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NASA's SPACE LAUNCH SYSTEM: Development and Progress

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Figure 1. Artist concept of SLS and mobile launcher rolling out of Kennedy Space Center (KSC) Vehicle Assembly Building.

ABSTRACT

NASA is embarked on a new era of space exploration that will lead to new capabilities, new destinations, and new discoveries by both human and robotic explorers. Today, the International Space Station (ISS) and robotic probes are yielding knowledge that will help make this exploration possible. NASA is developing both the Orion crew vehicle and the Space Launch System (SLS) (Figure 1), that will carry out a series of increasingly challenging missions leading to human exploration of Mars. This paper will discuss the development and progress on the SLS. The SLS architecture was designed to be safe, affordable, and sustainable. The current configuration is the result of literally thousands of trade studies involving cost, performance, mission requirements, and other metrics. The

initial configuration of SLS, designated Block 1, will launch a minimum of 70 metric tons (mT) (154,324 pounds) into low Earth orbit – significantly greater capability than any current launch vehicle. It is designed to evolve to a capability of 130 mT (286,601 pounds) through the use of upgraded main engines, advanced boosters, and a new upper stage. With more payload mass and volume capability than any existing rocket, SLS offers mission planners larger payloads, faster trip times, simpler design, shorter design cycles, and greater opportunity for mission success. Since the program was officially created in fall 2011, it has made significant progress toward launch readiness in 2018. Every major element of SLS continued to make significant progress in 2015. Engineers fired Qualification Motor 1 (QM-1) in

March 2015 to test the 5-segment motor, including new insulation, joint, and propellant grain designs. More than 70 major components of test article and flight hardware for the Core Stage have been manufactured. Seven test firings have been completed with an RS-25 engine under SLS operating conditions. The test article for the Interim Cryogenic Propulsion Stage (ICPS) has also been completed. Major work continues in 2016 as the program continues both flight and development RS-25 engine testing, begins welding test article and flight core stage tanks, completes stage adapter manufacturing, and test fires the second booster qualification motor. This paper will discuss the program's key accomplishments to date and the challenging work ahead for what will be the world's most capable launch vehicle.

1. BACKGROUND

NASA has begun a new era of deep space exploration with a long-range goal of a human mission to Mars in the 2030s. Unlike NASA's last human deep space program, the Apollo Program lunar landings, Mars is a significantly greater challenge. While the Earth/Moon distance ranges from 356,500 km (221,500 miles) to 406,700 km (252,700 miles), the Earth/Mars distance ranges from 56 million km (33.9 million miles) to 401 million km (249 million miles). The implications for propulsion, trip time, human health, communications etc. are magnified accordingly. It requires new technologies and capabilities that demand a longer horizon than Apollo. NASA has developed a stepwise approach to the challenges, characterized as "Earth-dependent," "proving ground," and "Earth-independent." The Earth-dependent realm encompasses current International Space Station operations and the developing roles for commercial crew and cargo resupply. For the Proving Ground and Earth Independent regions in the lunar vicinity and beyond, new capabilities are required. NASA is building SLS and Orion as the foundational transportation capabilities needed for the crews and large payloads needed for those deep space regions. This paper will focus on SLS.

SLS makes prudent use of the United States' existing investments in its civilian space program – technologies facilities, and skilled, experience workforce. It was these investments that allowed the SLS Program to get off to a fast, affordable start and make steady progress.

SLS is not optimized for a single design metric. Rather, it represents a balance of future mission requirements, affordability, evolvability, and overall mission safety, reliability and risk. And the SLS mission is deep space exploration involving highly trained human explorers and their supplies, large one-of-a-kind payloads, and complex, challenging missions of high-visibility worldwide importance.

The design foundation for the future is the Block 1 configuration. Standing 98.2 meters (m) (322 feet) tall and weighing 2.6 million kilograms (kg) (5.75 million pounds) fully fueled, the Block 1 will launch a minimum of 70 mT into low Earth orbit – significantly greater capability than any current launch vehicle. The basic elements are the core stage, four RS-25 engines powered by liquid hydrogen (LH2) and liquid oxygen (LOX), and a pair of solid rocket boosters. Liftoff thrust is in excess of 3.6 million kg (8 million pounds). The engines and boosters are derived from space shuttle main propulsion. In fact, early SLS missions will use remaining engines and booster case hardware from the Space Shuttle Program. The upper stage for EM-1 will be the Interim Cryogenic Propulsion Stage (ICPS), derived from the existing Delta Cryogenic Second Stage (DCSS). It is powered by the Aerojet Rocketdyne RL-10 B-2 engine producing 24,750 pounds of thrust. Vehicle layout is shown in Figure 2.

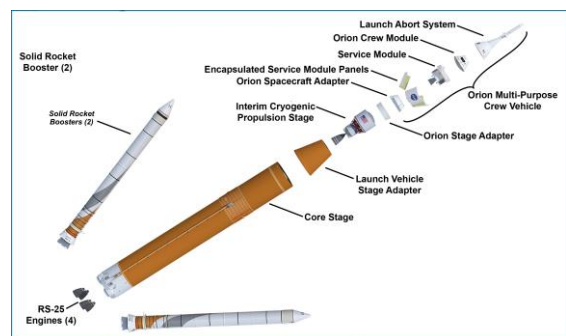


Figure 2. Expanded view of major SLS components.

The first SLS mission will be Exploration Mission 1 (EM-1). Scheduled for late 2018, EM-1 will serve as an initial test of the SLS, ground and mission infrastructure, and the first deep space test of the Orion crew vehicle, which will be launched farther into space than a human spacecraft has ever traveled. The flight will also accommodate 13 suitcase-sized secondary science payloads that will be launched from the Launch Vehicle Stage Adapter (LVSA) en route to the moon.

SLS is designed to evolve to a payload capability of 130 mT through the use of upgraded main engines, advanced boosters, and a new upper stage. SLS' unprecedented payload mass and volume offer mission planners larger payloads, faster trip times, simpler design, shorter design cycles, and greater opportunity for mission success.

The SLS Program was officially activated in 2011 at NASA's Marshall Space Flight Center, in Huntsville, Alabama. Since that time, the nationwide SLS government/industry team has made significant progress. Completing Critical Design Review (CDR) in 2015, the program now has qualification and flight hardware for every element. The following pages will touch on the major accomplishments to date and the work ahead in 2016.

2. CORE STAGE

The SLS core stage is designed and manufactured by the Boeing Company. The stage was designed around the existing RS-25 and solid rocket booster designs inherited from the Shuttle Program. It will be the largest stage in the world at 64.6 m (212 feet) tall and 8.3 m (27.6 feet) in diameter. It is designed to hold 144,000 kg (317,000 pounds) of LH2 and 820,000 kg (1.8 million pounds) of LOX. In addition to the propellant tanks, it consists of the engine section, intertank, and forward skirt. It supports the boosters through thrust structures in the intertank and engine sections. The stage also contains the flight avionics.

NASA's Michoud Assembly Facility, in New Orleans, Louisiana, previously used to build space shuttle external tanks and Saturn V stages, hosts core stage manufacturing. Likewise, stage testing will be conducted at NASA's Stennis Space Center, in Bay St. Louis, Mississippi, which also performed testing for shuttle and Saturn vehicles. Core stage manufacturing occupies a smaller factory footprint than the previous programs and is based around six major manufacturing tools: the Circumferential Dome Weld Tool, Gore Weld Tool, Enhanced Robotic Weld Tool (Figure 3), Vertical Weld Center, Segmented Ring Tool, and Vertical Assembly Center (VAC).



Figure 3. A technician inspects a core stage dome weld on the Gore Weld Tool at MAF, July 2015.

The VAC performs all the circumferential friction stir welds required to manufacture the liquid oxygen tanks, liquid hydrogen tanks, forward skirts, and engine sections for the core stage. Flight hardware welding is preceded by several earlier steps. Weld Confidence Articles (WCAs) are a series of "flight-like" structures that are welded, and then have sections of the welds cut out and tested to ensure properties are sufficient to build flight hardware. Structural Test Articles (STAs) follow the WCAs before flight article assembly begins.

Final assembly of major structures was held up for several months by an alignment issue with the VAC. The 170-foot-tall welding tool was discovered to be out of alignment roughly 5 centimeters (cm) (2 inches) from bottom to top of the tower. After evaluating the options, the tower was disassembled, corrected and reassembled. Welding resumed in late 2015 and progressed rapidly in 2016. (Figure 4)



Figure 4. SLS core stage liquid hydrogen tank weld confidence article, left, completed Welding on Vertical Assembly Center, February 2016, at Michoud Assembly Facility.

At the time this paper was written, the engine section, LH2 and LOX weld confidence articles

had completed welding on the VAC, and manufacturing is on track to complete all primary structural welding on structural test articles and the EM-1 core stage by the fall of 2016.

As welding was under way on the core stage, crews at NASA's Marshall Center were building the structural test facilities for the LH2, LOX, engine section, intertank, and Integrated Spacecraft/Payload Elements (ISPE) test articles. The new test facilities are scheduled for completion by the end of calendar 2016. (Figure 5).



Figure 5. Top, LOX Test Stand 4697 under construction. Bottom. Outfitting under way on LH2 Test Stand 4693, early 2016.

Vehicle flight software is being developed in-house at the Marshall Center. Development marked a transition in early 2016 when the System Integration Test Facility- Development (SITF-D) facility was disassembled in early 2016 and replaced by the System Integration Test Facility- Qualification (SITF-Q).

3. RS-25 CORE STAGE ENGINE

Performance, affordability, and schedule led NASA to the RS-25 engine to power the SLS. Engine development is typically one of the most costly and difficult parts of developing a new launch vehicle. The RS-25 successfully powered the space shuttle for more than 30 years. It underwent no less than five significant upgrades to improve engine life and reliability. It has amassed more than a million seconds of ground test and in-flight hotfire time, and it remains the most powerful, efficient engine of its type in the world, producing more than 232,239 kg (512,000 pounds) of vacuum thrust at 109 percent of rated power. Significantly, SLS began with 16 flown RS-25 engines and two development engines to support the new program.

In 2015, SLS conducted seven hotfire tests using development engine #0525 at Stennis Space Center. Total test time was more than 3,700 seconds. Test objectives included operating the engine under SLS performance requirements and operating environments. The LOX inlet temperature and pressure in the SLS application due to engine and tank positions and higher acceleration, as well as pre-launch engine conditioning procedure. Testing also supported development of a new Engine Control Unit (ECU), controller software, nozzle insulation needed for the higher base heating environment, and establishing a performance baseline for the refurbished A-1 test stand, including the new thrust measurement system.

Engine hotfire testing at the Stennis continued in 2016 with Engine #2059, a flown engine that will be part of the Exploration Mission 2 (EM-2) engine cluster. (Figure 6). The test provided a baseline for calibrating the A-1 stand using a well-characterized flight engine. It also was a green run of the engine's high pressure fuel turbopump and supported ongoing ECU development. Test objectives were met, and further testing was not required. Development Engine #0528 will replace #2059 in the test stand in 2016 for three more tests that will

support continued engine adaptation objectives, as well as green running new flight ECUs.

SLS also began working with Aerojet Rocketdyne on development of an expendable, more affordable version of the RS-25 and re-establishing the vendor base for future missions. The new engines will be certified to operate at 111 percent of rated thrust, a level tested but not flight certified during the Space Shuttle Program.



Figure 6. Top, EM-2 flight engine 2059 test fired at Stennis Space Center. Bottom, close-up showing engine operation.

4. 5-SEGMENT SOLID ROCKET BOOSTER

The solid rocket boosters, manufactured by Orbital ATK, provide most of the SLS liftoff thrust. Each booster measures 54 meters (177 feet) long and produces 1.6 million kg (3.6 million pounds) of thrust.

The booster design is based on the shuttle four-segment motor, and shuttle-era case hardware is available to support several SLS flights. However, the SLS design adds a fifth propellant segment, yielding 20 percent more thrust. Parachutes, flotation and other recovery hardware were removed to increase performance and make the boosters expendable. The motor features a new asbestos-free case insulation, new booster avionics, and a new grain design to fit the SLS ascent profile. The exhaust nozzle has been modified to fit the greater thrust. New avionics hardware replaces the shuttle-era avionics. Manufacturing processes have been streamlined through value stream mapping to improve affordability.

The five segment motor design has been hot-fired four times since 2009, pre-dating the SLS program. The most recent test, Qualification Motor 1 (QM-1) was conducted in March 2015 at the company's Provo, Utah, test facilities. The motor was heated to a mean bulk temperature of 32 degrees Celsius (90 degrees Fahrenheit) to verify environmental conditions. The next test, QM-2, is planned for mid-2016, and it will be a test of the booster's performance at a motor temperature of -1 degree Celsius (30 degrees F).

An unexpected result of the motor redesign was the discovery during x-ray inspection of the QM-1 segments of several voids and un-bonds in the aft motor segment insulation and propellant. The investigation that followed involved thousands of tests of material properties and various subscale test articles. The source of the issue was discovered to be the new insulation, which was off-gassing after insulation was applied to the case walls, and the warm solid propellant was poured into the segment. The bubbles led to the un-bonds between propellant and insulation and voids in the propellant itself, which could have created an overpressure in the motor. The solution was found to be the addition of a layer of adhesive already used to bond the insulation to the metal case and an added sheet of rubber insulation for structural integrity. X-ray inspection of a modified segment with the new insulation configuration showed that the segment was virtually defect-free. Post-test inspection showed no issues with the QM-1 motor, and the design change, as well as additional processes changes, were implemented for the QM-2 segments.

The fifth and final segment for the test was delivered to the Utah test site in early March 2016. Additionally, processing was under way on the motor case hardware for EM-1 at Orbital ATK's Utah and Kennedy Space Center facilities. OATK also delivered production simulation hardware to KSC to support booster hardware processing and support equipment checkout. (Figure 7).



Figure 7. Top, QM-2 aft segment delivery to test stand. Bottom, Pathfinder segment and cover placed on railcar for delivery to KSC.

5. ADDITIONAL DEVELOPMENT ACTIVITIES

Welding was completed for the Launch Vehicle Stage Adapter (LVSA) test article at Marshall Space Flight Center. (Figure 8). The LVSA will connect two major sections of the SLS – the core stage and the ICPS. When completed, the test hardware will be stacked with other structural test articles of the upper part of the rocket for ISPE structural testing in late 2016 at Marshall. In late 2015, United Launch Alliance (ULA) completed the ICPS test article for shipment to Marshall for structural testing. Fabrication is under way on the flight ICPS unit for EM-1.

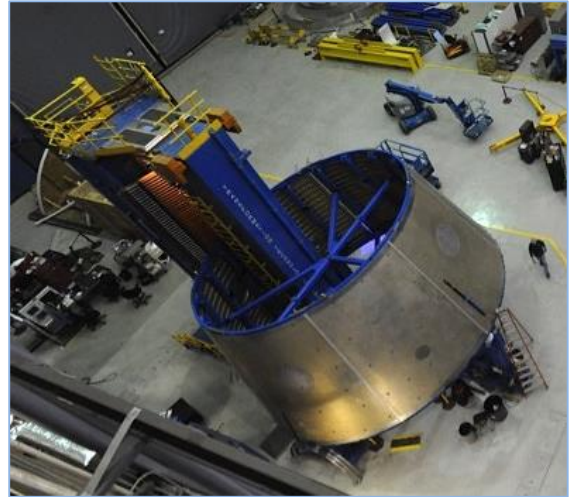


Figure 8. LVSA STA Forward and Aft Cones in MSFC Advanced Weld Facility prior to final welding.

Refurbishment of the B-2 stand at Stennis continued in 2015 with the addition of approximately one million pounds of structural steel to support the height and weight of the core stage as well as the weight of more than 733,000 gallons of LH2 and LOX and the force of the four-engine stage firing during green run testing of the EM-1 core stage. (Figure 9). The work also included complete renovation of the stand's plumbing, electrical, and other systems.

The Pegasus barge was delivered to Stennis in 2015 after the former shuttle external tank barge was cut apart and a new section added to increase the total length from 260 feet to 310 feet to support the larger core stage. (Figure 9). The expansion will allow Pegasus to ship core stage propellant tanks and other components to Marshall and Stennis for testing and ultimately to Kennedy Space Center for launch.

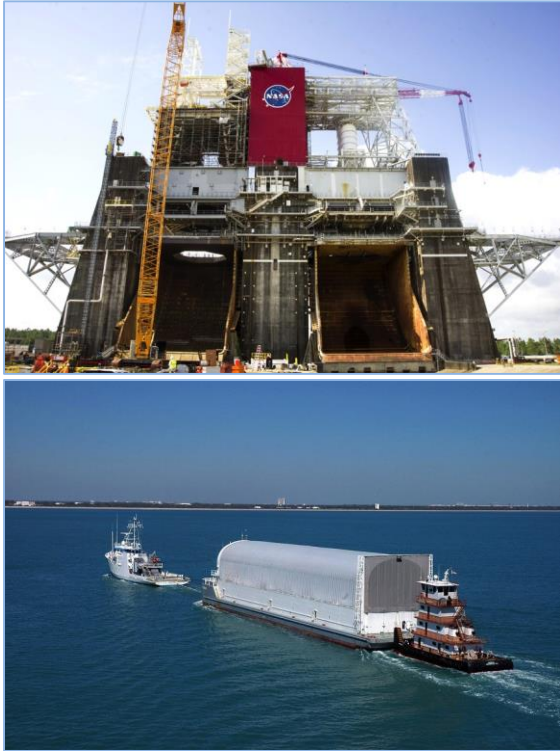


Figure 9. Top, Renovation work on the B-2 test stand at Stennis Space Center. Bottom, The lengthened Pegasus barge.

NASA and Boeing began development of an Exploration Upper Stage (EUS) with plans for a preliminary design review in late calendar year 2016. (Figure 10). The EUS will be powered by a cluster of four RL-10-C-3 LH₂/LOX engines, each producing more than 10,432 kg (23,000 pounds) of thrust in comparison to the ICPS single RL-10 B-2 producing more than 10,886 kg (24,000 pounds) thrust.



Figure 10. Artist concept of Orion and EUS stage departing Earth orbit.

6. CONCLUSION

SLS will be the world's most powerful, versatile, and capable launch vehicle for meeting the unprecedented challenges of deep space exploration. Manufacturing is underway on every major element. Work also is concurrently underway on the Orion crew vehicle and SLS launch facilities at Kennedy Space Center. When complete, SLS will open a new era of beyond-Earth human exploration, major new capabilities for robotic exploration, and scientific discovery for humanity