NASA'S SPACE LAUNCH SYSTEM GAINS MOMENTUM TOWARD INTEGRATION AND TESTING

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Figure 1: Artist rendering of SLS and Orion on the Mobile Launcher at Kennedy Space Center.

ABSTRACT

NASA's Space Launch System (SLS) (Fig. 1) entered a new phase in 2017, completing major structural manufacturing on the core stage and delivering for launch the first flight hardware of the world's most capable launch vehicle. The program is now in a stage of hardware assembly, integration and testing in preparation for the first integrated flight of SLS and the Orion crew vehicle. SLS is critical to U.S. leadership in future human and robotic space exploration, including a presence on the Moon in preparation for missions deeper into space. This paper will elaborate on SLS accomplishments in 2017 and plans for progress in 2018.

INTRODUCTION

National Space Policy calls for NASA to “lead an innovative and sustainable program of human and robotic exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations.”

NASA is leading the next steps of human exploration into cis-lunar space with missions to the Moon, where astronauts will build and begin testing the systems needed for challenging missions to other destinations, including Mars, and deeper into space. The space agency is working with domestic and international partners to solve the great challenges of living and working in space farther from Earth, in the process creating new knowledge that inspires the nation and benefits all of humanity.

NASA’s SLS, Orion and Exploration Ground Systems are the leading critical backbone elements for our future in deep space, beginning with the un-crewed Exploration Mission 1 (EM-1) mission in fiscal 2020, the first integrated launch of SLS and Orion around the Moon, and the crewed EM-2 mission around the Moon currently scheduled for 2023.

NASA will also begin to build the in-space infrastructure for long-term exploration and development of the Moon by accelerating to 2022 plans to deliver initial components of the Lunar Orbital Platform – Gateway (Fig. 2) to lunar orbit. This gateway to the Moon and beyond will give NASA a strategic presence in deep space that will drive activity with commercial and international partners and help further explore the Moon and its resources and translate that experience toward human missions to Mars.[1]

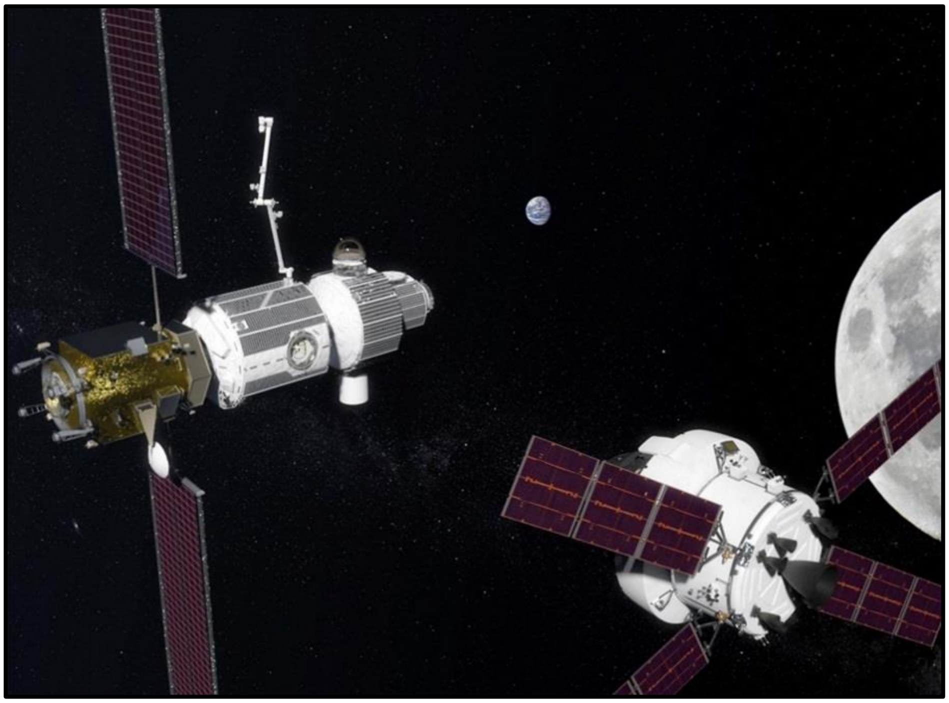

Figure 2: Artist rendering of Lunar Orbital Platform – Gateway (left), and Orion, right.

The focus of this paper is SLS. The founding tenants of SLS are safety, affordability, and sustainability. Traveling to deep space requires a large vehicle that can carry huge payloads needed for complex missions. SLS will carry more mass and volume than any current or previous launch vehicle. Its unmatched capability will reduce the complexity, cost, and risk associated with payload design, ground infrastructure, and in-space operations and provide the best opportunity for mission success.

The SLS Program, managed by NASA's Marshall Space Flight Center (MSFC), took advantage of available powerful, proven propulsion systems providing an affordable solution to what is typically the most difficult aspect of a new launch vehicle development. The four RS-25 engines, powered by liquid hydrogen (LH_2) and liquid oxygen (LOX), and two five-segment solid propellant boosters are based on the earlier Space Shuttle Main Engine and Space Shuttle four-segment booster, with updated materials and systems to meet contemporary standards as well as SLS performance requirements and environments.

SLS is designed as a human-rated exploration-class heavy lift launch vehicle. It is designed to evolve as objectives become more challenging. In its primary role as a deep space exploration vehicle, the evolving configurations of SLS will be able to send cargo to the Moon (trans-lunar injection, or TLI) ranging from greater than 26t for Block 1 to greater than 45t (55,000 – 99,000 pounds) for Block 2.

The Block 1 variant for EM-1 is the foundation for more powerful, capable SLS variants (Fig. 3). The un-crewed EM-1 lunar mission will provide a critical first end-to-end test of materials, manufacturing, testing, integration, and launch and flight operations for SLS, as well as the Orion crew vehicle, and launch facilities at NASA's Kennedy Space Center. It will also launch 13 small secondary payloads.

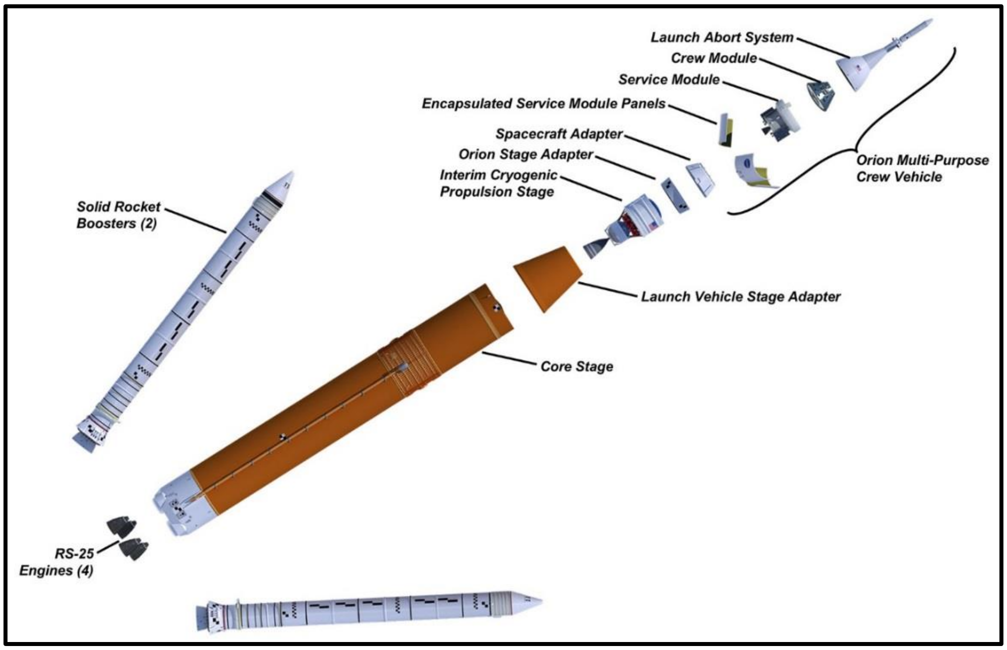

Figure 3: Expanded view of SLS Block 1 for EM-1 mission.

The SLS Block 1B crew configuration will be capable of launching 105t to LEO, including the Orion crew spacecraft and various co-manifested payloads such as large modules for the gateway facility. The Block 1B will be the workhorse of the 2020s cis-lunar missions, able to deliver 34-40 metric tons of payload to TLI, more than double the capacity of current launch vehicles. In the Block 1 configuration, the upper stage, designated the Interim Cryogenic Propulsion Stage (ICPS) is powered by a single RL10 engine. In the Block 1B, the ICPS is replaced by the Exploration Upper Stage (EUS), which is larger and uses four RL10 engines. Notably, SLS will be the only rocket capable of sending humans on Orion to deep space in a single mission and the only vehicle to send both Orion and a large payload such as a gateway module, to the Moon in a single mission.

In addition to payload mass, SLS provides greater volume than any other launch vehicle. Beginning with EM-2, the Universal Stage Adapter will allow a payload to fly with Orion with as much accommodation volume as the current industry-high 5-meter (m) fairing. The Block 1B configuration will also enable the use of an 8.4-m cargo fairing with 18,970 cubic feet for primary payloads, and the Block 2 vehicle with a longer 8.4-m long fairing will be able to carry 31,950 cubic feet of payload.

CORE STAGE PROGRESS

The core stage serves as the backbone of SLS and is designed around the attached engines and boosters. At more than 212 feet long and 27.6 feet in diameter, it holds up to 537,000 gallons of liquid hydrogen and liquid oxygen to fuel the four RS-25 engines at its base. It is designed to operate for roughly 500 seconds, reaching nearly Mach 23 and more than 530,000 feet in altitude before separating from the upper crew or cargo stages.

Core stage prime contractor Boeing has completed the major structural components for the EM-1 and ground test engine section, liquid hydrogen tank, intertank, liquid oxygen tank and forward skirt.[2] There is no test article for the forward skirt, having been accepted for test-by-analysis. The flight components and the flight hydrogen and oxygen tanks (Fig. 4) are currently in cleaning and hardware installation at NASA’s Michoud Assembly Facility (MAF). This includes installation of insulation, wiring, brackets, pipes, cables, and other hardware.

Figure 4: EM-1 liquid hydrogen tank (left), and EM-1 liquid oxygen tank (right).

The Systems Integration Test Facility – Qualification (SITF-Q) at MSFC completed software testing as part of EM-1 Intertank functional tests. The EM-1 forward skirt was ready to begin testing to demonstrate functionality of the avionics system harnesses. The EM-1 core stage sections are scheduled to begin integration later in 2018. Meanwhile, work has begun on manufacturing the major components of the EM-2 core stage.

All engine section structural testing was complete in early 2018.[3] Shipped from MAF, the structural test article (STA) was installed in a unique 50-foot-tall test stand, connected to more than 50 hydraulic actuators to simulate flight loads (Fig. 5, left). During tests, the actuators simulated more than 3 million pounds of upward RS-25 engine thrust loads and up to 750,000 pounds of loads on each side for the outward forces created by the solid rocket boosters. A series of tests also validated brackets designed to hold feedlines from the liquid oxygen tank. Engineers recorded and analyzed over 3,000 channels of data for each test case to verify the capabilities of the engine section and LOX downcomer feedlines. Teams compared the data to design and analysis models to validate the accuracy of the predicted loads.

The intertank structural test article was shipped from MAF to MSFC in March 2018 (Fig. 5, right), and it was being readied for testing as this paper was in preparation. LH_2 and LOX test articles are scheduled to be shipped to MSFC later this year for testing. The LH_2 and LOX test stands are complete and ready to receive the test articles in later 2018.

The core stage pathfinder was built and delivered to MAF in 2017 to begin practice operations for moving, lifting and transporting the EM-1 core stage. The shuttle-era Pegasus barge was modified to transport the SLS core stage. The B2 test stand at Stennis Space Center has been renovated to support core stage “green run” hotfire testing. Flame bucket activation on the B-2 stand is complete. Facility consoles are installed. Ground support equipment testing is continuing, including self-propelled module transporters (SPMTs) and common hardware interface structure (HIS) used to move the large core stage pieces.

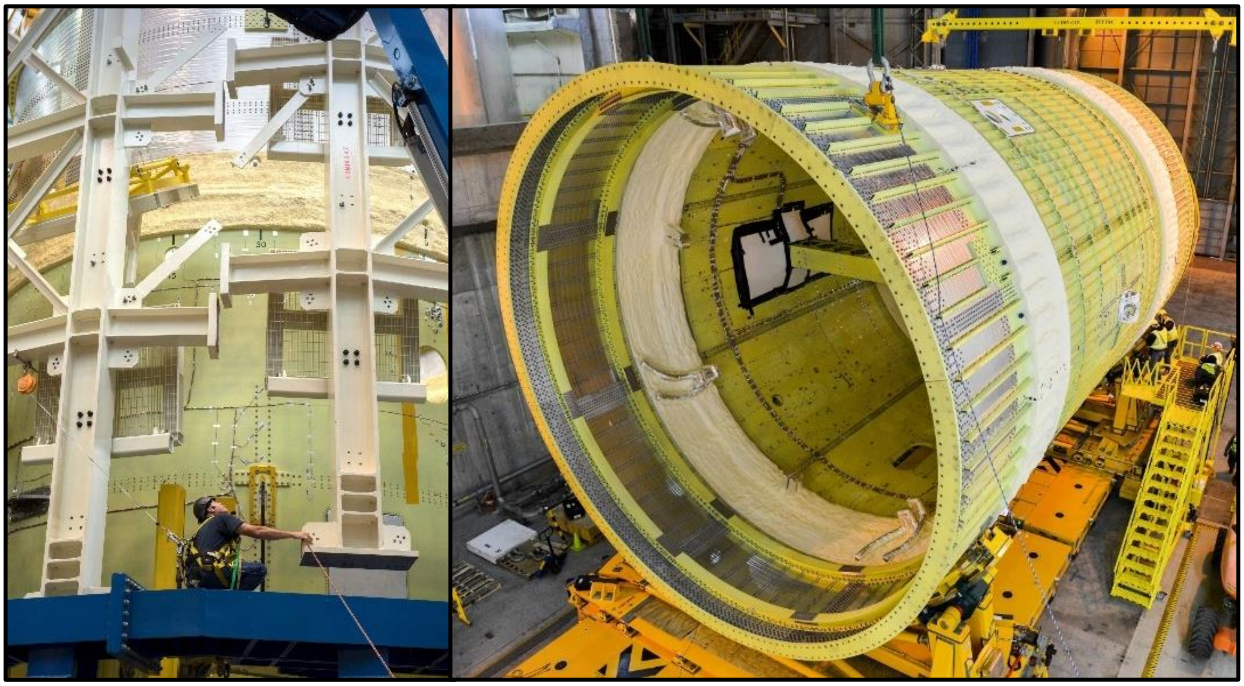

Figure 5: Engine section test article at MSFC (left) and intertank test article at MAF (right).

SOLID ROCKET BOOSTER PROGRESS

The SLS solid rocket booster is the largest, most powerful solid propellant booster ever built for flight. Standing 177 feet tall and 12 feet in diameter, each booster burns about six tons of propellant every second and generates a maximum of approximately 3.6 million pounds of thrust. During their two-minute mission, they provide about 75 percent of total SLS thrust.

The booster motor is based on the four-segment shuttle booster motor. In addition to a fifth segment, the booster features a new nozzle design, new asbestos-free insulation and case liner configuration, new avionics, and improved nondestructive evaluation processes in manufacturing. The program has conducted five full-scale test firings of the five-segment motor — two developmental tests and two qualification tests. The two qualification tests, performed in 2015 and 2016, tested the motor’s performance with propellant bulk mean temperature conditioned to 90 degrees Fahrenheit and 40 degrees Fahrenheit.[4]

All 10 EM-1 solid rocket motor segments have been cast with propellant at booster prime contractor Orbital ATK facilities (Fig. 6, left). Four are complete and ready to ship to KSC. The remaining six are in final processing. In addition, nozzles are complete and avionics have been tested.

For EM-2, three motor segments have been cast with propellant and six others are in various stages of manufacturing, including preparation of the steel cases, installing insulation and quality control testing using x-ray and other non-destructive tests. Nozzle manufacturing has begun.

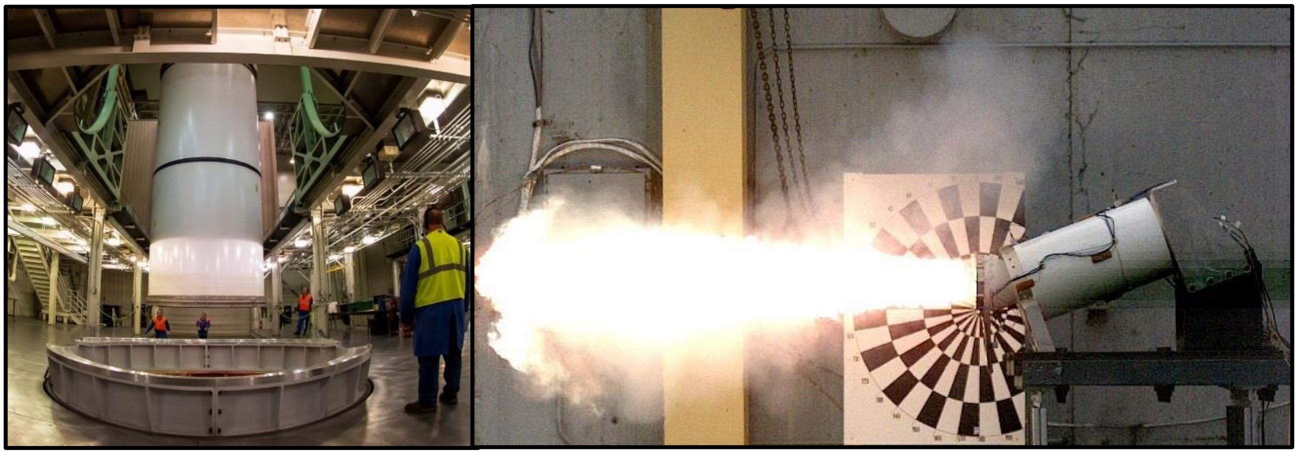

Figure 6: EM-1 motor casting at Orbital ATK (left), and booster separation motor test (right).

All five EM-1 booster avionics boxes have completed qualification testing at the system level and are scheduled to be tested with the core stage avionics. Refurbishment work on the EM-1 boosters forward assemblies and aft skirts is also ongoing at KSC. Battery qualification testing is complete. Aft skirt testing is under way, including full hydraulic pressure nozzle gimbal testing and hydrazine loading to the aft skirt test article thrust vector control (TVC) system.

Four of the 16 EM-1 booster separation motors are complete, and the remaining 12 are in work. The solid-fuel rockets, about 3 feet long, simultaneously fire with about 20,000 pounds of thrust each for one minute at the end of the larger solid rocket boosters' flight to separate the spent boosters from the core stage. Eight booster separation motors are attached to each solid rocket booster — four on each forward skirt and four on each aft skirt. Qualification testing of separation motor propellant for the EM-2 separation motors was conducted in March 2018 (Fig. 6, right). This testing also verified the loads environments for the EM-1 separation motors. Twenty-one subscale linear-shaped charge assemblies qualification units were successfully test-fired.

Looking ahead in 2018, the EM-1 solid rocket motor exhaust nozzles are complete and scheduled to be installed in their aft motor segments this spring.

RS-25 PROGRESS

Four RS-25 engines will power the SLS core stage. Together they will provide approximately two million pounds of thrust for the entire eight-minute core stage flight. The RS-25, formerly the Space Shuttle Main Engine (SSME), was selected for SLS based on its power, its successful performance over 135 shuttle missions, and its well-understood characteristics over more than a million seconds of ground and flight operating time. SLS was also able to take advantage of 14 flown engines with remaining flight life and two new engines assembled from shuttle program spares. For SLS, the engine inventory will receive new, updated controllers and software, as well as nozzle insulation due to the higher base heating environment. For SLS, the engines will operate at 109% thrust versus the 104.5% standard for shuttle missions.

As part of an initial SLS "adaptation" hotfire series and subsequent hotfire tests at NASA's Stennis Space Center (SSC) to qualify the new controllers and test new components for future engines, the two RS-25 development engines have accumulated 22 tests totaling just over 10,000 seconds of operating time.

All four EM-1 engines have completed processing for their mission (Fig. 7, left). All four controllers for those engines, as well as the EM-2 controllers, have been green run hot-fire tested, and the engines have completed acceptance reviews. Ablative insulation for the exhaust nozzles to protect them in the higher heating environment closer to the booster nozzles was being installed at the time this paper was in preparation. The engines remain at SSC until required for stage integration at MAF.

The RS-25 pathfinder has been delivered to MAF to verify engine operation and work instructions. Work is under way on processing the four EM-2 engines, which are also the EM-1 contingency engines, and their four controllers completed hotfire testing.

In December 2017, a ground test RS-25 was used to test a 3D-printed POGO accumulator (Fig.7, right), the first of several engine parts being manufactured using a variety of updated processes aimed at reducing the cost of future RS-25s by 30 percent overall. In the POGO accumulator additive manufacturing process, more than 100 welds were eliminated, reducing costs by nearly 35 percent and production time by more than 80 percent. Initial reports show the 3-D printed hardware performed as expected, opening the door for more additively-manufactured components scheduled for future tests. The accumulator was also part of a February 2018 test where an RS-25 was tested for the first time to 113 percent of rated thrust as part of a plan to certify new production engines to 111 percent.[5]

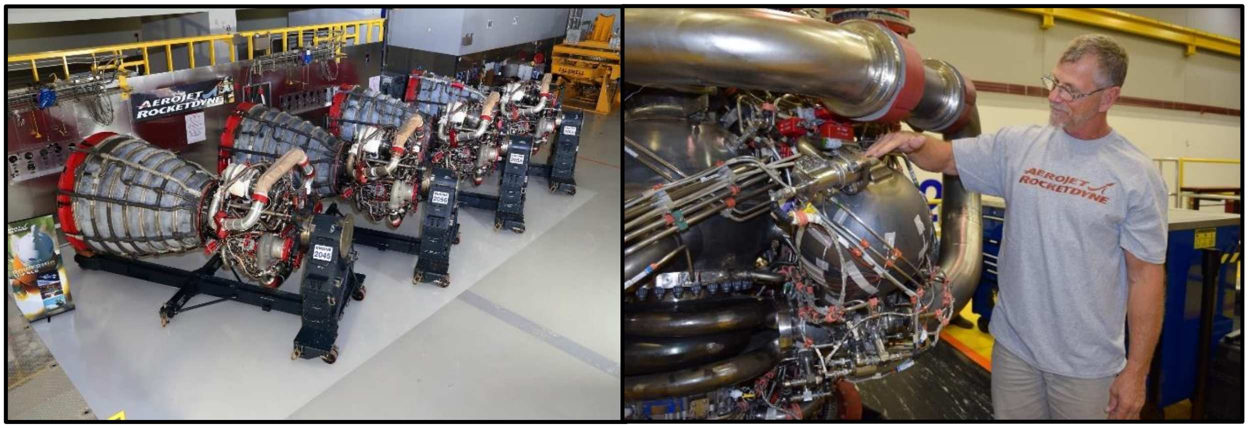

Figure 7: EM-1 RS-25 engines at SSC (left), and POGO accumulator on RS-25 at SSC (right).

Ahead in 2018, the test engine will be returned to RS-25 prime contractor Aerojet Rocketdyne to be retrofitted with additional hardware including a redesigned main combustion chamber (MCC) and redesigned flex ducts. A second development engine is also being retrofitted with a redesigned MCC and high-pressure fuel pump. The new MCC design significantly reduces pieces, welds, touch labor and cost. The SSC A-1 test stand is being modified to test engine gimbaling using the new ducts and undergoing additional maintenance in preparation for a new test series beginning in late summer 2018.

UPPER STAGE/PAYLOAD PROGRESS

Above the core stage are several structures. On the Block 1 vehicle is the Interim Cryogenic Propulsion Stage (ICPS), partially enclosed by the Launch Vehicle Stage Adapter (LVSA). Above that is the Orion Stage Adapter (OSA), and above that is a spacecraft adapter and the Orion crew vehicle, service module and Launch Abort System (LAS). The EM-1 ICPS was completed by United Launch Alliance (ULA) and Boeing in Decatur, AL, in 2017 and shipped to Kennedy Space Center – the first flight hardware delivered to the launch site. The Integrated Structural Test (IST) at MSFC, also completed in 2017, subjected full-size test articles of the LVSA, frangible joint assembly, ICPS, and OSA to flight-like loads. After checkout in the ULA facility at Cape Canaveral Air Force Station, the flight ICPS was transferred to the Space Station Processing Facility. (Fig. 8) In fall 2017, it was formally turned over to KSC's Exploration Ground Systems Program, which has responsibility for stacking and launching operations.[6]

Figure 8: EM-1 ICPS at KSC.

The flight OSA, about five feet tall and 18 feet diameter was designed and built at MSFC (Fig. 9, left). It was completed in early 2018 following tests of the avionics system that will deploy 13 secondary payloads and shipped to KSC on the NASA Super Guppy aircraft in April 2018.[7] Part of its processing for flight will include installation of 13 shoebox-sized CubeSats flying as secondary payloads to be deployed after Orion separates from SLS. Welding was completed on the EM-1 Launch Vehicle Stage Adapter (LVSA) and work is expected to be complete in 2018. At the time this paper was written, instrumentation had been installed and application of the thermal protection system was nearing completion.

Teledyne Brown Engineering of Huntsville, the prime contractor for the LVSA, completed manufacturing of the LVSA in 2017 (Fig. 9, right), and MSFC technicians completed thermal protection systems foam application using a manual process.[8] The LVSA, measuring 27.6 feet in diameter at its base and 28 feet tall, is the largest piece of the rocket built in Marshall's manufacturing area. It will connect two major sections of SLS – the 27.6-foot diameter core stage and the 16.4-foot diameter ICPS.

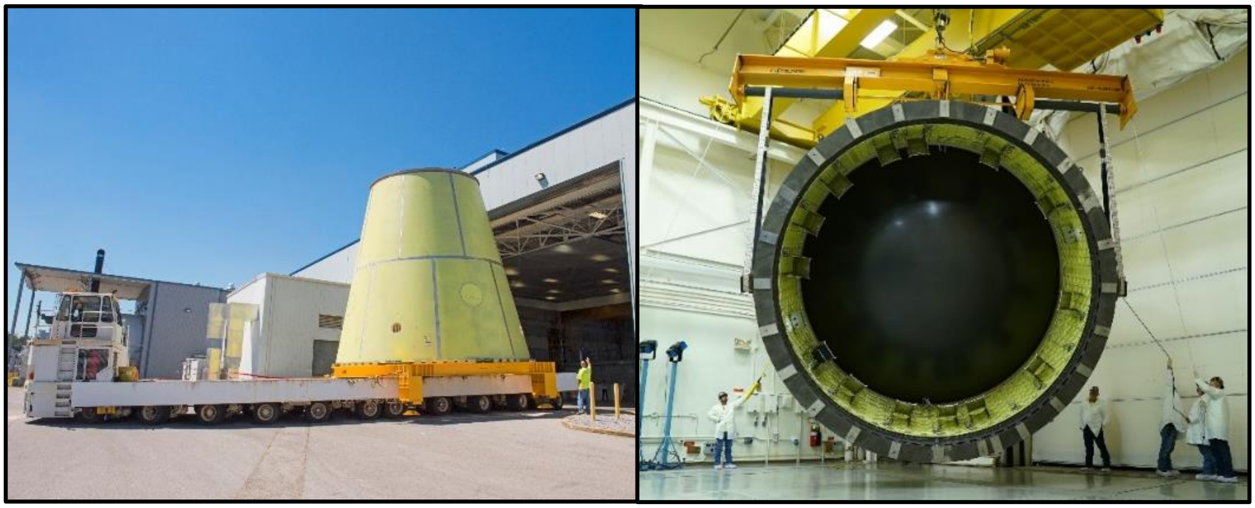

Figure 1: EM-1 LVSA at MSFC (left), and EM-1 OSA at MSFC (right).

SUMMARY AND CONCLUSIONS

SLS made significant progress in 2017 with delivering the first flight hardware to the launch site, completion of major structures for the core stage, and beginning a major test campaign for a strategic national capability to take human exploration to other worlds again. The components for the first and second launch vehicles are being integrated and tested with the goal of a first launch in fiscal 2020, and the evolution to greater capability has begun. SLS is vital to unprecedented human and robotic exploration of deep space. With unmatched payload mass and volume, SLS will reduce the complexity, cost and risk associated with payload design, ground infrastructure and in-space operations and offer unique opportunities or human and robotic exploration.

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REFERENCES

1. Falk, Dan, **NASA's Deep Space Gateway seen as key to bold plan for Mars and beyond**, https://www.nbcnews.com/mach/science/nasa-s-deep-space-gateway-seen-key-bold-plan-mars-ncna838056 (January 2018)
2. Spaceflight Insider, **Major Core Stage Hardware Completed for First SLS Flight**, http://www.spaceflightinsider.com/organizations/nasa/major-core-stage-hardware-completed-for-first-sls-flight/ (October 2017)
3. NASA, **Structural Testing Complete on SLS Core Stage Powerhouse**, https://www.nasa.gov/exploration/systems/sls/structural-testing-complete-on-sls-core-stage-powerhouse.html (February 2018)
4. NASAspaceflight.com, **Solid production – Booster segments readying for opening SLS launches**, https://www.nasaspaceflight.com/2017/06/solid-production-booster-segments-sls-launches/ (June 2017)
5. Sloss, P, **RS-25 hot fire pushes SLS engine to record 113 percent thrust level**, https://www.nasaspaceflight.com/2018/02/rs-25-hot-fire-sls-engine-113-percent/ (February 2018)
6. Granath, B., **First SLS Rocket Hardware Turned Over to Exploration Ground Systems at Kennedy Space Center**, https://www.nasa.gov/feature/first-sls-rocket-hardware-turned-over-to-exploration-ground-systems-at-kennedy-space-center (November 2017)
7. Roop, L, **NASA shows off SLS hardware made in Alabama, bound for deep space**, http://www.al.com/news/huntsville/index.ssf/2018/02/nasa_shows_off_sls_space_hardw.html (February 2018)
8. Sloss, P, **Preparing the adaptor – LVSA readies for NASA debut**, https://www.nasaspaceflight.com/2017/09/preparing-adaptor-lvsa-readies-sls-debut/ (September 2017)