NASA's Space Launch System: Artemis I Results and the Path Forward

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The Artemis era of human space exploration beyond low Earth orbit launched at 1:47 a.m. EST on November 16, 2022. Artemis I was the first integrated flight of the agency's new super heavy-lift rocket, the Space Launch System (SLS), and the next-generation spacecraft for astronauts, Orion. The mission sent an uncrewed Orion spacecraft into a distant retrograde orbit about the Moon. During the 25-day mission, NASA collected valuable data on the performance of the launch vehicle and crew spacecraft and information on the deep space environment where crews will soon operate. Orion splashed down approximately 80 miles off the coast of Baja, California, at the conclusion of the mission December 11. This paper will provide a summary of the launch campaign from vehicle integration and testing through completion of the upper stage phase with primary emphasis on SLS. It will also discuss highlights of progress on manufacturing and testing of SLS hardware and software for upcoming Artemis missions.

I. Introduction

At 1:47 a.m. EST on November 16, 2022, NASA's new super-heavy lift rocket, SLS, launched for the first time on the Artemis I mission, sending an uncrewed Orion spacecraft on a trip around the Moon (Fig. 1, 2).

SLS is a key part of NASA's Artemis campaign – the agency's efforts to return humans to Moon. The SLS Program is managed at NASA's Marshall Space Flight Center in Huntsville, Alabama, as part of the agency's Moon to Mars office. The launch vehicle produces more maximum thrust than any previous NASA rocket and can send 27 metric tons (t) of payload to translunar injection (TLI) in its initial Block 1 crew configuration. SLS is the only rocket capable of launching that much payload to the Moon in a single launch. Future variants of the rocket will increase the TLI mass to more than 46 t, and the rocket will be the only launch vehicle capable of launching astronauts in Orion and a 10 t co-manifested payload to the Moon in a single launch. The rocket can also be configured with wide-diameter payload fairings to launch a wide variety of large and heavy cargo and spacecraft, such as flagship science payloads or Mars habitats, to various deep space destinations (Fig. 3).

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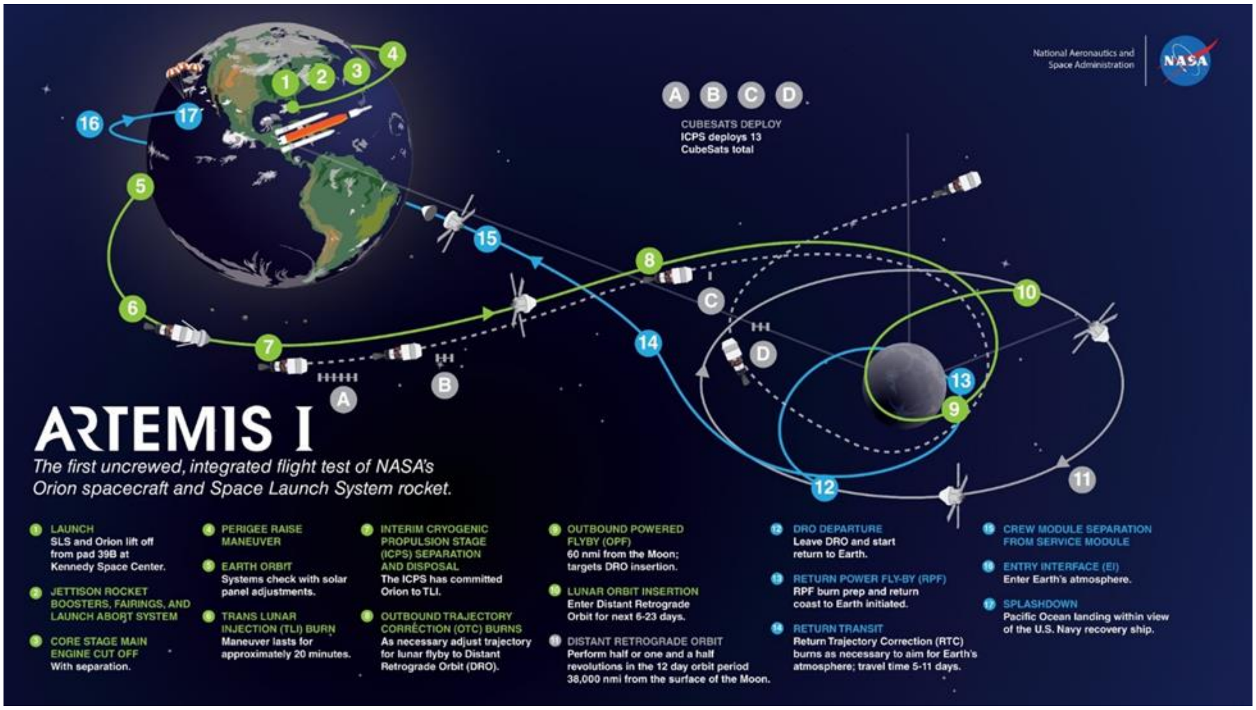

Fig. 1 The Artemis I test flight allowed NASA and its industry partners to thoroughly test all systems in deep space prior to commencing crewed lunar missions.

NASA is leading an international team to establish a sustainable, permanent presence in near-rectilinear halo orbit (NRHO) about the Moon and at the lunar South Pole, where astronauts can explore the surface, perform breakthrough scientific investigations, and test technologies to prepare for human missions to Mars.

II. SLS Architecture

The SLS architecture is designed to be flexible, evolvable, leverage proven spaceflight propulsion systems, and utilize 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 (Fig. 4). Maximum thrust in this configuration for the Block 1 vehicle is 8.8 million pounds (39,100 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. 3). The Block 2 variant, which will onramp evolved five-segment solid rocket boosters, will produce 9.4 million pounds (42,000 kN) maximum thrust.

Fig. 2 Inaugural launch of Artemis I Nov. 16, 2022, from NASA's Kennedy Space Center in Florida.

The interim cryogenic propulsion stage (ICPS), a derivative of the highly successful United Launch Alliance (ULA) Delta Cryogenic Second Stage (DCSS), is 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 and Boeing, 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 t to 38 t in crew configuration. When new, evolved solid rocket boosters are debuted on the ninth flight, mass to TLI in the crew configuration will increase to 43 t.

Stage	**Engine/Motor**	**Pounds Force of Thrust**	**Number of Engines**	**Propellant**	**Origin**	**Stage Manufacturer**	**Engine/Motor Manufacturer**	**SLS Configuration**
Core Stage	RS-25	418k (sea level); 512k (vacuum)	4	LH2/LOX	New design	Boeing	Aerojet Rocketdyne	All
Heritage Solid Rocket Boosters	Solid Propellant Boosters	3.6 M each/7.2 M total	Two five-segment boosters per vehicle	Polybutadiene acrylonitrile	Upgraded space shuttle hardware	Northrop Grumman	Northrop Grumman	Block 1, Block 1B
ICPS	RL10-2B	24,750	1	LH2/LOX	DCSS derivative	Boeing/ULA	Aerojet Rocketdyne	Block 1
EUS	RL10	97,360	4	LH2/LOX	New Design	Boeing	Aerojet Rocketdyne	Block 1B, Block 2
BOLE Solid Rocket Boosters	Solid Prop Boosters	Approx. 4.2 M/each	Two five-segment boosters per vehicle	Hydroxyl-terminated polybutadiene (HTPB)	New Design	Northrop Grumman	Northrop Grumman	Block 2

Table 1 The origins, uses, power, manufacturers, and other characteristics of SLS's major propulsion elements.

NASA and the SLS team leveraged hardware from the Space Shuttle Program. Modifications were necessary to the space shuttle flight hardware, so it can perform the ambitious deep space missions asked of it in the more extreme environments of SLS liftoff and ascent.

Including space shuttle flights, ground testing, and the Artemis I flight, the RS-25 design has accumulated more than 1 million seconds of hot-fire experience. Following the fourth flight of SLS, new production engines will be required. The production of these engines has started at prime contractor Aerojet Rocketdyne facilities, and engine certification testing is underway. The contractor has made significant improvements in reducing touch-labor and streamlining manufacturing, including incorporating additively manufactured parts.

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

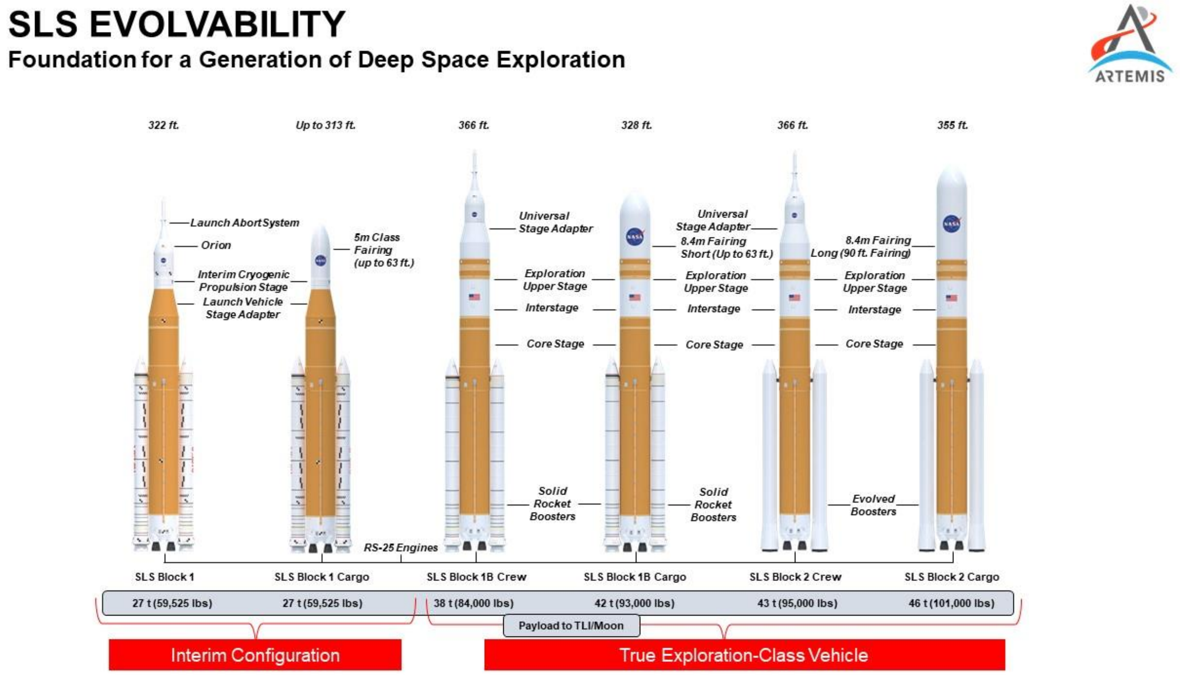

Fig. 3 SLS variants and projected performance.

III. Artemis I Test Flight Results

Post-flight data analysis and flight reconstruction recently concluded, and the post-flight analysis report is complete. Data indicate that the launch vehicle executed at a high level of precision and accuracy. All elements and systems performed well within safety and performance margins. Based on that data, preparations are in work to fly astronauts on the second flight – the Artemis II lunar flyby mission – as originally manifested with only mission-specific changes.

The SLS core stage and boosters inserted the ICPS and Orion into an initial Earth orbit at a velocity of 25,579.86 ft./sec. (7,796.74 m/sec.) – 6.58 ft./sec. (2.01 m/sec.) off nominal – a difference of 0.026 %. Orbital insertion apogee was just 2.9 mi. (4.67 km) shy of nominal. Predicted orbital insertion parameters were 975 mi. (1,560 km) by 16 mi. (25.7 km). Actual parameters were 972.1 mi. (1,564 km) by 16 mi. (25.7 km) – a difference of 0.30 %. The low perigee ensured the core stage would re-enter Earth's atmosphere. Following orbital insertion, the ICPS performed a perigee raise maneuver.

The ICPS and Orion spent approximately one revolution in Earth orbit before the upper stage burned its RL10 for record duration of approximately 18 min. for TLI. Orion separation from ICPS occurred shortly after. At the time of separation, the ICPS was traveling more than 22,000 mph (35,406 km/hr.). The stage's final burn was a disposal burn to place it in a heliocentric orbit. The 10 CubeSat secondary payloads, all 6 Unit (6U) form factor, deployed after completion of the disposal burn. The CubeSats, developed by NASA, universities, industry, and international partners, have experienced varying degrees of success to date.

Related to the performance of the individual elements of SLS, the twin solid rocket boosters burned out within 0.4 sec. of each other, hit peak thrust within 0.1 sec. of each other, and performed within 0.25% of each other during ascent. The 50-psi separation cue was within 0.04 sec. for all pressure gauges (three each) for both boosters.

The SLS core stage's 999 sensors and 45 miles (72 km) of cabling executed all functions. The cork-clad base heat shield successfully protected the structure from exhaust temperatures up to 3,200° F. Main engine cut off (MECO) occurred approximately eight min. into flight, while the vehicle was travelling more than 16,000 mph (25,750 km/hr.). The stage's RS-25 engines' thrust and mixture ratio control valves were within 0.5% of predicted values. Internal pressures and temperatures were within 2% of predicted values. Maximum acceleration on the launch vehicle occurred shortly before MECO and topped off at approximately 3.25 G.

The flight software's overall performance was well within required values. The transition from Ground Launch Sequencer (GLS) to Automated Launch Sequencer (ALS) at T-:33 seconds was nominal, and all ALS functions were 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.

Fig. 4 The Artemis I SLS's twin solid rocket boosters and four RS-25 engines propel the rocket and spacecraft off the launch pad for the first time on Nov. 16, 2022.

IV. Artemis I Launch Attempt Data

The first launch attempt countdown started approximately 46 hours ahead of the opening of the Aug. 29, 2022, launch window. Tanking operations commenced approximately seven hours before launch. Start of tanking was delayed by nearly an hour because of lightning in the area around Launch Complex 39B. In the early stages of loading cryogenic LH2 into the core stage LH2 tank, a leak was detected in the tail service mast umbilical (TSMU). A pre-established procedure to attempt to re-seat the seal – allowing the seal to warm up and then gradually cooling the seal – was successful. LH2 flow was momentarily paused again due to an over-pressurization in the lines. Essentially, when flow was started back after leak hold, the lines were warm and another minor chilldown was needed. Once chilled, the flow went smoothly (Fig. 5).

Approximately three hours before the opening of the launch window, an engine thermal conditioning test was conducted. During the test, data indicated that three of the four engines cooled adequately, though not fully. Engine 3, though, appeared to be further out of the expected temperature range than the others. Teams first warmed the bleed valve and cooled it back down to see if that procedure would cause it to respond properly. When that procedure did not yield satisfactory results, the bleed valves on the other three engines were closed, and the cryo flow was pushed through Engine 3. The temperature sensor still did not report the desired temperature, and a potentially dangerous high-pressure environment was introduced in the system.

Due to the tanking delay, weather considerations, and a suspected leak in a quick disconnect (QD) between the intertank and its umbilical, Launch Director Charlie Blackwell-Thompson – NASA's first female launch director – scrubbed for the day. Ultimately, engineers determined that the bleed valve problem was most likely an issue with the temperature sensor and not a problem with the engine itself. The leak in the intertank QD was determined to be the result of the seal getting warm during the time the engine conditioning anomaly was being resolved. When cryogenics started flowing across the seal again, it leaked. Warming the seal up and slowly cooling it back down allowed it to seal properly.

The procedure to condition the engines on the launch attempt was different than the one used during the core stage green run testing at Stennis, due in part to the need to conserve LH2 commodities at NASA's Kennedy Space Center in Florida. After data review, the procedures for conditioning were modified to closer mimic the Stennis procedures on future launch attempts.

A second launch attempt occurred on Sept. 3. The countdown resumed approximately seven hours before launch as the launch vehicle was still mostly configured from the first launch attempt. Soon after LH2 tanking began, a leak was detected in the 8-in. QD. Teams followed the warming-then-cooling procedure once again, but it was unsuccessful. Ground systems teams then closed valves and tried using the helium pressurization system to reseat the seal. It also did not work. Following troubleshooting and analysis, the warming-cooling cycle was attempted again. It was unsuccessful, and Blackwell-Thompson once again called a scrub.

Ground systems teams decided to remove and replace the 8-in. QD seal, eliminating further launch opportunities in that launch period (Launch Period 25). Technicians constructed a temporary structure on the mobile launcher platform at the launch pad, where the repairs were performed. Following repair, a cryogenic demonstration test was conducted to evaluate the repairs, during which the team confirmed a successful repair and collected valuable data about the vehicle.

Due to necessary repairs and flight termination system certification, teams then targeted a November launch attempt. While the SLS and Orion stack was parked at the pad, a low-pressure weather system developed that would quickly form into Hurricane Nicole. After careful consideration, engineers made the decision to leave the rocket at the pad, in part due to the short amount of time between when it became apparent that Kennedy was in the hurricane's path and when it would strike. Teams analyzed predicted forces on the vehicle and included consequences of a mechanical failure during the multi-hour rollback where the vehicle would be stuck part way between the launch pad and the Vehicle Assembly Building – the worst-case scenario. Post-storm data analysis concluded that the forces the vehicle experienced during the major weather event were within SLS limits and no significant damage occurred. Teams then pressed on to a launch campaign targeted for Nov. 16.

V. Thorough Testing Leads to Successful Flight

Critical to the successful Artemis I flight was a thorough test campaign that evaluated every component, element, and system of the SLS rocket and Artemis I system. Structural testing at Marshall provided teams with confidence of the strength of the core stage components, along with a quantitative understanding of the margins of those components. During the structural test campaign, five structural test articles (STAs) underwent a combined 199 tests and produced 421 gigabytes of data that were fed into computer models. The LH2 STA withstood more than 260% of expected flight loads for over five hours before a buckling point was detected. Point of failure then came at that location.

Flight software testing in Marshall's Software Integration Lab (SIL) and Software Integration Test Facility (SITF) flew the rocket thousands of times through a large envelope of flight conditions, enabling the actual flight to be successful.

The Green Run test series at Stennis evaluated the integrated core stage in tanking and launch environments. Various characteristics were collected during the campaign, which culminated in tanking the stage and two hot fire tests of the core stage. While the first hot fire test did not reach the full-duration, thus requiring a second hot fire test, important lessons were collected. Simply put, without the green run testing, the Artemis I mission would not have been successful. Many of the lessons learned from the test campaign proved vital during launch operations at Kennedy.

During final preparation of the launch vehicle at Kennedy, 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.

VI. Wet Dress Rehearsal

Artemis I first rolled out to Launch Complex 39B during the overnight hours of March 17-18, 2022, for the wet dress rehearsal (WDR) test.

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. During the tanking attempt – 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 QD in the TSMU. The warm-then-cool procedure was once again implemented but 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. Testing of this plan was performed in an alternate firing room in the Launch Control Center to ensure safety of the launch vehicle.

Following this procedure and software change, the team was able to get deep into the terminal countdown and performed several critical operations, including 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. Enough data were collected that the teams felt confident to progress toward a launch campaign. Before rollback to the Vehicle Assembly Building and launch preparations, a hot fire test of the hydrazine-powered booster thrust vector control (TVC) system occurred at the pad, completing the WDR objectives.

Fig. 5 Venting is seen from the Artemis I SLS during the first launch attempt on Aug. 29.

While the hardware, software, and systems were being tested and prepared, the teams also conducted multiple countdown and launch simulations, which prepared them for the Artemis I countdown and launch. Countdown simulations have been the backbone of NASA launch operations from the beginning. Hundreds of people at Kennedy, Marshall, NASA's Johnson Space Center in Houston, and multiple partner sites across the country support launch, ascent, and flight operations.

VII. Progress to Artemis II and Beyond

While much of the attention in 2022 and 2023 focused on the Artemis I mission, tremendous progress was made towards Artemis II and beyond.

A. Artemis II

At the time of this writing, the Artemis II SLS core stage is structurally complete, with the intertank, forward skirt, engine section, and LH2 and LOX tanks mated at NASA's Michoud Assembly Facility in New Orleans. The RS-25 engines are ready and are being integrated to the stage this month. The core stage is expected to ship to Kennedy late this year, depending on alignment with enterprise schedules of the many elements of the Artemis II mission. The booster segments for Artemis II have been complete for some time; they are currently being loaded on rail cars at prime contractor Northrop Grumman's facilities in Utah for shipping to Kennedy this fall. The aft skirt assemblies, with TVC, are also complete at Kennedy.

The ICPS completed primary assembly at ULA's manufacturing facility in Decatur, Alabama, and was shipped to the company's facilities at Cape Canaveral Space Force Station in July 2021. It is in storage before the hand off to NASA this fall. Both the launch vehicle stage adapter (LVSA) and Orion stage adapter (OSA) have completed manufacturing. The LVSA is complete and is in storage at Marshall. The OSA has completed painting, and additional processing is underway at Marshall.

In addition to the SLS rocket, significant progress is being made on the Orion spacecraft and Exploration Ground Systems for the Artemis II mission. The Orion spacecraft is undergoing testing before being mated to its service module. The mobile launcher, which will launch SLS and Orion, is outfitted with the Crew Access Arm and is at Launch Complex 39B for testing. The three NASA astronauts and one CSA (Canadian Space Agency) astronaut who will fly the mission are training for their lunar expedition (Fig. 6).

Fig. 6 The Artemis II crew consisting of (left to right) Pilot Victor Glover, Commander Reid Wiseman, Mission Specialist Kristina Koch, and Mission Specialist Jeremy Hansen from CSA (Canadian Space Agency) check out their Orion crew module inside the Neil Armstrong Operations and Checkout Building at Kennedy.

B. Artemis III

Artemis III is scheduled to be the first human landing on the Moon since the Apollo 17 mission in December 1972 and is targeted for no earlier than late 2025. The core stage LOX tank, LH2 tank, intertank, and engine section are being manufactured at Michoud. The intertank and forward skirt have completed thermal protection system (TPS) spray installation. The forward skirt is being outfitted for flight. The RS-25 engines are complete. The booster segments for Artemis III are also complete and ready at Northrop Grumman facilities in Utah. Refurbishment and buildup of the booster TVC systems are underway.

The Artemis III ICPS completed manufacturing at ULA's Decatur, Alabama, facilities and has been shipped to ULA's facilities at Cape Canaveral Space Force Station in Florida for final processing. The Artemis III OSA has completed manufacturing and is undergoing secondary structure and cable installation. The LVSA has been welded, and TPS installation is complete. The adapter's frangible joint assembly and pneumatic actuator system brackets have also been installed.

C. Progress to Artemis IV and Block 1B

Artemis IV is scheduled to be the debut of the SLS Block 1B variant, featuring the new EUS. Weld confidence articles are being manufactured at Michoud as well as Marshall. The EUS assembly area at Michoud has opened.

Work on the Artemis IV intertank, LOX tank, LH2 tank, and engine section is underway at Michoud (Fig. 7). The RS-25 engines are in processing and are scheduled to be complete later this year. Work on the Artemis IV boosters is also underway. Propellant segments are being cast, and refurbishment of forward structures is underway. Test and demonstration panels and articles for the EUS, interstage, payload adapter, and universal stage adapter are being manufactured and analyzed.

Manufacture, testing, and certification of new-production RS-25 engines that will be used on Artemis V and beyond is underway. These re-engineered engines are designed to be at least 30% more affordable than shuttle-era engines through the use of modern manufacturing technologies, including additive manufacturing. The engine certification test program, consisting of 12 certification tests of a new-production engine successfully concluded in June. The Retrofit 3b test series will start this fall, consisting of an additional 12 tests on the Fred Haise Test Stand at Stennis. It is necessary as some new-production components require two certification test series to be certified for use.

The flight software that will fly the new SLS variant is being developed at Marshall.

D. Progress to SLS Block 2

On the ninth SLS flight, the Block 2 variant of SLS will make its debut, featuring the EUS and the evolved BOLE solid rocket boosters. The boosters will feature composite carbon fiber-wound cases, replacing the heritage steel cases, thus reducing mass and increasing payload. A new propellant mixture will also be used. Thrust on the new boosters will increase from 3.6 million pounds (16,014 kN) to 4.2 million pounds (18,683 kN) each. The first full-scale horizontal static test-firing of the BOLE Demonstration Motor-1 is currently scheduled for Fall 2024. Motor segments are currently being cast at Northrop Grumman facilities in Utah for that test. In addition, process simulation articles are being manufactured to test and validate procedures to produce the BOLE boosters.

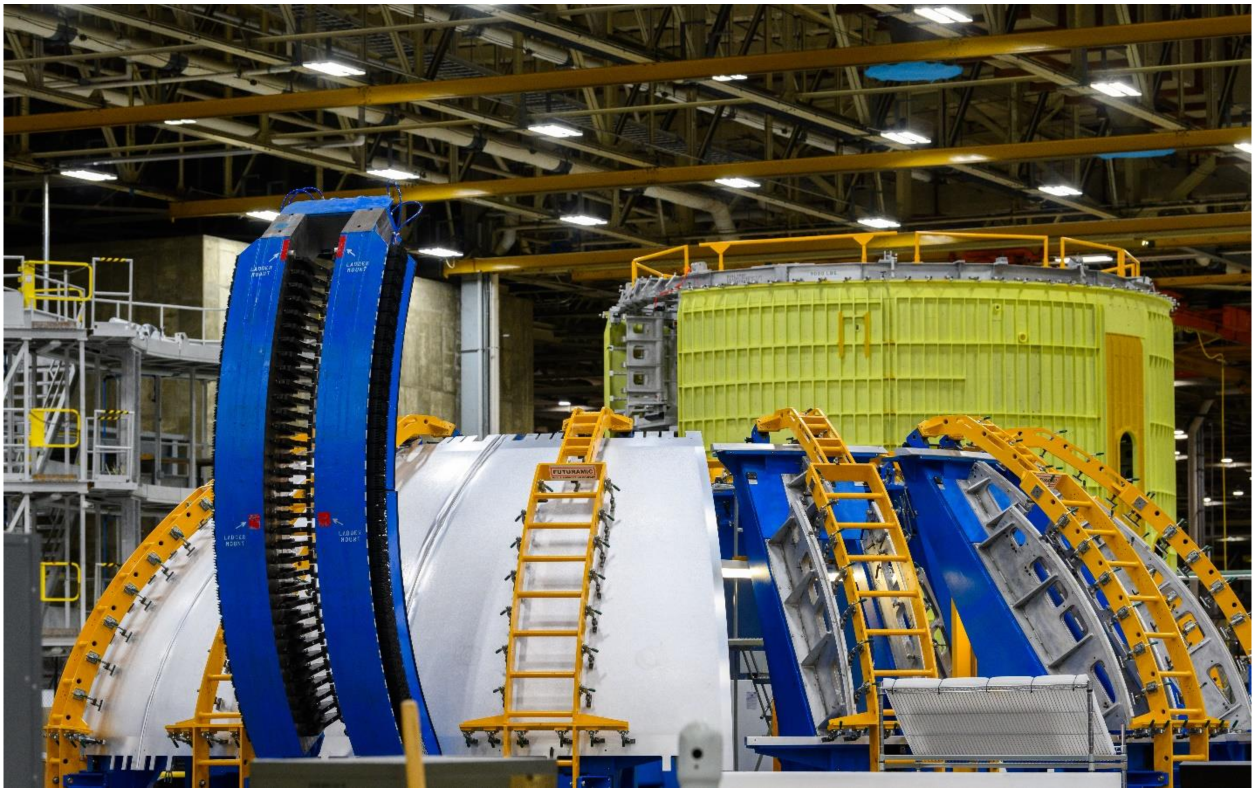

Fig. 7 The Artemis IV LOX dome, forward, and intertank, background, are being manufactured at Michoud. Shown are weld confidence articles.

E. Conclusion

The Artemis era of space exploration is underway, and in this era, humanity will explore the Moon more extensively than ever before and develop and test technologies that will be the foundation for human missions to Mars and back in the 2030s. Building on the success of the first flight of SLS, NASA and its partners are building, testing, and developing the hardware for the next four flights and Block 1B and Block 2 variants. This work ensures the nation will have assured access to deep space and a reliable, capable rocket as the backbone for its most ambitious missions.