67th International Astronautical Congress, Sept. 26-30, 2016, Guadalajara, Mexico
Session D2.1: Launch Vehicles in Service or in Development

IAC-16-D2.1

STATUS OF NASA'S SPACE LAUNCH SYSTEM

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Abstract

NASA's Space Launch System (SLS) continued to make significant progress in 2015 and 2016, completing hardware and testing that brings NASA closer to a new era of deep space exploration. Programmatically, SLS completed Critical Design Review (CDR) in 2015. A team of independent reviewers concluded that the vehicle design is technically and programmatically ready to move to Design Certification Review (DCR) and launch readiness in 2018. Just five years after program start, every major element has amassed development and flight hardware and completed key tests that will lead to an accelerated pace of manufacturing and testing in 2016 and 2017. Key to SLS' rapid progress has been the use of existing technologies adapted to the new launch vehicle. The existing fleet of RS-25 engines is undergoing adaptation tests to prove it can meet SLS requirements and environments with minimal change. The four-segment shuttle-era booster has been modified and updated with a fifth propellant segment, new insulation, and new avionics. The Interim Cryogenic Upper Stage is a modified version of an existing upper stage. The first Block I SLS configuration will launch a minimum of 70 metric tons (t) of payload to low Earth orbit (LEO). The vehicle architecture has a clear evolutionary path to more than 100t and, ultimately, to 130t. Among the program's major 2015-2016 accomplishments were two booster qualification hotfire tests, a series of RS-25 adaptation hotfire tests, manufacturing of most of the major components for both core stage test articles and first flight tank, delivery of the Pegasus core stage barge, and the upper stage simulator. Renovations to the B-2 test stand for stage green run testing was completed at NASA Stennis Space Center. This year will see the completion of welding for all qualification and flight EM-1 core stage components and testing of flight avionics, completion of core stage structural test stands, casting of the EM-1 solid rocket motors, additional testing of RS-25 engines and flight engine controllers This paper will discuss these and other technical and programmatic successes and challenges over the past year and provide a preview of work ahead before the first flight of this new capability.

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." [1] These regions are shown in Figure 1 summarizing NASA's human and robotic Mars exploration plans. 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 for those deep space regions. This paper will focus on SLS.

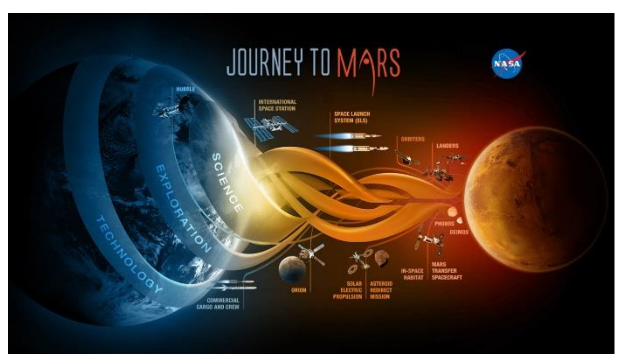

Figure 1. Graphic representation of NASA's Mars exploration plans.

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 t 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.

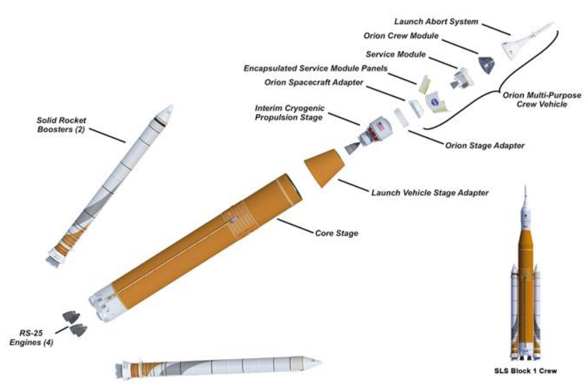

Figure 2. Block 1Expanded view of major SLS components.

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 briefcase-sized secondary science payloads that will be launched from the Orion Spacecraft Adapter (OSA) en route to the moon.

SLS is designed to evolve to a payload capability of 130 t 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. This evolutionary path is shown in Figure 3.

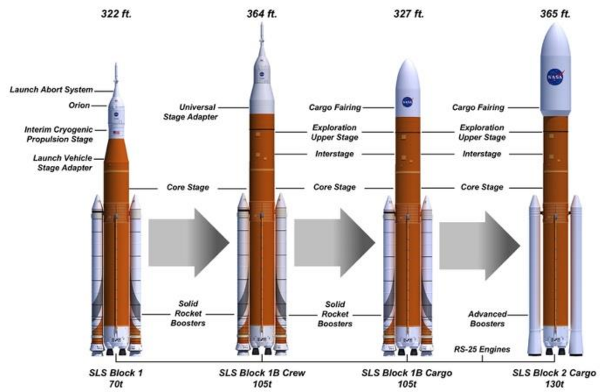

Figure 3. SLS evolutionary path.

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 (Fig. 4), Enhanced Robotic Weld Tool, Vertical Weld Center, Segmented Ring Tool, and Vertical Assembly Center (VAC).

Figure 4. 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. [2] 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, beginning with “weld confidence articles” (WCAs) for the engine section, LH2 tank (Fig. 5) and LOX tank.

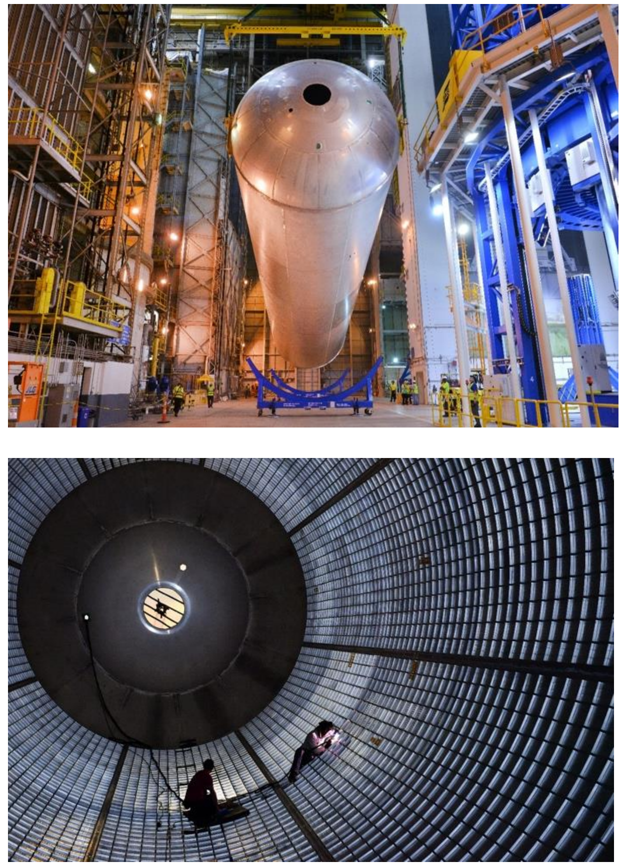

Figure 5. Completed LH2 test article, top, and welders completing complete plug welds on the test article, bottom, in August 2016 at Michoud Assembly Facility.

At the time this paper was written, welding had also been completed on the engine section and LH2 qualification articles, and work on the LH2 tank for the first launch was under way. [3] Production was on track to complete all primary structural welding on remaining structural test articles and the EM-1 core stage components in calendar 2016.

As welding was under way on the core stage, crews at NASA’s Marshall Center were building the structural test facilities and equipment for the LH2, LOX, engine section, intertank, and Integrated Spacecraft/Payload Elements (ISPE) test articles. [4] The new test facilities are scheduled for completion by the end of calendar 2016. (Fig. 6).

Figure 6. LH2 Test Stand 4697, top, and LOX Test Stand 4693, bottom.

Vehicle flight software is being developed in-house at the Marshall Center. [5] 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). (Fig. 7). The facility enables NASA to test SLS development and qualification software and hardware, including simulated environments as well as interfaces with the Orion spacecraft and ground support systems.

Figure 7. SLS Integrated Avionics Test Facility at Marshall Space Flight Center.

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 among the most powerful, efficient engines of its type in the world, producing more than 232,239 kg (512,000 pounds) of vacuum thrust at 109 percent of rated power. SLS began with 16 heritage 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. Engine LOX inlet temperature and pressure conditions are higher in the SLS application due to relative 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 refurnished 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. (Fig. 8). The test provided a baseline for calibrating the A-1 stand using a well-characterized flight engine. It also served as a green run of the engine's high pressure fuel turbopump and supported ongoing ECU development. [6] Test objectives were met, and further testing was not required. Development Engine #0528 replaced #2059 in the test stand in 2016 for a series of six more engine tests by the end of the year that will support continued engine adaptation objectives, controller development, and green run of new flight ECUs. As of August 1, 2016, the SLS Program had successfully conducted 9 development engines tests totaling more than 4,500 seconds of hotfire time. The ECU green run series will continue into 2017. EM-2 engines 2062 and 2063 are also scheduled for green run hotfire testing.

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 8. EM-2 flight engine 2059 test fired at Stennis Space Center, March 2016.

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 kgf (3.6 million pounds) of maximum thrust.

The booster design is based on the shuttle four-segment motor, and heritage hardware is available to support several SLS flights. However, the SLS design adds a fifth propellant segment, yielding approximately 20 percent more thrust. Parachutes, flotation and other recovery hardware were removed to 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 accommodate 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 five times since 2009, pre-dating the SLS program. The motor has undergone two full-scale qualification hotfire tests under SLS. An unexpected result of the motor redesign was the discovery of propellant/liner defects during x-ray inspection of the Qualification Motor-1(QM-1) segments. These defects consisted of several propellant voids and un-bonds at the propellant-to-liner bond line in the aft motor segment. The investigation that followed involved thousands of tests of material properties and various subscale test articles, and even some full-scale articles. The source of the issue was discovered to be the new insulation, which was outgassing volatiles into the propellant during the cast and cure processes. The solution was found to be the addition of a barrier that would not allow volatiles to permeate into the propellant. The QM-1 aft segment and all QM-2 segments incorporated the barrier design and were successfully static tested.

The Qualification Motor 1 (QM-1) test was conducted in March 2015 at the company's Promontory, Utah, test facilities. The motor was heated to a mean bulk temperature of 32 degrees Celsius (90 degrees Fahrenheit) to verify performance at the higher end of its operating range. Post-test inspection showed the QM-1 motor performed as expected, and the design change as well as additional process changes, were implemented for the QM-2 motor.

The QM-2 test occurred in June 2016. (Fig. 9) The motor was conditioned to a temperature of 4 degrees Celsius (40 degrees F), the lower end of its operating requirement. The two-minute firing provided NASA with critical data on 82 qualification objectives that will support certification of the booster for flight. Full data evaluation will take about a year, but preliminary results indicate the motor performed as expected, as measured by more than 500 instrumentation channels. Motor disassembly was under way as this paper was in preparation.

EM-1 booster flight hardware is underway at Orbital ATK in Utah and at NASA Kennedy Space Center in Florida. Aft skirt refurbishment is ongoing at KSC, with plans to begin forward skirt refurbishment in October 2016. Motor stacking and booster assembly operations will take place at KSC.

Figure 9. QM-2 motor firing in June 2016

5. Additional Development Activities

Welding was completed in June for the Launch Vehicle Stage Adapter (LVSA) test article at Marshall Space Flight Center. (Fig. 10 top). [7] 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. (Fig. 10 bottom) Fabrication is under way on the flight ICPS unit for EM-1. [8]

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. (Fig. 11 top). 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. (Fig. 11 bottom). 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 10. Completed LVSA structural test article at Marshall Space Flight Center, top, and ICPS test article arrives at Marshall, bottom.

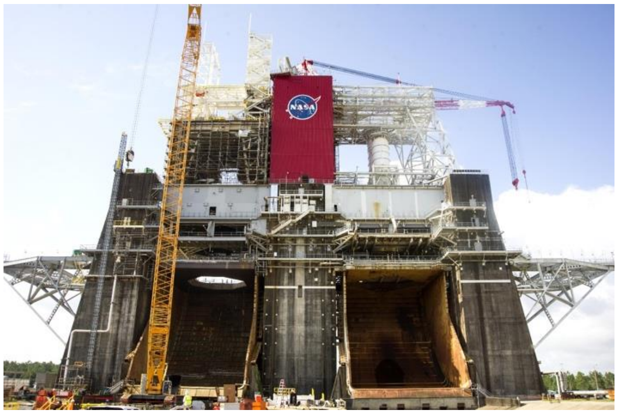

Figure 11. Renovation work on the B-2 test stand at Stennis Space Center.

NASA and Boeing began development of an Exploration Upper Stage (EUS) with plans for a preliminary design review in late calendar year 2016. (Figure 12). 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.

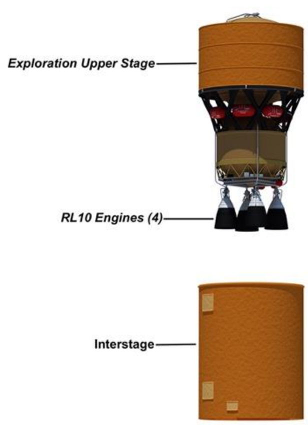

Figure 12. Artist concept of EUS showing major components.

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.

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