NASA's Space Launch System: First Mission Hardware Nears Completion

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Fig. 1. Artist rendering of EM-1 launch with SLS from Kennedy Space Center.

The Space Launch System (SLS) Program (Fig. 1) completed several significant production milestones in 2018 for its first mission and is poised for greater accomplishments in 2019. With manufacturing and hardware installation complete, Boeing completed the core stage forward join and shipped the liquid hydrogen tank structural test article to Marshall Space Flight Center for testing. The core stage aft join and LOX tank STA are expected to be completed in 2019 on the way to final stage integration. The four EM-1 engines are poised for stage integration in 2019. The Launch Vehicle Stage Adapter completed outfitting at Marshall and will be shipped to Kennedy Space Center in 2019. All solid rocket motor segments for the EM-1 boosters are cast, inspected and ready for shipment to KSC. The Program continues to work toward first launch of the nation's new super heavy lif 2020. SLS is designed, engineered and tested to launch the most challenging exploration missions, minimizing risk and providing the greatest opportunity for mission success and scientific discovery. This paper will discuss the technical and programmatic successes and challenges of the past year and look ahead to plans for 2019.

I. Introduction

NASA is returning to the Moon, not to repeat the Apollo Program explorations, but to build on them, establishing a permanent presence in cislunar space, developing the technologies and the operational experience necessary for successful deep space exploration. NASA's current plans are based on Space Po, issued in 2017, which

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requires the agency to ñ*lead innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other desti*nations.ò

NASAôs path for moving humanity into the solar syste... build a ... infrastructure that will make deep space accessible to all humanity. IT will develop incremental capabilities during human lunar expeditions that will inform future missions, deeper into the solar system. It will expand the near-Earth economy to establish a sustainable presence in deep space similar to the current low-Earth orbit economy. Finally, NASA will provide initial ñbackboneò ...tation system augmented with commercial transportation. Among the agencyôs strategic principles guiding this effort ... buildup, architecture openness and resilience, global collaboration and leadership, technology pull and push, and continuity of human space flight.

This new effort will build on NASAôs existing human ... International Space Station, commercial cargo and crew programs and long-standing collaborative partnerships with international space programs. NASA is developing the deep space transportation system required to support such a long-term vision with the Space Launch System (SLS), the Orion crew spacecraft, and the Exploration Ground Systems (EGS) necessary to integrate and launch SLS and Orion.

NASA has initiated plans for a ñGatewayò outpost in ... (Fig. 2). Gateway will be a human-tended outpost that will be supported by commercial and international partners. It will help advance lunar exploration and develop the technologies and operations necessary to continue exploration of the solar system.

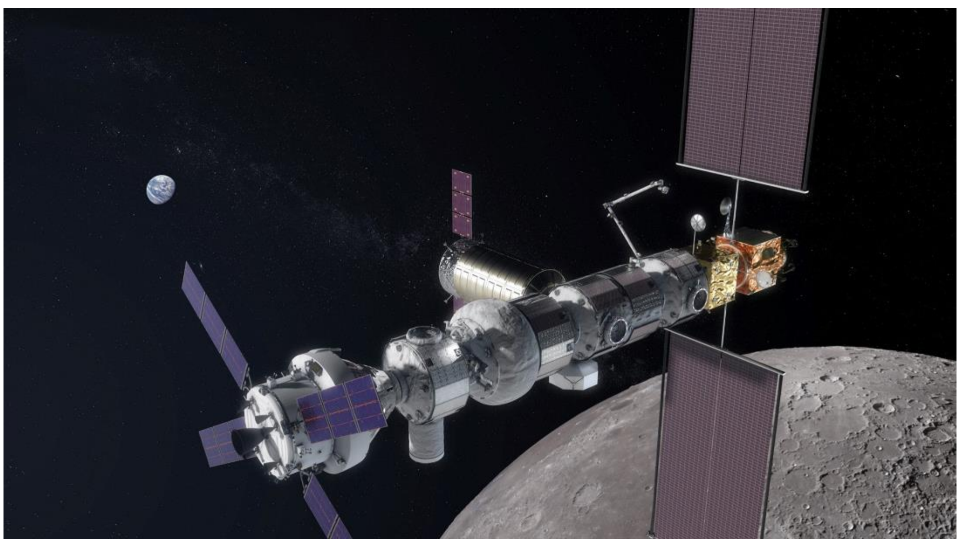

Fig. 2. Artist concept of the Gateway outpost at the Moon.

Gateway and supporting NASA and industry transportation provide for a more long-term sustainable architecture than the lunar surface-direct, Apollo Program-style access of the 1960s. Gateway enables reusable lunar systems, long-term multiple mission capability, initial refueling capabilities necessary in the future, robotic and human lunar vehicle checkout, maintenance and operations, increased international and commercial opportunities, longer-duration surface missions, an in-space platform for long-duration science, interoperability standards/open architecture, and a testing ground for Mars exploration.

No other existing launch vehicle can carry as much mass or volume to the Moon as SLS, reducing payload complexity and mission risk. SLS is the only vehicle that can take Orion to the moon ï in addition to a major-ñco-manifestedò payload including Gateway hardware. And cu... from the start to carry human crews.

SLS is critical to the success of Gateway and the entire cislunar architecture. Its first mission, Exploration Mission 1 (EM-1) will send an un-crewed Orion spacecraft into a near-lunar orbit. The EM-2 mission will follow a similar trajectory, this time with a human crew. Following these precursor missions, EM-3 will send a crewed Orion and a U.S. utilization module to the moon to rendezvous and dock with a power and propulsion element for Gateway launched earlier by a commercial un-crewed rocket. On future missions to the Gateway, SLS will transport Orion crews co-manifested with U.S. and international building block modules for Gateway as shown in the notional manifest in Fig. 3

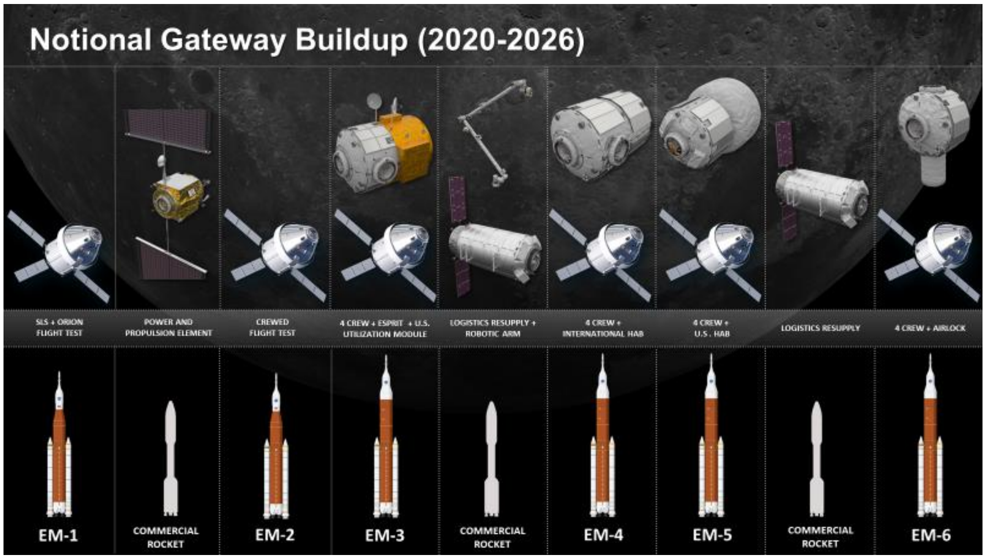

Fig. 3. Artist concept of the Gateway outpost at the Moon.

Additionally, it has the versatility to support robotic as well as human missions. It can send larger probes to the solar systemôs gas giants and their satellites, cutti exploration than existing launchers. The following sections will discuss the SLS design, accomplishments to date and the challenges ahead for SLS on its way to the launch pad.

II. The SLS Design

The SLS design emerged from hundreds of configurations analyzed against a range of missions. Figures of merit also considered in addition to mission capture were safety, reliability, and both design and architecture cost. It also leverages more than five decades of spaceflight knowle -skilled technical workforce. SLS is not one vehicle but an evolutionary capability designed to evolve naturally through block upgrades as exploration missions become more challenging. The SLS evolutionary path is shown in Figure 4.

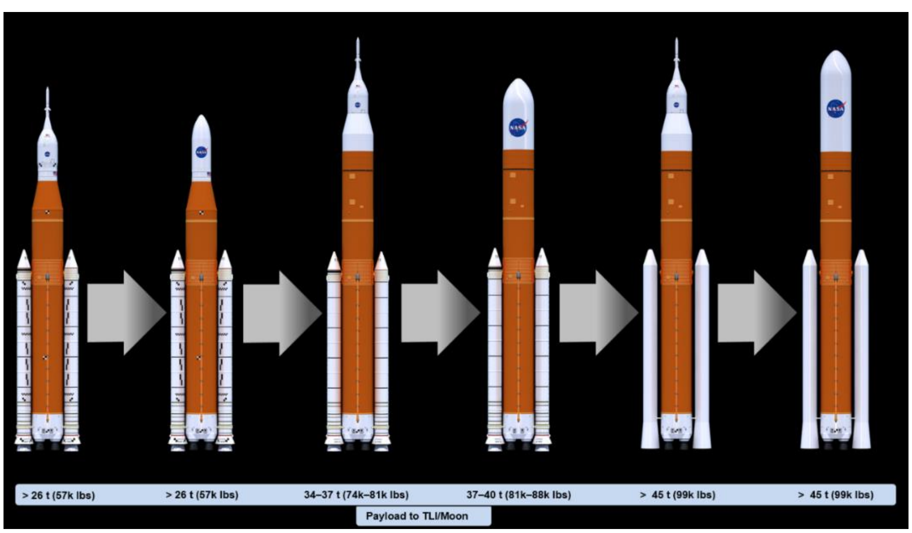

Fig. 3: The SLS vehicle evolution path illustrating the increasing mass and volume capability.

The initial Block 1 configuration will provide more than 26 metric tons (t) of payload mass to trans-lunar injection (TLI), more than any current launch vehicle. Payload mass will grow to 34-40 t to TLI in the Block 1B configuration, and the penultimate configuration, Block 2, will lift more than 45 t to TLI. Payload volume for the cargo configurations will increase from more than 200 cubic meters (m^3) to more than 900 m^3. Unique to SLS, Block 1B and Block 2 configurations will deliver in a single mission the crewed Orion spacecraft plus large systems such as habitats needed for living and working in deep space as co-manifested payloads.

Critical to that evolutionary capability is propulsion. Propulsion is considered the most challenging part of any launch vehicle design. SLS is built around the most powerful and proven propulsion systems in the world, updated for performance and affordability. Main propulsion is provided by the space shuttle-heritage RS-25 engine and solid rocket booster. The program starts with 14 flown and 2 new engines from the shuttle program and a new 5-segment booster design based on the shuttle 4-segment design. Upper stage propulsion initially will be provided by a modified Delta rocket commercial stage powered by an RL10 engine, with plans for new stage powered by four RL10 engines.

NASAôs plan to evolve SLS has been modified to supp -term human and robotic exploration plans. Congress provided NASA $350 million to build a second Mobile Launcher (ML) for SLS designed to support the Block 1B configuration. The second ML for Block 1B allows NASA to accelerate the SLS launch schedule for the first three missions using Block 1 rockets and the first ML while the ML for Block 1B is under construction. NASA will fly the Block 1 configuration for the first three SLS missions and then switch to the Block 1B for later missions as described below:

- Exploration Mission-1 (EM-1) will be the first integrated test flight of the SLS and the un-crewed Orion, currently planned to launch in fiscal year 2020.
- Exploration Mission 2 (EM-2) will be the first crewed flight of SLS and Orion and will take humans farther into deep space than ever before, currently planned to launch in 2023.
- Additionally, under consideration for the second or third flight of SLS is its first science mission, launching the Europa Clipper robotic probe to investigate the habitability of Jupiter's icy moon Europa onboard an SLS Block 1 cargo vehicle.

The following sections will discuss progress to date on SLS manufacturing and testing, as well as related progress toward flight.

III. Program Status

The SLS Program is managed at NASAôs Marshall Space F (MSFC) in Huntsville, AL. Between 2017 and 2018, SLS moved from design and manufacturing into assembly, integration and testing. All major hardware components for the EM-1 core stage, engines, boosters, and in-space stage are structurally complete, and the first flight hardware has been delivered to KSC. Flight software is progressing through testing, and the SLS Engineering Support Center (SESC) at MSFC is conducting testing to ensure connectivity with other mission-related facilities around the country.

A. Liquid Engines

Four RS-25 engines, located in the base of the rocket each supply 512,000 pounds of vacuum thrust at 109 percent rated power. Manufactured by Aerojet Rocketdyne, they will operate for the roughly eight-minute trip to orbit. NASA selected the RS-25 engine, powered by liquid hydrogen (LH^2) and liquid oxygen (LOX), based on its power, known performance over 135 space shuttle missions including more than a million seconds of ground and flight operating time, and adaptability to the SLS mission. Sixteen engines from the shuttle program are available to power the first four SLS missions.

Unlike the shuttle program, the engines will not be reused. The program has restarted engine production with the goal of developing an expendable engine costing at least 30 percent less than the shuttle era engines. These engines will be certified to operate at 111 percent of the ori By updating manufacturing tools, eliminating many of the materials and processes associated with reusability, and employing new techniques such as additive manufacturing, the program is well on its way to achieving the cost reduction goal.

An ñadaptationò program using two development engines (SSC) demonstrated that the engines will meet requirements to operate effectively at the colder temperatures and higher inlet pressures of the SLS environment versus the shuttle environment. Hot fire testing continued in 2017 to gain confidence, green run two new engines and certify new state-of-the-art engine controllers and software. The four EM-1 engines and their controllers are currently at SSC

(MAF) when needed for integration with the core stage. Hot fire testing continues in 2018 in order to green run new controllers and test new components for the restart engines such as an additively-manufactured pogo accumulator and a new hot isostatic pressure (HIP) bonded main combustion chamber. (Fig. 4)

The four RS-25 engines for the EM-1 mission have completed processing and are awaiting shipment from SSC to MAF for EM-1 core stage integration. Processing is under way on the EM-2 flight set.

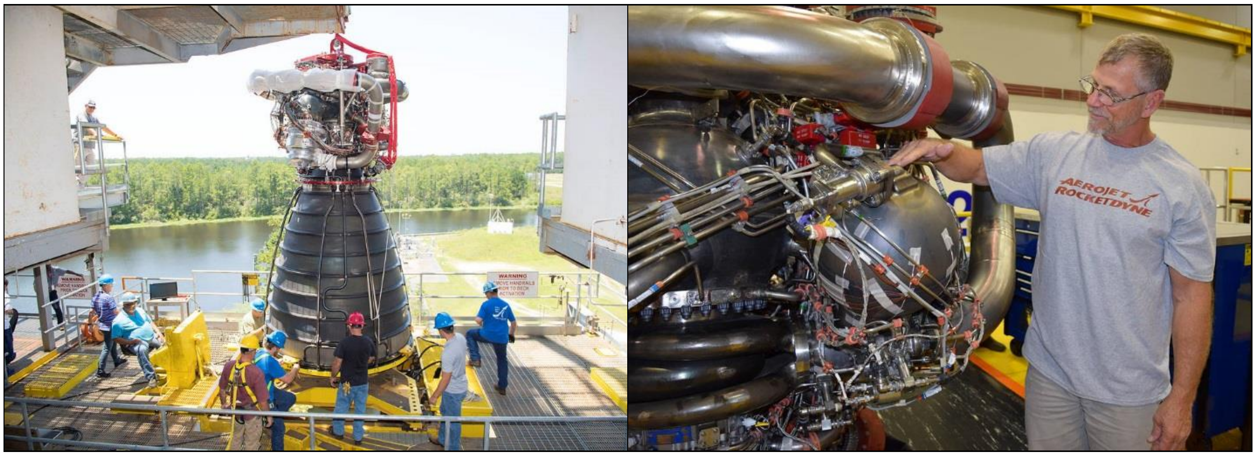

Fig. 4. RS-25 for 2018 test series is installed in the test stand at SSC, left. Additively-manufactured spherical pogo accumulator is shown in place on the engine, right.

B. Boosters

The five-segment solid rocket boosters for SLS are the largest ever made for flight, approximately 53.9 meters (m) tall and 3.6 m in diameter, and manufactured by Northrop Grumman. A pair of boosters for each SLS mission generates a total of approximately 7.2 million pounds of thrust, more than 75 percent of the vehicle's total thrust at liftoff. The boosters notably also carry the entire weight of the rocket on the launch pad. After burning roughly six tons of polybutadiene acrylonitrile (PBAN) propellant every second, the boosters burn out after roughly two minutes and are jettisoned. Unlike the shuttle boosters, they are not designed for recovery.

The five-segment motor is based on the four-segment space shuttle motor. Changes to the heritage design include additional propellant, a different propellant grain tailored for the SLS mission, asbestos-free case insulation, an updated avionics system, and improved non-destructive evaluation techniques to confirm flight readiness.

Seven of 10 motor segments for EM-1 mission are complete, and the last three segments are in final processing. Motor casting for EM-2 is underway. The EM-1 exhaust nozzle assemblies are complete. Igniter installation is under way. The forward assemblies for the EM-1 boosters are almost complete at KSC. Each forward assembly consists of the forward skirt, frustum, nose cone, avionics, and four solid fuel separation motors. Additionally, technicians at KSC are building up the thrust vector control (TVC) systems for installation in the aft skirts. Avionics are qualified at the system level and will be tested with core stage avionics in upcoming testing.

Fig. 5. Workers apply photogrammetric markings to a completed motor segment, left, and booster avionics undergoing qualification testing, right.

C. Stages

The SLS core stage is the only totally new design on the vehicle and it is the largest rocket stage in the world. Designed and manufactured by Boeing, the stage is 64.6 m tall and 8.4 m in diameter. It contains the four RS-25 engines, flight avionics, and propellant tanks and serves as the attach point for the boosters. The stage carries two million liters of LH^2 and 742,000 liters of LOX.

The stage is manufactured at Michoud as five main subassemblies, from bottom to top: engine section, LH^2 tank, intertank, LOX tank and forward skirt. Booster attach points are located on the engine section and the intertank. All subassemblies are welded, except the intertank, which is a bolted structure. Manufacturing is streamlined by the use of six major manufacturing tools: Circumferential Dome Weld Tool, Gore Weld Tool, Enhanced Robotic Weld Tool, Vertical Weld Center, Segmented Ring Tool and Vertical Assembly Center (VAC).

All major core stage hardware for structural testing and EM-1 is manufactured. The major sections are in various stages of cleaning, priming, thermal protection system (TPS) spraying, and installation of brackets, thrust structure, ducts, cabling, flight instrumentation and other equipment. (Fig. 6) The forward skirt is complete and its avionics have successfully been powered up. Workers are installing the TVC control system, pumps, manifolds, ducts and wiring harnesses in the engine section. The hydrogen tank has been proof tested, cleaned and primed. The oxygen tank was being sprayed with TPS foam.

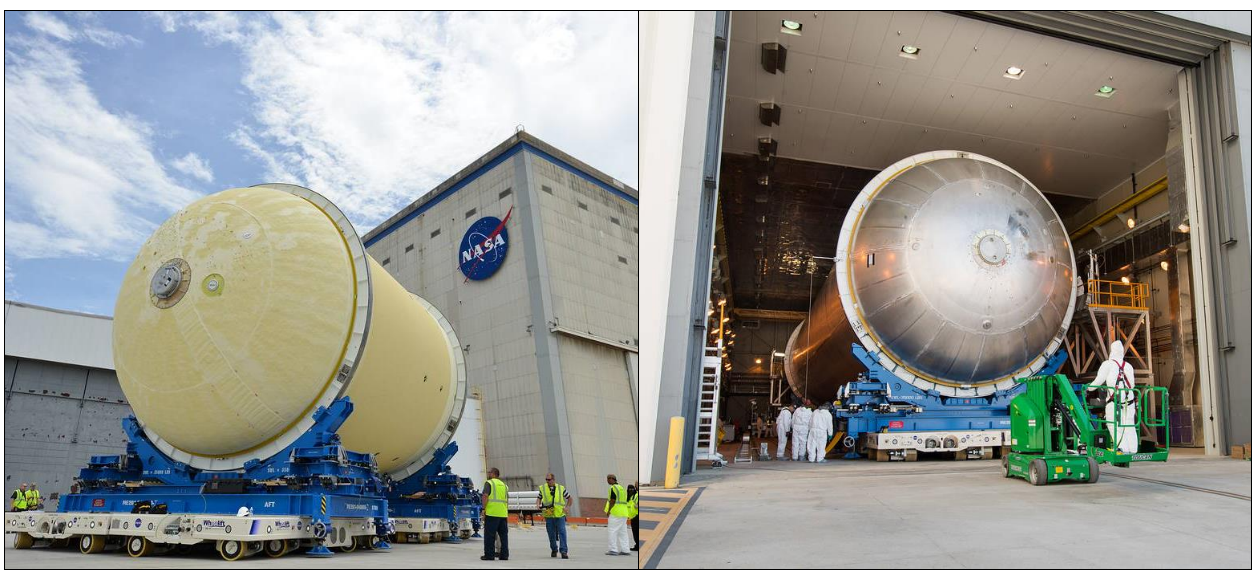

Fig. 6. EM-1 LOX tank moves after thermal protection foam application, left. The LH^2 tank moves into a manufacturing cell for priming and thermal protection foam, right.

Manufactured by Boeing and United Launch Alliance, the ICPS is based on the existing Delta Cryogenic Second Stage and modified with lengthened hydrogen tank, hydrazine bottles for attitude control, and related avionics modifications. The EM-1 ICPS was completed in 2017 and delivered to KSC for processing. (Fig. 8)

Fig. 8. The ICPS was the first EM-1 hardware turned over to KSC in April 2017.

The LVSA is structurally complete, and workers are installing actuators and mating the adapter to a frangible joint assembly. The OSA was completed and shipped to KSC in early 2018. It is ready for installation of 13 shoebox-sized CubeSat secondary payloads that will be deployed at sever ICPS trajectory. SLS is providing a secondary payload deployment system consisting of the avionics unit and cubesat mounting brackets.

Structural testing at Marshall in 2017 included completion of engine section testing, as well as testing the components of the in-space stage. The first major structural test completed was the Integrated Structural Test, which comprised the LVSA, frangible joint assembly, ICPS and OSA. The ICPS test article was pressurized with nonreactive liquid nitrogen rather than volatile LOX and LH^2. Twenty-eight hydraulic actuators subjected the stack to tension, bending, twisting, shear, and compression forces as high as 500,000 pounds of force during a series of more than 50 tests.

Fig. 9. The EM-1 OSA leaves MSFC for KSC in April 2018, left, while the EM-1 LVSA moves from TPS insulation to equipment installation at MSFC.

IV. Conclusion

NASA is leading the next steps in human exploration with missions to the Moon, where astronauts will build and begin testing the systems needed for challenging missions to other destinations, including Mars and beyond. SLS is vital to human and robotic exploration of deep space. It is built on the most powerful, proven propulsion systems in the world. Itôs unmatched mass and volume capability payload design, ground infrastructure, and in-space operations. The launch vehicle for the first mission is under construction and in testing now. Initial flight hardware has been delivered to KSC for processing. Manufacturing for the second launch vehicle is also under way. The planned first launch of SLS in fiscal year 2020 represents an important first step back into the solar system for human exploration. (Fig. 10) Along with the Orion crew vehicle and next-generation spaceport facilities, SLS will open an exciting new era of space exploration, bringing with it new knowledge and new discoveries.

Fig. 10. Artist rendering shows a wide-angle view of the lift-off of EM-1 from Kennedy Space Center.

Fig. 1. Artist concept of SLS and Orion on the mobile launcher at KSC.

Fig. 2: Expanded view of the SLS Block 1 configuration for EM-1.

The EM-1 mission provides a rare opportunity for these small satellites to reach deep space destinations, as most launch opportunities for CubeSats are limited to low-Earth orbit (LEO).