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NASA's Space Launch System: Progress ReportJerry Cook^a, Garry Lyles^b^a NASA Marshall Space Flight Center, United States of America, jerry.r.cook@nasa.gov^b NASA Marshall Space Flight Center, United States of America, garry.lyles@nasa.gov**Abstract**

After more than four decades exploring the space environment from low Earth orbit and developing long-duration spaceflight operational experience with the International Space Station (ISS), NASA is once again preparing to send explorers into deep space. Development, test and manufacturing is now underway on the launch vehicle, the crew spacecraft and the ground processing and launch facilities to support human and robotic missions to the moon, Mars and the outer solar system. The enabling launch vehicle for these ambitious new missions is the Space Launch System (SLS), managed by NASA's Marshall Space Flight Center (MSFC). Since the program began in 2011, the design has passed Critical Design Review, and extensive development, test and flight hardware has been produced by every major element of the SLS vehicle. Testing continues on engines, boosters, tanks and avionics. While the program has experienced engineering challenges typical of a new development, it continues to make steady progress toward the first SLS mission in roughly two years and a sustained cadence of missions thereafter. This paper will discuss these and other technical and SLS programmatic successes and challenges over the past year and provide a preview of work ahead before first flight.

1. Introduction

NASA continues to advance its ground-breaking work in human spaceflight, as well as science, technology and aeronautics. While maintaining a constant presence in low Earth orbit (LEO) in the form of the International Space Station (ISS), the agency is working to carry human exploration into deep space. NASA is working on the challenges of deep space human exploration to achieve the best opportunity for mission success. NASA is also fostering stronger partnerships between government agencies and private industry to make space travel safer, more affordable and more accessible.

NASA has outlined a phased exploration plan (see Fig. 1) that leads to a human landing on Mars in the 2030s. This phased approach divides the challenges into near-Earth, cis-lunar and beyond the Earth-moon system. Each phase is progressively further from Earth, requiring more support, more capable technologies and resulting in greater independence from our home planet.

That work is currently ongoing with the operation of ISS and development of commercial cargo and crew services to the station. Deep space exploration begins with the next phase – cis-lunar exploration – and development of the necessary supporting architecture. That endeavour is underway with the creation of a heavy lift launch vehicle – SLS, a deep space crew spacecraft – Orion, and the supporting integration and launch facilities. Exploration Mission 1 (EM-1) is the first in a series of exploration missions that will take humans into deep space. EM-1 is designed to be a flight

test of all three major components now in development, manufacturing and testing.

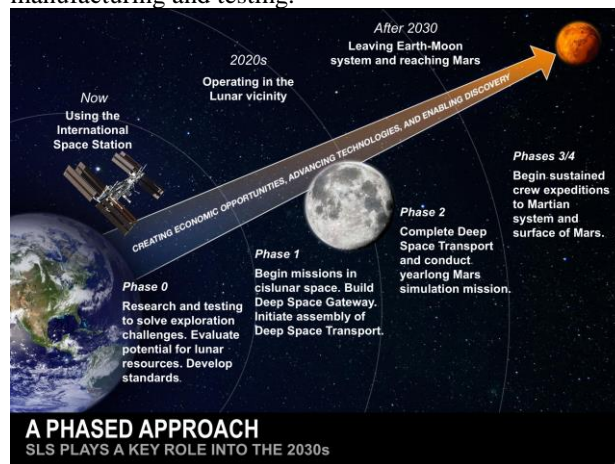


Fig. 1. Overview of NASA's vision for human exploration.

2. SLS overview

SLS is the result of thousands of trade studies involving stages, engines, technologies, trajectories and other factors. Rather than focus on a single objective, SLS represents a balance of mission requirements, affordability, mission safety, reliability and risk. Reflecting fiscal realities, SLS is based on proven propulsion technologies in a configuration capable of evolving as the nation's exploration goals become more ambitious and missions become more challenging and complex.

Work is currently focused on the Block 1 variant, which completed Critical Design Review (CDR) in July 2015. Block 1 will be approximately 322 feet (98 m) tall and weigh 5.75 million pounds (2.6 million kg) fueled, and will have a maximum thrust of roughly 8.8 million pounds. Block 1 will have a payload capability of more than 154,324 pounds (70 metric tons) to LEO (see Fig. 2).

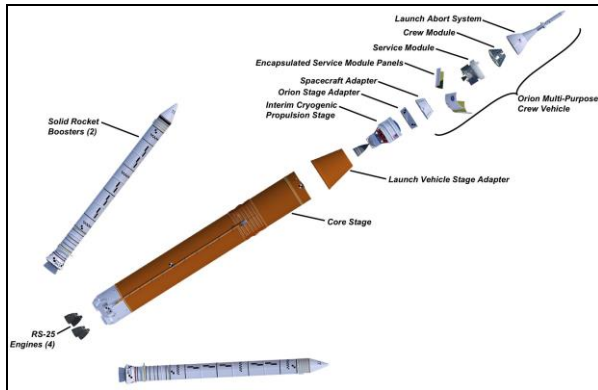


Fig. 2. Expanded view of SLS Block 1 configuration.

The SLS core stage will be the tallest stage ever built at 212 feet (64.6 m) and 27.6 feet (8.4 m) in diameter. It is designed to hold 537,000 gallons (2 million liters) of liquid hydrogen and liquid oxygen.

The core stage will be powered by four Aerojet Rocketdyne RS-25 engines originally developed for the space shuttle program but adapted to SLS performance requirements and operating environments. Among those SLS performance differences are higher inlet pressure and a higher base heating environment. The RS-25 is one of the most powerful and proven engines in the world, generating 512,000 pounds of thrust each at 109 percent operating power level. SLS has 14 previously flown RS-25s and two new RS-25s available to support the first four launches. To replace the obsolete shuttle-era engine controller, the program is developing a new controller to manage thrust, steering and other engine functions.

A pair of Orbital ATK five-segment solid rocket boosters will provide roughly 75 percent of vehicle thrust at lift-off. Based on the shuttle four-segment boosters, they are approximately 177 feet (54 m) tall and 12 feet (3.6 m) in diameter. Maximum thrust is approximately 3.6 million pounds each. The boosters feature a new nozzle design, non-asbestos case insulation and new avionics.

The Block 1 upper stage is a modified Delta IV Cryogenic Second Stage (DCSS), renamed the Interim Cryogenic Propulsion Stage (ICPS). The Boeing-United Launch Alliance (ULA) stage is approximately 43 feet (13 m) tall and 17 feet (5 m) in diameter. The ICPS is powered by one Aerojet Rocketdyne RL10 engine with

a maximum thrust of 24,750 pounds (110.1 kN). It will perform the trans-lunar injection (TLI) burn to push the un-crewed Orion out of Earth orbit and into a Distant Retrograde Orbit (DRO) around the moon during the EM-1 mission.

The Launch Vehicle Stage Adapter (LVSA), manufactured by Teledyne Brown Engineering at MSFC, connects the core stage to the ICPS upper stage. The Orion Stage Adapter (OSA) connects SLS to Orion. Thirteen shoebox-sized cubesats stowed in the OSA will be ejected from the adapter at intervals ranging from three hours to seven days after launch to perform various scientific investigations of the moon, Earth/moon environment, heliophysics and other subjects.

The Block 1 vehicle is designed to serve as a test vehicle for an un-crewed Orion spacecraft on a trip to and from the lunar vicinity. Block 1 will be the basis for several evolved variants (see Fig. 3).

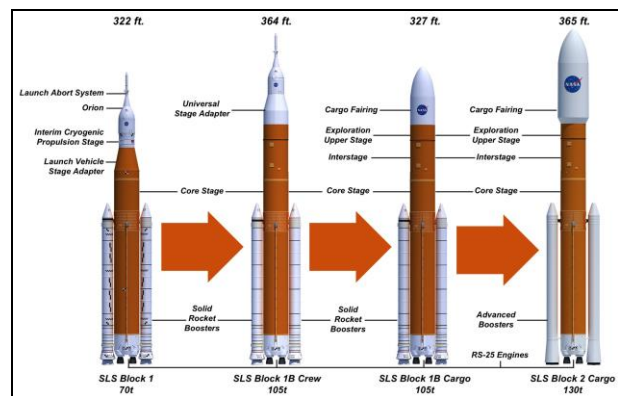


Fig. 3. SLS evolution showing commonality.

The Block 1B variant will succeed Block 1 for future launches requiring more lift capability. The ICPS will be replaced by a new Exploration Upper Stage (EUS) that will help increase payload mass capability to more than 231,485 pounds (105 mt) to LEO. Designed to launch a crewed Orion spacecraft and a cargo-carrying Universal Stage Adapter (USA), or topped with a payload fairing enclosing critical exploration hardware, Block 1B is designed to expand the reach and capability of human exploration. Among the first Block 1B co-manifested payloads are the components of NASA's Deep Space Gateway cis-lunar outpost that will test systems and operations for a future human Mars mission.

Unlike the ICPS, the EUS is a larger, human-rated stage with four Aerojet Rocketdyne RL10C-3 engines and is capable of performing orbital ascent and then propelling Orion or other large payloads on lunar or other deep-space trajectories. The EUS also provides longer stage life, more electrical power, debris protection and crew interfaces and control. EUS

increases SLS's TLI payload from 56,659 pounds (25.6 mt) to 88,185 pounds (40 t). EUS was one of several options evaluated for improving SLS performance. Based on mission requirements, budget availability and affordability, EUS was selected for its ability to perform a wider variety of missions sooner.

The evolution from the five-meter ICPS to the 8.4-meter EUS translates to an increase in the payload mass and volume capability of the 1B vehicle. In the 1B crew configuration, the USA that connects the EUS to the Orion spacecraft provides 12,572 cubic feet (356 cubic meters) of payload volume for carrying co-manifested payloads. Standing 32.4 feet tall, the USA matches the volume of the largest contemporary fairing.

The 1B cargo configuration allows the launch of payloads within an 8.4 m-diameter fairing — larger than any ever flown. Total payload volume is 21,824 cubic feet (618 cubic meters). This allows for missions in which large exploration systems can be delivered into the lunar vicinity along with a crewed Orion.

The ultimate SLS variant is Block 2, designed to lift 286,601 pounds (130 mt) into LEO, enabling ambitious human Mars missions. Block 2 employs the same core stage and RS-25 engines but replaces the boosters with advanced boosters for additional payload mass. Block 2 may add a new 10 m payload fairing to increase volume to accommodate the largest payloads scientists can dream of and build.

3. SLS development progress

3.1 Core Stage

Test and flight hardware welding is underway on the Vertical Assembly Center (VAC), the world's largest friction-stir welding tool, at NASA's Michoud Assembly Facility (MAF) (see Fig. 4).

Welding was held up in 2015 by an alignment issue with the VAC. Operations resumed after the 170-foot-tall welding tool was disassembled and reassembled to correct the alignment problem. Issues arose again in 2016 with the weld process used to assemble the liquid hydrogen and liquid oxygen tanks. Core stage manufacturing required construction of the world's largest self-reacting friction-stir welding tooling, as well as the thickest self-reacting friction-stir production welds – over half an inch. Welding resumed in 2017 after detailed analysis and testing prompted changes to the tooling and processes.

Major welding on two liquid hydrogen tanks, two liquid oxygen tanks, two engine sections and a forward skirt is completed, as well as two bolted intertanks assembled separately. These major components are now in various stages of proof testing, cleaning, and priming, along with sensor, thermal protection system (TPS) and hardware installation, to support testing and flight. As this paper was written, welding had started on a third liquid hydrogen tank. The major components for the

EM-1 core stage are expected to be complete and integrated into the flight core stage in fall 2018 and ready to ship to NASA's Stennis Space Center (SSC) for stage green run testing in the early 2019 timeframe. The liquid hydrogen, liquid oxygen and intertank test articles are also expected to be shipped to MSFC for structural tests in 2018.

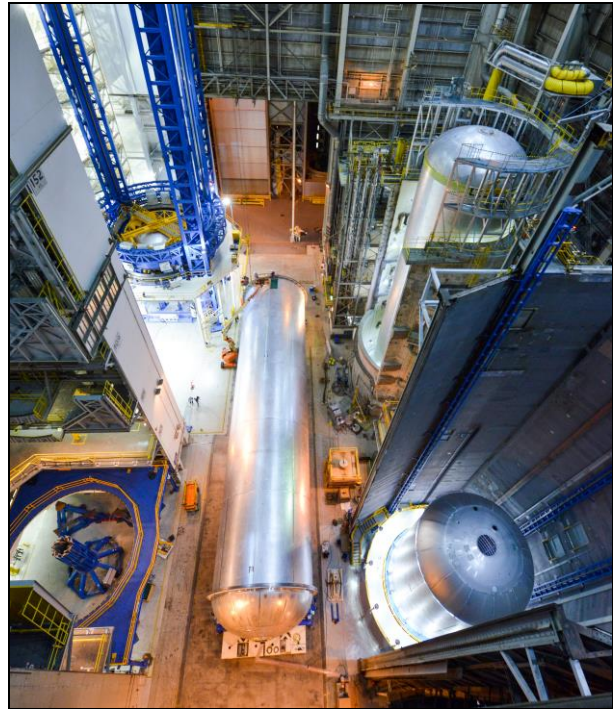


Fig. 4. MAF core stage production clockwise from top left: VAC, liquid hydrogen tank test article, liquid oxygen tank test article, vertical stacking area. Liquid hydrogen tank in the center aisle.

Structural test stands for the hydrogen and oxygen tanks, engine section, intertank and payload sections are complete at Marshall. The engine section for structural testing was completed and barged to MSFC in 2017 and was installed in its test stand to be readied for testing in fall 2017 (see Fig. 5).

Welding is also complete on the EM-1 flight engine section and it is being prepared for cleanroom conditions, where piping and wiring will be installed. The coming months will also see the arrival of the hydrogen and oxygen tank and intertank structural test articles at Marshall test stands.

The core stage pathfinder article is also complete and will be transported by commercial barge to Michoud to begin supporting a range of tests designed to test ground support vehicles and other ground support equipment, as well as the operators who will move completed flight core stages along roadways and into and out of test stands at MAF, SSC, and NASA's Kennedy Space Center (KSC).

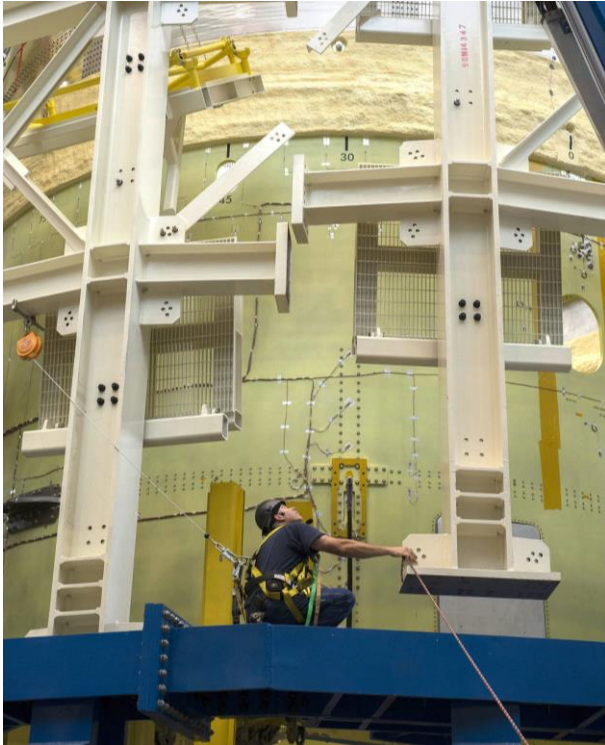


Fig. 5. Engine section test article test stand installation at MSFC.

3.2 Boosters

Orbital ATK successfully test-fired two qualification booster motors in March 2015 and June 2016 at company facilities in Utah (see Fig. 6). These tested performance at the high and low end of the motor's ambient temperature operating range. They also served as a test of the booster thrust vector control systems and new avionics.



Fig. 6. Qualification Motor-2 test firing.

Those tests were the last full-scale qualification motor tests for the SLS boosters before flight. Orbital has cast 10 booster motor segments (see Fig. 7), with four having completed final preparations and moved to storage before shipping to KSC. In addition, Orbital ATK technicians have installed nozzles in two EM-1 aft segments.



Fig. 7. A completed booster motor segment.

Additional motor segments are in various stages of motor case preparation. Additionally, aft skirts, forward skirts and nose cones are in processing at KSC. All five avionics boxes and harnesses are in qualification testing. Battery qualification is complete.

3.3 Engines

The program has completed adaptation testing on development engine #0528 to ensure the shuttle-heritage RS-25 can perform to the new SLS performance requirements and operating environments (see Fig. 8). A total of 16 hotfire tests amassing nearly 8,000 seconds of run time at SSC Test Stand A-1 have successfully enveloped and explored the SLS operating profile. Delivery of flight model engine controllers for qualification and green run testing began in 2017. Four hotfire tests of up to 500 seconds each had been conducted at the time of paper preparation to certify new engine controllers. Additional tests will be conducted in 2018. Delivery of four RS-25 flight engines from Stennis to MAF for future integration was scheduled for fall 2017.



Fig. 8. RS-25 hotfire test at Stennis Space Center.

3.3 Spacecraft and Payloads Integration & Evolution

The Spacecraft and Payloads Integration & Evolution (SPIE) element office manages both Block 1 ICPS, payload accommodations and secondary

payloads. The Integrated Structural Test (IST) of the ICPS, LVSA and OSA test articles was completed in early 2017.

ULA shipped the ICPS flight article for EM-1 to Cape Canaveral in 2017 to be readied for launch, including installing additional flight avionics and performing software development and testing (see Fig. 9).



Fig. 9. EM-1 ICPS at ULA facilities in Decatur, Ala.

The EM-1 LVSA completed welding this year and was moved from the Advanced Welding and Manufacturing Facility to the National Center for Advanced Manufacturing, both at MSFC, for TPS application. The EM-1 OSA completed major assembly in 2017, and installation of secondary payload brackets, cables, diaphragm and avionics is in process, with plans to ship this fall. After completing the IST test series, the OSA test article was loaded onto NASA's Super Guppy aircraft in Huntsville for delivery to Lockheed Martin in Denver for similar tests with the Orion spacecraft (see Fig. 10).



Fig. 10. SLS OSA loaded onto Guppy aircraft.

3.4 Block 1B

While the SLS Program is focused on getting the EM-1 mission to the launch pad, the program continues to make progress on the EM-2 mission and the Block

1B vehicle as well. Parts for the EM-2 core stage are at Michoud, and welding has begun. NASA awarded a contract, which will be managed by Glenn Research Center, for the USA that connects the EUS with Orion and provides room for co-manifested payloads. The EUS completed Preliminary Design Review (PDR) in January 2017; the next major review to come is CDR. Boeing and Aerojet Rocketdyne are under contract for the EUS, and work is continuing at MAF to accommodate production alongside core stage manufacturing. AMRO Fabricating Corp. has started development panel forming. Systems engineering work on Block 1B is maturing the configuration, including a variety of wind tunnel tests (see Fig. 11). NASA and Aerojet Rocketdyne have begun development work on an expendable variant of the RS-25 that will decrease engine cost 30 percent and will be certified to 111 percent thrust for future missions vs. the current RS-25 power level of 109 percent. The engines team is also developing a new RL10C-3 variant and participating in EUS integration work. PDR is planned for fall 2017. Orbital ATK has begun preparing EM-2 boosters. Secondary Payload Deployment System hardware is in development and testing.



Fig. 11. Block 1B wind tunnel testing at NASA's Ames Research Center.

4. Discussion

In an era of fiscal constraint, SLS will provide an unprecedented capability both human and robotic exploration. SLS has three major advantages over existing launch vehicles: volume, mass and departure energy. Those capabilities enable or enhance deep space missions in ways other launch vehicles cannot.

With an initial capability of greater than 70 mt to LEO, evolving to 105 mt and 130 mt, SLS will have up to five times greater mass-to-orbit capability than current launch vehicles. Its ability to launch larger mass and volume reduces payload design complexity and development cycles, as well as the risk and cost associated with multiple launches and in-space assembly operations. The margin provided by SLS means longer launch windows and reduced transit times

for deep space payloads. That translates into lower mission operations costs and earlier science return. Discussion of the benefits to specific missions is beyond the purview of this paper, although mission possibilities include Mars sample return, a Europa orbiter, large space telescopes surface landers and in-space infrastructure projects.

Significantly, SLS Block 1 and Block 1B are being manufactured and tested now. In early 2017, NASA assessed the feasibility of putting crew aboard the EM-1 mission rather than the planned un-crewed flight, followed by crew on the second mission.

NASA determined a crewed mission is technically possible, but it would be difficult to accommodate the changes necessary given the cost, risk and other technical factors.

As part of the same review, NASA examined the production schedules, expected budgets, delivery of the European Service Module, and a variety of manufacturing issues related to the core stage. As a result NASA announced it will adjust the target launch date for the EM-1 mission from late 2018 to 2019. The specific date is still under review.

5. Conclusions

Significant flight hardware for the first and second missions of SLS is in production now, along with the Orion crew spacecraft and the necessary ground systems to integrate, stack and launch the SLS vehicle at KSC. NASA is testing engines, boosters, fuel tanks, pieces of the in-space upper stage and avionics. While the program has experienced engineering and manufacturing challenges typical of a new development, the program continues to make steady progress toward the first SLS mission. Early planning has begun on exploration that would take astronauts back to the moon with SLS (see Fig. 12). With SLS, NASA is well on its way to resumed human exploration of deep space and new discoveries for humanity.

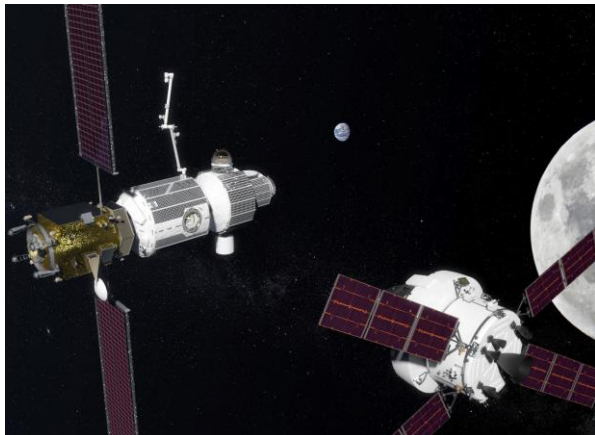


Fig. 12. NASA concept of cis-lunar exploration plans.