NASA's Space Launch System: Comprehensive Test Program Leads to Mission Success during Artemis I Flight Test

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NASA's SLS (Space Launch System) rocket had a successful first launch on Nov. 16, 2022, sending an uncrewed Orion spacecraft to the Moon on the agency's Artemis I mission and deploying 10 CubeSat payloads. Orbital insertion parameters, including insertion velocity and altitude, were within hundredths and tenths of a percent respectively of predicted values, corroborating data collected from the individual elements that showed similar performance accuracy. Artemis I was a true test flight designed to collect data, confirm, and refine computer models, and validate hardware test data. Key to its success was a comprehensive test program befitting a crew-rated launch vehicle. This paper and presentation will cover the SLS design and development programs that led to the successful Artemis I mission and set the stage to send the first astronauts back to cislunar space since the Apollo 17 crew in 1972.

I. Introduction

NASA's SLS (Space Launch System) rocket is the agency's super-heavy lift launch vehicle to send crew, cargo, and other necessities to the Moon through the Artemis campaign. The evolvable rocket, outfitted with a wide-diameter payload fairing, is also capable of sending large spacecraft and telescopes to destinations throughout the solar system. On Nov. 16, 2022, SLS launched for the first time on a historic mission that sent an uncrewed Orion spacecraft on a 25.5-day mission around the Moon.

SLS not only performed its mission, but it did so with high accuracy and precision. Post-flight data analyses show that SLS met a multitude of pre-flight parameters to within hundredths and tenths of a percent. Furthermore, the data indicate SLS is safe to launch astronauts, including the crew of four launching on the Artemis II lunar flyby mission, targeted for 2025.

SLS takes advantage of heritage space shuttle hardware, including Northrop Grumman-manufactured solid rocket boosters and Aerojet Rocketdyne-made RS-25 liquid hydrogen (LH2) and liquid oxygen (LOX) engines. The program also benefits from numerous government and industry team members with extensive operational experience from the Space Shuttle Program. These factors help reduce development and operational risk in comparison to developing a launch system with all brand-new propulsion elements. The interim cryogenic propulsion stage (ICPS), the upper stage for the SLS Block 1 variant, is a derivative of the Delta Cryogenic Second Stage that prime contractor United

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Launch Alliance (ULA) has flown for years. It uses a single RL10 engine, which has been a staple in the spaceflight industry for decades.

On Artemis IV, the fourth flight of SLS, the new Exploration Upper Stage (EUS) using four RL10 engines will debut, increasing the single launch capability from 59,000 pounds (27 metric tons [t]) to translunar injection (TLI) to 84,000 pounds (38 t) to TLI in crewed configuration. Called the Block 1B variant, it will fly multiple flights while the evolved boosters that will mark the Block 2 vehicle are developed. The Block 2 variant will further increase the single launch payload mass to TLI to 95,000 pounds (43 t) in crewed configuration. Cargo-only configurations have greater mass capability.

II. Artemis I Flight Results

The ultimate test of SLS came in November 2022 when SLS launched for the first time and in-flight data on SLS were collected (Fig. 1). The 25-day flight collected data that was analyzed for several months leading to final reports on every aspect of the mission.

SLS's performance was nominal, achieving precision and accuracy within 0.3 percent for many parameters. Highlights from launch include:

- 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.
- At main engine cutoff: the vehicle was traveling at 25,579.86 ft./sec. (7,796.74 m/sec.); predicted velocity was 25,586.44 ft./sec. (7,798.75 m/sec.).
- Orbital insertion was at an altitude of 87.3 nautical miles (161.7 km), and parameters were 972.6 nautical miles (1,801 km) by 15.9 nautical miles (29.4 km). Predicted parameters were 975 nautical miles (1,806 km) by 16 nautical miles (29.6 km).
- RS-25 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 18-minute TLI burn accelerated the stack to more than 22,000 mph (35,406 km/h.). The burn was a record long-duration burn of an RL10.
- 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.
- The flight software 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.

Figure 1. Artemis I launch on Nov. 16, 2022.

III. Testing Leads to Successful Flight

SLS was designed from the beginning to be part of a crew-rated launch system, and critical decisions and trade-offs were made to ensure that. A comprehensive test program on each component of the rocket was conducted, followed by additional series on the integrated elements and, ultimately, rocket.

A. Liquid Engine Testing

SLS inherited sixteen shuttle-era engines to support the first four launches. To ensure those heritage RS-25s were ready for SLS, teams subjected a pair of dedicated ground test engines to SLS performance requirements and operating environments. Instead of being mounted on the bottom of the spacecraft and on the side of the fuel tank (as they were with the space shuttle configuration), they are mounted at the bottom of the fuel tanks (i.e., the core stage) and between the solid rocket boosters on SLS.

In several series of test campaigns, engineers collected data on how the engine performed at higher thrust levels. While the engines routinely operated at 104 percent during shuttle missions, they would be required to operate at 109-percent of original rated power level (RPL) on SLS. In addition to the higher thrust levels, the engines experience higher propellant inlet pressures and lower temperatures than they did on the space shuttle due to the inline configuration directly below the propellant tanks. Testing also included development of engine software, additively manufactured parts, and green running new engine controllers. Two previously unassembled heritage RS-25 engines were green run hot fire tested as well.

The series accomplished a total of 6,465 seconds of hot fire time with 70 percent of the time (4,526 seconds) spent at 111 percent or higher power level. The test series successfully completed 73 different verification objectives and 30 development objectives required for the RS-25 Design Certification Review (DCR) planned later this summer. Since conception all SLS-related testing, RS-25 has accumulated 69 engine starts and over 34,000 seconds of hot fire time.

The thrust vector control systems used to steer the RS-25s during flight were tested at Redstone Arsenal in Huntsville, Alabama. The hydraulically powered actuators are heritage space shuttle hardware modified for SLS. Vibration testing was critical as the SLS flight environment results in higher force than the space shuttle environments. Using a shaker table, approximately 16,000 pounds of force (71.2 kN) were added to the actuator while under vibration.

B. Booster Testing

Subscale and full-scale booster testing were critical to the success of Artemis I. SLS's five-segment boosters are the most powerful solid rocket boosters ever developed for launch.

Multiple tests of the 24-inch (0.61 m) diameter subscale motor at NASA's Marshall Space Flight Center in Huntsville, Alabama, provided critical data. The 20-foot (6.1 m) long motor was hot fired vertically to collect data on insulation, propellant, and nozzle performance in a launch orientation, as well as to look for evidence of slag material that could build up in the base of the motor. Multiple horizontal tests occurred, and more are scheduled to support the advanced booster development, which will result in the new boosters coming online beginning with Artemis IX.

Five full-scale motor tests were conducted at prime contractor Northrop Grumman's Promontory, Utah, facilities. The motor is 12 feet (3.66 m) in diameter and more than 150 feet (45.7 m) long.

The first qualification test demonstrated acceptable booster performance at 90 degrees Fahrenheit – the highest end of the boosters accepted propellant temperature range. During the full duration test, temperatures inside the booster reached more than 5,600 degrees Fahrenheit. More than 530 instrumentation channels collected data to help assess 102 design objectives – including propellant performance, motor insulation and liner performance, and the overall design of the new nozzle.

The fifth test evaluated the booster on the coldest end of the acceptable temperature range – 40 degrees Fahrenheit. During the test, 82 test objectives were measured through more than 530 channels. The successful two-minute, full duration test provided valuable data to understanding the effect of low temperatures on propellant performance.

C. Structural Testing

One of the largest test programs was qualifying the vehicle's elements structurally. Test articles of the ICPS, launch vehicle stage adapter (LVSA), and core stage LH2 tank, LOX tank, intertank, and engine section were evaluated in new test stands at Marshall. Hydraulic pistons exerted forces on the components that mimic expected launch and ascent environments.

Engine section structural testing was completed in 2018 in a self-reacting test stand. More than 50 actuators simulated more than 3 million pounds of force (13,345 kN) of upward thrust and up to 750,000 pounds of force (3,336 kN) of loads on each side to simulate the boosters. Over 3,000 channels of data were collected during each test.

The LH2 tank was tested in a new stand at Marshall. Using hydraulic actuators, a series of 37 tests simulated liftoff and flight stresses on the tank. No signs of deformation were found, and the tank design was qualified for flight. In order to collect the full envelope of structural characteristics, the tank was then tested to failure. It was the largest test-to-failure ever of a NASA rocket stage fuel tank. The tank withstood over 260 percent of expected flight loads for more than 5 hours before a buckle was detected.

Similarly, the LOX tank was evaluated. NASA and Boeing completed 24 tests on the tank. The LOX tank withstood all the pressures necessary, and its test-to-failure point was within 2 percent of the predicted value, failing circumferentially in a weld location as predicted (Fig. 2).

Figure 2. The LOX tank (left) and LH2 tank structural test articles were tested to failure.

The Orion stage adapter (OSA), ICPS, and LVSA were all tested as a single unit to qualify them for flight. The core stage intertank was also tested and qualified.

During the test campaign five structural test articles underwent 199 separate test cases and more than 421 gigabytes of data were collected to add to computer models used to design the rocket.

A prototype of the OSA was also evaluated both structurally and in flight as part of the Exploration Flight Test-1 (EFT-1) that launched in December 2014. EFT-1 sent an Orion spacecraft test article on a 3,600-mile (2,160 km) high-altitude mission. Launch was on a Delta IV Heavy, and while testing the Orion spacecraft was the primary objective, a test article of the OSA was flown, connecting the spacecraft to the launch vehicle. Prior to the flight, the adapter was structurally evaluated. Twenty-five test cases showed that the adapter could withstand loads higher than seen in flight.

Prior to the LH2 and LOX structural test campaign, the Shell Buckling Knockdown Factor Project evaluated a test tank on its structural integrity. The resulting data helped engineers design, build, and test the LH2 and LOX tanks. The aluminum-lithium tank was made from unused space shuttle tank hardware and marked with in 70,000 black and white polka dots that helped high-speed cameras measure any buckles, rips, or strains.

D. Software Testing

The flight software for SLS is designed, written, and tested at Marshall. Flight software was tested in Marshall's Systems Integration Lab (SIL) – the most accurate representation of SLS's entire avionics and software system. In addition to having flight computers and avionics, the lab also has emulators for SLS's propulsion systems, Orion, and Launch Control Center (Fig. 3).

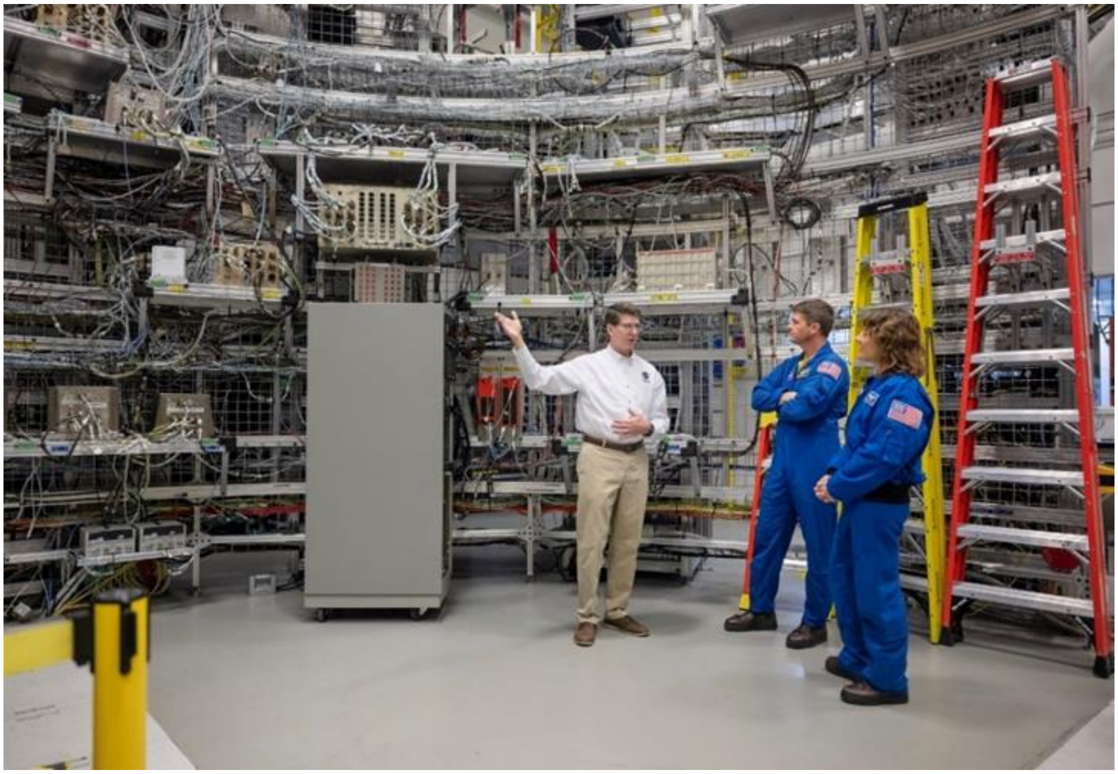

Figure 3: Dan Mitchell, NASA's lead SLS integrated avionics and software engineer (left), shows Artemis II astronauts Reid Wiseman (center) and Christina Koch (right) software test facilities at Marshall.

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. The software was tested across three integration labs.

An early test program called the Launch Vehicle Adaptive Control (LVAC) experiment helped refine and improve the flight software. Using an F/A-18 fighter jet out of NASA's Neil A. Armstrong Flight Research Center in Edwards, California, the adaptive algorithms for SLS's flight control systems were loaded onto the aircraft and SLS flight profiles were flown. These tests enabled evaluation of the algorithms, particularly for SLS handling in the event of unexpected winds or higher than expected thrust. Dozens of tests were conducted over multiple flights, with each test scenario lasting up to 70 seconds.

As noted in the Artemis I Progress section, the software performed nominally during Artemis I.

E. Wind Tunnel Testing

One of the earliest test programs was the wind tunnel testing. Scale models were placed in various chambers to evaluate the vehicle design at different stages of flight.

Liftoff transition testing of a 67.5-inch (1.71 m) model of SLS was completed in a subsonic wind tunnel at NASA's Langley Research Center in Hampton, Virginia. During the tests, the model was vertically oriented to simulate launch configuration. Air was moved across the model at high angles, simulating possible wind angles SLS sees on the launch pad and during launch. These low-speed wind tunnel tests were critical in understanding the dynamics of the vehicle as it liftoffs and clears the mobile launch tower. Four different payload configurations of SLS were tested.

Figure 4. Wind tunnel testing of booster separation. Pressurized air was blown through the solid rocket boosters to simulate the booster separation motors firing.

Supersonic wind tunnel tests at NASA's Ames Research Center in Silicon Valley, California, simulated unsteady aerodynamics to understand local vibrations on the rocket. Four models of three different crew and cargo configurations of SLS were tested. The models were outfitted with transducers to collect data. Wind speeds from 0.7 Mach to 1.4 Mach were used as were a series of buffet tests to see how SLS responds at low frequencies. Mach numbers were then increased, ranging from Mach 1.55 to Mach 2.5, simulating high-supersonic flow.

One of the most dynamic phases in SLS's ascent is booster separation. Eight motors on each booster push the depleted rockets away from the rest of the vehicle. Wind tunnel tests at Langley provided insight into the aerodynamic forces the vehicle sees during this phase of flight. Booster clearances were also validated to ensure that the boosters do not recontact the vehicle at separation. Speeds over 2,400 mph (3,862 km/h) were simulated during the 800 runs (Fig. 4).

F. Subscale Testing

Subscale testing was tremendously valuable for SLS development (Fig. 5). In addition to the aforementioned wind tunnel testing, data on base heating, ignition overpressure, and acoustic effects during launch were collected using subscale models. An early set of tests assembled four small engines in a cluster to collect vibration and noise data in the engine section and booster area. Both high and low frequency vibration data were collected to understand the launch and flight environments as they affected the vehicle, payloads, and the launch structure.

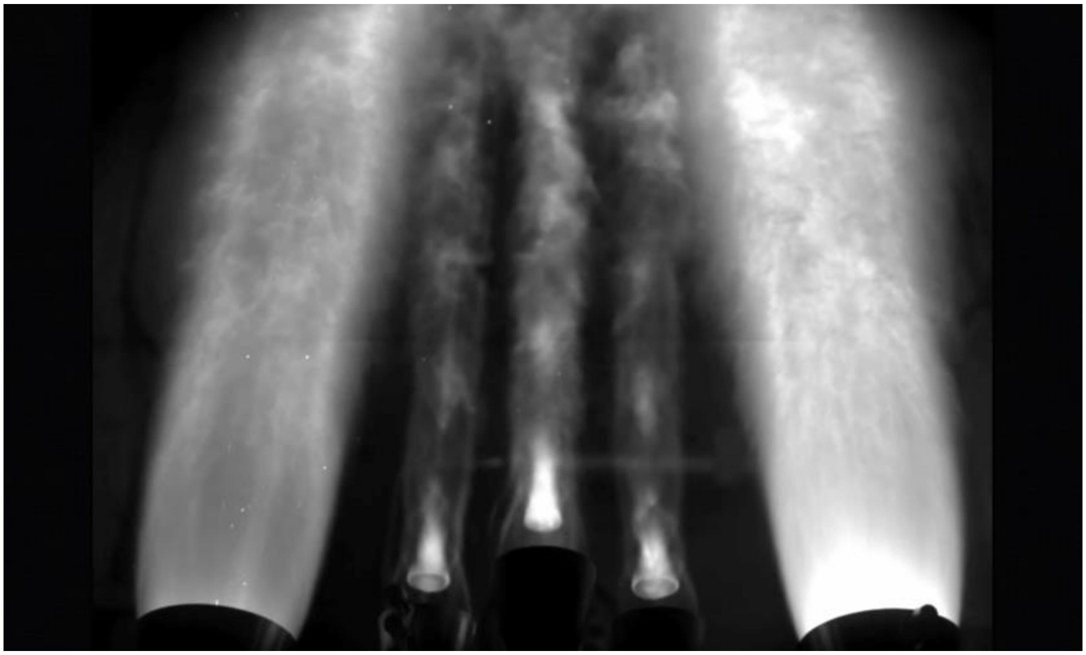

Figure 5. The 2-percent scale models of the SLS boosters and core stage engines are ignited for a 100 millisecond, hot fire test.

In an effort to understand the base heating characteristics of SLS, engineers designed, built, and hot fire tested 2 percent scale models of the SLS engines and boosters. The entire model was 6.5 feet (1.98 m) tall. The models were fired for approximately 50-150 milliseconds per test, which provided data on the convective heating environment at the base of the rocket. The full-stack configuration had 200 heat flux and pressure sensors. Approximately 85 tests were conducted. The data were then used to help set the specifications for SLS's base thermal protection system.

Early career engineers also gained critical hands-on and problem-solving experience working through these test programs.

G. Additional Testing

In addition to structural, avionics and software, engine and booster, and wind tunnel testing, other test programs to the development of SLS were vital.

Testing of a new cryogenic insulation foam at Marshall evaluated how the foam performs across a spectrum of environments, including through aerodynamic heating seen at launch, long duration storage, and measuring the density of the materials. To evaluate the material, hundreds of 24-inch by 24-inch (0.61-m by 0.61-m) panels were sprayed with foam and studied.

The insulation protects against ice build-up during pre-launch activities and mitigates heat flow to the propellants during ascent. On average, the foam on SLS is approximately 1 inch (2.54 cm) thick but can vary depending on the hardware being insulated. The closed-cell materials provide greater strength and higher resistance to heat flow and moisture. The foam is more environmentally friendly than its predecessor, as its materials are non-ozone-depleting and flame resistant.

Due to the different launch environment of SLS, new hydrogen burn-off igniters (HBOIs) had to be designed for SLS. The igniters clear out any excess hydrogen near the engines at ignition to prevent any unintended explosions that could damage the launch vehicle. SLS uses 12 HBOIs on each launch, dispersing sparks at least 15 feet (4.6 m) to the right locations under the vehicle. During testing, high-speed cameras recorded the performance, including the throw distance and area of coverage of the particles.

Qualification work not only focused on the engine side of the system but also on the core stage side of operation. An extensive anti-geyser test program for the LOX tank used a 40-foot (12-m) tall replica of the LOX tank feed system to ensure that when LOX is loaded onto the vehicle, heat buildup does not occur. Should heat be introduced into the system, it can cause bubbles in the LOX, which displaces the liquid and allows it to crash down – which is known as geysering. To prevent the energetic phenomena, helium is injected during tanking, which causes the LOX to circulate and remain homogeneous throughout. The test program ran more than 120 hours of testing, providing data into system-specific behaviors and for model validation.

While developing structural test articles and flight hardware, the SLS team also built three pathfinder articles. The structures mimic the size and shape of the core stage, RS-25 engine, and solid rocket booster, enabling teams to practice the procedures needed to move and place the flight hardware. Through use of the pathfinder articles, the team gained critical experiences and procedures were refined prior to the handling of the flight hardware.

Training the SLS and Artemis I launch teams was another critical investment. Beginning many months prior to launch, SLS began conducting simulations on different aspects of pre-launch and launch, including tanking and ascent. Joint simulations with Exploration Ground Systems and Orion followed, ensuring the hundreds of people at multiple sites around the country were properly prepared.

H. Green Run Testing

The Green Run test series at NASA's Stennis Space Center in Bay St. Louis, Mississippi, evaluated the integrated core stage in tanking and launch environments. Various characteristics were studied, and data were collected during the campaign, which culminated in tanking and core stage hot fire.

The Green Run tests were:

- Test 1: Apply forces simulating launch to the unpowered, suspended core stage to ensure the stage can withstand the forces of launch
- Test 2: Turn on and check out the avionics on the core stage to ensure the computers and software boot up as expected
- Test 3: Simulate potential issues to test systems that shut down other systems if there is a problem to verify the vehicle will detect and protect itself and systems in the event of a failure or anomaly
- Test 4: Test main propulsion components that connect to the engines to ensure the commands are performed as expected and the valves and other hardware respond as expected
- Test 5: Test thrust vector controls and check out all of the related hydraulic systems, verifying the RS-25 engines can steer the rocket
- Test 6: Simulate launch countdown to validate timeline and sequence of events
- Test 7: Load and drain more than 700,000 gallons of LH2 and LOX from the stage
- Test 8: Fire all four RS-25s for up to eight minutes

Only one hot fire test was planned, but the test did not reach full duration. In order to collect necessary data, a second test was conducted. Lessons learned from both attempts proved critical, especially when it came to launching SLS. Simply put, without Green Run testing, the Artemis I mission would not have been successful.

I. Integrated Test and Check-Out

During final preparation of the launch vehicle at NASA's Kennedy Space Center in Florida, the Integrated Test and Check-Out (ITCO) test campaign collected data on the integrated Artemis launch vehicle – including the Orion spacecraft and Exploration Ground Systems. The 10 tests included modal testing, end-to-end communication check-outs, and software checkout and testing and culminated with the wet dress rehearsal (Table 1).

Artemis I first rolled out to Launch Complex 39B March 17-18, 2022, for the wet dress rehearsal (WDR) test. During rollout, the Dynamic Rollout Test occurred as data on the vibrational forces caused by rolling from the Vehicle Assembly Building to the launch pad were recorded. Vibrational datapoints were also collected during the roll back from the launch pad.

Between April 1 and 14, teams conducted three WDR attempts, collecting data and lessons learned each time. WDR 4 began on June 18 with tanking on June 20. Using lessons learned from the first three attempts, both the core stage and ICPS tanks were fully loaded with cryos and put in top-off replenish mode. During tanking, an LH2 leak was discovered in a quick disconnect in the tail service mast umbilical (TSMU). A process had been developed to attempt to rectify leaks in this kind of scenario whereby the seal was allowed to warm up to allow it to reseat before chilling it back down and flowing LH2 across it. The procedure was unsuccessful. In an effort to get the most data possible, the team developed a plan that would mask the problem in the ground control computers and software, hiding hold-initiating data associated with the leak to get as far as possible into the countdown while still maintaining a safe hydrogen gas level in the TSMU. The plan was tested in an alternate firing room before being implemented onto the launch vehicle.

The team was able to get deep into the terminal countdown and performed several critical operations, such as the critical transfer of the count from the GLS to ALS. As predicted, the ALS on SLS detected an out-of-specification setting shortly after the handoff and stopped the countdown at T-29 sec. However, enough data were collected to progress toward a launch campaign. One final test was held before rolling back to the Vehicle Assembly Building and initiating launch preparations: a hot fire test of the hydrazine-powered booster thrust vector control (TVC) system occurred at the pad, completing the WDR objectives.

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 the OSA test article and Orion mass simulator using hydraulic shakers and calibrated hammers.
Interface Verification	Also performed with the OSA 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 Vehicle Assembly Building.
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 Vehicle Assembly Building 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 1. 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.

IV. Progress to Next Flights

While we focus on the testing that led to and through the successful Artemis I mission, significant progress to the next flights is being made. SLS was designed from the beginning to launch astronauts to deep space. The next launches will do just that.

NASA's Artemis II mission will send four astronauts on a lunar flyby mission aboard an Orion spacecraft, targeted to fly in 2025. SLS hardware for the mission is largely complete. Highlights include:

- The Artemis II core stage is nearing completion at NASA's Michoud Assembly Facility in New Orleans. The RS-25 engines were the last major pieces to be installed. The flight software has been loaded onto the core stage flight computers.
- The ICPS for Artemis II is complete at prime contractor United Launch Alliance's facilities at Cape Canaveral in Florida.
- Solid rocket booster segments for Artemis II are at Kennedy.

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 core stage primary structures, including the LH2 and LOX tanks for Artemis III, are structurally complete and in various stages of outfitting and processing.
- The solid rocket booster segments for Artemis III are all cast and stored at prime contractor Northrop Grumman's Utah facilities, and propellant casting for Artemis IV segments is underway.

- 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 Aerojet Rocketdyne, an L3Harris Technologies company. 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 was completed in April 2024.
- New flight software for the SLS Block 1B variant is in development.

V. Conclusion

SLS's launch capabilities enable the most ambitious deep space exploration missions. Single launch payload mass and volume capabilities provide NASA the ability to launch crewed missions for the Artemis campaign and have the potential to launch significant cargo, telescope, and uncrewed spacecraft to support the nation's and world's scientific exploration of the cosmos.

Critical to the success of the rocket was a thorough test campaign that evaluated the elements of the launch vehicle before ever reaching the launch pad. The ultimate test, the Artemis I launch, was incredibly successful and sets the stage for an era of unparalleled space exploration.