NASA'S SPACE LAUNCH SYSTEM BEGINS MOVING TO THE LAUNCH SITE

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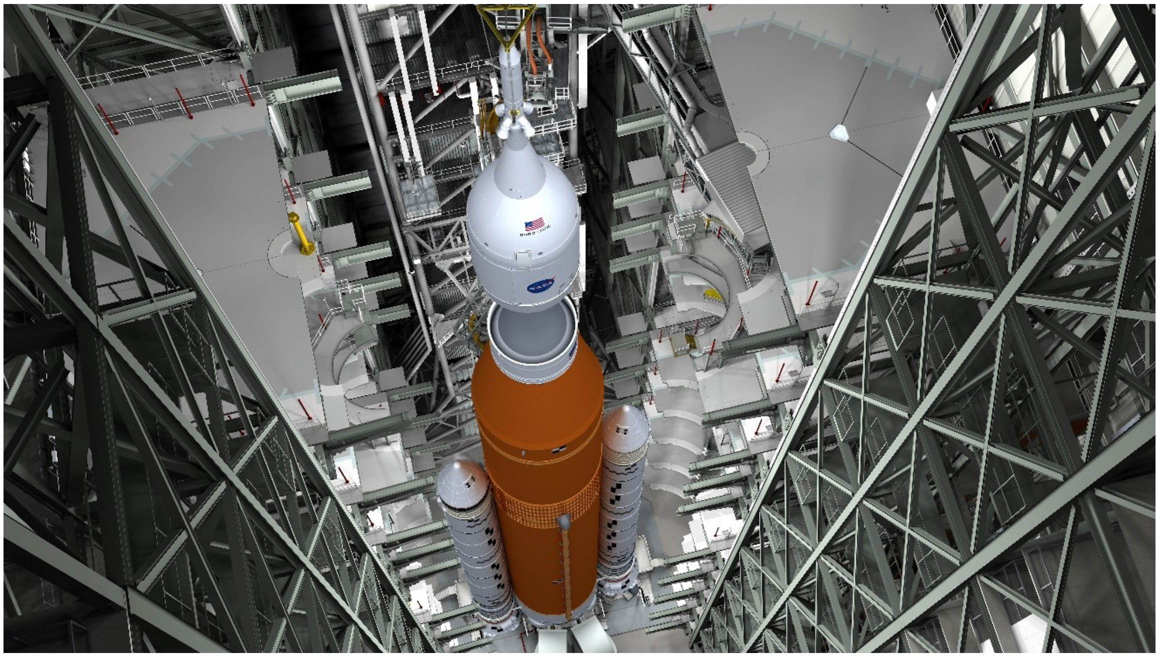

Figure 1: Artist's concept of the Artemis I SLS/Orion launch vehicle during integration at Kennedy Space Center

ABSTRACT

NASA is accelerating plans for a human return to the Moon. NASA was directed by the White House in 2019 to land the first woman and next man on the Moon by 2024. NASA's backbone for future deep space exploration is the Space Launch System (SLS), as well as the Orion crew spacecraft, (Fig. 1) Gateway outpost, and Human Landing System as part of the Artemis program. While the SLS upper stage, the Interim Cryogenic Propulsion Stage (ICPS), based on an existing commercial stage was shipped to Kennedy Space Center (KSC) in 2017, major completed components of SLS will soon begin their eastward journey that will see them at KSC in 2020 to be integrated for their history-making launch back to the Moon. Core Stage prime contractor Boeing completed the Artemis I core stage in 2019 at NASA's Michoud Assembly Facility (MAF) and shipped it to NASA Stennis Space Center (SSC) for stage green run testing in 2020 and then to KSC. Northrop Grumman, prime contractor for the 5-segment solid rocket boosters, is scheduled to begin overland shipment of the Artemis I motor segments from Utah to KSC in 2020 to await integration. This paper will discuss SLS progress to date and planned 2020 milestones.

INTRODUCTION

NASA and its commercial and international partners are on their way to the Moon in line with Space Policy Directive 1 from the White House. We are going to stay with continual access to any part of the Moon with landers, rovers, robots and humans. The Moon is the start of a long-term commitment that will lead to human exploration of Mars and beyond. On March 26, 2019, Vice President Mike Pence announced on behalf of the President that “It is the state policy of this Administration and the United States of America to return American astronauts to the Moon within the next five years.” The new lunar return effort was christened Artemis after the sister of Apollo, goddess of the Moon in Greek mythology. NASA is now working toward a 2024 landing date. The flight manifest, adjusted to align exploration hardware to the new requirement calls for three SLS flights leading to the landing. Artemis I will be an un-crewed test flight of SLS and the Orion crew spacecraft to the Moon. Artemis II will be a similar crewed lunar test flight. Artemis III will carry the crew of the first human landing and surface logistics equipment. In parallel, three commercial launch vehicles would transport components of a small “Gateway” outpost near the moon, where three more commercial launchers would send a lander descent and ascent stages and a transfer stage to be integrated and rendezvous with Orion before lunar descent. (Fig. 2)

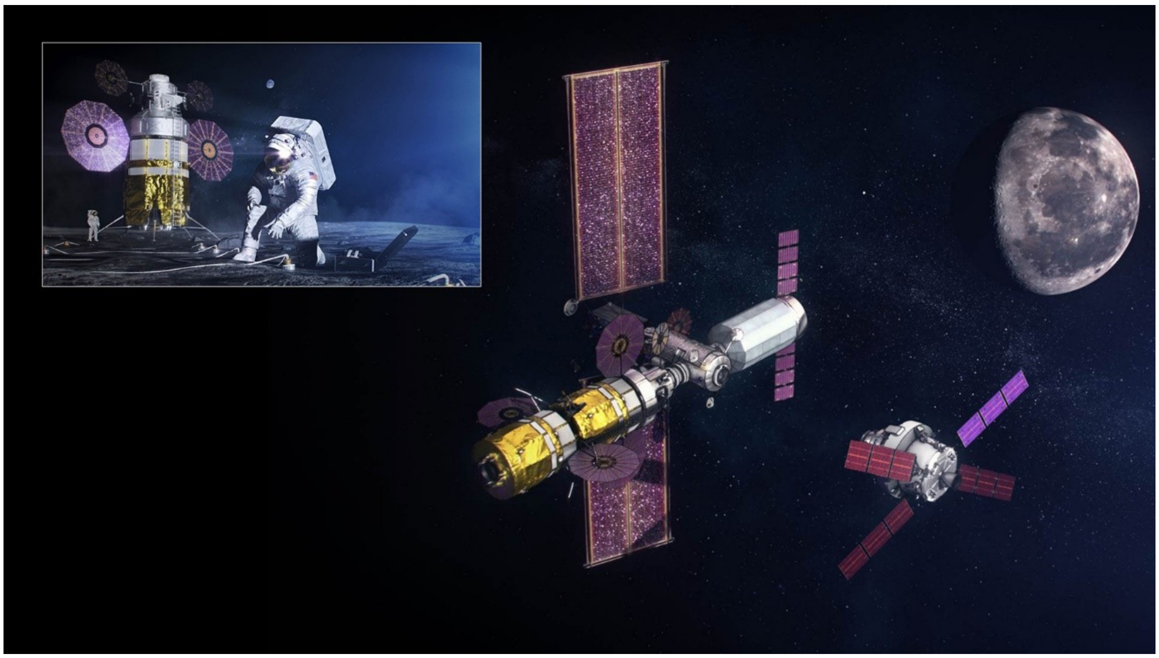

Figure 2: Artist’s concept of Orion, human lander, and Gateway.

SLS DESIGN AND ARCHITECTURE

The SLS design is based on the most proven and powerful technologies to support the most ambitious plans yet for deep space human and robotic exploration, the greatest scientific return and the most opportunity for mission success. The evolutionary family of human-rated SLS vehicles is based on a common basic configuration designed to grow in capability as the nation’s exploration plans become more ambitious.

SLS propulsion, typically the most challenging aspect of any launch vehicle development, begins with liquid and solid components with an experience base of more than 40 years. The SLS five-segment solid rocket boosters (SRBs) are based on the space shuttle four-segment SRBs with the selected upgrades. The RS-25 liquid engines are substantially the RS-25 Space Shuttle

Main Engine (SSME) adapted to SLS performance and environments. The newly designed core stage contains the propellant tanks and main propulsion system for the liquid engines, houses flight avionics and serves as the attach point for the boosters. These components are common across all six variants of SLS. (Fig. 3)

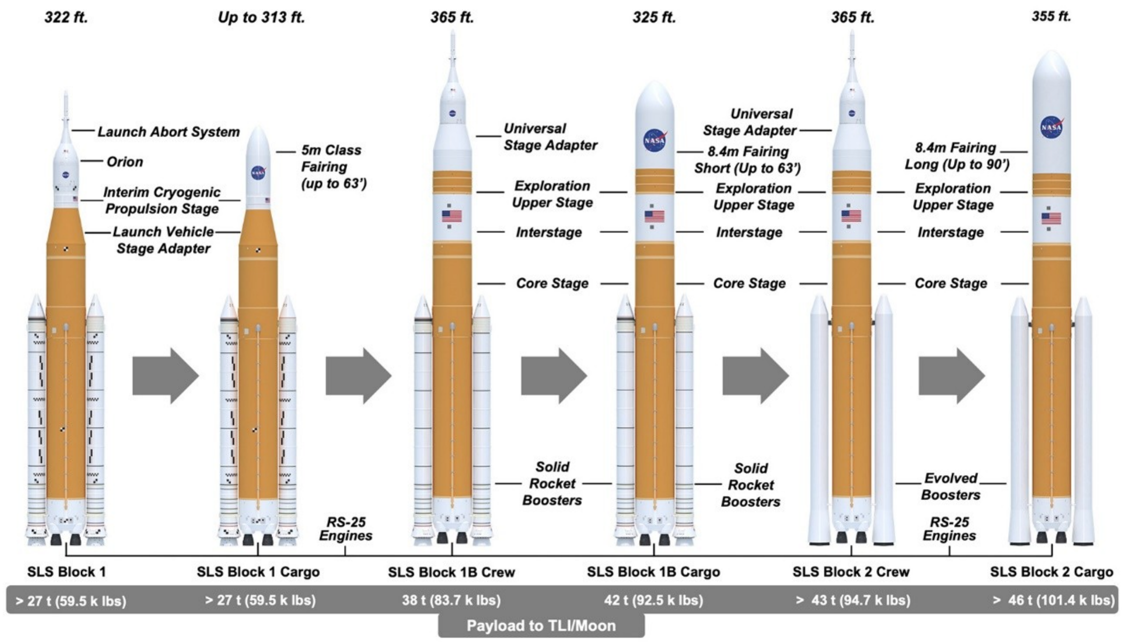

Figure 3: Primary components and performance of the planned SLS variants.

The Block 1 crew variant is 322.4 feet tall with a fueled weight of 5.75 million pounds. Maximum thrust is 8.8 million pounds. Payload to trans-lunar injection (TLI) is more than 59,535 pounds. Upper stage propulsion for Block 1 is provided by an Interim Cryogenic Propulsion System, also modified hardware and based on the existing Delta IV Cryogenic Second Stage. It is powered by a single RL10 LOX/LH2 engine with 24,750 pounds thrust. Block 1 can launch either the Orion crew vehicle or more than 8,000 cubic feet of cargo. The Artemis I configuration is shown below. (Fig. 4)

The Block 1B variant is 365 feet tall with a fueled weight of 6 million pounds. Maximum thrust is 8.9 million pounds, slightly higher than the Block 1 due to replacement of heritage RS-25s operating at 109% thrust with new-build RS-25s certified to operate at 111% thrust. The ICPS is replaced with a new Exploration Upper Stage (EUS) powered by four RL10 engines with 97,360 pounds thrust. TLI payload increases accordingly to more than 83,766 pounds for the crewed Orion version and more than 92,594 pounds for the cargo version. The payload fairing is 62.7 feet long and 27.6 feet in diameter, providing an available payload volume of 21,930 cubic feet. An extended fairing is also under consideration.

The ultimate Block 2 variant is 365 feet tall with a fueled weight of 7.4 million pounds. Maximum thrust is 9.5 million pounds primarily with the replacement of the existing SRBs with Evolved Solid Rocket Boosters, which increase thrust from 3.6 million pounds each to 3.9 million pounds each. The EUS continues to serve as the upper stage. TLI payload increases to more than 94,799 pounds for the crew variant and more than 101,413 pounds for the cargo variant. The Block2 cargo payload fairing is 90 feet tall and 27.6 feet in diameter, providing 34,910 cubic feet of available volume.

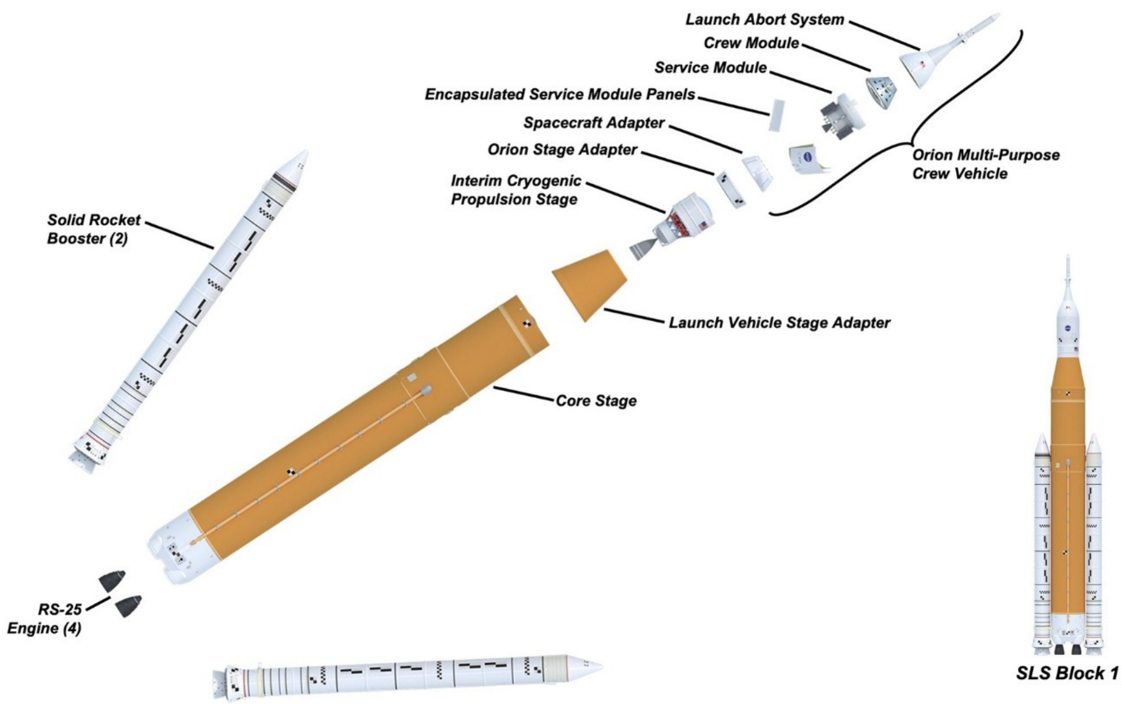

Figure 4: Expanded view of the Artemis I Block 1 vehicle

SLS PROGRESS

NASA has made major progress on the first vehicle for the Artemis program in 2019 and 2020. The Artemis I core stage finished manufacturing and is currently in testing. The Orion spacecraft with its European service module reached testing as well. Manufacturing is under way on SLS and Orion vehicles for subsequent missions. This section will provide highlights on progress to date and upcoming milestones for SLS.

BOOSTERS

Manufactured by Northrop Grumman, the twin five-segment boosters will provide 3.6 million pounds of thrust each at liftoff and provide roughly 75 percent of vehicle thrust for the first two minutes of flight. Based on the space shuttle four-segment boosters, the SLS boosters have been upgraded with new case insulation, new avionics and other improvements.

The Artemis I booster motor segments are completed and in storage at Northrop Grumman in Utah awaiting shipment to KSC in the May timeframe. (Fig 5 left). After arriving at a processing facility to be readied for final processing, they will move to the VAB for vehicle integration

The booster team conducted a successful hot fire of the righthand aft skirt TVC system in February 2019. The Artemis I right hand aft exit cone arrived at KSC in December 2019.[1] The forward skirt is undergoing mechanical installation.

For future missions, all Artemis II segments and four segments of the Artemis III flight set are cast and in storage.[2] Northrop Grumman is working to cast the Artemis III Booster Separation Motors (BSMs). Development is under way on NASA's Booster Obsolescence and Life Extension (BOLE) program, with a successful 24-inch subscale motor test in December 2019 to evaluate the effect a new propellant has on the performance of motor insulation and nozzle materials.[3] BOLE boosters will be ready when the existing inventory of shuttle heritage case hardware is expended. BOLE boosters will have upgraded motor case and nozzle hardware, propellant, fore and aft structures, nose cap and frustum structures, avionics and thrust vector control systems. Via improved propellant design and weight reduction, BOLE is expected to increase LEO payload by at least 3 metric tons.

NASA's Exploration Ground Systems (EGS) team practiced lifting and stacking operations with pathfinder segments of Northrup Grumman's solid rocket boosters earlier this year in High Bay 4 of the Vehicle Assembly Building (VAB) at KSC. (Fig. 5 right) Stacking practice helped prepare the team, particularly new technicians, engineers, crane operators, and quality control staff, for processing the Artemis I vehicle. The pathfinder segments are inert, full-scale replicas of the actual solid rocket boosters, with the same weight (300,000 pounds) and center of gravity.

Figure 5: Artemis I solid rocket motor segments, left, at Northrop Grumman, and inert motor stacking exercises, right, at KSC.

During launch hardware processing, the booster segments will be shipped by train to Kennedy from the Northrup Grumman facility in Utah. They will arrive at a processing facility to be configured for final processing, then move to the VAB, where the launch processing team will stack them vertically on the mobile launcher. After the boosters are stacked, the SLS Core Stage will be lowered onto the mobile launcher and will be mated to the boosters.

<u>LIQUID ENGINES</u>

In addition to the solid propellant boosters, SLS is powered by four liquid hydrogen/liquid oxygen (LH2/LOX) RS-25 engines. Manufactured by Aerojet Rocketdyne, each engine provides approximately 416,000 pounds of thrust at launch and more than 512,000 pounds in vacuum, operating for the entire roughly 480-second core stage operation. The RS-25 engine for SLS has more than 40 years of experience as the Space Shuttle Main Engine (SSME). That experience base includes five distinct upgrades for improved reliability and safety. SLS began with 14 flown and two new RS-25s from the Shuttle Program. Over a series of some 40 development engine tests, the RS-25 was tested to ensure it performs to SLS mission requirements and environments. For SLS, NASA has developed a new controller and controller software and installed insulation batting on the engines.

The Artemis I flight engines were processed and installed in the first flight Core Stage at Michoud in 2019 to complete assembly of the stage. (Fig. 6 left)[4] Additionally, the last of the four flight engines for Artemis II completed processing. All four are stored and available as contingency engines for Artemis I.

Planning for missions after the existing engine inventory is expended, work is underway on an improved RS-25 engine. The engine "restart" program is building six new engines with plans to next acquire 18 more engines. The goal is an engine with the same performance and reliability but costing at least 33 percent less than the shuttle heritage engine. Engineers have already tested an additively-manufactured pogo accumulator and a HIP-bonded main combustion chamber. Earlier in 2020, Aerojet Rocketdyne completed the braze on the first redesigned nozzle. Development test engine 0528 is undergoing modifications to support production restart development hot fire testing beginning in June.

Aerojet Rocketdyne is under contract to produce 10 RL10C-3 engines for EUS. Six are complete. Four are in manufacturing. Two will be diverted to power two ICPS stages assigned to Artemis II and Artemis III Block 1 rockets and will be reconfigured to RL10C-2 configuration. The two RL10s slated for Artemis II and II have been accepted by SLS and are scheduled to be converted to the C-2 configuration beginning in April 2020. Both converted engines are scheduled to be shipped to United Launch Alliance (ULA) in Decatur, Ala. closer to their mid-2020 and late 2021 need dates.

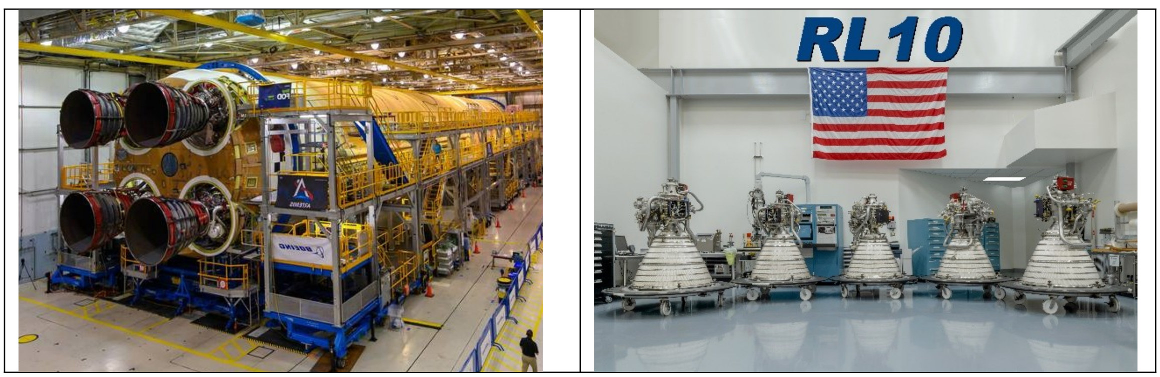

Figure 6: RS-25 engines installed in Artemis I core stage, left and SLS upper stage RL10 engines, right.

STAGES

The SLS core stage is the largest production stage in the world at 212 feet tall and 27.6 feet in diameter. Manufactured by Boeing, it houses four RS-25 main engines, supplied by a liquid hydrogen tank and liquid oxygen tank with capacities of 537,000 gallons and 196,000 gallons, respectively. The Artemis I core stage completed manufacturing and initial testing at Michoud Assembly Facility (MAF) in 2019 and was shipped in January 2020 to Stennis Space Center to undergo a series of "green run" tests before shipment to KSC for vehicle integration.[6] By late January, the flight stage had been installed in the B-2 Test Stand at Stennis. Stage rollout from Michoud (left) and installation in the SSC B-2 stand (right) are shown below.

Figure 7: Artemis I departing Michoud with engines installed, left, and the core stage lifted into the B-2 test stand at SSC, right.

Green run represents the largest stage ground test since the Apollo Saturn V S-IC in the 1960s and will ensure that it satisfies design objectives and validates design models. It is the first full test of the integrated core stage, including valves, ducts, avionics and engines and concluding in a planned roughly 500-second static hot fire test. The series conducted on the B-2 test stand at Stennis Space Center got underway this year and is expected to take 7-10 months and amass up to 100 terabytes of data, not including voice and video, for analysis. Green run represents several first-time events for the core stage that will result in smoother vehicle integration, checkout, countdown and launch:

- Perform modal (vibration) test on the core stage
- Employ new access hardware (support equipment)
- Full cryogenic loading/de-tanking
- Engine countdown/start/shutdown sequences
- Thermal conditioning of engines using core stage (LH2 bleed)
- Core stage start box demonstration (LH2 and LOX)
- Programmable Interrupt/Discrete loops for heaters will see actual environments
- Spinning core stage auxiliary power units (CAPUs) off of common ground helium supply
- Thrust vector control (TVC) drive gas transitions from helium to hydrogen from the RS-25 engines
- Tanks pressurized and TVC driven off engine gas through shutdown
- Demonstration of Hydrogen Burn Off Igniters (HBOIs) effectiveness
- Base heat shield exposed to combined ground test environments
- Mated umbilicals see hot-fire environments (full duration)
- Feedline assembly usage and depletion – Geyser suppression system

- Main propulsion system (MPS) valves and seals (hazardous gas) performance during hot firing
- Purge and vent systems and compartment temperature in cryogenic environment
- NASA flight software loaded and run from flight vehicle
- Avionics will drive core stage hardware, exposed to operating environments
- TVC loads with engines running
- RS-25 input to the pogo analysis will be tested with core stage design
- Facility wiring integrated with vehicle exercised
- Core Stage-to-facility interfaces will be validated during thermal conditions
- Propellant tank sensor mast design in cryogenic environment
- Low-level sensor demonstration
- Redundancy management during hot firing
- Test Commit Criteria (TCC)/Launch Commit Criteria (LCC) limits demonstration, Advance-to-Shutdown
- Hazardous gas during operation
- Demonstration of Foreign Object Debris (FOD) control effectiveness during firing
- Management team protocol for major integrated testing

The Green Run series began in early 2020 with a modal test of the structure. (Fig. 8) For the test, a crane lifted the stage a few inches out of the B-2 stand, while a combination of shakers and impulse hammers were used to vibrate the structure. The team conducted the entire series in one night rather than over several days as initially planned.[7]

The next major test in the series in wet dress rehearsal (WDR), which is an operational test up to the automated launch sequence start in which the flight computers take over the countdown and stage operation. The tests begin with vehicle power-on checks, safing checks, leak checks, hydraulic and thrust vector control checks and leading into propellant loading, tank pressurization, full avionics power-up, countdown and countdown hold demonstrations, and transition internal power before countdown termination.

The following hot fire test will repeat those same steps, allowing the countdown to reach zero and ignite the four RS-25 engines. The team is evaluating the potential to go straight from WDR straight into the hot fire. Following safing, data evaluation, stage and engine refurbishment, the stage will be ready to ship to KSC for vehicle integration.

While the hot fire is expected to cover a roughly-500-second mission, the team will also have to evaluate whether an early cut-off, due to stage or facility issues, will require a second test. Most test objectives will have been reached at 250 seconds. Successful engine start alone verifies many of the computer models. Around 30-35 seconds verifies the heat transfer models on the LH2 tank. About 60 seconds verifies thermal predictions on the LOX tank. A full test would provide data on the tank fuel level sensors and a complete flight profile test of the engine TVC actuators and engine throttling. Notably, the amount of work required to ready the stage for a second hot fire would be significant in cost and time.

While the Artemis I core stage is in testing, the Artemis II core stage is in full production at MAF. The engine section is in mechanical installation. The LOX tank is being mechanically cleaned internally. The LH2 tank is complete and has passed proof testing. The intertank has completed TPS trim work. The forward skirt is undergoing mechanical installation.

Having completed structural testing on the payload structures, the engine section, intertank, and liquid hydrogen tank, the last structural test article, the LOX STA, is in a second phase of testing at MSFC, having completed limit and ultimate test cases. To explore the limits of the world's tallest stage, the MSFC test team took the hydrogen test article to failure in late 2019.[8] The data will not only inform SLS but also future launch vehicles. The test marked the largest-ever controlled test-to-failure of a NASA rocket stage pressurized tank, withstanding more than 260% of expected flight loads over five hours before failing. (Fig 8)

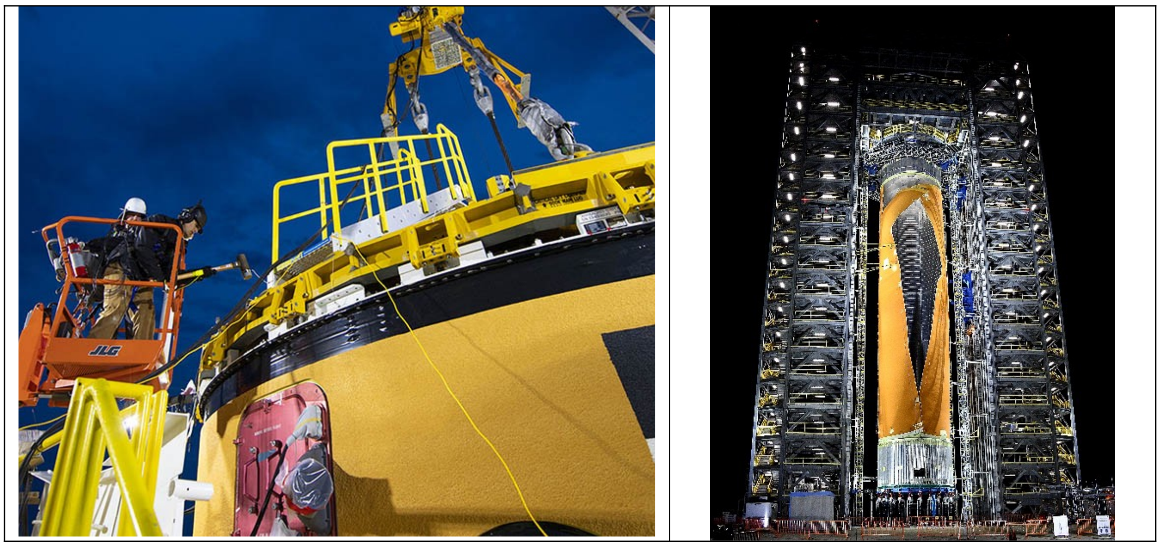

Figure 8: Test engineer taps Artemis I core stage during modal testing at SSC, left, and Core Stage structural test article following deliberate test to failure at MSFC, right.

Work also is progressing on the Exploration Upper Stage (EUS) for the Block 1B variant that will enable 40% more cargo to the Moon than Block 1. Since EUS preliminary design review was completed in 2017, work has continued on the design and facilities for the powerful new upper stage that will replace the ICPS. The EUS team optimized the EUS design for the Artemis program.[9] SLS has formed a Block 1B formulation team that will focus on a plan to complete the EUS critical design review by 2021. Funding has been obligated for facility modifications at Michoud and for the RL10 engines needed to power the stage, and the Universal Stage Adapter and Payload Adapter to carry payloads.

PAYLOADS

The Artemis I upper stage and payload components are nearing completion. The ICPS and Orion Spacecraft Adaptor(OSA) have been completed and in storage at KSC since 2017. The Launch Vehicle Stage Adapter (LVSA) was receiving acoustic blankets this spring prior to shipping to KSC. The CubeSat small payloads that will ride in the OSA are in the final stages of testing. Dispensers have bene shipped, to Tyvak Nano-Satellite Systems, which will install the payloads in the dispensers and ship the integrated payload/dispenser assembly to KSC.

Additionally, for Artemis II, the manufacturing team has started machining panels for OSA, LVSA and ICPS. Welding on the OSA is scheduled to begin in April at MSFC in the Advanced Weld Facility, followed by the LVSA in June. Janicki Industries has manufactured the diaphragm for OSA-2, which is currently in non-destructive evaluation.

SUMMARY AND CONCLUSIONS

SLS will soon power a new era of human and robotic deep space exploration. Its combination of super heavy lift payload mass and volume, proven propulsion systems, and evolutionary architecture make it the flagship for unprecedented human-rated missions to the Moon and later to Mars, as well as the most ambitious probes to the outer planets. Through refinement of the design and actual manufacturing experience, expected payload mass to TLI has increased, exceeding any existing launch vehicle. The first Block 1 crew vehicle is fully manufactured. The core stage including its engines is undergoing testing. The booster motors are manufactured and set to ship to KSC this year. The payload components have also completed manufacturing. Production has started on the second and third core stages. Early work has also started on the powerful, new EUS and Evolved Boosters for later SLS variants. These developments set the stage not only for the Artemis I mission but years of expanded lunar exploration and missions to Mars and the outer planets.

ACKNOWLEDGMENTS

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