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Successful First Flight of NASA's SLS (Space Launch System) Super Heavy-Lift Rocket Lays Groundwork for U.S.'s Most Ambitious Missions

Figure 1: Artemis I launch at 1:47 a.m. EST, Nov. 16, 2022.

ABSTRACT

In late 2022, NASA's SLS (Space Launch System) super heavy-lift rocket launched for the first time. Artemis I sent an uncrewed Orion spacecraft on a 25.5-day round-trip mission to lunar orbit. The near-perfect performance laid the groundwork for the next flights and for NASA's return of humans to the Moon. The SLS team is now preparing for the launch of Artemis II, which will be the first launch of astronauts to cislunar space since Apollo 17 in December 1972. In addition to preparations on the Artemis II launch vehicle, significant progress is being made on the hardware and software for future flights. Artemis II will include a test of a new military-grade GPS system, which will be fully utilized on Artemis III. Progress is also being made on the exploration upper stage (EUS) for the Block 1B SLS variant, which will debut on Artemis IV. New production RS-25 liquid-propellant engines will be used beginning with Artemis V. These new engines, which are in a final qualification test firing program at the time of writing, realize a cost savings of at least 30 percent and reduced production time due to streamlined manufacturing and advances in technology, including additive manufacturing. The evolved solid rocket boosters, which will debut on Artemis IX as part of the Block 2 variant, are in development now. In addition to propulsion updates, each variant of SLS maintains payload configuration flexibility and can fly crew-only, cargo-only, and crew-cargo combinations. This adaptability ensures that SLS, with its significant mass and volume capability – including the ability to launch large co-manifested payloads with Orion directly to trans-lunar injection (TLI) – can support the country's most ambitious missions. Results from the Artemis I mission, as well as progress to the next flights and SLS variants, will be covered in the paper and presentation.

INTRODUCTION

NASA's SLS (Space Launch System) is a key national asset for the agency's return of humans to the Moon, first crewed missions to Mars, and scientific missions throughout the solar system and beyond. The super heavy-lift launch vehicle has enormous single launch payload capability – both mass and volumetrically – in crewed and cargo configurations.

Through a rigorous development campaign, the first launch on Nov. 16, 2022, proved to be the definitive test (Fig. 1). The Artemis I mission sent an uncrewed NASA Orion spacecraft on a 25.5-day, 1.4-million-mile mission into a distant retrograde orbit (DRO) around the Moon and back.

In summer of 2023, the SLS Program concluded the post-flight assessment of the launch vehicle performance. The rocket performed its mission to a high degree of precision and accuracy. Teams are now preparing the Artemis II SLS for stacking and launch. The mission will send four astronauts on a free-return lunar flyby mission to collect vital data on Orion spacecraft performance with humans-in-the-loop. Hardware and software are also in development for Artemis III, Artemis IV, and the SLS Block 1B and Block 2 variants.

Results of the Artemis I test flight are discussed, the imperative test campaign is briefed, and progress updates for Artemis II, III, Block 1B, and Block 2 are given.

SLS ARCHITECTURE

The SLS architecture is designed to be flexible and evolvable, leveraging proven spaceflight propulsion systems, and utilizing new avionics hardware and software. Remaining consistent – in both the crew and cargo configurations – are a core stage powered by four RS-25 liquid hydrogen/liquid oxygen (LH2/LOX) engines and two five-segment solid rocket boosters. Maximum thrust in this configuration for the Block 1 vehicle is 8.8 million pounds (39,144 kN). The rocket stands 322 feet (98 m) tall and weighs 5.75 million pounds (2.6 million kg) in the Block 1 crew configuration at liftoff (Fig. 2). SLS's Block 1B crewed configuration will stand 366 feet tall (112 m), will produce 8.84 million pounds (39,300 kN) of thrust, and be capable of sending 84,000 pounds (38 metric tons (mt)) of payload to TLI. The Block 2 variant will produce 9.4 million pounds (42,000 kN) maximum thrust.

The interim cryogenic propulsion stage (ICPS), a derivative of the United Launch Alliance (ULA) Delta Cryogenic Second Stage (DCSS), is used as the upper stage on Block 1. It uses one RL10 engine and produces approximately 24,750 pounds of thrust (110 kN). Beginning on the fourth flight, a new upper stage developed by NASA called the exploration upper stage (EUS), will debut using four RL10 engines. The stage will produce 97,360 pounds (433 kN) of thrust. Mass-to-TLI will increase from 27 mt to 38 mt in crew configuration. When new, evolved solid rocket boosters are debuted on the ninth flight and the start of the Block 2 variant, mass-to-TLI in the crew configuration will increase to 43 mt and 46 mt in the cargo-only configuration in a single launch.

NASA and the SLS team leveraged hardware and technology left over at the end of the Space Shuttle Program. Hardware was upgraded with new materials and manufacturing methods and modified as needed to meet SLS requirements and environments.

Including space shuttle flights and ground testing, the RS-25 design has accumulated more than 1 million seconds of hot fire experience. Following the fourth flight of SLS when heritage engines are expended, new production engines will be required. The production of these engines has started at prime contractor Aerojet Rocketdyne, an L3Harris Technologies company, facilities, and engine certification testing is already underway.

NASA has enough booster hardware from the Space Shuttle Program for the first eight flights, including the Artemis I mission. The evolved boosters will debut on the ninth flight. That development – called the Booster Extension and Obsolescence (BOLE) effort – is already underway with SLS and booster prime contractor, Northrop Grumman.

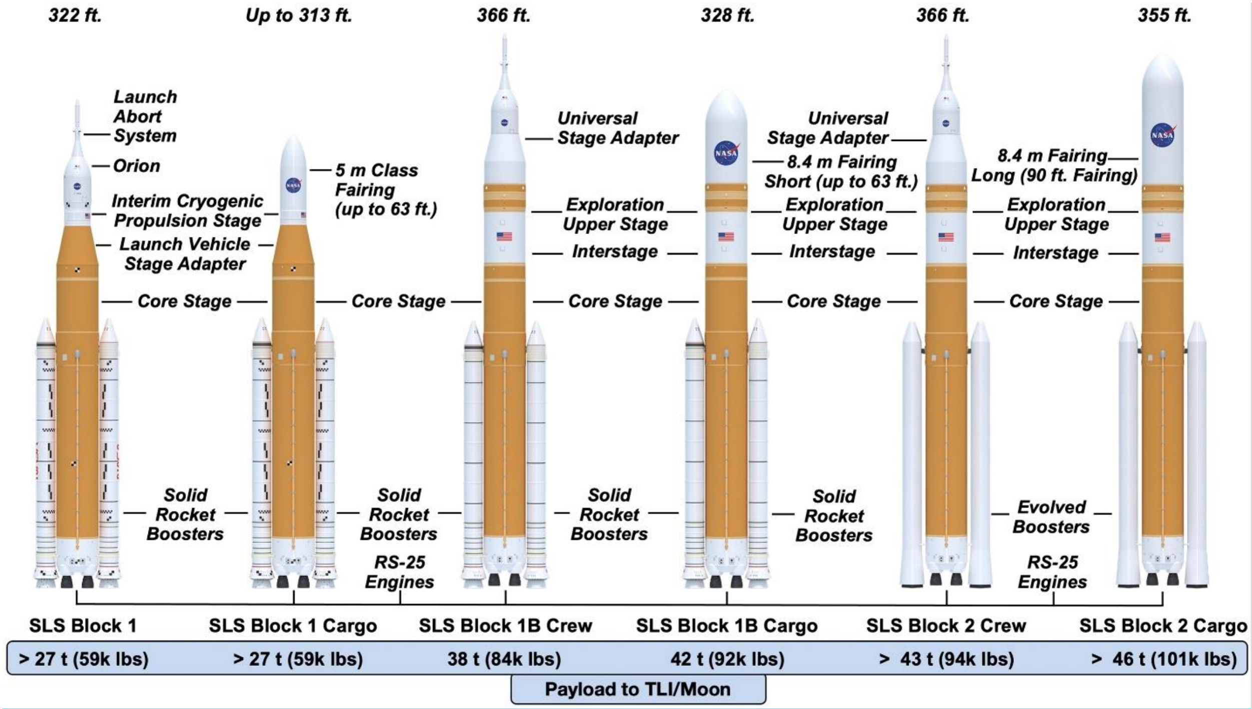


Figure 2: SLS variants and projected performance.

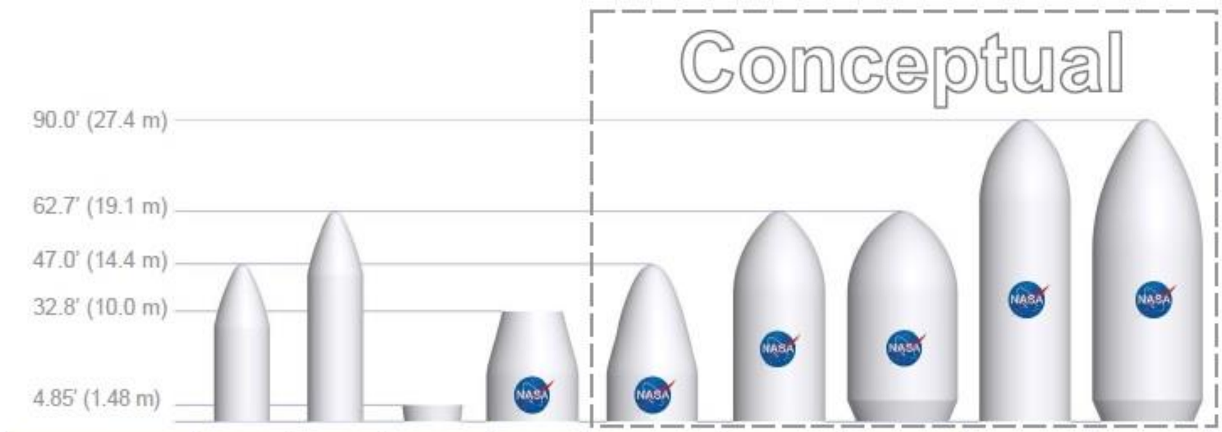
PAYLOAD CONFIGURATION CAPABILITIES

While SLS is currently manifested to launch NASA's Artemis missions, the launch vehicle has significant flexibility and evolvability to launch a wide variety of payloads (Fig. 3).

The Block 1B variant, which will come online beginning with Artemis IV, will increase payload mass-to-TLI from 59,000 pounds (27 mt) to 84,000 pounds (38 mt) in the crewed configuration. The configuration features a co-manifested payload capability of up to 10 mt. On Artemis IV, the International Habitation (I-Hab) module of the Gateway lunar orbit outpost will launch with a crewed Orion spacecraft. In addition to a co-manifested payload, CubeSats up to 27U can launch inside the payload adapter in a new deployment ring called the Nest. Block 1B can also support cargo-only missions with mass-to-TLI of 93,000 pounds (42 mt).

SLS Block 2 will feature more powerful solid rocket boosters, increasing mass-to-TLI to 95,000 pounds (43 mt) in a single launch in crewed configuration and 101,000 pounds (46 mt) in cargo-only configurations.

Payload fairings for the cargo-only configuration are being studied and include 8.4-meter diameter fairings with volumes from 11,260 cubic feet (319 cubic meters) to 34,910 cubic feet (989 cubic meters). Even larger 10-meter diameter fairings with more than 32,000 cubic feet (909 cubic meters) are also under investigation.



Enclosure	5.1m PLF	5.1m PLF	OSA	8.4m USA	8.4m USA PLF	8.4m PLF, Short	10m PLF Short	8.4m PLF, Long	10m PLF Long
Payload Type	5m PPL	5m PPL	5m SPL	8.4m CPL	8.4m PPL	8.4m PPL	10m PPL	8.4m PPL	10m PPL
Length	47.0 ft	62.7 ft	4.85 ft	32.8 ft	47.2 ft	62.7 ft	62.7 ft	90 ft	90 ft
	14.3 m	19.1 m	1.48 m	10.0 m	14.4 m	19.1 m	19.1 m	27.4 m	27.4 m
Diameter	16.7 ft	16.7 ft	17.7 ft	27.6 ft	27.6 ft	27.6 ft	33.0 ft	27.6 ft	33.0 ft
	5.1 m	5.1 m	5.4 m	8.4 m	8.4 m	8.4 m	10.0 m	8.4 m	10.0 m
Internal Diameter	15.1 ft	15.1 ft	16.7 ft	24.6 ft	24.6 ft	24.6 ft	29.9 ft	24.6 ft	29.9 ft
	4.6 m	4.6 m	5.1 m	7.5 m	7.5 m	7.5 m	9.1 m	7.5 m	9.1 m
Available Volume	5,358 ft^3	8,118 ft^3	516 ft^3	10,100 ft^3	11,260 ft^3	21,930 ft^3	32,470 ft^3	34,910 ft^3	46,610 ft^3
	151.7 m^3	229.9 m^3	14.6 m^3	286.0 m^3	319 m^3	621 m^3	919 m^3	988 m^3	1,320 m^3
Potential Availability *(No Earlier Than)*	COTS	COTS	2020	2024	2025	2025	2029	2029	2029

COTS: Commercial Off-the-Shelf CPL: Co-manifested Payload OSA: Orion Stage Adapter PPL: Primary Payload SPL: Secondary Payload PLF: Payload Fairing

Figure 3: SLS payload fairing options.

ARTEMIS I FLIGHT DATA

The Artemis I launch on Nov. 16, 2022, was the final test of the first SLS rocket. While comprehensive testing was done through the vehicle's development, some data can only be collected in the flight environment.

Launch occurred at 1:47:44 a.m. EST when the solid rocket boosters ignited and first vertical motion was detected. Six seconds prior, at 0.12-second intervals, the four RS-25s were ignited. As they were brought to 100 percent rated power level (RPL), the engine computers performed health status checks to verify performance before the booster ignition command was given by the onboard computers. The engines were brought up to 109 percent RPL at booster ignition. It is important to note that RPL refers to the original power level of the RS-25, not the current operating level of the upgraded systems for SLS.

Maximum dynamic pressure (maxQ) occurred 1 minute, 11 seconds into flight with the RS-25s at 100 percent RPL. Maximum dynamic pressure on the vehicle was 661 pounds-per-square-foot and occurred at Mach 1.7. Solid rocket booster burnout followed by separation occurred at approximately T+2 minutes 10 seconds. During booster separation, the RS-25s were throttled back to 85 percent RPL to aid in separation bolt load relief.

Booster performance was nominal. The boosters burned out within 0.5 seconds of each, hit peak thrust within 0.1 seconds of each other, and performed within one-quarter of a percent of each other during ascent. The 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. The Artemis I boosters are the closest match pair boosters NASA has ever flown, including through all 135 space shuttle missions.

Main engine cutoff occurred 8 minutes, 1 second into the mission, and core stage separation was approximately 12 seconds after insertion. The vehicle was traveling at 25,579.86 ft./sec. (7,796.74 m/sec.). The orbital insertion parameters were 972.6 nautical miles (1,801 km) by 15.9 nautical miles (29.4 km), and the vehicle inserted into that orbit at an altitude of 87.3 nautical miles (161.7 km). Predicted parameters were 975 nautical miles (1,806 km) by 16 nautical miles (29.6 km) with a velocity of 25,586.44 ft./sec. (7,798.75 m/sec.).

The RS-25s' thrust and mixture ratio control valves were within 0.5 percent of pre-flight predicted values. Internal pressures and temperatures were within 2 sigma of pre-flight predicted values. The engines and core stage performed as expected throughout the flight.

Staging of the core stage from ICPS and Orion was at T+8 minutes, 13 seconds. The ICPS and Orion entered into a 45-minute coast phase before the ICPS performed at perigee raise maneuver, followed by the TLI burn.

The TLI burn accelerated the stack to more than 22,000 mph (35,406 km/h.). The 18-minute burn was a record for long-duration burn of an RL10. Following shutdown, Orion staged, and the ICPS performed a disposal burn.

The 10 secondary payloads were deployed after disposal burn completion. The deployment characteristics of the ICPS were within the predicted bounds provided to the payload development teams.

SLS's flight software – developed in-house by the SLS team at NASA's Marshall Space Flight Center in Huntsville, Alabama – performed well within requirements. The transition from Ground Launch Sequencer (GLS) to Automated Launch Sequencer (ALS) was nominal, and all ALS functions performed without issue. No avionics hardware issues occurred during flight, nor were there any trigger-level "close" calls in the abort monitor system. There was excellent core stage LH2 and LOX closed-loop ullage control.

TESTED FOR FLIGHT

Prior to and during the Artemis I launch, the SLS team collected terabytes of data on vehicle characteristics, including 31 TB of imagery during on-pad pre-launch and launch activities. Components, elements, and the integrated vehicle were tested throughout the development program to verify the design, refine computer models, and ensure vehicle reliability.

Material properties were evaluated early-on and throughout the development. Subscale wind tunnel tests studied the aerodynamic properties of SLS in a variety of velocity regimes (Fig. 4).

Structural test articles were tested to evaluate element level characteristics and verify designs. SLS structural testing was centered at Marshall and involved stressing structural test articles of the ICPS, LVSA, and core stage LH2 tank, LOX tank, intertank, and engine section. New test stands were built in the center's west area for the LH2 tank and LOX tank, and a new stand inside Marshall's Building 4619 evaluated the engine section. ICPS structural testing used the LOX tank stand. The intertank used an upgraded and modified space shuttle external tank test stand in Building 4619.

The components were verified to meet the demands of launch, and the LH2 and LOX tanks were ultimately tested to failure to determine their full structural envelope. The LOX tank withstood all the pressures necessary, and its test-to-failure point was within 2 percent of the predicted value. The LH2 withstood over

260 percent of expected flight loads for more than 5 hours before a buckle was detected. Data collected were fed back into computer models, grounding the models with real-world information.

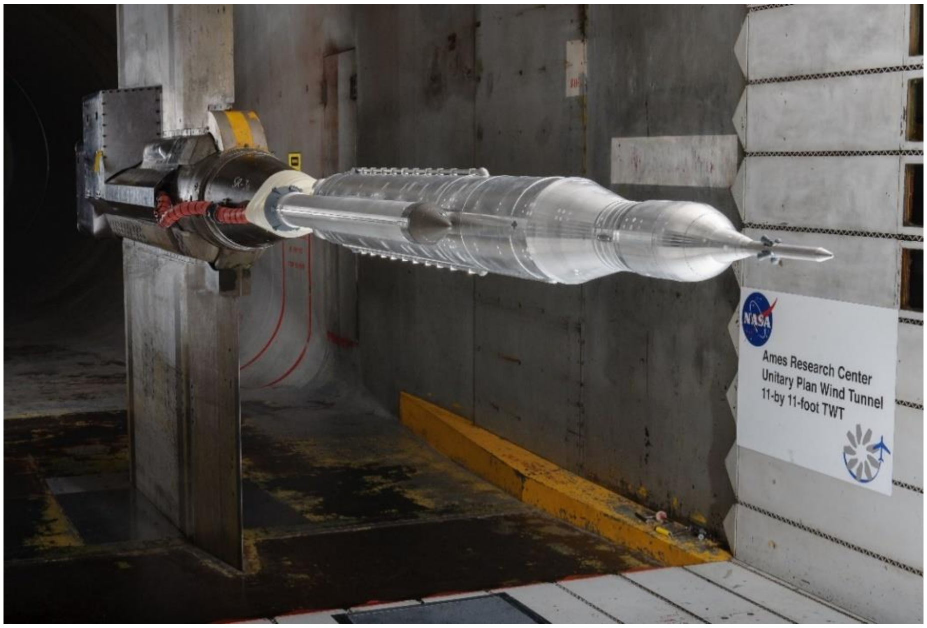


Figure 4: Wind tunnel testing of SLS Block 1.

Flight software was tested in Marshall's Systems Integration Lab – the most accurate representation of SLS's entire avionics and software system. In addition to having flight computer computers and avionics, the lab also has emulators for SLS's propulsion systems, Orion, and Launch Control Center (Fig. 5).

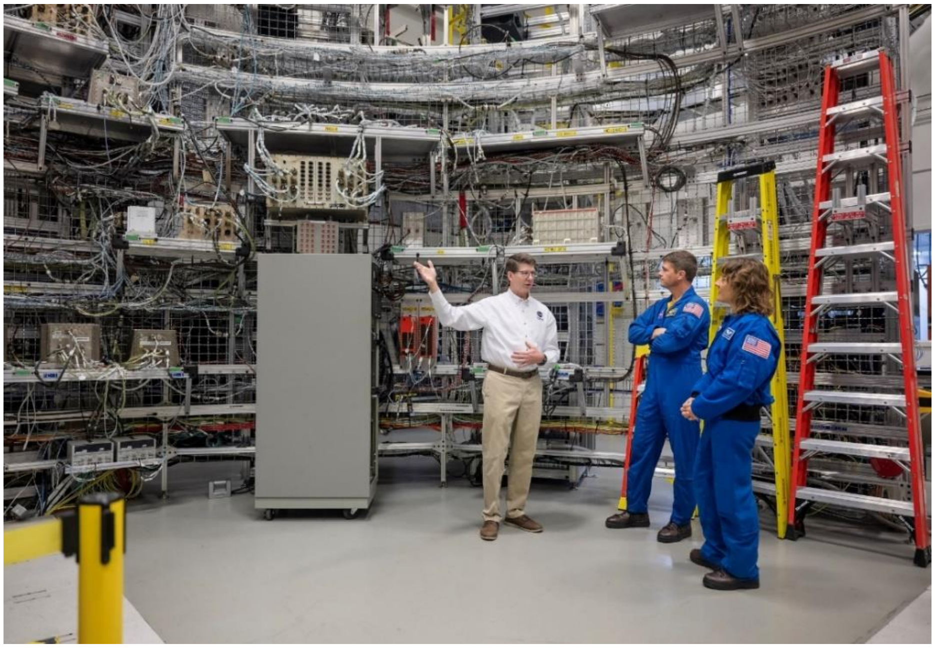


Figure 5: Dan Mitchell, NASA's lead SLS integrated avionics and software engineer (left), shows Artemis II astronauts Reid Wiseman (center) and Christina Koch (right) software test facilities at Marshall.

The iterative process tested all phases of flight. Before flight, thousands of test cases “flew” SLS through a full envelope of flight environments, including nominal and off-nominal scenarios. As noted in the Artemis I Progress section, the software performed nominally during Artemis I.

The core stage’s Green Run test campaign occurred in the B-2 test at NASA’s Stennis Space Center in Bay St. Louis, Mississippi. Following manufacturing completion at NASA’s Michoud Assembly Facility in New Orleans, the Artemis I core stage was transported to Stennis. Green Run testing evaluated the stage, including its avionics, thrust vector control systems, and capability to detect problems and properly shutdown, among other tests. The campaign culminated with a wet dress rehearsal and a full-duration hot fire test. The first hot fire attempt did not reach full duration; however, the second test did and was incredibly successful. Lessons learned through Green Run testing, particularly the main propulsion system conditioning and start process, proved critical during launch operations.

Another vital test series was the Integrated Test and Check-Out (ITCO) campaign. ITCO was performed in the Vehicle Assembly Building (VAB) at NASA’s Kennedy Space Center in Florida, once the boosters, core stage, LVSA, and ICPS were stacked on the mobile launcher. ITCO included verifying the interfaces between SLS, Orion, and the ground systems; functional checkout of SLS’s systems; and wet dress rehearsal.

In addition to the structural, aerodynamic, software, and many other test programs, the flight certification process itself was vital to the success. The comprehensive process ensured that the systems were verified to performance expectations and mission requirements.

ARTEMIS II PROGRESS

NASA is targeting September 2025 for the Artemis II launch. Unlike the uncrewed 25.5-day Artemis I mission which went into a DRO about the Moon, Artemis II will be a 9.5-day lunar flyby mission with astronauts, using a free return trajectory.

The Artemis II SLS will launch from Launch Complex 39B at Kennedy, insert into Earth orbit, and its ICPS will perform multiple burns to place the Orion spacecraft and ICPS in a high Earth orbit with an orbital period of approximately 23.5 hours. Apogee will approach 40,000 nautical miles (74,000 km). In this high Earth orbit, the four astronauts will perform check outs of Orion’s systems. They will also perform a series of flight test maneuvers called the proximity operations demonstration.

The demonstration will involve the astronauts flying the Orion spacecraft through a pattern of maneuvers, based around targets on the ICPS and OSA. Data from the flight test will inform the next astronauts, flight controllers, and computer models on the actual handling characteristics of the Orion spacecraft and performance of the reaction control system thrusters.

Following completion, the ICPS will perform a departure burn and re-enter Earth’s atmosphere, disintegrating over the Pacific Ocean. Orion and its service module, already in a high Earth orbit, will perform the TLI burn and set a course for the Moon. The free return trajectory reduces risk and ensures the crew can return from the Moon, should a component or system fail.

The OSA is being equipped with brackets and dispensers capable of deploying four 12U CubeSats. At the time of writing, potential CubeSats are being evaluated for flight.

Significant progress has been made to the hardware and software for the mission. The SLS booster segments arrived at Kennedy in September 2023. The motor segments, aft assemblies, and forward assemblies are in various stages of final processing. Booster stacking is targeted to begin later in 2024, approximately one year before launch (Fig. 6).

The core stage completed final integration functional testing in January 2024 and is being prepared for shipment to Kennedy this summer. The four RS-25 engines were installed and integrated on to the stage in late 2023.

Figure 6: The booster motor segments are being prepared at Kennedy for Artemis II.

The LVSA is complete and is awaiting shipment to Kennedy this spring. The OSA is undergoing final assembly and outfitting at Marshall. The targets the crew will use during the proximity operations demo are installed on the OSA. The agency is working with international partners to fly up to four 12U CubeSats as secondary payloads in the OSA. The ICPS is complete and in storage at ULA's Cape Canaveral Space Force facilities.

In addition to a test of a new military-grade GPS system, other minor changes to the Artemis II launch vehicle based on analyses of Artemis I and the addition of crew include rotation of the booster separation motors and an active launch abort system.

ARTEMIS III PROGRESS

Significant progress is being made across the entire Artemis campaign, including SLS, for Artemis III. The booster motor segments are cast and in storage at Northrop Grumman's facilities in Utah, and the nozzles are being prepared.

The core stage tanks are being manufactured and outfitted with their respective baffles and thermal protection system (Fig. 7). The forward skirt and intertank secondary structure installation is in work, and the engine section is being outfitted at Kennedy. Additionally, High Bay 2 in the VAB is being prepared to support vertical work on the core stage. Tooling installation in High Bay 2 is underway.

The ICPS was shipped by ULA to their Cape Canaveral Space Force facilities in 2023, where it is undergoing final testing and checkout. The LVSA is in the final phase of integration and assembly with developmental flight instrumentation installed. The OSA is structurally complete and painted. Its diaphragm, which prevents gasses from the vehicle below from reaching Orion, has been delivered to Marshall.

Figure 7: Technicians finished welding the 51-foot Artemis III liquid oxygen tank structure, left, inside the Vertical Assembly Building at NASA's Michoud Assembly Facility in New Orleans Jan. 8, 2024. The Artemis III liquid hydrogen tank, right, completed internal cleaning Nov. 14, 2023.

PATH TO BLOCK 1B AND BEYOND

In addition to progress being made for the next two missions, hardware for both the Block 1B and Block 2 variants is underway. The EUS, the new in-space stage for Block 1B, will feature four RL10 engines, with a combined thrust of 97,360 pounds (433 kN). Avionics for SLS will move from the core stage forward skirt to the EUS equipment shelf. Components for the structural qualification article and weld confidence article are currently being manufactured and tested.

Engineering development units and development test articles of the new adapters for Block 1B and Block 2 are being installed in test stands (Fig. 8).

Additionally, new-production RS-25 engines, which will be used beginning on Artemis V, are being manufactured right now. A two-part certification test series, comprised of 24 total tests, will wrap in the spring of 2024 at Stennis. The program is certifying the design, components, and manufacturing for the new production engines realizing a cost savings of at least 30 percent and reduced production time due to streamlined manufacturing and advances in technology, including additive manufacturing. This latest test series, called Retrofit 3b, will accumulate more than 6,000 seconds of hot fire time. More than 30 redesigned engine components or components produced with new manufacturing methods are installed on the engine, including propellant turbopumps, valves, ducts, and the main combustion chamber.

Following the conclusion, RS-25 testing will only be done a handful of times a year to acceptance test each new engine. Production at Aerojet Rocketdyne's facilities is significant with the first new flight engine more nearly 40 percent complete. Multiple nozzles, powerheads, and other components are also in the flow.

Figure 8: The developmental test article of the Universal Stage Adapter is moved into Building 4619 for test stand installation at Marshall.

The Block 1B flight software is under development, and the systems test labs are being outfitted.

The evolved solid rocket boosters are the major change from Block 1B to Block 2. Booster thrust increases from 3.6 million pounds (16,014 kN) for the current five-segment SRB to 4.2 million pounds (18,683 kN) for the BOLE booster. Using composite cases and new propellant, the thrust-to-weight ratio increases, enabling greater capability of the launch vehicle. A full-scale hot fire demonstration test will take place later this year, which will prove out the new design. Motor segments are being cast for that development motor test.

CONCLUSION

SLS is America's rocket, built by thousands of American workers and hundreds of companies. It is a cornerstone in NASA's Artemis campaign, a key capability for enabling the success of this nation's most ambitious spaceflight missions.

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