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NASA'S SPACE LAUNCH SYSTEM PROGRAM UPDATE

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Hardware and software for the world's most powerful launch vehicle for exploration is being welded, assembled, and tested today in high bays, clean rooms and test stands across the United States. NASA's Space Launch System (SLS) continued to make significant progress in the past year, including firing tests of both main propulsion elements, manufacturing of flight hardware, and the program Critical Design Review (CDR). Developed with the goals of safety, affordability, and sustainability, SLS will deliver unmatched capability for human and robotic exploration. The initial Block 1 configuration will deliver more than 70 metric tons (t) (154,000 pounds) of payload to low Earth orbit (LEO). The evolved Block 2 design will deliver some 130 t (286,000 pounds) to LEO. Both designs offer enormous opportunity and flexibility for larger payloads, simplifying payload design as well as ground and on-orbit operations, shortening interplanetary transit times, and decreasing overall mission risk. Over the past year, every vehicle element has manufactured or tested hardware, including flight hardware for Exploration Mission 1 (EM-1). This paper will provide an overview of the progress made over the past year and provide a glimpse of upcoming milestones on the way to a 2018 launch readiness date.

I. INTRODUCTION

NASA's Journey to Mars has begun. By integrating its science, technology, and exploration efforts, the agency has created a vector that leads ultimately to a human mission to the Red Planet. Recognizing the magnitude of the challenge and the resources required, the agency has developed a stepping stone path to humans on Mars that is unlike the Apollo Program model but accomplishes the same objectives. Based on the bipartisan NASA Authorization Act of 2010 and U.S. National Space Policy, NASA's current vision extends to many beyond-Earth-orbit destinations.

The journey to making this vision reality is progressively evolving capabilities and pursuing increasingly complex missions as NASA's sphere of human operations expands further from Earth. NASA and industry studies identified heavy lift as key to enabling that expansion. NASA analysed thousands of design concepts that traded factors such as performance, cost, existing infrastructure, technology readiness, safety, and the potential for evolving capability. From those studies emerged the current SLS architecture for an evolutionary, exploration-class launch vehicle that is human-rated, with the mass and volume capability to support new human and robotic exploration of the solar system. (Fig. 1)



Fig. I: SLS Block I on the Mobile Launcher leaves the Vehicle Assembly Building in this artist concept.

NASA's "Journey to Mars approach to exploration is illustrated in Figure II. It begins with the current sphere of operations in Earth orbit, including the International Space Station and the developing capabilities of NASA's commercial cargo and crew partners. Exploration is entirely dependent on supply from Earth. As capabilities evolve, NASA will move to demonstrating their proficiency through missions to an asteroid or to the vicinity of the moon and demonstrating the ability to be less dependent on the Earth. The final step is developing the capabilities to operate for months or years totally independent of the

Earth and setting bourse for Mars and destinations beyond.

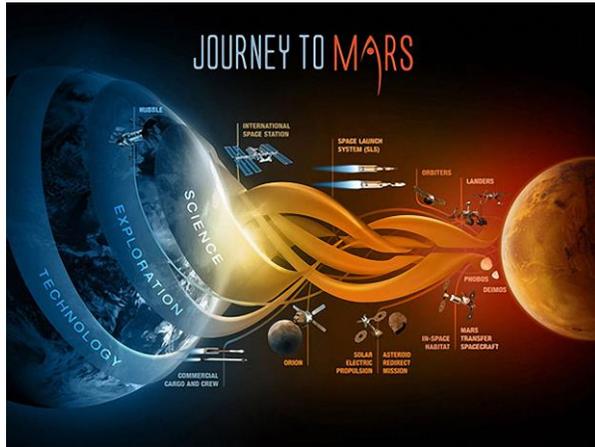


Fig. II: The components of NASA's Journey to Mars.

The SLS architecture is designed to evolve with those increasingly ambitious goals while recognizing current budget realities. Overall vehicle design deliberately provides robust margins to minimize changes and redesign cycles. The main propulsion elements are based on the powerful and proven liquid and solid propulsion systems originally developed for the Space Transportation System. The only new development is the Core Stage, which is designed around those elements to minimize redesign. Every element has employed value stream mapping and related analyses to streamline development, manufacturing, and development. Additionally, new technologies such as additive manufacturing and structured light scanning are being used in current and advanced development work.

The initial Block I design will be 98.2 meters (m) (322.4 feet) tall and weigh 2.5 million kilograms (kg) (5.7 million pounds) fully fueled. (Fig. III) It will have approximately 39.1 million Newtons (8.8 million pounds) of thrust at liftoff – 10 percent more thrust than the Saturn V and more than twice the payload mass of existing rockets. With 70t (154,000 pounds) of payload, Block 1 will be powered by four RS-25 liquid oxygen/liquid hydrogen (LOX/LH₂) propellant engines and two five-segment solid rocket boosters measuring 53.9m (177 feet) long and 3.6m (12 feet) in diameter. Both engines and boosters are derived from the engines and boosters from the Space Shuttle program. In fact, early missions will reuse flown Shuttle-era hardware adapted to SLS performance requirements. The new Core Stage design will hold 952,000kg (2.1 million pounds) of liquid hydrogen and liquid oxygen. At 64.6m

(212 feet) tall and 8.4m (27.6 feet) in diameter, it is the largest stage in the world.

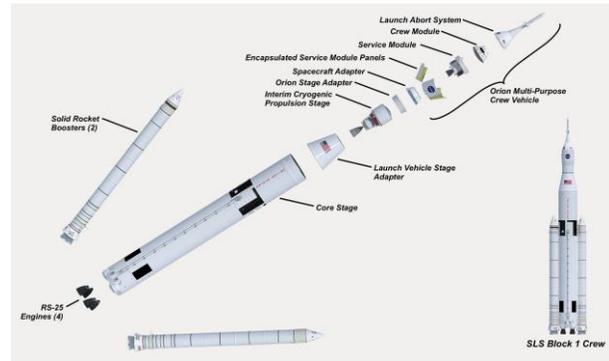


Fig. III: Expanded view of SLS Block 1.

There are several evolutionary options beyond the Block I design. Missions after the first four will use newly-manufactured RS-25s certified to operate at higher thrust without major design changes. There are also options for a new LOX/LH₂ Exploration Upper Stage (EUS) and advanced liquid or solid boosters. The size of the payload fairing can also be increased to nearly 10m (33 feet) in diameter.

The first flight test of SLS – Exploration Mission 1 (EM-1) – will use the Block 1 SLS to launch an uncrewed Orion spacecraft beyond low-Earth orbit to test the performance of the integrated system. The second mission, EM-2, will launch the first crewed Orion on a mission that will carry humans around the moon and deeper into space than the Apollo missions.

Missions and payloads for subsequent missions are not defined, although several options are under study, including a crewed rendezvous with an asteroid and a robotic science probe to Jovian moon Europa. SLS' evolving capability will make possible ambitious missions such as Mars sample return, landers to the moons of the gas giants, and large-aperture space telescopes, as well as enhancing other mission characteristics such as faster transit times, reduced design cycles, and less required on-orbit assembly.

II. QM-1 DEMONSTRATES SOLID MOTOR

Two 5-segment Solid Rocket Boosters (SRB) each provide 1.6 million kg (3.6 million pounds) of thrust – or 75 percent of total vehicle thrust for the first two minutes of flight. Compared to the Space Shuttle 4-segment motor, the 5-segment motor provides about 20 percent more thrust and 24 percent greater total impulse.

The first SLS missions will include boosters with Shuttle-heritage motor cases.

Designed and built by Orbital ATK, the heritage design has been modified with non-asbestos case insulation, a larger exhaust nozzle to accommodate the greater internal pressure, propellant grain changes to meet SLS requirements, and new control avionics. The aft Core Stage attach point has been moved lower than the Shuttle External Tank attach point.

The five-segment motor is the largest component of the booster, containing roughly 680,000 kg (1.5 million pounds) of propellant. The metal case segments are lined with sheets of rubber insulation to protect them from extreme internal temperatures during operation. (Fig. IV)

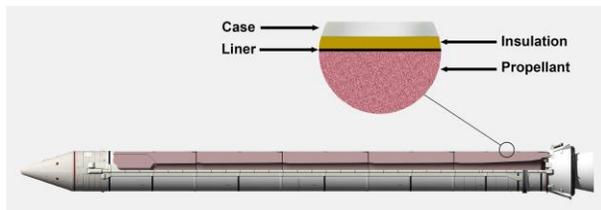


Figure IV: Cutaway image of the SLS booster showing the motor case and case insulation configuration.

Two Qualification Motor (QM) tests were planned to prove the new design. During x-ray inspection of the QM-1 segments in 2012, engineers discovered anomalous voids and un-bonds in the aft motor segment insulation and propellant. In the subsequent investigation, thousands of tests, including material properties and five full-scale engineering and process simulation articles were conducted.

The source was discovered to be the new asbestos-free insulation, selected to comply with environmental regulations. In fact, it had better thermal properties and saved 4,500 kg (10,000 pounds) of weight compared to the Shuttle-era booster. But after the insulation was applied and cured in the motor segments, it emitted gas bubbles when the segments were filled with propellant. The outgassing created un-bonds at the interface between the propellant and insulation, as well as voids in the propellant.

Testing revealed that the adhesive used to bond the insulation to the metal case was impervious to the levels of outgassing observed. The adhesive successfully blocked gas from the insulation from reaching the solid propellant. So an additional layer of adhesive and an additional thin sheet of rubber insulation was added

between the existing insulation and the liner material that provides a bonding surface for the solid propellant.

Several other process improvements and enhanced inspection techniques were developed during the effort. For instance, the application process for the rubber motor case wall insulation was modified to significantly reduce the amount of air trapped in the process. A new aft segment was cast. Inspection determined it to be the most defect-free aft segment ever produced.

Firing of Qualification Motor-1 (QM-1) in March 2015 validated the investigation and the changes instituted to ensure safe motor operation. (Fig. V) Post-test inspection and data review were positive and preparations for manufacturing of the QM-2 motor quickly began. As of this writing, the QM-2 aft and forward segments were cast and inspected with no resulting insulation voids, a vast improvement in comparison to an average of 25 insulation voids per motor during the Shuttle program. Preparations continue for the QM-2 test firing in spring 2016. While the QM-1 motor was conditioned to 32 degrees C (90 degrees F), the QM-2 motor will be conditioned to 4 degrees C (40 degrees F) to cover the motor's planned operating range.



Fig. V: Orbital ATK workers detach center-forward segment of QM-1 motor test fired at the company's Provo, Utah facility.

III. RS-25 Completes Initial Hotfire Adaptation Series

The RS-25 will power the Core Stage throughout the ascent to orbit. Each engine will produce roughly 232,000 kg (512,000 pounds) (vacuum) thrust at 109% of rated engine thrust, compared to roughly 204,000 kg (450,000 pounds) at 104.5% thrust employed by the engine during the Shuttle program. SLS inherited 16 flight engines and 2 development engines to support

adaptation of the RS-25 to SLS performance requirements and the first four SLS missions.

The focus of engine development for the past year was adapting the engine to SLS performance requirements. A series of seven hot-fire tests totaling more than 3,000 seconds using engine #0525 concluded in August 2015. (Fig. VI) Key goals of the adaptation series were:

- validating new propellant inlet conditions and resulting changes to the start sequence
- validating interface condition changes including a new base heating environment
- hardware acceptance testing and life extension including flow dynamics
- and development and certification of a new controller and software

Notably, increasing engine thrust was not a test objective. While shuttles flew routinely at 104.5% thrust, the engine was tested and certified to 109 percent thrust as an engine-out capability. Even so, the engine operated during the series in performance regions that had never been explored.



Figure VI: The third RS-25 engine adaptation test, June 11 (top) and RS-25 and controller (bottom).

Based on experience and modelling data, the series was expected to be successful, but the series was

notable for experiencing no failure indications in the data and no early engine shutdowns despite the challenging objectives.

A second series with RS-25 #0528 is planned for 2016. In between, the RS-25 element will conduct tests of the flight engines for the EM-2 mission. That series includes “green run” testing of the new engine controllers for the flight.

Engine production will be re-started for later missions, with designer Aerojet Rocketdyne optimizing the design for affordability and expendability and certified to 111% thrust, a level tested during the shuttle program but never certified for flight.

NASA is working with its corporate counterparts to develop details for the design and recertification of this new engine with a potential contract award in late 2015. Plans tentatively include manufacturing of one new engine for recertification test firing and subsequent production of six new engines for future missions prior to an extended production contract.

During the recertification effort, value stream mapping will be the basis for component/Line Replaceable Unit (LRU) level work. Selective redesign of components and parts may be done. Manufacturing sequences and processes may be changed. Work associated with its reusability requirements may be discontinued. The effort will also evaluate the use and impact of new technologies such as additive manufacturing and structured light scanning. The engine team will leverage knowledge gained with previous Aerojet Rocketdyne engine programs. The team has identified dozens of possible parts for additive manufacturing and estimates a possible 30 percent reduction in unit cost depending on the SLS flight rate.

IV. Core Stage Major Structural Work Continues

The Core Stage will be the world’s largest rocket propulsion stage at roughly 64.6 m (212 feet) tall and 8.4 m (27.6 feet) in diameter. The stage is built by The Boeing Company at NASA’s Michoud Assembly Facility in New Orleans. The five major components are the LOX tank, which will hold 742 cubic meters (196,000 gallons), and the LH₂ tank, which will hold 2,032 cubic meters (537,000 gallons), the forward skirt, the intertank, and the engine section. Rings connect and provide stiffness between domes and barrel segments, which will make-up the five major structures.

Significant progress has been made in installing the major assembly tooling, as well as the barrels, domes, and rings that make up the stage. (Fig. VII) In

September 2014, workers completed assembly of the Vertical Assembly Center (VAC) at Michoud. Standing 51.8 m (170 feet) tall and 23.8 m (78 feet) wide, the VAC is the largest spacecraft welding tool in the world and the last to be erected of six major state-of-the-art manufacturing tools for assembly of the Core Stage. However, the vertical components of the structure were out of alignment roughly 5 centimeters (2 inches) over their length, requiring the tower be disassembled, corrected, and reassembled. That work is complete, software checkout is under way, and welding is expected to begin later this year.



Figure VII: Vertical Assembly Center (VAC) (top) and LH₂ tank dome on Gore Weld Tool (bottom) at Michoud Assembly Facility.

All barrels, domes and rings are complete for the qualification LOX and LH₂ tanks and the engine section. Likewise, the rings for the EM-1 flight stage are complete and the barrels, domes and engine section are nearing completion.

Work is also progressing with build-up of the two new Structural Test Article (STA) Test Stands at Marshall, as well as the renovation of the B-2 Test Stand at Stennis Space Center (Fig. VIII). The STA Test Stands have completed foundation cure and are progressing with tower construction, scheduled for completion in mid-2016. Structural testing is scheduled to begin in 2017. Work is also underway on test

equipment for engine section and intertank structural testing at Marshall. Work on the B-2 stand at Stennis is scheduled for completion in June 2016, when it is scheduled for activation in advance of testing the first flight unit at Green Run which is currently planned to begin in late 2017.

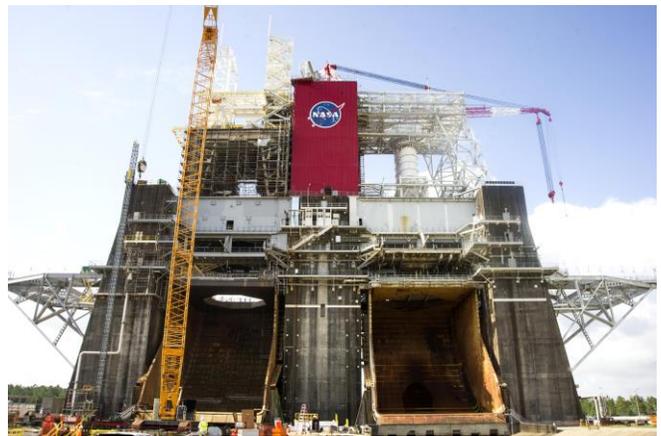


Figure VIII: 215-foot Core Stage LH₂ STA stand rises at Marshall (top) and addition of 1 million pounds of structural steel to B-2 test stand at Stennis (bottom).

V. Other Work

The first piece of SLS-designed hardware, the Orion Stage Adapter (OSA), was flown on Exploration Flight Test 1 (EFT-1) in December 2014. The OSA will connect the Orion crew vehicle to the rocket, and the inclusion of it on EFT-1 helped with risk mitigation. Production of the OSA flight unit for EM-1 began in April 2015, and is scheduled for completion in the summer of 2017.

Another major vehicle component, the Launch Vehicle Stage Adapter (LVSA), entered manufacturing in early 2015.

Production of the ICPS flight unit for EM-1 began in July 2015 and is scheduled for completion in late 2016. The ICPS test article is scheduled for completion in fall 2015. The ICPS is based on the proven Delta IV Cryogenic Second Stage (DCSS) and modified with stretched propellant tanks, hydrazine bottles for attitude control, avionics changes, and other modifications as needed to accommodate SLS loads and environments.

The Pegasus Barge was delivered to Stennis Space Center on August 13, 2015 (Fig. IX) after modifications that expanded the total length of the barge from 79.2m (260 feet) to 94.4m (310 feet). The expansion will allow the barge to transfer Core stage propellant tanks and other components to Marshall and Stennis for testing and eventually to Kennedy Space Center for launch.



Figure IX: Refurbished Pegasus barge arrives at Stennis for outfitting and eventual Core Stage transportation duty.

VI. Critical Design Review Completed

Successful completion of the Critical Design Review (CDR) was a significant program milestone for SLS and marked the first CDR on a NASA exploration class vehicle since the Space Shuttle almost 40 years ago. Some 1,088 files and 154.30 gigabyte (GB) of data were part of the comprehensive assessment process that began in May 2015 and concluded in September.

Thirteen review teams made up of senior engineers and aerospace experts from across NASA and industry concluded that the design is technically sound, capable and mature to continue with full scale fabrication, assembly, integration, and testing. In addition to the internal review, an independent review by a Standing Review Board of independent experts confirmed that

the program remains on target to meet the schedule and cost goals established at Key Decision Point-C (KDP-C) and is in a good position to meet any remaining challenges during the final phase of the design program. The CDR activities culminated in a decision by the CDR Board that the Block 1 SLS vehicle is ready to proceed to production and test.

On August 13, 2015, the Standing Review Board (SRB), an independent review board that participated in the SLS Program CDR, presented a snapshot briefing to the Agency Program Management Council (APMC). The SRB chairman presented a review overview and summary findings, which was concluded with an evaluation that SLS conducted an excellent CDR and has a technically robust design with significant performance margin. The SRB recommended that the SLS program proceed to Design Certification Review (DCR), which is planned for 2017 after manufacturing, integration, and testing to compare the resulting vehicle to the design. The final milestone will be the Flight Readiness Review just before first flight.

VII. Summary and Conclusions

The journey to Mars and other destinations has begun. The launch vehicle that will carry out that exploration is taking shape. Working within current budgetary constraints and leveraging current technology and capabilities, SLS has made significant progress. This paper provides an overview of that progress, but it by no means comprehensive. SLS is beyond the concept and design stages, and, today, every major element has produced hardware and started testing. Only SLS represents the exploration-class capability to carry explorers to new destinations in the solar system, spur economic growth, expand knowledge and maintain U.S. leadership in space.