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## NASA's Space Launch System Progress Report

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Fig. 1. Artist's rendering of SLS Block 1 on Mobile Launcher for Artemis I mission

### Abstract

NASA's Space Launch System (SLS) continues to achieve assembly and testing milestones on its way to the launch of the first human-rated spacecraft to the Moon since the Apollo Program. Major flight hardware for Artemis I (see Fig. 1), formerly known as Exploration Mission 1 (EM-1), is complete, including the liquid and solid main propulsion systems. The Artemis I core stage is fully assembled and engine integration and checkout is underway. Structural testing on the core stage engine and payload sections and intertank are complete. Liquid hydrogen tank structural testing is under way, and liquid oxygen tank structural testing will begin in fall 2019. Major structural components for the second and third flights are also in production; hardware has been fabricated for each element of the Artemis II vehicle. SLS and the Orion crew vehicle along with the Exploration Ground Systems (EGS) launch facilities at Kennedy Space Center are critical to the nation's plans to return to the Moon to stay in a measured, sustainable fashion. Lunar exploration will expand our understanding of Earth's formation, serve as a proving ground for technologies for pushing deeper into the solar system, and inspire a new generation. This paper will discuss details of 2018-2019 progress and the work ahead to ready SLS for launch.

**Keywords:** NASA, Space Launch System, Artemis I, Artemis II

## 1. Introduction

NASA is leading a sustainable return to the Moon with commercial and international partners to expand human presence into the solar system and bring back new knowledge and **opportunities**. The Moon is a natural stepping stone to the longer-term goal of human Mars. At the Moon, NASA will demonstrate technologies such as *in situ* resource use and pursue **commercial opportunities** needed for deeper space exploration.

Anchoring NASA's plans for deep space exploration are the Space Launch System (SLS), the Orion crew spacecraft and the Gateway outpost in lunar orbit, and Exploration Ground Systems (EGS) launch infrastructure at Kennedy Space Center (KSC).

Additionally, national Space Policy Directive 1 provides direction for NASA to more effectively enlist commercial and international partnerships to develop a sustainable presence on the Moon and beyond. Going forward to the Moon is part of a larger, sustainable exploration campaign with international and commercial partners. With the technologies, infrastructure and experience gained from the lunar missions, NASA will send robotic and human explorers to Mars.

In early 2019, NASA's lunar exploration program was given the formal name of Artemis [1]. In Greek mythology, Artemis is twin sister of Apollo and goddess of the Moon. The near-term goal of Artemis is to send American astronauts to the Moon by 2024 for a landing on the lunar South Pole. The agency continues to pursue all means necessary to meet that goal.

NASA's exploration campaign cuts across three strategic areas: low-Earth orbit, the Moon, and Mars and deeper into space. The initial Artemis missions (see Fig. 2) include:

- Artemis I: First flight test of SLS and Orion as an integrated system
- Artemis II: First flight of crew around the Moon aboard SLS and Orion
- Artemis III: First crew to the lunar surface (via a human landing system from the Gateway in lunar orbit)

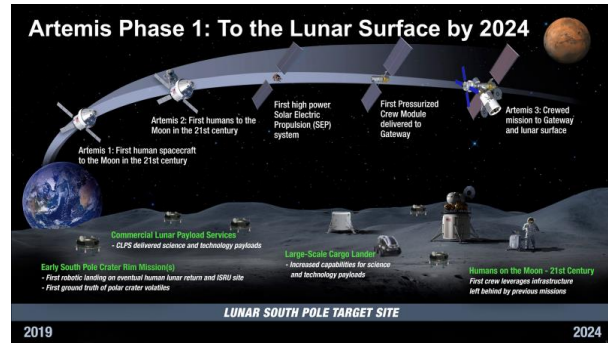


Fig. 2. Artemis missions leading to human lunar return

Gateway (see Fig. 3) [2] will serve as a command center and aggregation point for lunar missions. SLS will be capable of launching crews and cargo to the Gateway, while commercial vehicles send Gateway and lander components to be assembled. The initial Gateway comprises the minimum systems needed to support a 2024 human lunar landing. It will serve as a building block for future, expanded capabilities on and around the Moon and continuing to be a staging point for missions that allow astronauts to explore more parts of the lunar surface than ever before.

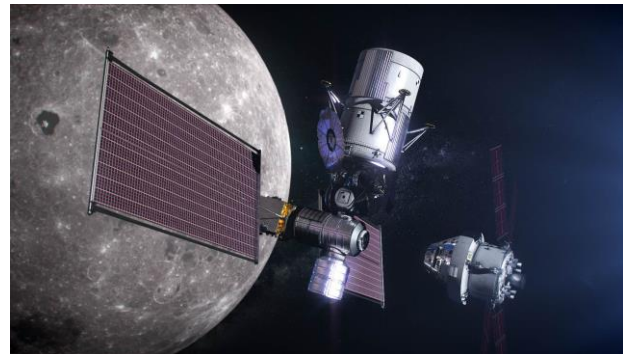


Fig. 3. Artist's concept of Orion docking with the initial Gateway configuration, and lunar lander

## 2. SLS Capability and Role

SLS is the world's most powerful rocket, and a critical enabling capability for the Artemis program's mission of establishing a sustainable human future in deep space. It is the only rocket built from the ground up to carry astronauts and one-of-a-kind exploration and science payloads farther and faster, providing game-changing benefits for space exploration.

SLS can deliver greater mass and volume with greater departure energy than commercial launch vehicles. SLS is also the only launcher designed to send a fully-equipped Orion with the European Service Module to the Moon. A much more robust spacecraft than the Apollo-era vehicles, Orion can accommodate up to six astronauts (four are expected to fly on Artemis II and III) and provide life support for up to 21 days.

In addition to transporting astronauts and large exploration cargo to the Moon and beyond, SLS’s unrivalled payload volume and departure energy make it a superior choice for the science community’s boldest missions – such as to Jupiter’s moons, the ice giants or even to interstellar space [3]

SLS’s mass and volume are significantly greater than any other current rocket – both to low Earth orbit (LEO) and to trans-lunar injection (TLI). There are several important benefits of the highly reliable SLS heavy-lift capability to the challenging lunar endeavor. The ability to carry large mass and volume reduces payload and operational complexity of the entire architecture. It saves time and money and increases chances for mission success.

The initial SLS Block 1 variant can transport 26 metric tons (t) to the Moon. With selected upgrades, SLS can evolve to much greater capability. The Block 1B configuration can be launch up to 40 t – 50 percent more mass and with an 8.4 m-diameter fairing -- twice the volume than existing rockets can provide. Relevant upgrades include replacement of the Block 1 upper stage, a modified Delta IV Heavy single-engine upper stage, with a more powerful four-engine Exploration Upper Stage (EUS). The ultimate version, SLS Block 2, can carry more than 45 t by replacing the current booster with a new advanced booster. (see Fig. 4)

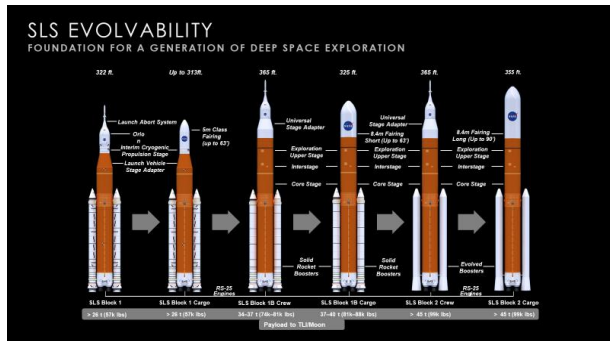


Fig. 4. SLS crew and cargo variants and commonalities

Because propulsion is typically the most expensive and time-consuming part of any new vehicle development, NASA chose powerful, proven space shuttle propulsion technology. All variants of SLS are powered by four RS-25 engines, manufactured by Aerojet Rocketdyne and each providing more than 500,000 pounds of vacuum thrust and powered by liquid hydrogen (LH<sub>2</sub>) and liquid oxygen (LOX). The SLS Program began with 16 engines from the shuttle program, including two new engines -- enough to support the first four SLS flights. The existing engines will operate at 109 percent of original rated thrust versus 104.5 percent used during shuttle launches.

More than 75 percent of the vehicle’s thrust for the first two minutes is provided by two five-segment solid rocket boosters with 3.6 million pounds of thrust each – 20 percent more than the shuttle heritage four-segment booster – and manufactured by Northrop Grumman. These boosters are based on the shuttle boosters, with the addition of a fifth motor segment, new avionics and new case insulation.

The Block I upper stage is the Interim Cryogenic Propulsion System (ICPS), based on an existing Delta rocket upper stage. It is powered by a single RL10 LOX/LH<sub>2</sub> engine, which provides more than 27,000 pounds of thrust.

For Block 1B and Block 2, the ICPS, built by United Launch Alliance (ULA), will be replaced by an EUS with 96,000 pounds of thrust provided by four RL10 engines. The EUS is currently under development by Boeing. For Block 2, a pair of advanced boosters would each provide more than five million pounds of thrust.

For all variants, the core stage will hold up to 537,000 gallons (2 million liters) of LH<sub>2</sub> and 196,000 gallons (742,000 liters) of LOX. The 212-foot tall stage is the tallest in the world and under contract to Boeing. The core stage is manufactured in five major sections – engine section/boat tail, LH<sub>2</sub> tank, intertank, LOX tank and forward skirt. It includes an avionics package that controls the vehicle until stage separation.

The core stage is topped with a Launch Vehicle Stage Adapter (LVSA) that partially encapsulates the ICPS and the Orion Stage Adapter (OSA) that connects the ICPS to Orion. Both are produced by Teledyne Brown Engineering. For Block 1B, the LVSA is replaced by a Universal Stage Adapter (USA) to enclose the larger EUS engine cluster. Both the OSA and USA have volume to accommodate CubeSat payloads. The Block 1 configuration is shown in Fig. 5.

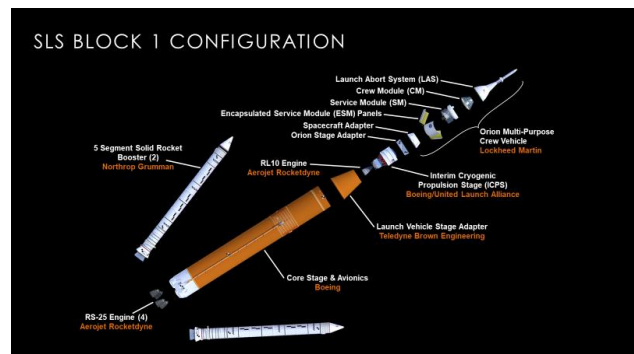


Fig. 5. Expanded view of Block 1 major components

### 3. SLS Progress

The SLS Program is in final testing, outfitting and assembly of the vehicle for the first SLS flight – Artemis I. Core stage structural components, boosters and engines for second and third flights are in various stages of production, testing and processing. This

section will provide highlights of vehicle manufacturing and testing progress.

### 3.1 Core Stage Manufacturing and Testing

With propulsion consisting largely of heritage hardware, the most challenging aspect of SLS development has been the core stage, the only all-new design of the SLS Program. SLS is in final testing, outfitting and assembly of the Artemis I core stage. Structural components for the core stage, LVSA OSA, boosters and engines for the second and third Artemis flights are also in production, processing and testing.

Boeing completed mating of the Core Stage 1 LH<sub>2</sub> and LOX tanks, intertank and forward skirt in mid-2019, while outfitting of the complex engine section was completed. Following a functional test of the engine section, it was mated with the rest of the core stage to reach its structural mate complete in mid-September. This marked completion of the Artemis I core stage itself (see Fig. 6). [4]



Fig. 6. Artemis I engine section and core stage mate

Engine integration of four RS-25 engines was pending as this paper was written and will continue into November before the stage undergoes final checkout and shipment to Stennis Space Center for green run testing, currently planned for December 2019.

Core stage structural qualification testing paralleled flight stage production and was 80 percent complete as of fall, 2019. The hydrogen tank test article test team at Marshall Space Flight Center (MSFC) is working through roughly 38 test cases, including margin expansion, collecting more than 2,900 channels of data. Primary influence testing is complete, as are the required green run test cases. (see Fig. 7) [5] Margin testing was scheduled to continue through October.



Fig. 7. LH<sub>2</sub> structural test article in test stand

The oxygen tank test article (see Fig. 8) was completing installation at MSFC with testing scheduled to begin in September. The test program includes approximately 24 load cases and collection of more than 2,600 channels of data.



Fig. 8. LOX structural test article during installation

These final two tests follow the Integrated Structural Test (IST) of the ICPS, Orion Stage Adapter and LVSA stack in 2017 with roughly 50 tests and 1,800 channels of data. Intertank structural testing finished in July 2018 with 21 influence, 18 limit, and two ultimate cases and one test-to-failure. The team collected some 2,800 channels of data on this structure, which carries the majority of the enormous thrust loads of the solid rocket boosters.

Boeing and Aerojet Rocketdyne worked collaboratively to complete three engine pathfinder installation and removal tests at Michoud Assembly

Facility (MAF). The teams have reviewed all 256 engine installation steps – 64 per engine – including procedures and approvals requiring installers to lean on flight hardware in the confined engine section. Checkouts following installation include developmental flight instrumentation (DFI) sensors, engine controller power-on testing and leak checks of 28 fluid interfaces between the engines and the core stage main propulsion system (MPS).

Notably, because of the angles and the access required for horizontal integration, one final connection per engine will have to wait until the stage is vertical in the B2 test stand at SSC. The hydrogen tank feed line on each engine low-pressure fuel pump will have to be secured to the hydrogen pre-burner valves on the core stage MPS while in the B2 stand.

Systems-level core stage avionics qualification testing was complete in May at MSFC. The Boeing Stage Controller test team recently began integrating the Stage Controller to the Systems Integration Test Facility-Qualification (SITFQ) ring in support of risk reduction testing for Stage Controller validation testing. This will be the first time the Stage Controller has been connected to non-simulation avionics equipment in this configuration. The test team will continue to add complexity in the connections in a phased approach. This work is in support of stage green run.

The core stage pathfinder, a simulator matching the dimensions and weight of a flight core stage, completed transportation lifts and transportation training at MAF in 2019 and moved to SSC in August 2019 for similar training (see Fig. 9). [6] The transportation team completed four horizontal-only de-integration/re-integration lift cycles using the Multi Purpose Transportation System (MPTS) and one pathfinder breakover to vertical insertion into the B2 stand. The team then performed the reverse operation back to the MPTS. It will be barged to KSC for launch site training.



Fig. 9. Core stage pathfinder at Stennis B2 stand

As Core Stage 1 assembly approaches completion, the multiple challenges encountered are worth mention as they relate to Core Stage 2 now in production. Many of the typical first-unit manufacturing issues are resolved. Manufacturing processes have been streamlined with lessons learned on Core Stage 1 and applied to Core Stage 2. The manufacturing team is benefiting from a steady stream of process improvements. Each step of production has been analyzed and optimized.

At Michoud, Core Stage 2 for Artemis II is under construction with the forward skirt, intertank and LOX tank structurally complete. Although SLS has prioritized its resources to completion of the Artemis I core stage – attenuating Artemis II core stage progress – the Artemis II core stage production schedule currently is averaging 50 percent improvement in schedule over the Artemis I core stage. For example, the MAF workforce has achieved a 70 percent improvement in labor hours on the engine section and 33 percent improvement on the intertank.

Several improvements are contributing to the overall production improvements. For example, in the engine section, the most complex component of the core stage, significant improvement is noted in manufacturing discrepancies, a 97 percent improvement in rework hours and an overall 70 percent improvement in baseline labor hours required.

Those improvements are the result of numerous process improvements, including: shorter, more precise work instructions; a new one-shot drilling technique; thermal protection system (TPS) application improvements; sensor installation improvements; a new job kitting process that has parts, tools and instructions ready when each shift arrives; implementing standard rework techniques; and placing NASA program

management on the factory floor to accelerate decision-making.

### 3.2 Core Stage Propulsion Manufacturing and Testing

The Artemis I RS-25 flight set is now at MAF to prepare for installation on the core stage. Artemis II engine processing under way (see Fig. 10). [7]



Fig. 10. Artemis I RS-25 flight set at MAF

The ability to use the RS-25 for SLS was validated by a series of hot-fire tests (see Fig. 11) using RS-25 development engines to ensure the space shuttle-heritage engine can operate to the different SLS requirements and environments such as a different propellant inlet temperature, start process and thrust profile. Hot-fire tests were also used to develop and certify new engine controllers and software. A total of 32 tests amassed nearly 15,000 seconds of hot-fire time. Testing included running the engine 113 percent of its original designed thrust to show it can operate safely at the planned 111 percent.



Fig. 11. RS-25 hot-fire test at SSC

Aerojet Rocketdyne has begun developing a new generation of expendable RS-25 engines designed and produced with the latest manufacturing techniques to cost at least 30 percent less than heritage RS-25 engines. Testing to date has included developmental components such as a pogo accumulator and a main combustion chamber for eight new-build RS-25 engines for development and flight. Engine testing resumes in 2020

and will include green run tests of additional controllers for future engines.

Aerojet Rocketdyne has also completed six RL10 engines to support EUS production, including four for flight and two spares.

All 10 motor segments for the Artemis I Solid Rocket Boosters (SRBs) are complete and ready to ship to KSC. Forward assemblies and aft skirts are still in processing but nearing completion. Both nozzles for Artemis I are finished at Northrop Grumman facilities in UT. Booster separation motors are complete on the left-hand and right-hand aft skirts. At MSFC, the avionics recently finished qualification testing and will be tested with vehicle avionics later this year. Motor casting for Artemis II segments is complete (see Fig. 12).



Fig. 12. Artemis II solid rocket motor segment casting

### 3.3 Payload and Related Progress

Above the core stage (and below Orion) are the ICPS and adapters. The ICPS, built by Boeing and ULA, is a Delta Cryogenic Second Stage that has been modified by lengthening the LH<sub>2</sub> tank, adding hydrazine bottles for attitude control and minor avionics changes. It is powered by one Aerojet Rocketdyne RL10B-2 engine with 24,750 pounds of thrust. It provides the TLI burn for Orion during the Artemis I mission. The IST of the ICPS, LVSA and the OSA was completed in 2017 at MSFC. The ICPS and OSA were shipped to KSC in 2017 and 2018; they're stored in the Space Station Processing Facility (SSPF) until needed for vehicle integration (see Fig. 13)



Fig. 13. Artemis I ICPS and OSA ready for integration at KSC

The OSA was delivered with the secondary payload deployment system, including the avionics unit, tested and installed. The LVSA at this writing is undergoing final processing at MSFC and expected to ship to KSC in 2020. Panels are being formed for the Artemis II LVSA and OSA, and procurement of upper stages and other long-lead items to support future Block 1 flights is in progress.

At MSFC, the historic support center once used to support Saturn and space shuttle missions was updated in 2018 to support SLS.[8] The SLS Engineering Support Center (SESC) (see Fig. 14) participated in a connectivity test in August 2018 (Figure 9). The test verified voice communications among 13 locations, including the Launch Control Center (LCC) at KSC and the Mission Control Center (MCC) at Johnson Space Center (JSC) and the U.S. Air Force Patrick Air Force Base and Cape Canaveral Air Force Station, as well as several NASA contractor sites. While the data stream in the shuttle era was no greater than one megabit per second, the SESC will receive more than 25 times that amount of data. Voice, imagery and data used to monitor the engines, boosters, core stage, avionics and the upper stage have been upgraded to provide technical expertise to launch and mission controllers at KSC and JSC. While support centers in the shuttle era could link about 20 groups – or “voice loops” – the SESC will be able to connect up to 156 groups. More than 160 engineers will be monitoring real-time data from the rocket during pre-launch and flight operations in the SESC. Tests, as well as console and training simulations, are continuing.



Fig. 13. SLS Engineering Support Center, MSFC

### Conclusions

The world’s most powerful rocket for an ambitious new era of human space exploration program in history is nearly complete. The SLS Program is dedicated to ensuring the success of the Artemis program’s mission of establishing a sustainable human future in space. SLS is the only rocket built from the ground up to carry astronauts and cargo farther and faster than any rocket in history. Building this kind of transformational rocket is not easy, and NASA and its contractors must get it right. The extent and rigor of testing in almost every component of the vehicle is done to prove the design and manufacturing processes result in a vehicle that is as safe as reasonably possible in the harsh environments of launch and deep space. With SLS, NASA cements U.S. leadership in space, enabling human and scientific exploration, and, if needed, supporting highly demanding national missions. The SLS NASA-industry team is focused on delivering the SLS for its first flight, Artemis I, and continuing humanity’s exploration of space.

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