NASA SPACE LAUNCH SYSTEM INTEGRATED, PREPARING FOR LAUNCH

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Figure 1: The Artemis I vehicle at Launch Pad 39B at NASA's Kennedy Space Center during pad testing.

ABSTRACT

NASA is in the final stages of preparing for the first launch of the Space Launch System (SLS) rocket, the first rocket designed for deep space human exploration since the Saturn V. A successful year in 2021 resulted in the completed stacking of SLS and the Orion spacecraft for the Artemis I test flight. SLS is a super heavy-lift vehicle to send large, strategic payloads to the Moon, Mars, and beyond. It is the backbone of the Artemis human lunar exploration program. Multiple test programs were completed in advance of the first mission that will send an uncrewed capsule to distant retrograde orbit about the Moon before returning to Earth. On March 17-18, the integrated stack rolled out to Launch Complex 39B for the wet dress rehearsal (WDR) and other pad tests. Following three WDR attempts, the vehicle was rolled back to the Vehicle Assembly Building (VAB) at Kennedy Space Center (KSC) for repairs while a KSC supplier made upgrades to its facilities. WDR will be completed later this summer before the Artemis I stack is rolled back to the VAB for final closeout operations before a targeted launch in 2022. Teams at KSC, Marshall Space Flight Center (MSFC), Johnson Space Center (JSC) and several contractor locations are conducting multiple launch and mission simulations to prepare for a new era of lunar missions. In addition to preparations and launch of the Artemis I SLS, the Artemis II and Artemis III vehicles are coming together, with core stages, engines, boosters, and upper stage hardware complete or in various stages of manufacturing and/or processing. Progress is also being made on hardware for SLS vehicles for the Artemis IV and Artemis V missions that will use the upgraded Block 1B SLS variant. Block 1B will feature a more powerful four-engine Exploration Upper Stage to increase payload to the Moon from 27 metric tons (t) to 38 t. In addition, test hardware for the SLS Block 2, which uses evolved solid rocket boosters, has been manufactured. Agreements exist for hardware development for Artemis IX and beyond. This paper will detail the progress made in 2021 and the expected milestones leading toward launch in 2022.

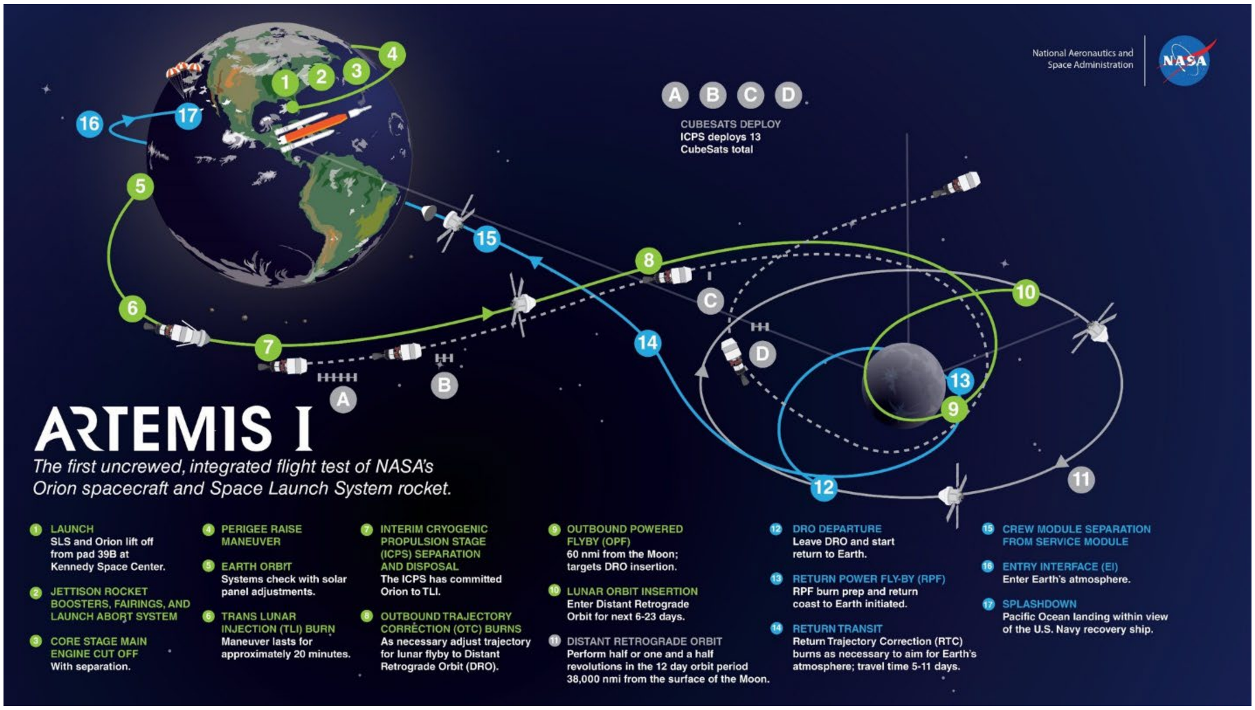
INTRODUCTION

NASA and its industry and international space agency partners are on the verge of a new generation of space exploration: the Artemis generation. Led by the Artemis program, humanity will explore the Moon like never before and will set the stage for human missions to Mars. Key to the Artemis missions, which land the first people on the Moon in over half a century, is the Space Launch System (SLS) rocket and the Orion capsule. The Artemis program will land the first woman and person of color on the Moon.

NASA is currently in the final stages of preparing the first SLS for launch with the Orion capsule on the Artemis I test flight. SLS is the most powerful rocket the agency has ever developed. The backbone of the Artemis program, along with the Orion capsule and Exploration Ground Systems (EGS), SLS will enable a new era of deep space human exploration that will see humanity's return to the Moon and first crewed voyages to Mars.

The rocket is being prepared for the final ground tests at Launch Pad 39B, which include the wet dress rehearsal (WDR). While the data from the tests are being analyzed and engineers confirm the vehicle is ready for flight, EGS teams at Kennedy Space Center (KSC) will complete closeout activities on the rocket to prepare it for its final rollout to the launch pad and flight. The flight will be the ultimate test of the integrated rocket-capsule system, a vital step towards the Artemis II mission, which will launch the first crew on SLS and in Orion and mark the return of NASA's human spaceflight program to cislunar space.

This paper will detail the progress made on the rocket in 2021 and 2022, including competition of stacking and multiple test campaigns. We will also discuss progress made on SLS vehicles for Artemis missions II, II, IV and progress made on the next variants of SLS: Block 1B and Block 2.



ARTEMIS I

The first uncrewed, integrated flight test of NASA's Orion spacecraft and Space Launch System rocket.

1. **LAUNCH** SLS and Orion lift off from pad 39B at Kennedy Space Center.
2. **JETTISON ROCKET BOOSTERS, FAIRINGS, AND LAUNCH ABORT SYSTEM**
3. **CORE STAGE MAIN ENGINE CUT OFF** With separation.
4. **PERIGEE RAISE MANEUVER**
5. **EARTH ORBIT** Systems check with solar panel adjustments.
6. **TRANS LUNAR INJECTION (TLI) BURN** Maneuver lasts for approximately 20 minutes.
7. **INTERIM CRYOGENIC PROPULSION STAGE (ICPS) SEPARATION AND DISPOSAL** The ICPS has committed Orion to TLI.
8. **OUTBOUND TRAJECTORY CORRECTION (OTC) BURNS** As necessary adjust trajectory for lunar flyby to Distant Retrograde Orbit (DRO).
9. **OUTBOUND POWERED FLYBY (OPF)** 60 nmi from the Moon; targets DRO insertion.
10. **LUNAR ORBIT INSERTION** Enter Distant Retrograde Orbit for next 6-23 days.
11. **DISTANT RETROGRADE ORBIT** Perform half or one and a half revolutions in the 12 day orbit period 38,000 nmi from the surface of the Moon.
12. **DRO DEPARTURE** Leave DRO and start return to Earth.
13. **RETURN POWER FLY-BY (RPF)** RPF burn prep and return coast to Earth initiated.
14. **RETURN TRANSIT** Return Trajectory Correction (RTC) burns as necessary to aim for Earth's atmosphere; travel time 5-11 days.
15. **CREW MODULE SEPARATION FROM SERVICE MODULE**
16. **ENTRY INTERFACE (EI)** Enter Earth's atmosphere.
17. **SPLASHDOWN** Pacific Ocean landing within view of the U.S. Navy recovery ship.

Figure 2: The Artemis I test flight, lasting several weeks, will give NASA the opportunity to thoroughly test all systems in deep space prior to commencing crewed lunar missions.

SLS ARCHITECTURE

SLS launch vehicles are the platform to launch NASA's most ambitious missions for decades to come. The rocket provides more mass, volume, and departure energy than currently existing commercial launchers. SLS uses heritage technologies and hardware initially developed for the Space Shuttle Program to optimize the opportunity for safe and successful missions. These technologies and hardware components have been upgraded to fly the more demanding missions to deep space. The SLS evolvable platform, starting with Block 1, enables improvements in performance throughout the rocket's life (Fig. 3).

At the heart of any rocket is the propulsion system. SLS uses a 2.5-stage configuration with RS-25 liquid-propellant engines that served as the Space Shuttle Main Engines (SSMEs), built by prime contractor Rocketdyne, now Aerojet Rocketdyne, and shuttle's twin solid rocket boosters (SRBs), built by prime contractor Northrop Grumman. Upgrades to both propulsion systems were needed to launch SLS and its more demanding mission requirements. During the Space Shuttle Program, three SSMEs were mounted on the base of the orbiter, which flew on the side of the external tank. For SLS, a fourth engine was added, and they have been moved to the base of the core stage – directly between the SRBs. Due to the new thermal environment, the engines were also upgraded with new insulation. The engine controllers were also updated for SLS. The SRBs each used four propellant segments during the Space Shuttle Program, but for SLS they use five propellant segments. New avionics and insulation were also added to the boosters.

The core stage is a new stage (manufactured by Boeing). In addition to housing the four RS-25s and their liquid hydrogen (LH2) and liquid oxygen (LOX) tanks, it is the backbone for the rocket as it serves as the attach point for the SRBs, the home of the rocket's flight computers, and the base for the integrated spacecraft and payload element. The stage holds approximately 537,000 gallons (2.03 million liters) of LH2 and 196,000 gallons (742,000 liters) of LOX. This base architecture will be used for all variants of SLS (Fig. 3).

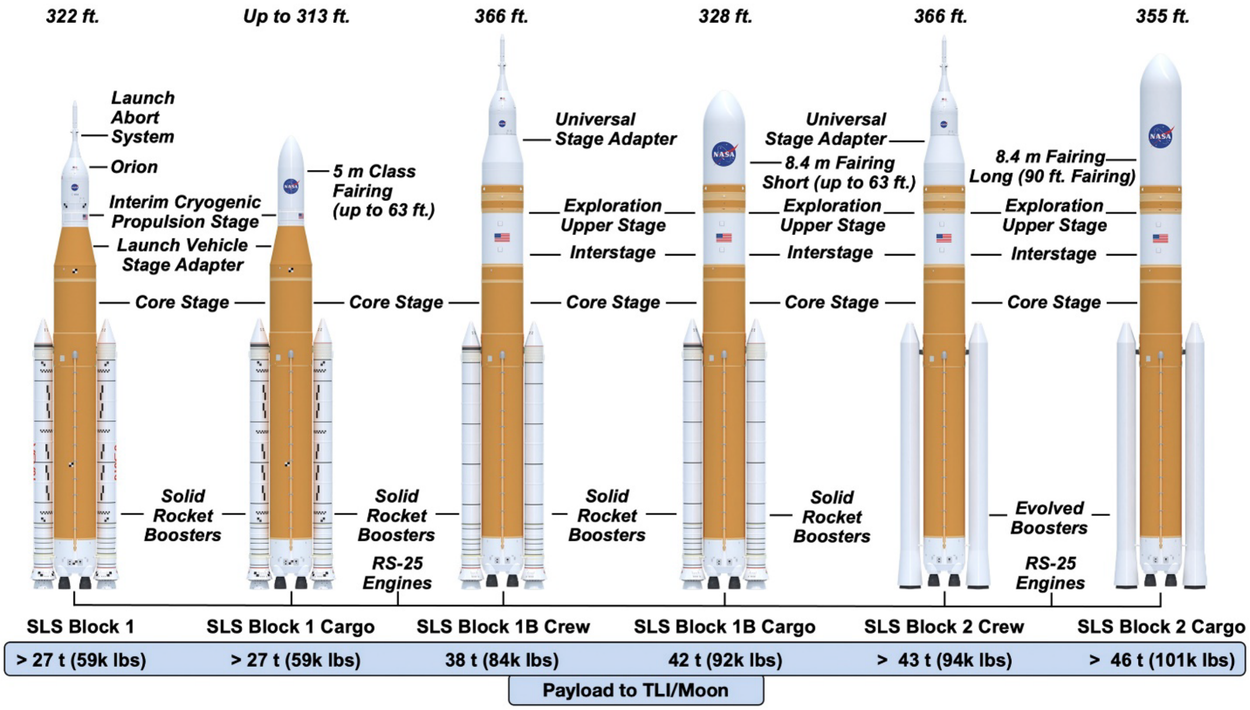


Figure 3: SLS variants and projected performance.

SLS Block 1 stands 322.4 feet (98 m) tall and weighs 5.75 million pounds (2.61 million kg) fueled in crew configuration (with Orion), which will be used on Artemis I. The vehicle has a maximum thrust of 8.8 million pounds with the SRBs providing approximately 7.2 million pounds (32,000 kN) and the remaining 1.6 million pounds (7,117 kN) coming from the RS-25s. During the first two minutes of flight, the SRBs provide at least 75 percent of the thrust. Approximately 416,000 pounds (1,850 kN) of thrust come from each RS-25 at launch; the engines produce more than 512,000 pounds (2,277 kN) of thrust once they reach vacuum conditions. The engines operate for the entire roughly 480-second core stage operation. Using the Interim Cryogenic Propulsion Stage (ICPS), SLS Block 1 is capable of sending more than 59,535 pounds (27,000 kg) of payload to trans-lunar injection (TLI). The ICPS provides the upper stage propulsion for Block 1. It is powered by a single Aerojet Rocketdyne RL10 LH2/LOX engine with 24,750 pounds (110 kN) of thrust. The stage is extended version of the United Launch Alliance (ULA) Delta IV Cryogenic Second Stage. The Artemis I crew configuration is shown below (Fig. 4).

Block 1B will succeed Block 1 and is 366 feet (112 m) tall and will weigh six million pounds (2.72 million kg) fueled. The ICPS will be replaced with the Exploration Upper Stage (EUS) with four RL10s. The EUS is designed by Boeing. The new stage will produce 97,360 pounds (433 kN) thrust, increasing the payload to TLI capability of the rocket. Heritage RS-25s performing at 109 percent thrust will be replaced with new-production engines operating at 111 percent rated power level (RPL), which also contributes slightly more thrust while incorporating newer manufacturing techniques, such as additive manufacturing, to streamline production. In the crewed Orion configuration, Block 1B will be able to send more than 83,766 pounds (38,000 kg) and more than 92,594 pounds (42,000 kg) in the cargo configuration into TLI. The 8.4 m-diameter payload fairing is available in varying lengths. A 62.7-foot (19.1 m) shroud will provide an available payload volume of 21,930 cubic feet (621 cubic m). A 10 m-diameter fairing is also under consideration.

SLS Block 2 will stand 366 feet (112 m) tall, weigh 7.4 million pounds (3.4 million kg) fueled, and have a maximum thrust of 9.5 million pounds (42,256 kN). The current SRBs will replaced with evolved boosters, increasing thrust from 3.6 million pounds (16,000 kN) each to 3.9 million pounds (17,300 kN). The evolved boosters will feature composite cases, instead of the steel cases used today. The current propellant will also be replaced with a more energetic propellant. The new boosters will first take flight on Artemis IX, following the end of the supply of the space shuttle-era cases. The EUS will be the upper stage. TLI payload capability increases to more than 94,799 pounds (43,000 kg) in crew configuration, while the cargo configuration has a TLI payload capability of more than 101,413 pounds (46,000 kg). Block 2 will retain the 8.4 m diameter payload fairing availability, and the 10 m fairing concept being studied.

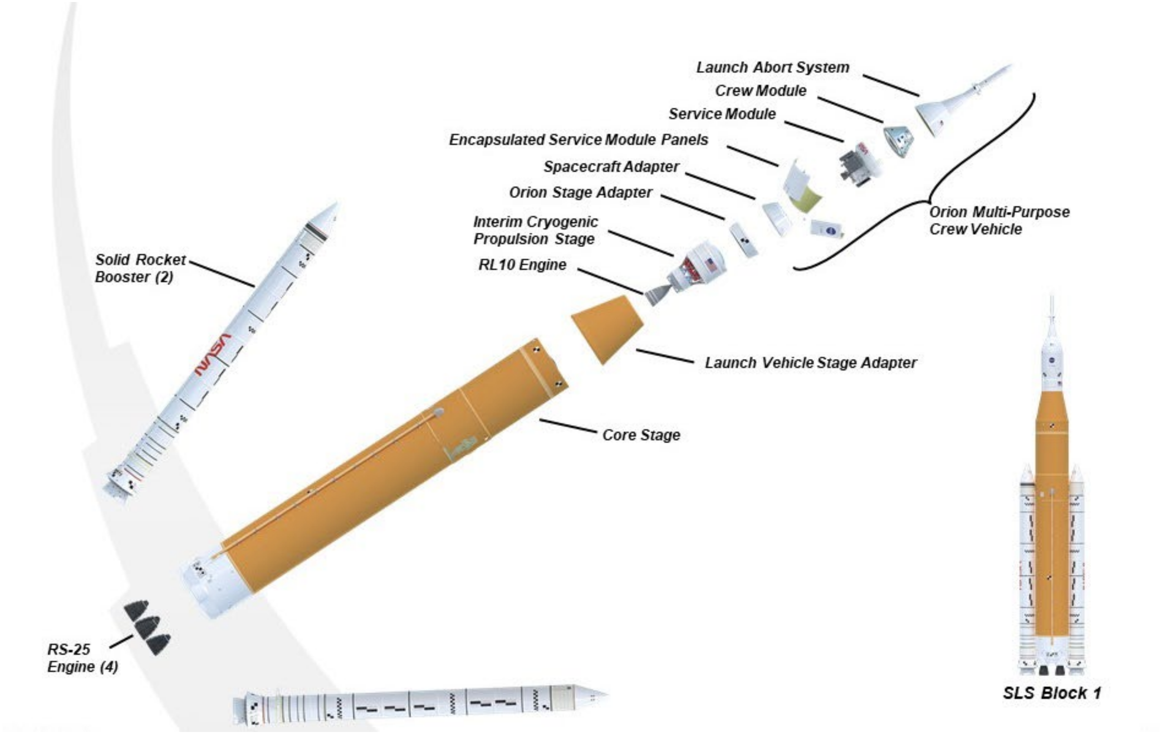


Figure 4: Expanded view of the Artemis I Block 1 vehicle.

ARTEMIS I TEST FLIGHT

The Artemis I mission will be the debut test flight of SLS and will launch the Orion spacecraft to a distant retrograde orbit (DRO) about the Moon. During the mission, Orion will travel approximately 40,000 miles (64,000 km) beyond the Moon – the farthest distance a spacecraft designed for humans has ever traveled. The highly elliptical lunar orbit will bring Orion as close as 62 miles (100 km) to the lunar surface. The mission duration is dependent on the exact launch date and will be between 25-42 days. The SRBs and core stage will inject the ICPS and Orion into an initial Earth orbit of approximately 20 by 1,000 nm (37 by 1,852 km). Following a perigee raise maneuver by the ICPS, the orbit will be approximately 100 nm by 1,000 nm (185 by 1,852 km).

After half of an orbit, the ICPS will perform the trans-lunar injection burn approximately 90 minutes after launch. Following spacecraft separation, the ICPS will deploy 10 secondary payload CubeSats at pre-determined times (Table 1).

Artemis I CubeSat	Mission	Estimated Deployment Time	Mission Orbit	Mission Duration
ArgoMoon	Perform proximity operations with the ICPS post-disposal; take external imagery of Earth and Moon by testing an advanced software imaging recognition system with high-definition cameras	L + ~ 3 hrs. + 40 min.	Geocentric	180 days
CuSP	Study solar and interplanetary particles supporting space weather research by determining proton radiation levels during Solar Energetic Particle (SEP) events and identifying suprathermal properties that could help predict geomagnetic storms	L + ~ 8 hrs. + 3 min.	Heliocentric	75 days
LunaH-Map	Research to understand the quantity of hydrogen-bearing materials in cold traps in permanently shaded craters of the Moon's South Pole	L + ~ 5 hrs. + 33 min.	Lunar	601 days (1.6 years)
LunIR	Perform a lunar flyby using a miniature high-temperature Mid-Wave Infrared (MWIR) sensor collecting spectroscopy and thermography data to address questions related to surface characterization, remote sensing, and site selection for future missions	L + ~ 6 hrs. + 3 min.	Lunar flyby	30 days
BioSentinel	Contains a yeast radiation biosensor that will measure effects of space radiation on DNA	L + ~ 3 hrs. + 40 min.	Lunar flyby	1 year
Lunar IceCube	Search for water in ice, liquid, and vapor forms as well as other lunar volatiles using a compact infrared spectrometer	L + ~ 3 hrs. + 40 min.	Lunar	< 2 years

NEA Scout	Equipped with a solar sail to rendezvous with an asteroid, gather detailed imagery, and observe the asteroid's position in space	L + ~ 5 hrs. + 10 min.	Earth and lunar flybys, targeting cislunar escape, enabling rendezvous with near-Earth asteroid	2.5 years
OMOTENASHI	Land on the lunar surface to demonstrate the feasibility of the hardware for distributed cooperative exploration systems	L + ~ 3 hrs. + 40 min.	Lunar	5 days
EQUULEUS	Fly to a libration orbit around the Earth-Moon L2 point and demonstrate trajectory control techniques within the Sun-Earth-Moon region	L + ~ 3 hrs. + 40 min.	Lunar	270 days
Team Miles	Fly autonomously using a sophisticated onboard computer system with propulsion supplied by evolutionary plasma thrusters	L + ~ 7 hrs. + 3 min.	Heliocentric	1 year max.

Table 1: The CubeSat payloads that will fly on the Artemis I mission have a wide variety of missions, destinations, and deployment times.

Artemis I originally had 13 6U CubeSats manifested, with universities providing several of the payloads. These university labs, as well as some NASA projects providing Artemis I CubeSat payloads, were adversely affected by the COVID-19 pandemic. In order to give the payload developers additional time to ready their CubeSats, NASA's Exploration Systems Development (ESD) decided to use the OSA structural test article (STA) temporarily in the stack for modal vehicle tests while the small satellites are simultaneously being installed in the flight OSA in a parallel processing flow. Ultimately, 10 payloads were able to make the deadline for installation into commercial off-the-shelf (COTS) dispensers and battery charging. The Outstanding MOon exploration Technologies demonstrated by NAno Semi-Hard Impactor (OMOTENASHI) CubeSat from the Japanese Space Agency (JAXA) can be seen in Fig. 5 as its team prepares it for the Artemis I launch.

Figure 5: The OMOTENASHI (Outstanding MOon exploration Technologies demonstrated by NAno Semi-Hard Impactor) team prepares its secondary payload for a ride on SLS. If successful, OMOTENASHI will be the smallest spacecraft ever to land on the lunar surface and will mark Japan as the fourth nation to successfully land a spacecraft on the Moon.

STACKING AND INTEGRATION MILESTONES

Stacking of the Artemis I launch vehicle began in November 2020 with the aft assemblies of the boosters, consisting of the aft segments, nozzles, and aft skirts, being integrated in KSC's Rotation, Processing & Surge Facility. The aft assemblies were then transferred to the mobile launcher (ML) and marked the first Artemis I hardware to be hard-mated to the ML. Remaining booster segments were then pinned together and built up on the ML. Following booster integration and the core stage Green Run test series in spring 2021, the core stage was transported from Stennis Space Center (SSC) to KSC where it underwent work to prepare it for its summertime stacking operations. The core stage was lifted out of the VAB transfer aisle and placed between the twin boosters on June 12, with the entire operation taking X hours. Following core stage integration with boosters, the Launch Vehicle Stage Adapter (LVSA), built by Teledyne Brown at Marshall Space Flight Center (MSFC), was added to the vehicle on June 22, followed by the ICPS on July 5. As previously mentioned, instead of stacking the flight Orion Stage Adapter (OSA), built by MSFC, and Orion capsule, the OSA STA and an Orion mass simulator were added on the stack for modal tests. Upon completion of the modal tests, the OSA STA and Orion mass simulator were de-stacked, and the flight OSA – with CubeSat payloads in dispensers – and Orion capsule were added to the stack on October 12 and October 20, respectively (Fig. 6). Prior to stacking, Orion's Launch Abort System (LAS) was integrated with the crew and service modules in KSC's Launch Abort System Facility (LASF).

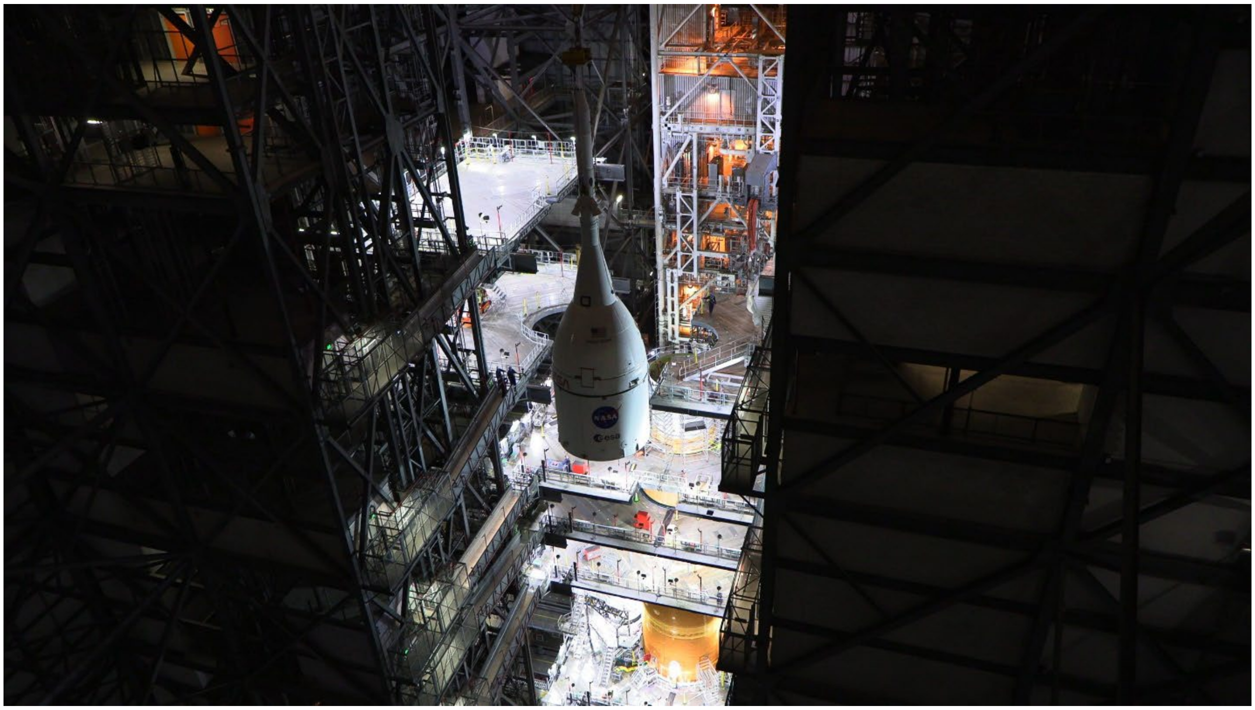


Figure 6: The Orion capsule is added to the Artemis I stack in the VAB at KSC on October 20, 2021.

TEST CAMPAIGN RESULTS

Throughout the vehicle's stacking, multiple test campaigns were conducted to ground computer models with real vehicle hardware characteristics (Table 2). Following the completed stacking of the boosters in early 2021, push-pull tests were conducted to collect data on their modal properties.

Following core stage, LVSA, ICPS, OSA STA, and Orion mass simulator stacking in the summer of 2021, the modal test program took place. The modal test series sought to understand the vehicle's natural frequencies to help ground computer models and improve the flight computers that will fly the rocket. The team placed hydraulic shakers at seven locations on the rocket and imparted forces. Additionally, a small hammer delivered calibrated taps near key parts of the navigation system to understand the dynamics local to those spots. A hammer on a dolly was also moved to different locations on the mobile launcher to impart further vibrations. In all, approximately 300 sensors attached to the rocket and mobile launcher detected, recorded, and transmitted the data to the engineers.

The test series was performed over multiple days, for 10 hours each day, during the overnight shift in the VAB when activity level in the building and surrounding areas is low. This quieter environment helped ensure a higher quality of data. The sensors remain on the vehicle and collected vibration data during rollout of the launch vehicle to Launch Pad 39B for WDR.

ITCO TEST	TEST EVALUATION OBJECTIVES
Modal	These tests characterize vehicle dynamics and include booster push/pull testing, a modal tap test, and integrated modal testing on the mobile launcher and crawler-transporter with Orion stage adapter test article and Orion mass simulator using hydraulic shakers and calibrated hammers.
Interface Verification	Also performed with the Orion stage adapter test article and Orion mass simulator as well as with the Artemis I Orion, this test verifies functionality and interoperability of SLS-to-Orion interfaces.
Communications End-to-End	This critical test validates communications between the vehicle and tracking network.
Umbilical Release and Retract	Testing the timing of booster arming and firing and the command for umbilical release.
Vehicle Assembly Building Project-Specific Engineering	Element-level testing of SLS in the VAB
Countdown Sequence	Training the launch team with Artemis I flight hardware in the loop.
Flight Safety System	Rehearsal for pre- and post-wet dress and ordnance and flight termination system communications.
Dynamic Rollout (x2)	Rolling the vehicle from the VAB to Launch Pad 39B and back to compare actual loads to analytical models
Pad Project-Specific Engineering	At the launch pad, testing radio frequency; guidance, navigation, and control; and performing final ordnance tests.
Wet Dress Rehearsal	Testing propellant loading procedures, structural response, thermal conditioning and loading procedures; vehicle control systems; avionics and software checkout; electromagnetic interference; guidance and navigation; main propulsion system; and engine and booster nozzle steering

Table 2: After element-level and "Green Run" testing, the Integrated Test and Check Out (ITCO) series analyzed and checked out the integrated Artemis I launch vehicle and prepared teams for launch.

In addition to the modal tests, teams also completed a number of other tests, including the Interface Verification Test, the Communications End-to-End Test, the Umbilical Release and Retract Test, and the Countdown Sequence Test (Fig. 7). They also uploaded the flight software that will fly the mission.

During one of the evaluations, which involved powering up the RS-25 engines, a problem was discovered with one of the engine controllers – the computers on the RS-25 engines. After analysis, the decision was made to remove and replace the engine controller – the first time this procedure has been done with SLS on the mobile launcher. The controller was sent to manufacturer Honeywell for further analysis, where the issue was tracked to a memory chip in the controller. Proper flight rationale has been developed, and the problem is not an issue for flight.

Following the complex series of program-specific engineering tests (PSETs), multiple integration tests, and closeout activities, the vehicle was rolled to Launch Pad 39B for further tests, including WDR. During rollout to Launch Pad 39B, which started in the evening of March 17 and concluded on the morning of March 18, the DRT captured further vibration data. The rolling launch vehicle and ML reached a top speed of 0.82 miles per hour (1.3 km/h). Teams had a complex throttle profile for the rollout, which included multiple "abrupt" stops, to collect data. Preliminary information indicates that the launch vehicle performed well during rollout, and the computer models are well-grounded. In total, the 4.2-mile (6.72 km) trip from the VAB to the launch pad took 10 hours, 28 minutes. During non-test conditions, it is estimated that the rollout will take approximately 8 hours.

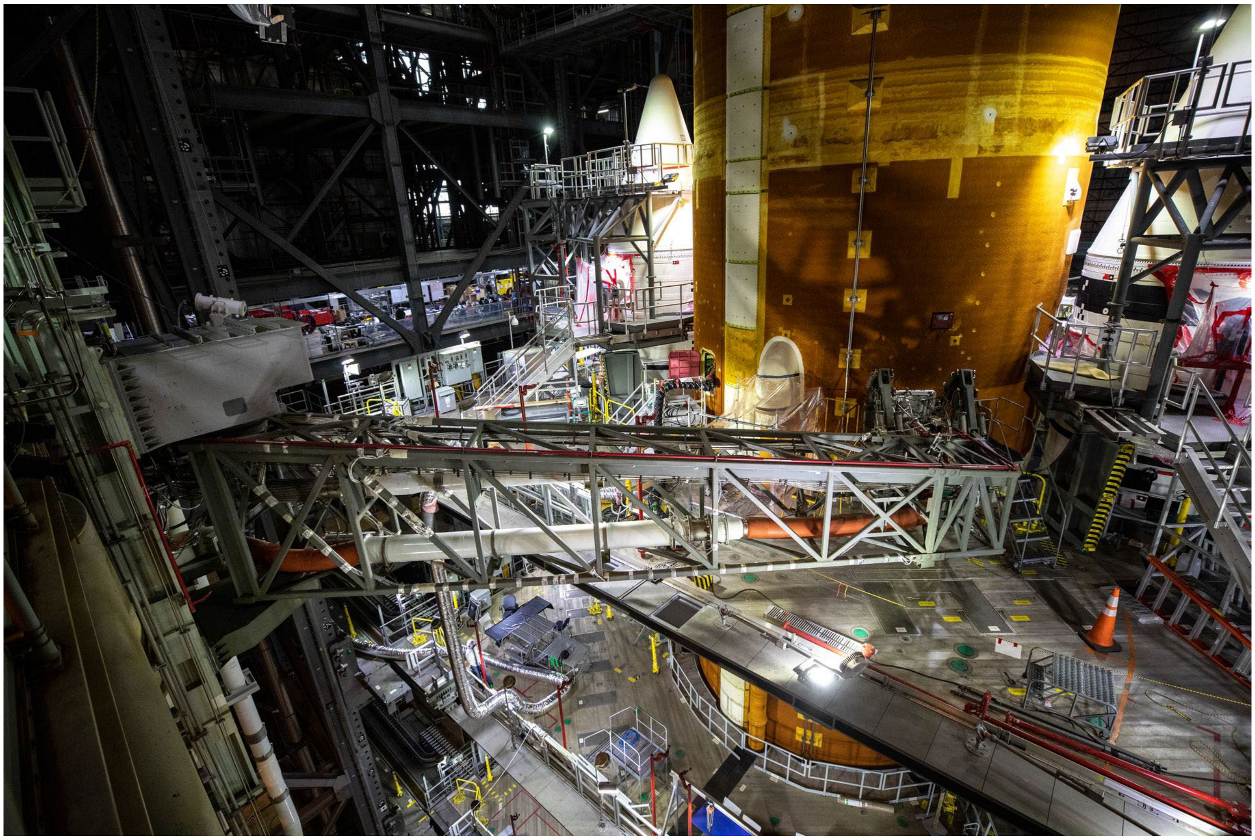


Figure 7: The core stage intertank umbilical – one of multiple connections on the mobile launcher that will provide power, communications, and pressurized gases to the rocket – is attached to SLS in the VAB as part of the ITCO test series.

Once on the launch pad, teams conducted another series of PSETs. The first objective was to mate the ML and vehicle to the launch pad's cryogenic, power, and communications systems. These systems fill the vehicle with cryogenic propellants, supply it with ground power, and relay communications from Firing Room 1 in the Launch Control Center (LCC) to the vehicle and data from the vehicle to the LCC and the various other support centers around the country. The pad PSETs include RF and polarimetry testing before WDR. WDR simulates launch operations by filling the core stage and ICPS with the more than 700,000 gallons of liquid hydrogen and liquid oxygen. The test is designed to simulate the final portion of pre-launch activities, including a launch countdown beginning approximately two days before "launch." The test runs through cryogenic propellant loading, stopping before RS-25 engine start at T- 6.6 seconds. Following the stop, the team performs a recycle to the terminal countdown hold at T- 10 minutes and runs through the latter part of the test again. Following those operations, teams de-tank the propellants, safe the vehicle, and prepare it for rollback to the VAB (including a second round of dynamic rollback test readings.)

Figure 8: Liquid cryogenics vent from the Artemis I SLS during WDR.

WDR initially started on April 1, with a call-to-stations. During the afternoon hours of April 1 and overnight into April 2, the 600-foot (183-m) tall lightning towers were struck by lightning. Three strikes were on Tower 2 with a fourth strike on a catenary wire running between the towers. Teams reviewed the data, practicing lightning strike analysis protocol, and determined that SLS, Orion, and the ground systems were safe to continue with the countdown. The lightning protection system performed as designed. Prior to the first tanking attempt on April 3, positive pressure fans that prevent hydrogen vapors from accumulating in enclosed spaces on the ML were found to be not operating properly. If allowed to accumulate, the gaseous hydrogen could ignite with a small spark and result in an explosion on the pad. In the interest of safety at Launch Pad 39B, a 24-hour scrub was initiated to remedy the solution. On April 4, as the count was preparing to resume, the vendor that supplies gaseous nitrogen (GN2) to KSC suffered an outage of all six of their pumps. Gaseous nitrogen is used to purge lines of any contaminants. Once the problem was resolved, the count was resumed at T-6 hours, 40 minutes.

LOX Slow Fill successfully began, which helped condition the tanks for the cryogenic temperatures. As the team progressed into the next phase of LOX loading, temperatures in the system increased due to the pump speed increases. The possibility of geysering was introduced, so teams held the count to solve the problem. Once the LOX loading plan was re-worked, the countdown resumed. During chill down of the LH2 lines in preparation of LH2 loading, the panel that controls the vent valve on the ML was found to be non-responsive. After troubleshooting, teams were forced to call a scrub in order for crews to go to the pad and fix the issue. At the time of the scrub, the core stage LOX tank was approximately 49 percent full.

On April 14, the next attempt to fill the tanks as part of WDR was initiated. Teams used a modified approach that called for filling the core stage LH2 and LOX tanks and chilling down the ICPS connections to cryogenic temperatures to look for leaks in the upper stage connections. The modifications were necessary due to a faulty helium check valve discovered in the ICPS. With the valve operating improperly, it is not possible to fill the ICPS tanks. Replacement of the valve can only be done in the VAB. During the test, the gaseous nitrogen system failed, delaying the start of cryogenic loading. When LOX flow was initiated, a high-temperature geysering issue occurred. Teams continued to work through the problems and were able to resume LOX load and start LH2 loading. During simultaneous flow of both fuel and oxidizer into the core stage, high pressure in the LH2 occurred, causing an automatic stoppage of LH2 flow. An LH2 leak was discovered in the tail service mast umbilical, requiring a scrub. Propellants were drained and the vehicle was safed, as teams evaluated the problems and developed solutions. Chill down of the ICPS systems was complete, and those objectives were met. At the time of scrub, the LOX tank was approximately 49 percent full, while the LH2 tank was approximately 5 percent full. Venting of cryogenics during a WDR attempt can be seen in Figure 8.

Following data analysis, the decision was made to move the vehicle and ML back to the VAB while the supplier of the GN2 makes necessary upgrades to its systems. Going back to the VAB enables the EGS teams to replace the broken ICPS check valve and fix the LH2 umbilical leak while protecting the vehicle from further stresses caused by the outdoor environment conditions. When work is complete, SLS, Orion, and the ML will roll back out to Launch Pad 39B for WDR. Upon completion of WDR, it will be rolled back to the VAB for closeouts and launch later this year.

Figure 9: The Artemis I launch vehicle is rolled to Launch Pad 39B on March 17-18 for WDR and other tests.

While engineers and technicians have been preparing and testing the hardware and software, operations teams have been conducting simulations to prepare the teams and communications systems that will be used during Artemis I. Teams are also preparing for launch by conducting countdown and mission simulations. These activities include teams at KSC, the SLS Engineering Support Center (SESC) at MSFC, the Flight Operations Directorate at JSC, and several contractor locations that are critical to pre-launch and launch success. The simulations provide the teams practice with the procedures and enable refinement of the communication pathways, as the SESC will be monitoring data and camera views of the rocket to support the KSC Launch Control Center (LCC). The SESC also supported the core stage Green Run test series, collecting and storing data for analysis.

PROGRESS TO ARTEMIS II AND BEYOND

Progress is not limited to the Artemis I mission. Hardware for Artemis missions II, III, and IV is well underway.

For Artemis II, the core stage elements have all been manufactured, and on March 18 the forward join – consisting of the liquid oxygen tank, intertank, and forward skirt – was mated to the liquid hydrogen tank. This formed the “fourth-fifths join.” The final element of the core stage that will be assembled is the engine section, which will be added later in 2022. All of the booster propellant segments for the mission are complete and are in storage. The LVSA has completed manufacturing and thermal protection system installation at MSFC. The frangible joint assembly has completed installation, and outfitting of sensor wiring is ongoing. The OSA is also manufactured and painted. The ICPS completed manufacture at ULA’s Decatur, Alabama facility and is in final processing at ULA’s Cape Canaveral facility. It will be transferred to NASA later this year. The RS-25 core stage engines and the RL-10 ICPS engine are also complete.

An important facet of the Artemis II mission is the proximity operations activity that will be performed after TLI. After Orion separates from the ICPS and OSA, the astronauts will turn the spacecraft around and test the vehicle’s maneuverability and handling characteristics. Targets will be placed on the ICPS, which will provide visual marks for lining up and evaluating how the spacecraft behaves. Those operations will be critical for docking procedures for subsequent Artemis missions. Following completion the proximity operations, the ICPS will perform its disposal burn, which will place it in an Earth-centric disposal orbit. The Artemis I ICPS, for comparison, will be placed in a heliocentric disposal orbit after it deploys the CubeSat payloads.

Figure 10: The Artemis II core stage forward join – consisting of the LOX tank, intertank, and forward skirt – is mated to the LH2 tank at Michoud Assembly Facility.

Artemis III core stage elements are being manufactured now. The liquid hydrogen tank has completed proof testing and is undergoing leak tests. The liquid oxygen tank is structurally complete, and the engine section is undergoing bracket and hardware installation. Welding is currently in progress on the forward skirt and intertank. One of the four RS-25 engines is complete with the remaining three in processing. All 10 booster motor segments are cast with propellant, and nine of them are complete. Work on the forward and aft booster assemblies is underway at KSC. Welding is complete on the OSA, and the LVSA is being welded. Manufacturing of the ICPS is underway at ULA's Decatur facility, with that upper stage being more than 60 percent complete at the time of writing.

Figure 11: Two RS-25 engines for the Artemis III mission undergo inspection at SSC, left, and an RS-25 nozzle from the new production line for Artemis V and beyond, right.

Artemis IV will debut the SLS Block 1B variant, featuring the more powerful EUS in-space stage. Early work has begun on core stage's forward skirt, liquid oxygen tank, liquid hydrogen tank, and engine section at Michoud. The RS-25 engines are scheduled to be processed and stored for shipment later this year. Refurbishment and production has begun on the booster hardware motor segments. Two of the ten motor segments have been cast with propellant. Welding on the demonstration unit and confidence articles for the EUS are underway.

Beginning with Artemis V, new-production RS-25 engines will be used. Manufacturer Aerojet Rocketdyne is building the first six of the new engines that will cost less to manufacture and will operate at 111 percent thrust compared with the current engines that will operate at 109 percent thrust. These new engines incorporate modern fabrication techniques, including 36 additively manufactured parts.

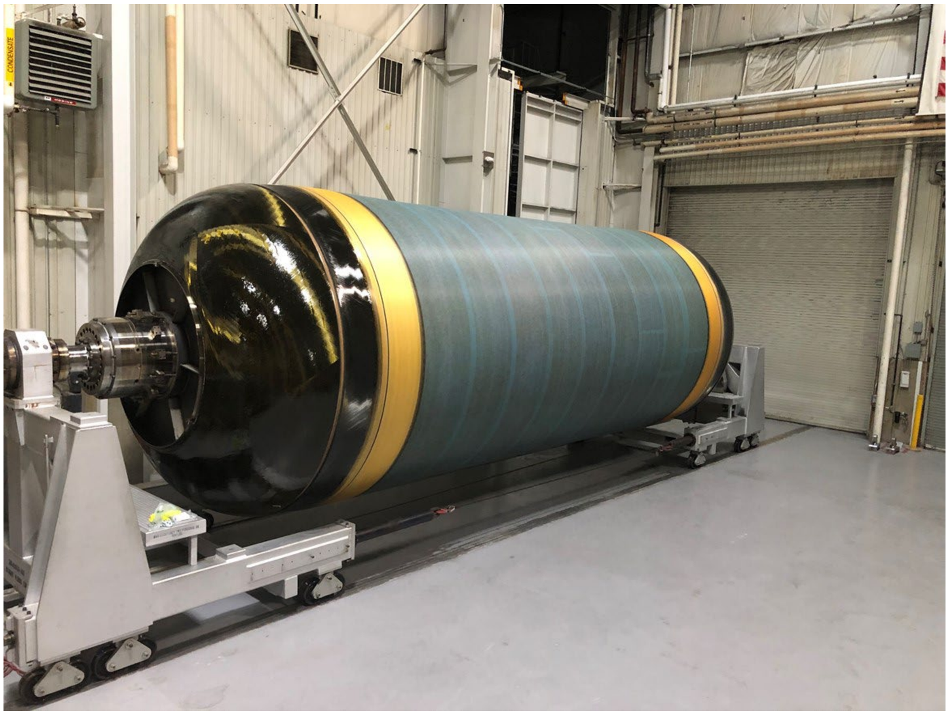


Figure 12: The evolved boosters for SLS Block 2 will use composite cases, instead of the steel cases remaining from the Space Shuttle Program. In this image, we show a composite case that will be used as a pathfinder test article.

While new engines and engine components are being built, the Retrofit 3 test series is underway at SSC. The test series is focused on evaluating and qualifying the components and engines. In March, the first part of the test series, Retrofit 3a, was completed. The Retrofit 3a test series was comprised of five engine tests.

Figure 13: An RS-25 rocket engine is tested at SSC in February as part of the Retrofit 3a test series.

Artemis IX will debut the SLS Block 2 variant. Block 2 includes evolved solid rocket boosters. The NASA and Northrop Grumman teams are designing, developing, and testing these next-generation boosters, which will feature composite case and a more energetic propellant than used today. The boosters will debut on Artemis IX, when the supply of cases from the space shuttle era has run out. The first full-scale static test of the new booster is scheduled for 2024, and the forward dome, aft cylinder, and nozzle hardware have been produced for the test. In 2021, teams performed three 24-inch (0.61 m) solid rocket motors test at Marshall to evaluate new booster nozzle and insulation materials.

Figure 14: A subscale solid rocket motor test, left, at MSFC supports the evolved boosters, while a full-scale SRB test Utah, right, evaluates potential new materials and processes for missions beyond Artemis III.

CONCLUSION

NASA's Artemis I mission will capture valuable flight data of the agency's new rocket. The data will validate computer models, providing the flight rationale for the Artemis II mission which will be the first with astronauts onboard, further laying the groundwork for humanity's return to the Moon and future missions to Mars.

While work on Artemis I continues, progress towards Artemis missions II, II, IV, and IV continues. Metal is being welded, wires and plumbing are being routed, and software is being written and tested. The forward work ensures that the launch vehicles for the next missions are ready to support NASA’s human exploration goals.

SLS is the backbone to the agency’s next era of deep space human exploration. The rocket, capable of carrying crew and cargo, will serve the nation and support the country’s most ambitious human and robotic exploration missions. On the shoulders of SLS, history and science books will be re-written, and life on Earth will improve for everyone.

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