NASA SPACE LAUNCH SYSTEM COMPLETES KEY HOTFIRE TEST AND BEGINS VEHICLE INTEGRATION

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Figure 1: The Artemis I SLS core stage moving to the Vehicle Assembly Building (VAB) at Kennedy Space Center.

ABSTRACT

NASA and its commercial and international partners are on the way back to the Moon. As directed by the White House in 2019, the agency team is striving to return humans to the Moon and land the first woman and the first person of color on the lunar surface. NASA and its commercial partners made significant progress in the second half of 2020 and the first half of 2021 on the agency's Space Launch System (SLS), one of the key parts of the Artemis program. The team is preparing for a 2021 launch of Artemis I, the first integrated launch of the Block 1 variant of SLS with the Orion crew capsule. Hardware for the Artemis II launch, which will be the first to launch crew on SLS and Orion, is progressing through assembly, and hardware for Artemis III has started manufacturing. Artemis IV manufacturing has also started, and engines for Artemis V are in development/manufacturing. This paper will discuss the progress made in the last year and the items currently in work on for future SLS flights and variants.

INTRODUCTION

NASA and its commercial and international partners are on the way to the first human landings on the Moon in more than 50 years, as instructed in Space Policy Directive 1. The agency is working towards that goal to land the first woman and first person of color as part of the Artemis program.

To accomplish the goal, NASA and its teams are developing the rocket, spacecraft, in-space habitat and life support, and lander technologies required. The first three flights of SLS leading to the first human landing since Apollo, will be followed by more missions which will build a sustainable presence on and around the Moon. Lessons learned from long-term lunar presence will serve as the foundation for crewed missions to Mars, which remains the agency's horizon goal.

The first flight, Artemis I, will be an uncrewed test flight of SLS and the Orion spacecraft. The flight is targeted to launch near the end of 2021. Launch opportunities in 2021 assume no major issues are encountered at Kennedy Space Center (KSC) in Florida, where prime contractor Jacobs is integrating the vehicle for the first time. The major components of the rocket and capsule are all at KSC[1]. Stacking and integration has begun. Hardware for the Artemis II, III, and IV missions are in various stages of manufacture, assembly, and testing at the Michoud Assembly Facility in New Orleans, Marshall Space Flight Center (MSFC) in Alabama, Stennis Space Center (SSC), Mississippi, and numerous industry partners around the United States.



Figure 2: Artist's concept of astronauts working on the Moon with a lander behind them.

SLS DESIGN AND ARCHITECTURE

SLS will serve as a generational capability for NASA's crewed and robotic exploration for decades to come. Using technologies developed for the Space Shuttle Program and improved since then, the first block of SLS and its future evolutions will maximize payload mass and volume to deep space destinations while providing the highest chance for mission success as well as reliable, safe transportation for crew.

At the heart of SLS are the RS-25 liquid-propellant engines that served as the space shuttle main engines (SSMEs) and shuttle's twin solid rocket boosters (SRBs). Both systems have been upgraded in performance and adapted to the new SLS environments and for the new deep space missions. A newly designed core stage serves as the backbone for the rocket, housing the RS-25s and their liquid hydrogen (LH2) and liquid oxygen (LOX) tanks, as well as the avionics for the rocket. The core stage also has the attach points for the SRBs. This will be the basic architecture used for all six variants of SLS (Fig. 3).

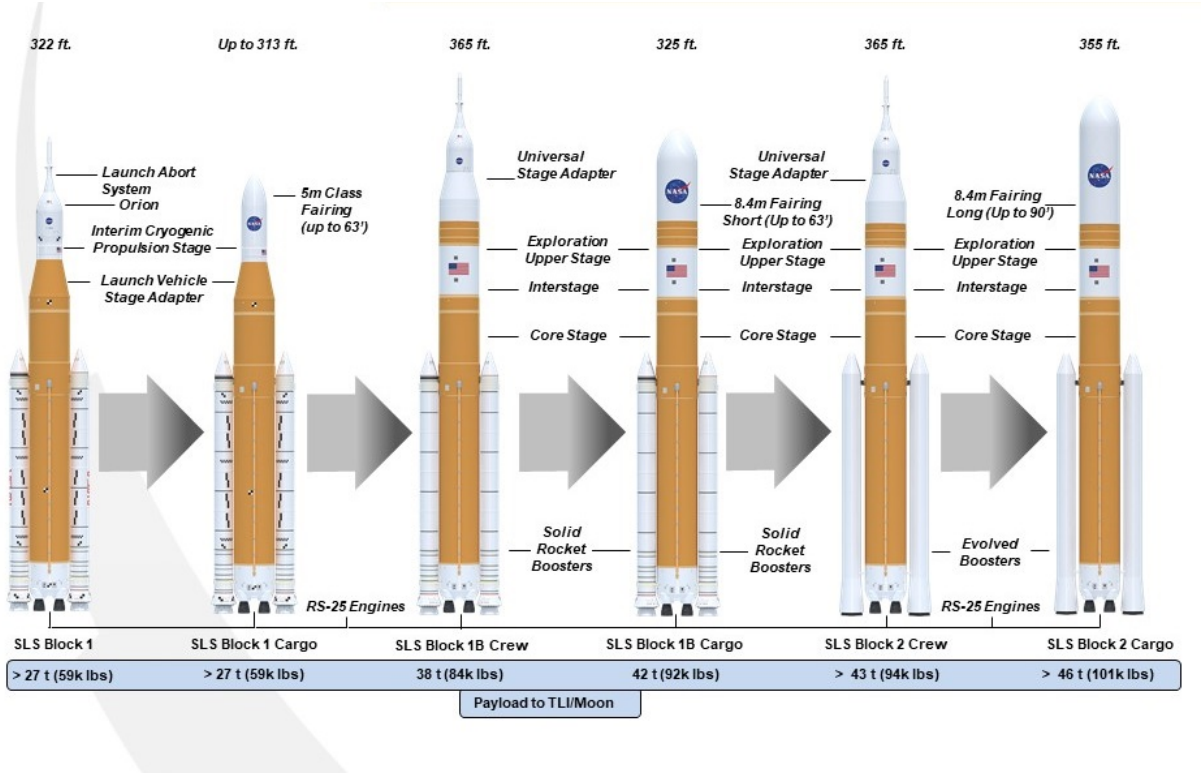


Figure 3: Primary components and performance of the planned SLS variants.

The SLS Block 1 in crew configuration stands 322.4 feet tall and weighs 5.75 million pounds fully fueled. Maximum thrust is 8.8 million pounds, and its payload to trans-lunar injection (TLI) is more than 59,535 pounds. The ICPS provides the upper stage propulsion for Block 1 and is powered by a single RL10 LH2/LOX engine with 24,750 pounds thrust. The ICPS is based on the existing United Launch Alliance (ULA) Delta IV Cryogenic Second Stage. Block 1 can launch either the Orion crew vehicle or more than 8,000 cubic feet of cargo in a 16.4 ft. (5 m) -class payload fairing. The Artemis I crew configuration is shown below (Fig. 4).

Following the Block 1 is the Block 1B – taller, slightly heavier, and more powerful. Block 1B is 365 feet tall and weighs six million pounds fueled. The Exploration Upper Stage (EUS) with its four RL10s replaces the single-engine ICPS and has 97,360 pounds thrust, accounting for most of the Block 1B TLI payload increase. Replacement of heritage RS-25s performing at 109% thrust with new-production engines operating at 111% also contributes slightly more thrust while lowering engine cost by approximately 30 percent. Block 1B will be able to send more than 83,766 pounds in the crewed Orion configuration and more than 92,594 pounds in the cargo configuration. The payload fairing is 27.6 feet in diameter and available in varying lengths. A 62.7-foot shroud will provide an available payload volume of 21,930 cubic feet. A 32.8-foot diameter fairing is also under consideration.

The final Block 2 variant stands 365 feet tall and weighs 7.4 million pounds fueled. Due primarily to the replacement of current SRBs with evolved SRBs, maximum thrust is 9.5 million pounds. The boosters have increased thrust from 3.6 million pounds each to 3.9 million pounds each. The EUS remains the upper stage. The crew configuration TLI payload increases to more than 94,799 pounds, and

the cargo configuration increases to more than 101,413 pounds. The 27.6-foot diameter payload fairing is available for the Block 2 vehicle, with the 32.8-foot fairing concept being studied.

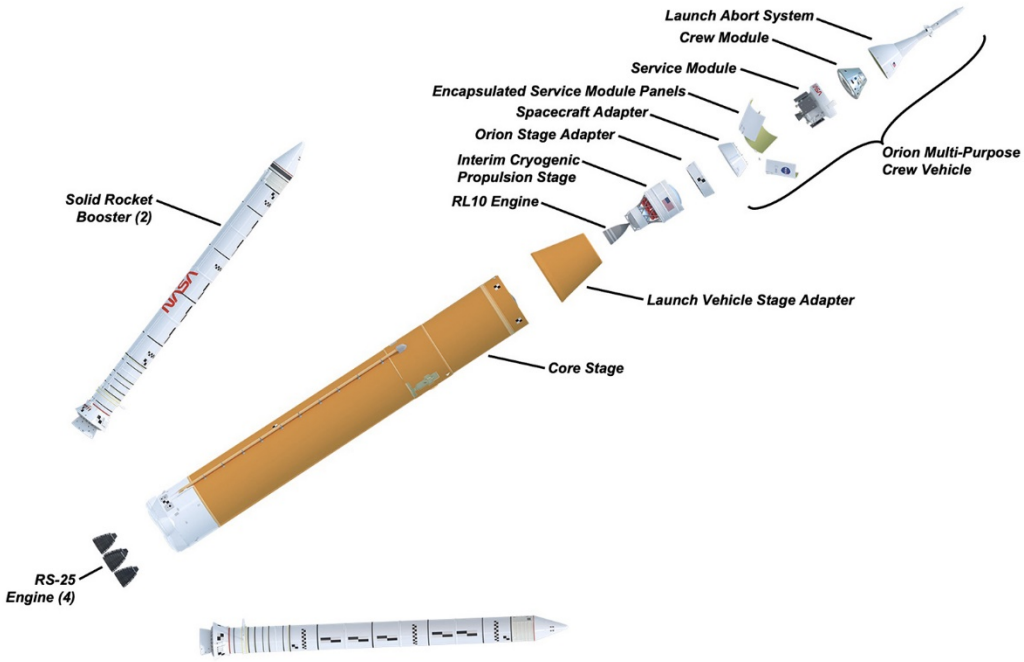


Figure 4: Expanded view of the Artemis I Block 1 vehicle

SLS PROGRESS

The NASA-industry team reached many important milestones over the past year in preparation for the launch of the Artemis I mission and the assembly and development for the next missions and versions of the SLS rocket. The SLS core stage completed the Green Run test series, the Artemis I SRBs were stacked, and hardware for future Artemis missions continued to be manufactured and assembled. This section will detail the progress made.

BOOSTERS

Providing roughly 75 percent of the vehicle's thrust for first two minutes of flight – approximately 3.6 million pounds of thrust each – are the two five-segment SRBs. Based on and using heritage hardware from the Space Shuttle Program's four-segment boosters, the boosters for SLS – manufactured by Northrop Grumman – have been upgraded with an additional propellant segment, new case insulation, new avionics, and other improvements.

In late 2020, teams completed rehearsal stacking of the SRBs onto the mobile launcher as practice for stacking the flight boosters. On November 24, stacking of the flight boosters began at the Vehicle Assembly Building (VAB) at KSC. The four-month process was completed on March 9, 2021 (Fig. 5). Teams are now preparing the boosters to be joined with the core stage, which will be integrated into the stack this summer with a targeted launch later this year[2]. A map showing the mission of Artemis I is seen in Fig. 6.

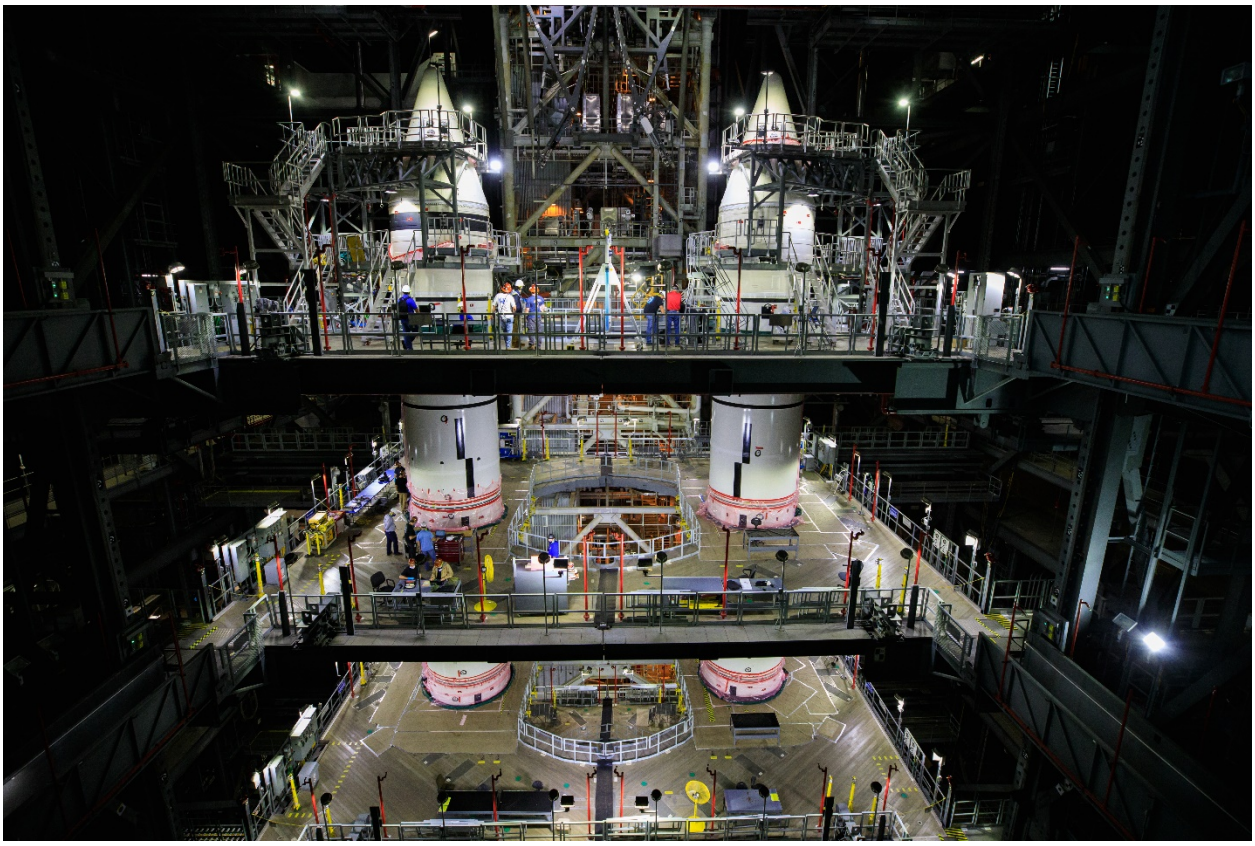


Figure 5: The boosters for Artemis I are stacked on the mobile launcher inside the VAB at Kennedy Space Center.

The booster segments for the Artemis II mission completed propellant casting and are in storage at Northrop Grumman's facility in Utah. The Artemis III segments are all cast. Work on the thrust vector control systems for the Artemis II and III boosters is underway. All of the fuel segments for Artemis III have been cast. Artemis IV will also use heritage hardware from the shuttle program, and those motor cases are being refurbished now. The SLS Program will run out of shuttle-heritage booster cases after the eighth flight of SLS. For the ninth flight, composite cases and other upgrades for the evolved boosters will be introduced. These evolved boosters will define the Block 2 SLS variant.

In addition to the flight hardware, NASA and its partners conducted multiple hot fire tests both in Utah and at Marshall Space Flight Center. Some of these tests are evaluating new propellant ingredients from new vendors to help build the supplier base, reduce cost, and improve performance of the boosters[3]. Other tests provided data to help qualify the current SLS SRBs. Additionally, new solvents and other materials for preparation of the boosters and for use in the boosters are also under evaluation in this test program. Part of the Booster Obsolescence and Life Extension (BOLE) contract modification, the data will be critical to building and using new booster segments when the supply of Space Shuttle Program segments has been depleted. BOLE boosters will have upgraded motor cases, nozzle hardware, propellant, fore and aft structures, nose cap and frustum structures, avionics, and electronic thrust vector control systems.

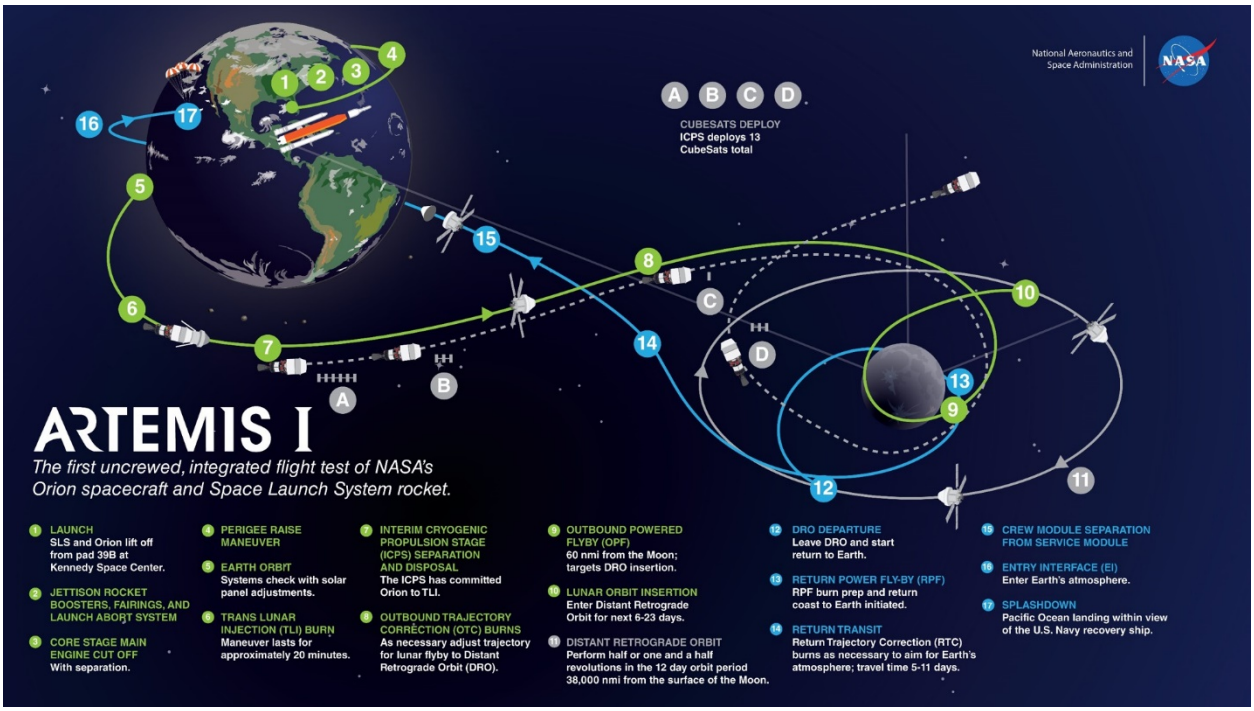


Figure 6: The Artemis I test flight will last several weeks and give NASA the opportunity to thoroughly test all systems in deep space prior to commencing crewed lunar missions.

LIQUID ENGINES

The core stage of SLS is powered by four LH2/LOX RS-25 engines. Working in conjunction with the SRBs to get the vehicle off the launch pad and into space, these Aerojet Rocketdyne-manufactured engines each have approximately 416,000 pounds of thrust at launch and more than 512,000 pounds in a vacuum and operate for the entire roughly 480-second core stage operation. The RS-25 engine for SLS has more than 40 years of experience, including as the SSME. Sixteen RS-25s remained at the end of the shuttle program – 14 flown and two new engines. Teams subjected the RS-25 to a series of 35 ground development engine tests to ensure it will perform as needed for SLS's missions and environments. Upgrades to the engine include a new controller and controller software and insulation batting on the engines.

The four RS-25 engines for the Artemis I flight were installed on the core stage in 2019. As will be discussed later in this paper, they were tested as an integrated unit with the core stage during the Green Run test series in 2020 and 2021.

In January 2021, NASA and Aerojet Rocketdyne kicked off the latest series of RS-25 single engine tests in support of SLS. The test program will have seven hot-fire tests in the A-1 test stand at SSC that will help engineers evaluate new engine components while reducing risk during engine operation. The test engine will be tested in a variety of conditions to verify its capabilities. Data from the test series will be used to enhance production of the engines and engine components using cutting-edge and cost saving technologies such as additive manufacturing[4].

The first four flights of SLS will use the shuttle-era engines, upgraded and prepared for SLS. The Artemis II engines are complete, and the Artemis III engines are in processing. Construction of the first new engines, to be flown on the Artemis V and future missions, is underway. Exhaust nozzles and their regenerative cooling tubes are currently being stacked and brazed by Aerojet Rocketdyne[5]. Powerheads, main combustion chambers and turbomachinery are also in various phases of manufacturing (Fig. 7).

One Aerojet Rocketdyne RL10 engine will propel the ICPS on each of the first three flights of SLS. Beginning with Artemis IV and the SLS Block 1B, the ICPS will be replaced with the EUS. The new upper stage uses four RL10s and will deliver enhanced payload capability to the vehicle. The EUS passed its critical design review in December 2020[6]. The Artemis IV RL10 engines are complete. Weld confidence panels for the interstage, which will partially enclose the EUS, have been produced at Michoud. Welding of an EUS structural test article (STA) is scheduled to begin late in 2021.



Figure 7: 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 VI, right.

STAGES

The core stage for SLS measures 212 feet tall and 27.6 feet in diameter. It houses the four RS-25 main engines, which consume 537,000 gallons of LH2 and 196,000 gallons of LOX from the core stage tanks. Manufactured by Boeing, it is the largest production stage produced for a NASA launch vehicle.

The core stage reached multiple significant milestones this past year. The eight-part Green Run test series of the Artemis I core stage began in February 2020, and on January 28, 2021 the first hot-fire test of all four engines and the core stage was conducted. Despite shutting down earlier than planned, the test resulted in useful data for engineers. On March 18, a full-duration hot-fire test was successfully conducted, and the Green Run test series was complete[7] (Fig.8).

The hot-fire test was the final, culminating test of the program, which included a number of tests and first-time events to ensure smooth integration and operation of the core stage. Those 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's a problem to verify that 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 that 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 the more than 700,000 gallons of LH2 and LOX from the stage

- Test 8: Fire all four RS-25s for up to eight minutes



Figure 8: The SLS core stage undergoes a successful hot fire test as part of the Green Run test series at SSC[8].

Following the second hot-fire test, the stage was removed from the B-2 test stand and loaded on the Pegasus Barge for transport to KSC (Fig. 9). The barge and its payload arrived at KSC's turn basin April 27, 2021, and the core stage was transported to the transfer aisle of the VAB on April 29. Teams from NASA's Exploration Ground Systems (EGS) and lead integration contractor Jacobs are preparing the stage for stacking (Fig. 10).



Figure 9: The Artemis I core stage is removed from the B-2 test stand at SSC, left, and is on the Pegasus barge, right.

In June, the core stage is scheduled to be lifted and mated with the Artemis I solid rocket boosters on the mobile launcher. The LVSA and the ICPS will be mated onto the vehicle following that. After the ICPS is integrated with the vehicle, either the Orion Stage Adapter (OSA) or the OSA STA will be stacked on the ICPS for modal testing. At the time of writing, the processing flow was still being evaluated.

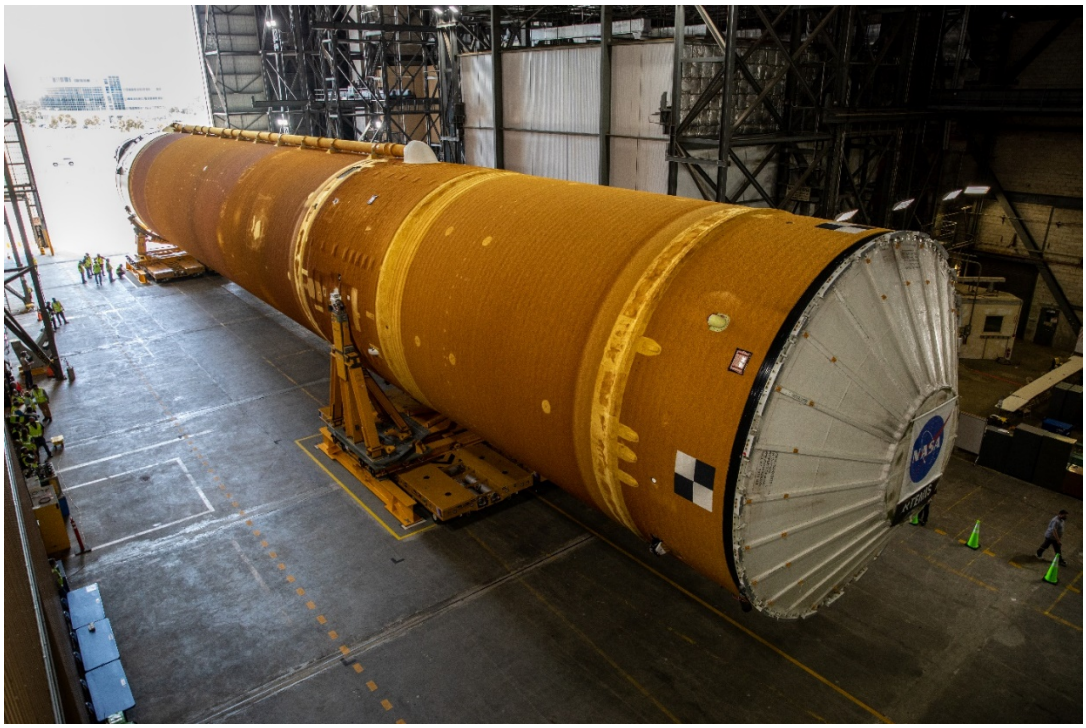


Figure 10: The Artemis I core stage is in the transfer aisle of the VAB at KSC.

The major structures for the Artemis II core stage have been fabricated and are in various stages of processing. The forward join, which connects the intertank with the LOX tank has started and will continue through the summer (Fig. 11). Components for the Artemis III and Artemis IV core stages have started production[9].

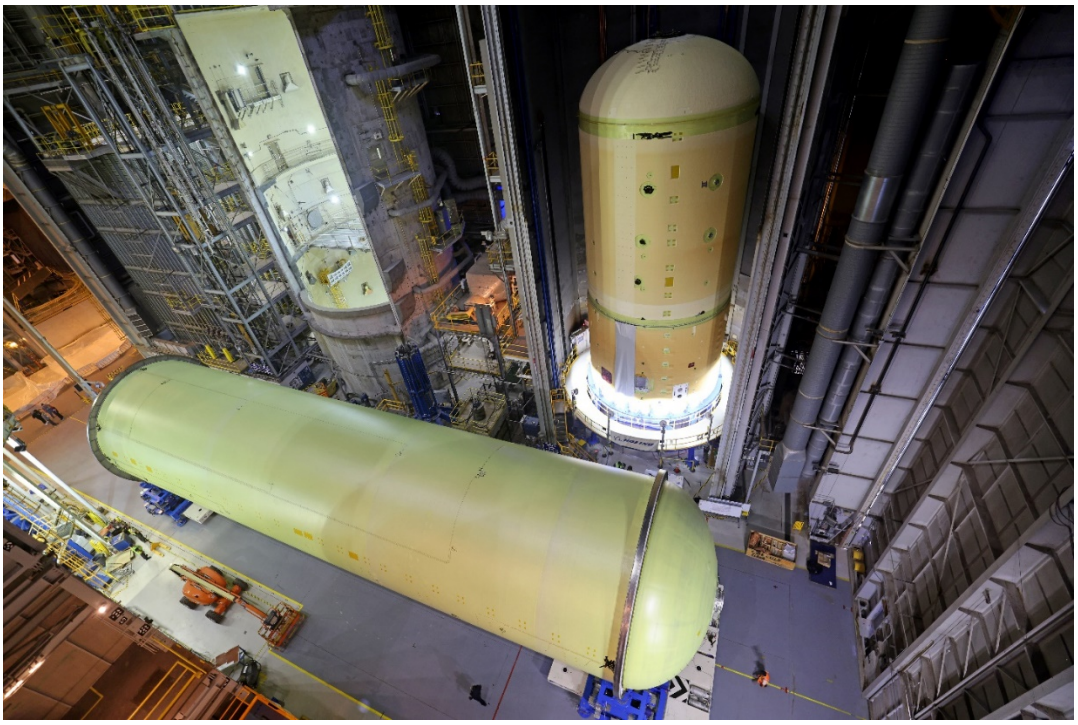


Figure 11: The forward join of the core stage for Artemis II is underway, rear, while the LH2 tank for core stage 2 is shown in the foreground.

The structural test articles that NASA and partners used to verify the designs and models of the core stage's LH2 tank, LOX tank, intertank, and engine section have completed their test program. The final test was the LOX test to failure, which occurred last summer (Fig. 12).

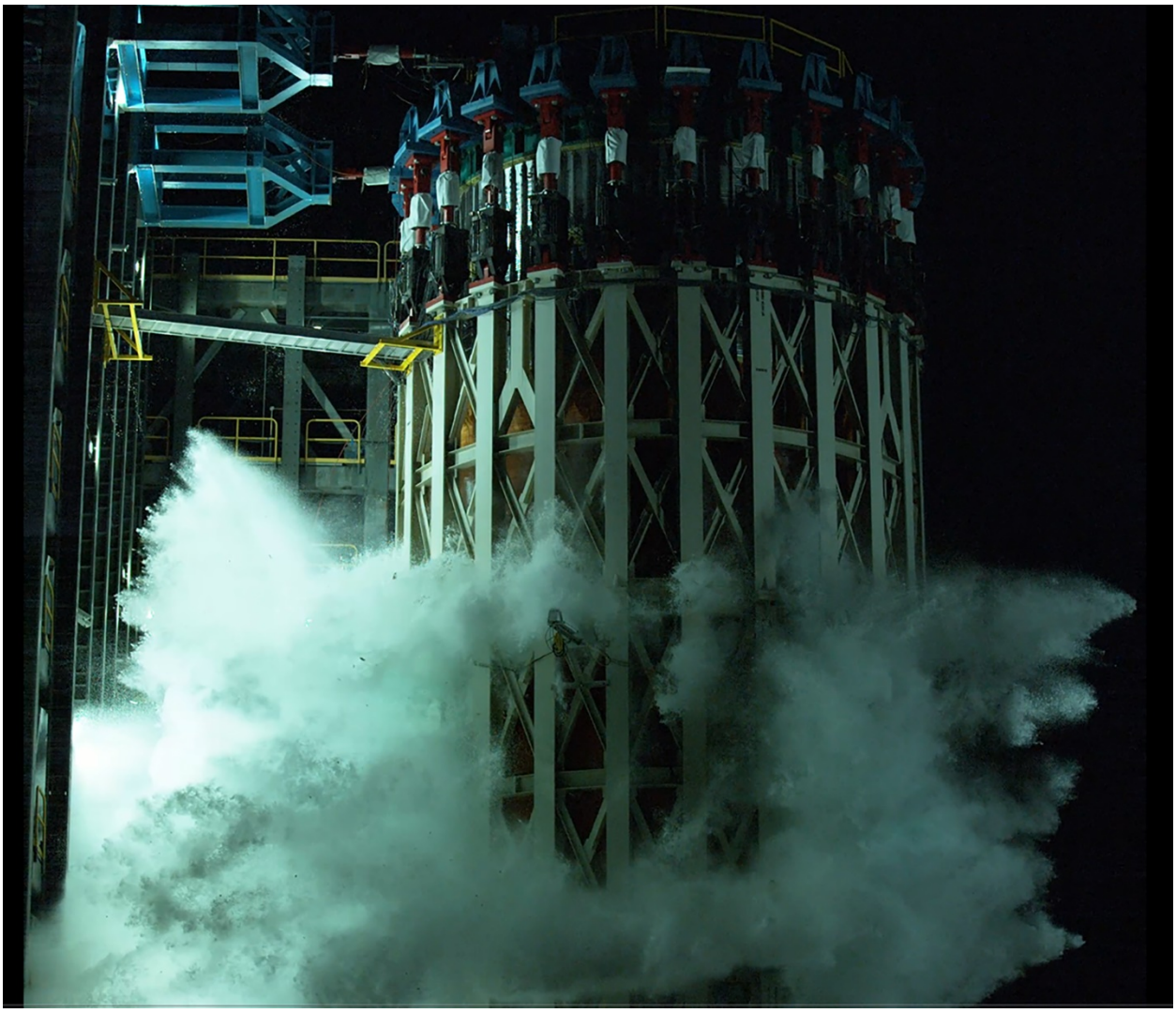


Figure 12: The SLS core stage LOX tank is tested to failure at MSFC.

UPPER STAGE and PAYLOAD SECTION

The Artemis I ICPS is currently in the Multi Payload Processing Facility (MPPF) at KSC in preparation for hydrazine loading. The Artemis I OSA, which serves as the interface between the core stage and Orion capsule and service module, is in the Space Station Processing Facility (SSPF) at KSC. Both will be moved to the VAB for integration later this year along with the CubeSat secondary payloads which will be integrated into the adapter for launch.

The major subassemblies for the Artemis II ICPS are nearing completion, and welding for the mission's OSA has been completed. Production is slated to begin later this year on the Artemis III ICPS; its RL10 engine is complete.

The LVSA for Artemis I is in the VAB awaiting stacking with the core stage and SRBs this summer. The adapter for Artemis II has completed welding at MSFC's Advanced Weld Facility, and work on the Artemis III hardware has begun[10] (Fig. 13).

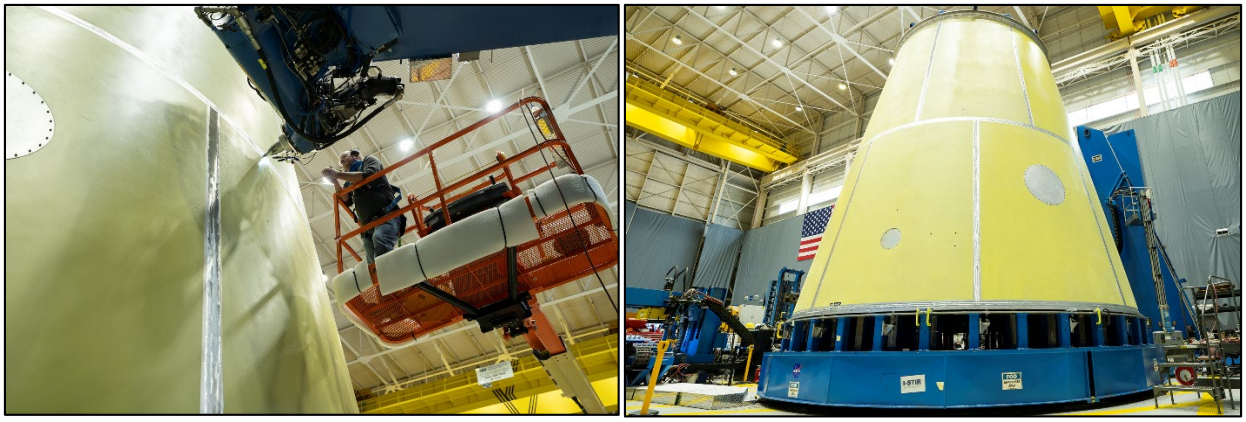


Figure 13: Technicians welding the LVSA for Artemis II, left, and the completed weldment, right.

Artemis I has 13 6U CubeSats manifested, with universities providing several of the payloads[11]. 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) may decide to use the OSA STA temporarily in the stack for certain vehicle tests while the small satellites are simultaneously being installed in the flight OSA in a parallel processing flow. Following stacking the OSA or OSA STA, a mass simulator for the Orion capsule will be placed on the vehicle for a series of modal tests to be conducted in the VAB. Following the tests, the Orion mass simulator and, if necessary, the OSA STA, will be de-stacked and the flight hardware will be stacked and integrated.

OPERATIONAL PREPAREDNESS

While teams are preparing the vehicle for flight, other teams are conducting countdown and mission simulations. These simulations include teams at both KSC and the SLS Engineering Support Center (SESC) at MSFC and help teams practice pre-launch and launch activities. They enable the teams to define and refine 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 Green Run test series, collecting and storing data for analysis.

SUMMARY AND CONCLUSIONS

NASA and its industry partners made significant progress on the SLS rocket both for Artemis I and future Artemis missions in the second half of 2020 and the first half of 2021. Completion of the Green Run test series and transportation of the core stage to KSC mark important steps toward returning humans to the Moon. Successful stacking of Artemis I SRBs on the ML at KSC laid the foundation for the next step, integrating the core stage. Later this summer, the rest of the rocket will be stacked, followed by power-on of the elements, attachment of umbilicals, testing of umbilical retract mechanisms, and intermodal testing. Following testing and completion of the flight stack, the vehicle with the Orion spacecraft will roll out to launch complex 39B for wet dress rehearsal. The final major test prior to launch, wet dress rehearsal, will test teams, systems, and countdown procedures, including tanking and de-tanking propellant. After wet dress rehearsal, the vehicle will roll back to the VAB one final time prior to launch. There, teams from EGS and Jacobs will perform final checks and closeouts to prepare for launch. Once all these steps are complete, the team will look for launch opportunities for Artemis I.

Progress on hardware for Artemis II, III, IV, and V continues, ensuring the launch vehicles for the next missions are ready and that the contractor base is strong and capable of delivering for the nation's Moon program.

The SLS rocket, including its advanced iterations, will anchor NASA's human and robotic exploration programs for decades to come. The unparalleled capability of the rocket will continue to be a

national resource as NASA and its partners break the chains of Earth and explore space like never before.

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