SLS booster design leverages the success of the SSP while incorporating design improvements for a safe, affordable, and sustainable heavy-lift launch vehicle. Orbital ATK (OATK) is the prime contractor for design and development as well as flight hardware and support. Similar to the SSP solid rocket boosters, the Block 1 SLS booster design includes three assemblies: forward, solid rocket motor, and aft. The forward assembly contains the forward skirt, avionics boxes, frustum, nose cone, and booster separation motors (BSMs). In a notable change from the SSP, the forward assembly does not contain parachutes because the SLS booster is designed to be expendable. The forward assembly is also the location for the booster's thrust takeout. Unlike most other launch vehicles that utilize strap-on boosters with thrust takeout in the aft area of the launch vehicle, the forward thrust takeout location is legacy from the SSP and helps reduce core stage mass. The solid rocket motor is the largest of the three assemblies and includes five motor segments, nozzle, aft exit cone (AEC), and igniter. The aft assembly is comprised of an aft skirt, thrust vector control (TVC) system, and avionics boxes. The components of the solid rocket motor assembly are manufactured at OATK facilities in Utah and shipped via rail to Kennedy Space Center (KSC) where they are assembled for flight. The aft and forward assembly elements are already in place at KSC. There, they will be refurbished and built into an assembly. The three assemblies are stacked into a booster assembly and then integrated with the core stage, completing the launch vehicle.

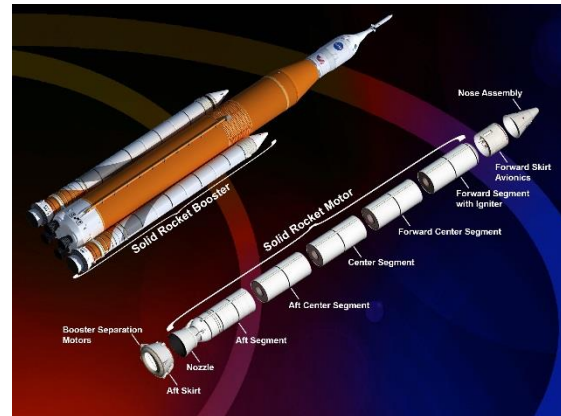


Figure 2: Major components of SLS solid rocket booster.

## 3. QUALIFICATION STATUS

The SLS Booster Office completed its Critical Design Review (CDR) in August 2014 and continues to refine the design through analysis and/or qualification testing with a goal of design certification in August 2017. Qualification hardware fabrication and testing is underway and progressing well at the subsystem level. Additionally, some subsystems managers have chosen to fabricate both qualification and flight hardware during the same production run; those details will be discussed later in this paper.

L3 Cincinnati Electronics (L3 CE) is manufacturing the booster avionics subsystem through a subcontract with OATK. Four different Line Replacement Unit (LRU) designs will be utilized by each booster. A booster LRU is a box mounted in the forward or aft skirts containing computer boards that control the stage, take measurements, and communicate with the rest of the vehicle. All qualification LRUs are currently in manufacturing at various stages of completion. Box-level qualification testing (environments) of individual avionics boxes, or LRUs, will be conducted at L3 CE and is scheduled to begin in the April 2016 timeframe and conclude in early 2017. System-level qualification (SLQ) testing will follow box-level qualification and will be conducted at NASA's Marshall Space Flight Center (MSFC) in Huntsville, Ala. The SLQ testing will integrate the LRUs into a flight-simulated avionics ring that will test command and communication between booster avionics and TVC. Following SLQ testing, the LRUs will be integrated with SLS flight avionics systems to simulate flight and test the functionality of the entire SLS command and communications system. Once system-level testing is complete at MSFC, the LRUs will be delivered to KSC and used to support flight readiness through Assembly

Checkout (ACO) of the forward and aft skirt assemblies.

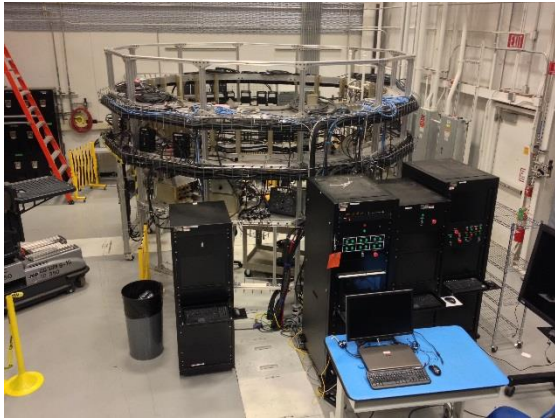


Figure 3: Booster avionics undergoes system-level testing at MSFC.

BST Systems and Goodrich Corp. are manufacturing the booster battery and Flight Safety System (FSS) Linear Shaped Charge (LSC), respectively. This battery design will be utilized by both the booster avionics and FSS. Fabrication began in late February 2016 for units that will undergo qualification testing this summer. Fabrication of the booster FSS LSC is also underway. The first lot of FSS LSC is intended to be used for both qualification testing and as flight units for EM-1 and EM-2. Qualification testing with the LSC is scheduled to begin in early 2017.

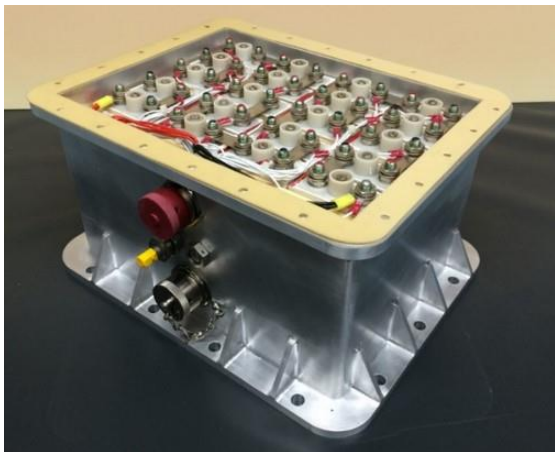


Figure 4: Booster batteries are being manufactured by BST Systems.

OATK is manufacturing and testing the five-segment solid rocket motor. Three previous development motors and one qualification motor have been successfully manufactured and tested. Qualification Motor-1 (QM-1) was a full-size motor that was successfully static-tested in March 2015 at OATK's Promontory, Utah test site. The QM-1 motor was heated for approximately two months before the test to

evaluate the motor's performance at 32 degrees Celsius (90 degrees Fahrenheit). QM-1 incorporated two design changes that will be discussed in detail later in this paper. Both design changes successfully mitigated the respective issues. The second and final qualification motor, QM-2, is scheduled for static testing in the summer of 2016. QM-2 will be cold-conditioned to measure the motor's performance at 4 degrees Celsius (40 degrees Fahrenheit).



Figure 5: The QM-1 static test verified booster operations at 32 degrees Celsius (90 degrees Fahrenheit).

#### 4. CHALLENGES

Throughout the development and qualification process, several challenges and issues have been discovered and overcome with design solutions. A summary of these issues and solutions follows.

The SSP's Reusable Solid Rocket Motor (RSRM) baseline insulation design used asbestos and silica-filled nitrile butadiene rubber (ASNBR) as an insulator. Due to the inherent health issues of ASNBR, new formulations of non-asbestos insulators were developed and tested as candidates to replace ASNBR. The polybenzimidazole nitrile butadiene rubber (PBI-NBR) formulation was selected as the SLS booster baseline insulation design based on its performance in the areas of high erosion and increased tack. From an erosion performance standpoint, PBI-NBR was a significant improvement over ASNBR. However, processing of PBI-NBR presented some challenges. Three development motors were successfully processed with PBI-NBR and performed well, but PLI unbonds were found during x-ray inspection of the first qualification motor's aft segment. Extensive material testing and innovative subscale tests were performed. Insulator outgassing was determined to be the root cause of the unbonds. The initial mitigation approach was to drive out all gases from the insulator with a vacuum devolatilization cycle (VDVC). However, this approach resulted in an unsuccessful cast of a second aft segment. The follow-on investigation performed additional subscale and substantial full-scale testing

along with excavation and dissection of the second aft segment and validated insulator outgassing as the original root cause of the unbonds. The new mitigation approach included an improved insulation layup and vacuum cycle and added a barrier and cap ply design to prevent gases from reaching the PLI interface. The investigation significantly increased understanding of the PBI-NBR insulator and the improved design resulted in a successful QM-1 static motor test in March 2015.

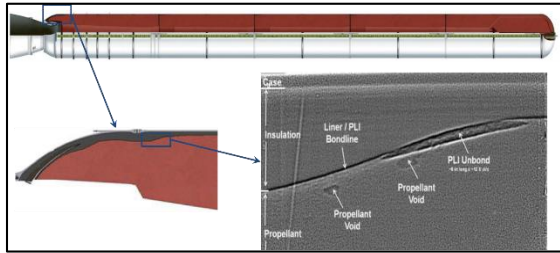


Figure 6: The location PLI unbonds caused by outgassing.

A follow-on effort to the PLI unbond resolution is underway to determine the PBI-NBR insulator's fracture capability. The replacement of the SSP's ASNBR with PBI-NBR necessitated a system analysis to better understand its behavior during long-term storage. Moreover, the incorporation of the barrier and cap ply required additional analyses that are currently being conducted by OATK and NASA MSFC in support of certification. This effort has advanced the state of the art for analyzing PLI systems. Material and subscale testing are also being conducted in support of the certification effort. These activities are scheduled to continue through early 2017.

Another challenge addressed during the development and qualification of the motor concerned abnormal nozzle erosion. The second development motor experienced atypical erosion on the bottom portion of the Forward Nose Ring (FNR). This erosion was more severe than the erosion observed on previous motors. The third development motor was instrumented with 21 ultrasonic gauges to capture the timing and magnitude of the erosion. The erosion phenomenon was successfully captured by the ultrasonic gauges and occurred very early (~16-18 seconds) into the two-minute burn. Additional subscale motor testing and Computational Fluid Dynamics (CFD) analysis determined that motor sag caused by the horizontal motor orientation, which only occurs during static testing, worsened particle impingement. The mitigation efforts and design changes included a ply angle and material change in the FNR region as well

as an additional mid-span support system to reduce the sag and better simulate flight conditions. These changes were implemented on QM-1 and post-test evaluation of the nozzle revealed no abnormal erosion like what was seen on the two development motors.

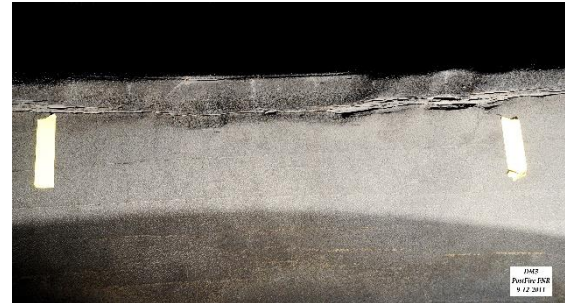


Figure 7: DM-3 post-test analysis revealed abnormal nozzle erosion on the FNR.

The booster office also resolved some challenges surrounding the capability of heritage hardware to meet the predicted loads of the SLS vehicle. As previously stated, the SLS forward skirt also houses the booster thrust takeout point to the core stage. This design is heritage from the SSP. The predicted SLS loads at the forward thrust post are greatly increased over what was seen during the SSP and testing was required to determine the load-bearing capability of the forward thrust post. Two forward skirt structural test articles were tested to failure, with the result that both tests determined the failure point was adequate. These two successful tests provided valuable data and a clear understanding of the structural response and repeatable failure mode of the forward skirt. In sum, testing and analysis showed that the heritage forward skirt design can be used for SLS, eliminating the need for redesign.

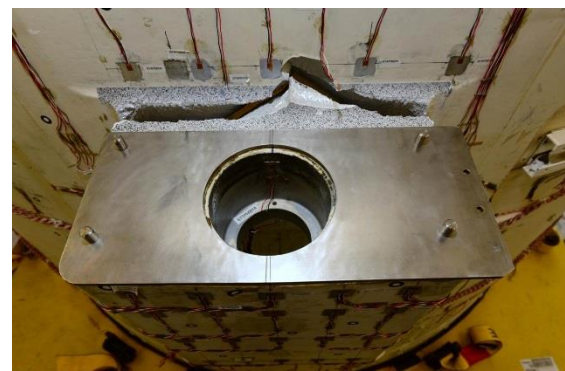


Figure 8: The forward skirt thrust post shown post-test.

In order for the vehicle to gain more performance, booster designers answered a challenge to move the booster-to-core attach location farther aft. The booster design was able to accommodate an approximately 6 m

(240 inch) move by rearranging the segments that comprise the aft motor segment. Relocating the aft attach point enables a longer core stage, which in turn provides additional core stage propellant capacity and vehicle payload capability.

## 5. PROGRESS ON EM-1 HARDWARE

The first SLS flight, EM-1, is scheduled for 2018 and manufacture of booster EM-1 hardware is well underway. Percent of completion varies from subsystem to subsystem. For example, some EM-1 hardware is complete and in storage, awaiting flight. On the other hand, some EM-1 hardware processing is not scheduled to begin until later this year.

Currently, eight of 10 EM-1 motor segments are being processed at OATK. The segments are at various stages of production, from refurbishment to insulation complete and awaiting cast. The first EM-1 segment cast was successfully completed in late April 2016. Casting operations will continue through early 2017 with final assembly following. Both motor igniters are complete and in storage, awaiting installation into the forward segment. The EM-1 nozzle structures are nearing completion with phenolic wrapping and machining underway. All 10 EM-1 motor segments and both nozzle AECs will ship via train to KSC in late 2017.



Figure 9: EM-1 LH booster aft dome refurbishment.

All four EM-1 BSMs are manufactured and in storage at OATK. The BSMs will ship to KSC later this year where they will be integrated into the forward and aft skirts.

As previously mentioned, the FSS LSC fabrication is underway for both qualification and EM-1 flight units. Qualification testing is scheduled to begin in 2017 with flight unit availability scheduled for later that year. Component refurbishment for the booster TVC system is scheduled to begin later this year with

the buildup and assembly of the EM-1 TVC scheduled for completion early next year. The TVCs will then be integrated into the aft skirts later next year, prior to ACO.

Avionics LRUs, cables, and battery designs are currently in qualification build and testing. The EM-1 LRUs fabrication is scheduled to be complete by March 2017 to support operational readiness of KSC facilities in the spring of 2017. The operational readiness will assess the ability of the KSC facilities to perform Assembly Checkout of the EM-1 forward and aft skirts once they are fully assembled and prior to stacking operations with the motor segments.

Refurbishment efforts are underway at KSC for both EM-1 aft skirts and will continue through early summer when assembly operations are scheduled to begin. As part of assembly, technicians will install BSMs into the EM-1 aft skirts later this year; TVC installation is scheduled for early 2017. Both forward skirts will be refurbished this summer and assembly will start later this year. Avionics LRU boxes will begin installation mid-2017 in preparation for ACO of the EM-1 forward and aft skirts.



Figure 10: The LH booster aft skirt slated for EM-1 undergoes refurbishment at KSC's Hangar AF.

## 6. CONCLUSION

SLS boosters have incorporated design improvements and are progressing well through qualification testing and analysis. Multiple issues and challenges have been discovered throughout the design development process. The resolutions that have been developed in response to these challenges have spawned an improved and more robust booster design. In addition, flight hardware build is progressing rapidly and is on schedule to support the first SLS flight in 2018.