NASA's Space Launch System: Powering Artemis and Enabling Discovery

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The debut launch of NASA's super-heavy lift SLS (Space Launch System) rocket in November 2022 opened a new era of deep space exploration. Called the Artemis I mission, the launch sent an uncrewed Orion spacecraft more than 268,000 miles from Earth into a distant retrograde orbit (DRO) about the Moon, before splashing down in the Pacific Ocean 25 days later. While the mission was critical for multiple reasons to NASA's Artemis campaign, the data collected during the first launch of SLS was vital to understanding how the launch vehicle performs in the flight environment. The test flight provided real-world data to ground and improve models, on-ground testing, and vehicle performance. Data returned show a nominal launch, with many parameters accurate to pre-flight predictions to within tenths of a percent. Equipped with the data, the SLS team is readying the Artemis II vehicle. Beginning with the fourth flight, SLS variants will have multiple upgrades, which increase the capability of the rocket to enable the nation's most ambitious missions of returning astronauts to the Moon and lunar vicinity. Current hardware progress, as well as Artemis I flight data, will be provided. Additionally, the test programs that enabled the successful first flight will be discussed.

I. Introduction

NASA's SLS (Space Launch System) rocket is a super-heavy lift launch vehicle. Its current primary use is to launch crew and payloads to the Moon under the NASA-led Artemis campaign. Artemis's goal is to return astronauts to the Moon, test technologies on the lunar surface and in lunar orbit, and prepare for crewed missions to Mars. The launch vehicle also has significant capability to launch cargo-only missions and non-crewed spacecraft missions to destinations throughout the solar system.

SLS has an initial mass-to-translunar injection (TLI) single launch capability of 59,000 lbs. (27 metric tons [t]) in crewed configuration with NASA's Orion spacecraft. The vehicle produces 8.8 million pounds (39,100 kN) of thrust.

The single launch payload capability significantly increases to more than 84,000 lbs. (38 t) on the fourth launch, which debuts the more powerful Block 1B variant featuring the larger, more capable exploration upper stage (EUS). Block 1B can also fly in a cargo-only configuration with a mass-to-TLI capability of 93,000 lbs. (42 t). The vehicle can send an Orion spacecraft and crew of four, along with a 10-t co-manifested payload, to the Moon on the same launch. The vehicle's capabilities are further increased on Block 2 variant, which will feature evolved solid rocket boosters (Fig. 1).

On Artemis V, the second flight of the Block 1B variant, new-production RS-25 liquid hydrogen (LH2)/liquid oxygen (LOX) engines will begin flying. The RS-25 was a key propulsion system on the space shuttle. Sixteen engines left over at the end of the Space Shuttle Program were outfitted for SLS and are flying the first four flights

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of the rocket. The new production engines, which take advantage of modern manufacturing technologies, will produce more thrust than the heritage engines.

Further progress on hardware and software for the future flights of SLS will be detailed in the paper.

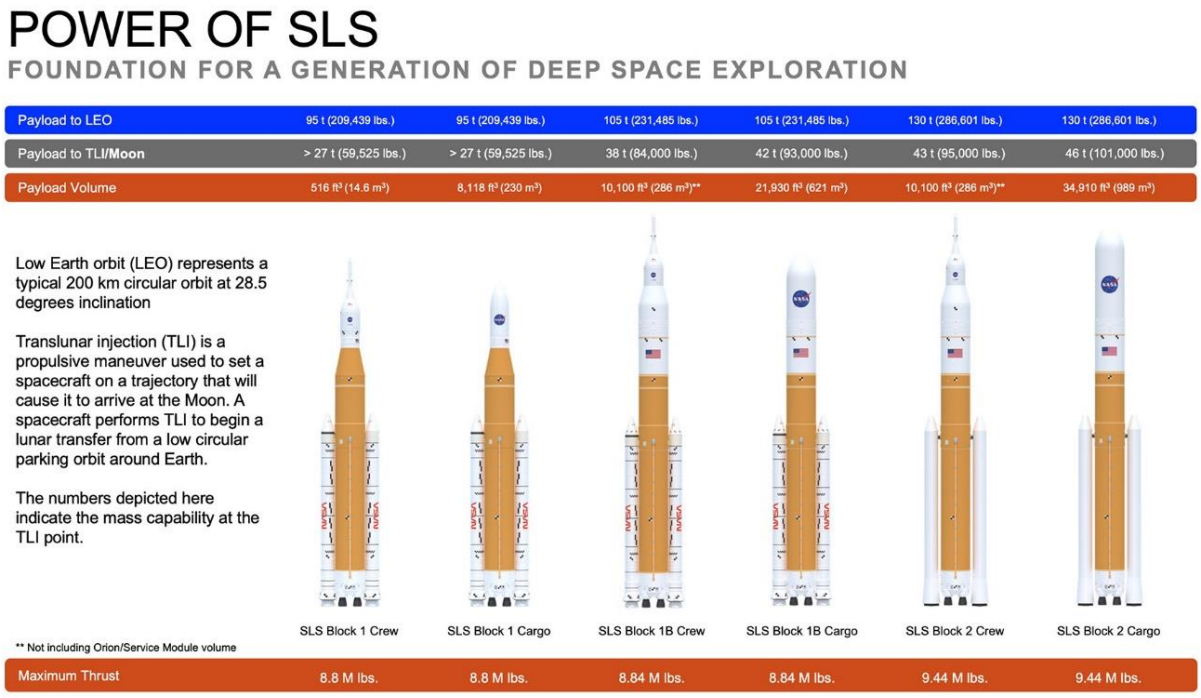


Fig. 1 SLS variants will feature upgrades which will result in significant performance increases.

II. Artemis I Flight Data

SLS was put through a rigorous ground test program before flight. The Artemis I mission, launched on November 16, 2022, was a test flight of the rocket (Fig. 2). The mission sent an uncrewed Orion spacecraft on a 25-day mission around the Moon into a distant retrograde orbit about the Moon and back. Data collected from the launch were analyzed over the course of the following months to learn as much about the behavior of the vehicle in the flight environment as possible. On the debut flight, SLS performed incredibly close to pre-flight predictions, including:

- Targeted prelaunch predicted velocity was 25,586.43 ft./sec. (7,798.74 m/sec.). Actual Earth orbital insertion velocity was 25,579.86 ft./sec. (7,796.74 m/sec.) – a difference of 6.58 ft./sec. (2.00 m/sec.) or 0.026 percent.
- Targeted apogee was 975 nautical miles (1,569.1 km). Actual Earth orbital insertion apogee altitude was 972.6 nautical miles (1,564.4 km). This difference of 2.4 nautical miles (4.667 km) was just 0.25 percent from the preflight prediction.
- The booster 50-psi separation signal, which is based on measurements during the tailoff pressure, was sent to each booster within 0.04 seconds of each other. Data indicate that the booster pair are the closest match pair ever flown, including through all 135 space shuttle missions.
- The core stage's 999 sensors and 45 miles (72 km) of cable executed all functions nominally.
- The interim cryogenic propulsion stage (ICPS) set a record for longest duration burn of the RL10 engine during the translunar injection burn at approximately 18 minutes.
- The flight software performed as designed.



Fig. 2 Artemis I launch November 16, 2022.

III. SLS Evolution

SLS is a multi-variant launch vehicle, with upgrades planned and already in work.

The first three flights occur on the Block 1 configuration, featuring four RS-25 LH2/LOX engines fueled by the core stage, two five-segment solid rocket boosters, and the ICPS as the upper stage. While the core stage was a new development stage, the RS-25 engines and solid rocket boosters used heritage hardware remaining from the Space Shuttle Program. The ICPS is based on United Launch Alliance's (ULA) Delta Cryogenic Second Stage (DCSS). In crewed configuration with the Orion spacecraft, the vehicle stands 322 ft. (98 m) tall and produces 8.8 million pounds (39,100 kN) of thrust.

The first substantial upgrade will be in the form of the new EUS, marking the SLS Block 1B variant. The ICPS was meant only to fly the first few flights, help get SLS operational and the Artemis missions underway, and be a key enabler of the early part of the program. While based on the reliable DCSS platform, a more powerful upper stage will help take SLS to its true capability.

The EUS continues to use the RL10 engine used on the ICPS, increasing from one engine on each stage to four. The stage's thrust increases from 24,750 pounds (110 kN) to 97,360 (433 kN) and increases the single-launch payload mass-to-TLI from 59,000 pounds (27 t) in crewed configuration to 84,000 pounds (38 t). The performance increase enables NASA to launch crew and a 10-t co-manifested payload to the Moon on the same launch.

Along with the block upgrade's hardware, the flight software and avionics will also be upgraded. The avionics will move from the core stage forward skirt to the EUS equipment shelf, requiring and enabling it to control the entire flight of each SLS. The software and avionics are in development.

A cargo-only variant of the Block 1B is also possible. A 62.7-foot (19.1-m) tall, 27.6-foot (8.4-m) diameter fairing is possible, providing 21,930 cubic feet (621 cubic meters) of payload volume [2]. A larger, 90-foot (27.4-m) tall, 27.6-foot (8.4-m) diameter fairing is possible, providing 34,910 cubic feet (989 cubic meters) of payload volume. A 62.7-foot (19.1-m) tall, 32.8-foot (10-m) diameter is also possible. The combination of the large payload volume with the EUS means significant cargo can be sent to the Moon in a single launch, or large telescopes or interplanetary probes can be sent throughout the solar system. Balancing the forces, smaller probes can be sent to destinations in deep space years quicker than on currently available rockets.

While Block 1B is flying, new RS-25 engines will be brought online. The engine, used on the space shuttle and now SLS, has flight-proven success. Between ground and flight operations, teams have more than 1 million seconds of hot fire experience with the engine. As the engines for the first four flights are heritage engines from the Space Shuttle Program, new engines will be needed beginning with Artemis IV. In April 2024, the new production engines completed a two-part, 24-test hot fire test series to certify the design and components concluded. The first production engine is scheduled to be complete in early 2025. It will then undergo an acceptance hot fire test at NASA's Stennis Space Center in Mississippi, before being installed on its core stage.

The new engines take advantage of modern manufacturing technologies, including additive manufacturing, enabling prime contractor L3Harris Technologies company, to significantly reduce the time, cost, and complexity of producing the engines. Teams at NASA's Marshall Space Flight Center in Huntsville, Alabama, are doing significant research into additive manufacturing of the nozzle's channel walls, which would further reduce the production time and cost of liquid rocket engines.

About 70% of its components have been redesigned, simplified, and improved, yielding an engine that can be produced quicker, is 30 percent more affordable, and operates at two percent higher thrust than the 16 shuttle heritage engines that will power the first four flights.

The third variant, called SLS Block 2, features evolved solid rocket boosters. As the heritage space shuttle steel booster cases will run out following the eighth flight of SLS, new boosters featuring composite cases will debut on the ninth flight. Other upgrades to the boosters will include new propellant, new insulation, and new thrust vector control systems to handle the wider nozzle and increased power.

The boosters further increase SLS's capability. Maximum vehicle thrust increases to 9.44 million pounds (42,000 kN), and the mass-to-TLI increases to 95,000 lbs. (43 t) in crewed configuration and 101,000 (46 t) in cargo-only configuration.

IV. Powering Artemis and Enabling Discovery

SLS will launch large segments of the agency's Gateway lunar orbiting outpost. Gateway will be composed of multiple modules, including the Lunar I-Hab module which will launch on Artemis IV and the Lunar View refueling module that will launch on Artemis V. The modules will be co-manifested payloads with Artemis crews on the Orion spacecraft. The missions will be both crewed landing missions with Gateway assembly happening concurrently. SLS's capability enables these missions, which reduces the number of launches to accomplish the objectives.

In addition to co-manifested payloads, all variants possess the capability to launch CubeSats as secondary payloads [1]. On Artemis I, 10 6U secondary payloads were launched. Artemis II will launch five 12U CubeSats, developed by international partners. The Block 1B and Block 2 variants include a new mounting structure for CubeSats. Called the Nest, the ring-like structure will fit inside the payload adapter fairing, and CubeSats will be manifested on missions that have mass and volume availability (Fig. 3).

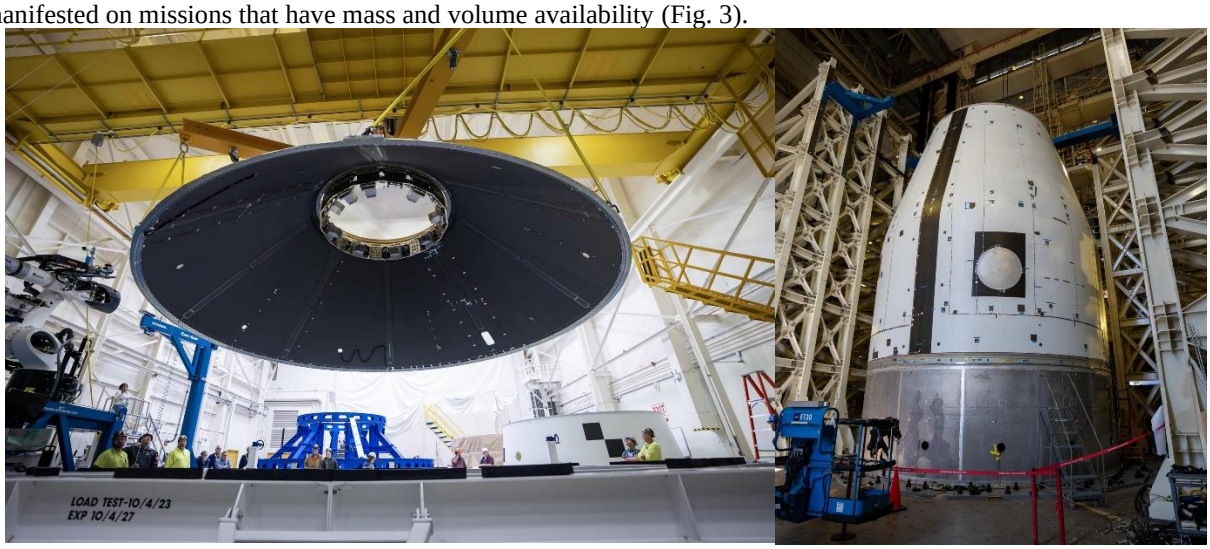


Fig. 3 The payload adapter (left) and universal stage adapter (right) will be able to house large co-manifested payloads as well as CubeSat secondary payloads on the Block 1B and Block 2 variants. Note the Nest ring inside the top opening of the payload adapter.

SLS's role in the Artemis campaign will lead to significant discoveries on the lunar surface as astronauts explore the Moon both from the surface and from the Gateway in lunar orbit. As previously discussed, it is possible for SLS to fly cargo-only missions to the Moon or in other destinations throughout the solar system. SLS has significant departure energy, enabling the launch of massive telescopes and spacecraft [3,4]. The vehicle can also launch smaller payloads and get them to their destinations quicker than currently operational launch platforms.

V. Test Programs

Significant test programs evaluated and certified the components, elements, and overall launch vehicle before the Artemis I mission. Structural test campaigns ensured the pieces could withstand the immense forces of launch. Wind tunnel testing provided data to models on how the vehicle would perform through different aerodynamic regimes. Booster, engine, and green run and wet dress rehearsal testing certified the modifications to the heritage RS-25 engines, solid rocket boosters, and the newly developed core stage for the new environments and requirements of SLS. Software and avionics testing ensured the brains of the vehicle could properly fly and operate SLS.

Prior to launch, the Integrated Test and Checkout test campaign evaluated the systems at a vehicle level.

Launch was, ultimately, the key, final test to understanding how SLS performs. The machine did the job it was designed to do at a high-level of precision.

VI. Current Hardware Progress

After thorough review of the data, teams concluded that performance was sufficient to fly crew on the second flight – NASA's Artemis II mission, which will send four astronauts on a lunar flyby mission aboard an Orion spacecraft. The mission is targeted to fly in 2025. SLS hardware for the mission is largely complete and at NASA's Kennedy Space Center in Florida.

The Artemis II core stage completed manufacture at NASA's Michoud Assembly Facility outside New Orleans. The stage was shipped to Kennedy in July 2024 on NASA's Pegasus barge and transported into the Vehicle Assembly Building (Fig. 4). Teams are finalizing work on it, including installation of the linear shape charges for the flight termination system and system tunnel closeouts. When complete, the stage will be ready for stacking on the mobile launcher with the solid rocket boosters.

The solid rocket booster propellant segments were transported via train from prime contractor Northrop Grumman's Utah manufacturing facilities in late 2023 and are currently in storage at KSC. The aft and forward segments were completed in Kennedy's Booster Fabrication Facility and are in the Vehicle Assembly Building. The segments will remain in storage until needed for stacking.

The ICPS for Artemis II is complete at prime contractor United Launch Alliance's facilities at Cape Canaveral in Florida. The launch vehicle stage adapter, which will connect the ICPS to the core stage was shipped from Marshall in August 2024 on the Pegasus barge. The Orion stage adapter has been outfitted with the brackets for the secondary payloads. It is targeted to arrive on the Super Guppy at Kennedy from Marshall when needed.



Fig. 4 Artemis II core stage arrived at Kennedy July 24.

In addition to preparations for the Artemis II mission, significant progress is being made on the launch vehicles for Artemis III, IV, V, and beyond.

- The Artemis III core stage primary structures, including the LH2 and LOX tanks, are structurally complete at NASA Michoud. The tanks are in the process of having their thermal protection systems applied.
- The solid rocket booster segments for Artemis III are all cast and stored at prime contractor Northrop Grumman's Utah facilities.
- The Artemis III engine section boattail and Artemis IV engine section were shipped to Kennedy in August 2024.
- Weld confidence articles, structural test articles, and flight hardware components for the new EUS are being manufactured and tested.
- New production RS-25 engines for Artemis V and beyond are being made by prime contractor L3Harris. These new engines take advantage of modern manufacturing technologies and streamlined processes, resulting in an engine that is 30 percent more affordable with a small increase in thrust than heritage space shuttle engines.
- A test program to certify the new production engines at Stennis completed in April 2024.
- Flight software for the SLS Block 1B variant is in development.

VII. Summary

SLS is an powerful, evolvable launch vehicle developed to support the country's most ambitious crew, cargo, and spacecraft missions. It is a key enabler of the Artemis campaign and is the only rocket capable of launching astronauts to lunar orbit. The evolvability will further allow it to launch large co-manifested payloads with crews, reducing the complexity of the Artemis campaign. The payload capability also will provide for significant scientific return, both through Artemis and through other spacecraft needing rides to destinations throughout the solar system.

Furthermore, SLS is reinvigorating the American industrial base as contractors and suppliers in 45 states are working on the pieces and parts for SLS.

SLS and the Artemis missions are happening now. The missions will enable the study of the early solar system through the lunar geology and will pave the way to Mars. The lessons learned as we explore will have uncountable impacts on science and technology and will inspire the next generation of explorers to push further.

VIII. References

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