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NASA's Space Launch System Moves Into Testing and Integration

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Abstract

NASA's Space Launch System (SLS) has moved from design and manufacturing into testing and integration for its first flight in fiscal year 2020. In 2017, the NASA/industry team completed manufacturing of all major structural elements for the launch vehicle for Exploration Mission-1 (EM-1). This work included shipping the first major flight hardware element to the launch site. Current work is focused on the initial Block 1 variant of SLS, capable of launching more than 70 metric tons (t) to low Earth orbit (LEO). As the needs of the nation's deep space exploration program grow, SLS performance is designed to evolve to a payload mass of 130 t to LEO and up to 45 metric tons (t) to trans-lunar injection (TLI). The advantages of this mass – as well as volume – are critical to the entire exploration architecture for deep space exploration. They translate to greater capability, greater infrastructure and operational simplicity, less overall mission risk, and opportunities to accomplish unprecedented exploration and discovery.
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1. Introduction

More than 40 years has passed since humans last ventured into deep space. Since the last Apollo mission, human spaceflight has operated in low Earth orbit. With the end of the Space Shuttle Program in 2011, national leaders directed NASA to set its human spaceflight sights beyond low Earth orbit.

That policy was reemphasized in 2017 with National Space Policy Directive 1 calling for NASA to "*lead an 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 destinations.*"

NASA is working with domestic and international partners to solve the great challenges of living and working in space farther from Earth, and in the process creating new knowledge that benefits all of humanity and inspires the nation.

NASA's deep space architecture for human exploration consists of the Orion crew vehicle managed at Johnson Space Center, the Space Launch System (SLS), managed at Marshall Space Flight Center (MSFC), and Exploration Ground Systems at Kennedy Space Center (KSC).

The agency's overall exploration strategy (see Fig. 1) also encompasses the International Space Station, commercial and international partnerships in low Earth orbit, and robotic and human exploration of the Moon and Mars. The first commercial robotic landing on the Moon could come as early as 2019.

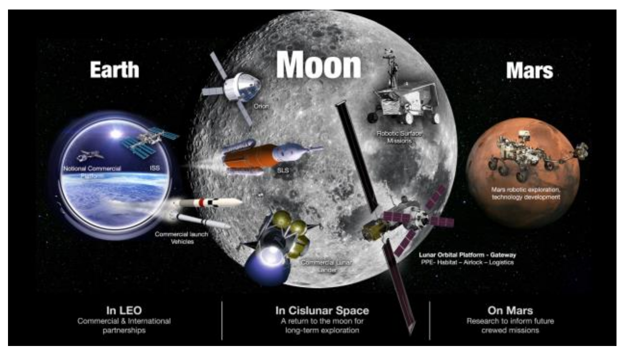

Fig. 1. NASA's exploration plans

Further, NASA has accelerated to 2022 plans to deliver the first element of a Gateway space station to the Moon. It will be a power and propulsion module, which will be followed by habitation, airlock and logistics modules. The Gateway will operate from a variety of lunar orbits, powered by electric propulsion and can operate in crew-tended or robotic modes. The Gateway can contribute to lunar surface activities and will have applications to farther destinations in the solar system, including Mars. It serves both a function as training and hardware maturation element, as well as operational element needed to send humans beyond low-Earth orbit (see Fig. 2).

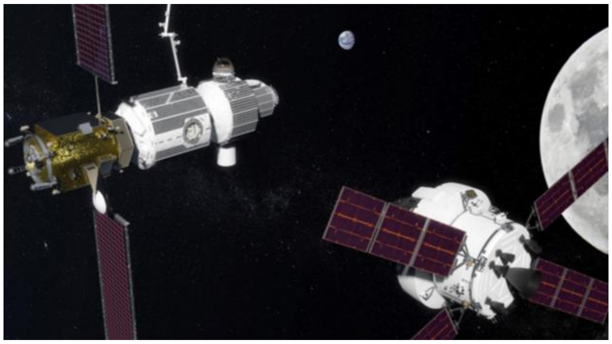

Fig. 2. Notional artist rendering of NASA's Gateway station and Orion crew vehicle

NASA is discussing components that International Space Station partners could provide to the Gateway. NASA and its partners will use the Gateway for deep space operations including missions to and on the Moon with decreasing reliance on Earth. Using lunar orbit, the agency will develop its exploration systems and gain the experience necessary to extend human presence farther into the solar system than ever before.

SLS is an enabling capability for this ambitious vision. This paper will discuss SLS development, progress to date and planned future work.

2. The SLS Design

SLS is a critical enabling capability to NASA's plans to expand exploration into the solar system. SLS is a family of heavy lift vehicles designed to evolve as mission requirements become more ambitious. SLS will carry more mass and volume than any launch vehicle since the Apollo Saturn V. There are multiple advantages to heavy lift for space exploration. It simplifies payload design, mission operations and logistics, and improves overall odds for mission success.

SLS benefits from 60 years of U.S. investment in spaceflight technologies, infrastructure and workforce. SLS is designed around proven propulsion systems with more than 30 years of flight experience with the Space Shuttle Program. The rocket is powered by four Aerojet Rocketdyne RS-25 engines fuelled by liquid hydrogen (LH^2) and liquid oxygen (LOX) – and two Northrop Grumman five-segment solid rocket boosters (SRBs) fuelled by polybutadiene acrylonitrile (PBAN). Both have benefitted from several upgrades to improve performance and safety during the shuttle program and during subsequent development. The Boeing-designed and built core stage serves as the backbone of the vehicle, containing propellant tanks, engines and attach points for the SRBs.

There are currently six configurations of the SLS, including three crew and three cargo versions, all sharing major systems (see Fig. 3), including the core stage. The Block 1 crew and cargo versions will use RS-25 engines operating at 109 percent thrust remaining from the shuttle program, a pair of five-segment SRBs, and a commercial off-the shelf (COTS) upper stage with one engine. Block 1B will use the last existing engines before switching to new-production RS-25s operating at 111 percent, five-segment boosters and a new upper stage with four engines that account for most of its greater TLI capability. Block 2 will increase performance with the development of an evolved booster design.

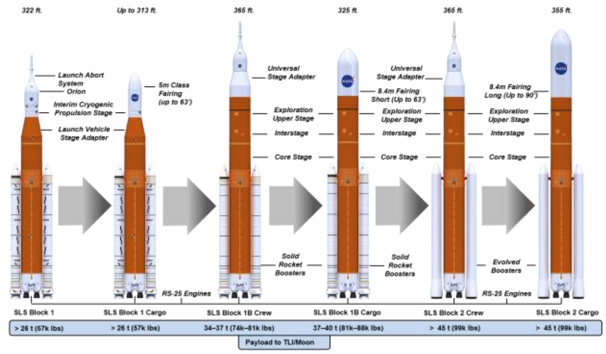

Fig. 3. SLS evolution showing various configurations

All have more payload mass and volume than existing launchers, most significantly payload mass to deep space. The Block 1 variant will have more than 26 t (57,320 lb) of payload to the Moon. Block 1B will have 34 to 40 t (74,957 – 88,185 lb) to the Moon, depending on crew or cargo configuration. Block 2 cargo will have more than 45 t (99,208 lb) payload to the Moon in crew and cargo configurations. SLS payload volume for the cargo configurations will increase from more than 200 cubic meters (m^3) to more than 900 m^3.

SLS will also be human-rated, reflecting additional safety measures and testing. This enables Block 1B, the lunar exploration workhorse variant, to deliver both crew and large cargo to TLI in a single launch.

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

3. Progress toward EM-1

Work now focused on the first launch vehicle for EM-1. The un-crewed EM-1 lunar mission will provide a critical first end-to-end test of materials, manufacturing, testing, integration, and launch and flight operations for SLS, as well as the Orion crew vehicle, and launch facilities. It will also launch 13 small cubesat secondary payloads.

The SLS Program is managed by NASA's Marshall Space Flight Center (MSFC) in Huntsville, AL. Between 2017 and 2018, the SLS Block 1 vehicle for the EM-1 mission moved from design and manufacturing into assembly, integration and testing (see Fig. 4). 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 for its role in SLS launches.

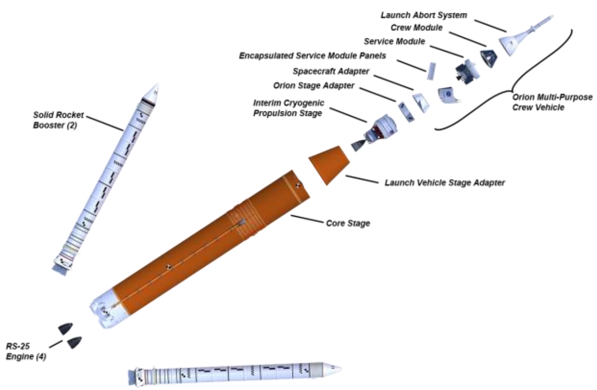

Fig. 4. SLS Block 1 configuration expanded view

3.1 Core Stage

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 Assembly Facility (MAF) 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, including the largest component, the LH^2 tank, which is more than 39 m long and will weigh more than 1,000 t fueled (see Fig. 5).

Fig. 5. Completed EM-1 LH^2 tank at Michoud Assembly Facility

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. The EM-1 forward skirt (see Fig. 6) became the first major piece of the core stage to reach completion and complete a powered test earlier this year.

Fig. 6. Completed EM-1 forward skirt

Workers are installing the thrust vector control (TVC) 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 (see Fig. 7).

Fig. 7. EM-1 LOX tank with TPS applied

The major components will be bolted together in two major subassemblies before being bolted into the completed stage. The forward section, consisting of the intertank, LOX tank and forward skirt is scheduled for mating in 2018. The aft section consists of the engine section, boat tail fairing, and LH^2 tank and is scheduled for completion in early 2019. Both joins will be made in vertical assembly cells, after which they will be lowered horizontally for final integration in spring 2019. The flight stage is then scheduled to be shipped to Stennis Space Center (SSC) for green run hot fire testing in 2019 before the trip to KSC for flight integration and launch.

A significant aspect of core stage development is full-scale structural testing at MSFC of the major subassemblies. New test stands or facilities were built for all sections except the forward skirt, which is tested by analysis, and are ready to support testing. All test articles are structurally complete. The first test article to arrive at MSFC was the engine section. Roughly 59 test cases were successfully completed in 2017 and early 2018, demonstrating the structure could support more than three million pounds of engine thrust loads and up to 750,000 pounds of loads created by the boosters. More than 3,000 channels of data provided data to validate the engine section design.

The intertank test article arrived at MSFC in early 2018 (see Fig. 8). The newly constructed test stand for the intertank test article uses about 100 actuators to impart up to roughly eight million pounds of force to simulate flight loads. The first load cases were underway at the time this paper was written. The planned test series includes 21 influence (50 percent loads) test cases, including one cryo test case, and 20 mechanical test cases. Limit (100 percent loads) and ultimate (140 percent loads) test cases are scheduled to be completed by the end of 2018.

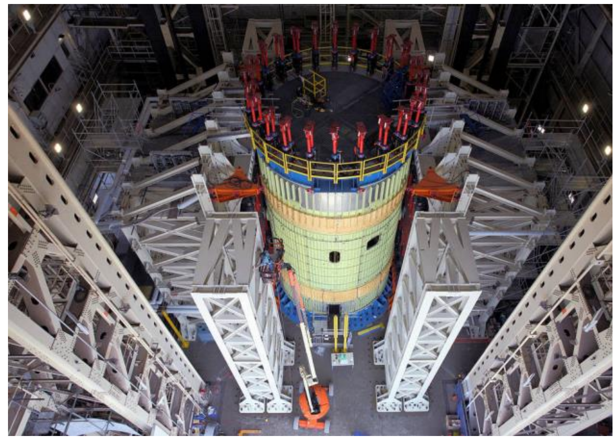

Fig. 8. Intertank test article at MSFC

The LH^2 and LOX test articles were in assembly at MAF at the time of writing and scheduled to be shipped to MSFC in 2018 to begin testing.

3.2 Five-segment Solid Rocket Booster

The five-segment SRB is based on the four-segment space shuttle booster. The five-segment SRBs for SLS are the largest ever made for flight, approximately 53.9 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 lift-off. The boosters notably also carry the entire weight of the rocket on the launch pad. After burning roughly 5.5 tons of PBAN solid propellant every second, the SRBs burn out after about two minutes and are jettisoned. Unlike the shuttle boosters, they are not designed for recovery.

Changes to the heritage booster 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. All 10 motor segments for EM-1 mission are complete (see Fig. 9).

Fig. 9. Technicians apply tracking markings to an EM-1 booster motor segment at Northrop Grumman

Motor casting for EM-2 is underway. 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 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.

3.3 RS-25 Main Engine

Like the boosters, the RS-25 engine was first developed for the space shuttle, and 16 engines from that program will power the first four SLS missions. Four engines, located in the base of the rocket each supply 512,000 pounds of vacuum thrust at 109 percent rated power versus the shuttle standard thrust of 104.5 percent. Manufactured by Aerojet Rocketdyne, they will operate for the entire eight-minute trip to orbit. SLS benefits from an extensive database of more than one million seconds of flight and ground test time, including 135 space shuttle 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 original engine's rated power, or roughly 521,000 pounds of thrust. 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.

To adapt the RS-25 to the SLS mission, the program is using two development engines for hot fire testing. The initial series was completed in 2016 at 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 awaiting shipment to MAF when needed for integration with the core stage. Hot fire testing continues in 2018 (see Fig. 10) 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. Processing is underway on the EM-2 flight set.

Fig. 10. Engine 0525 readied in July for new RS-25 hot fire test series at SSC

3.4 Upper Stage

The SLS upper stage is the Interim Cryogenic Propulsion Stage (ICPS), which will perform the TLI burn for the EM-1 mission. Built by Boeing and United Launch Alliance (ULA), the stage is based on the current Delta Cryogenic Second Stage modified by extending the LH^2 tank, adding hydrazine bottles for attitude control and minor avionics changes. The ICPS will operate for about 700 seconds. The EM-1 ICPS was completed in 2017 and delivered to KSC (see Fig. 11). It will remain in Space Station Processing Facility (SSPF) until needed for stacking.

Fig. 11. EM-1 ICPS at KSC

During launch, the ICPS will be protected by the Launch Vehicle Stage Adapter (LVSA). The Orion Stage Adapter (OSA) will connect the ICPS to the Orion crew vehicle's service module. The LVSA is structurally complete (see Fig. 12), and workers are installing actuators and mating the adapter to a frangible joint assembly. The LVSA is scheduled to ship to KSC on the Pegasus barge in late 2018.

Fig. 12. EM-1 LVSA at MSFC

The OSA was completed and shipped to KSC in early 2018 (see Fig. 13). The OSA will remain in the SSPF until the cubesat secondary payloads are integrated, then it will be stacked. It is ready for installation of 13 6U CubeSat secondary payloads that will be deployed at several "bus stops" along the ICPS disposal trajectory after Orion has separated from the upper stage during EM-1. SLS is providing a secondary payload deployment system consisting of the avionics unit and cubesat mounting brackets.

Fig. 13. EM-1 OSA at MSFC

The first major SLS structural test completed was the in-space stage in 2017. The Integrated Structural Test comprised the LVSA, frangible joint assembly, ICPS and OSA. The ICPS test article was pressurized with nonreactive 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.

4. SLS Missions Updated

Congress passed and the President signed a spending bill for the remainder of 2018 that provides 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.

SLS manufacturing was previously coordinated with plans to use a Block 1 crew vehicle for EM-1 and the Block 1B crew and cargo variants for subsequent missions until Block 2 becomes available. In 2018, NASA elected to use the Block 1 vehicle for the first three SLS missions as follows:

- EM-1 will be the first integrated test flight of the SLS and an 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 a Block 1 is its first science mission, launching the "Europa Clipper" robotic probe on a direct trajectory to investigate the habitability of Jupiter's icy moon Europa.

5. Conclusions

The launch vehicle for renewing human exploration of deep space has moved from development and manufacturing into integration and testing. The program continues to target a fiscal year 2020 rollout and launch (see Fig. 14). Initial flight hardware has been delivered to KSC for processing, and production of the second launch vehicle has begun. Along with the Orion crew vehicle and next-generation spaceport facilities, SLS will open an exciting new era of space exploration and discovery.

Fig. 14. EM-1 rollout artist concept

SLS is a generational asset critical to U.S. leadership in future human and robotic space exploration. SLS' unmatched capabilities of mass, volume and departure energy make it possible to safely and efficiently deliver components of NASA's Gateway outpost and future exploration systems. The Block 1 vehicle now in production is the foundation for more powerful and capable variants to come. Its unmatched capability will reduce the complexity, cost, and risk associated with payload design, ground infrastructure, and in-space operations. Based on proven propulsion systems and engineered for human flight, SLS will lead humanity's pioneering missions to the Moon. As explorers acquire the operational experience for longer missions, SLS will evolve to carry them safely to other destinations such as Mars.