

NASA'S SPACE LAUNCH SYSTEM TAKES SHAPE: PROGRESS TOWARDS SAFE, AFFORDABLE EXPLORATION

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Fig. 1: Artist's concept of SLS Block 1 at launch

ABSTRACT

Development of NASA's Space Launch System (SLS) exploration-class heavy lift rocket has moved from the formulation phase to implementation in 3 years and will make significant progress this year toward its first launch, slated for December 2017. SLS represents a safe, affordable, and evolutionary path to development of an unprecedented capability for future human and robotic exploration and use of space. For the United States current development is focused on a configuration with a 70 metric ton (t) payload to low Earth orbit (LEO), more than double any operational vehicle. (Fig. 1) This version will launch NASA's Orion Multi-Purpose Crew Vehicle (MPCV) on its first autonomous flight beyond the Moon and back, as well as the first crewed Orion flight. SLS is designed to evolve to a 130 t lift capability that can reduce mission costs, simplify payload design, reduce trip times, and lower overall risk. Each vehicle element completed its respective Preliminary Design Reviews, followed by the SLS Program. The Program also completed the Key Decision Point-C milestone to move from formulation to implementation in 2014. NASA has authorized the Program to proceed to Critical Design Review, scheduled for 2015. Accomplishments to date include: manufacture of core stage test hardware, as well as preparations for testing the world's most powerful solid rocket boosters and the main engines that flew 135 successful Space Shuttle missions. The Program's success to date is due to prudent use of existing technology, infrastructure, and workforce; streamlined management approach; and judicious use of new technologies. This paper will discuss SLS Program successes over the past year and examine milestones and challenges ahead. The SLS Program and its elements are managed at NASA's Marshall Space Flight Center (MSFC).

INTRODUCTION

As the Space Shuttle Program ended in 2011, NASA was already planning the next phase of human exploration. It would be based on three important, mutually-supportive capabilities: continuing long-duration research and operations in space aboard the International Space Station, lowering the cost of access to space by developing commercial cargo and crew launch services to LEO, and development of a new deep-space exploration capability beginning with the Orion crew spacecraft and the SLS heavy lift launch vehicle.

Heavy lift has been identified as a key enabling capability in several NASA and industry studies. The current SLS configuration is the result of a series of trade studies and literally thousands of configurations evaluated for safety, development and life cycle costs, mission objectives, maintaining critical industrial base capability, and transitioning the workforce effectively.

Three families of vehicles emerged from these studies for further analysis: liquid oxygen/liquid hydrogen (LOX/LH2) Shuttle-derived, liquid oxygen/hydrocarbon (RP1) similar to the Saturn vehicles, and a modular core vehicle using commercially-available hardware. Internal and independent reviewers found the Shuttle-derived design to be the safest, most capable available in the shortest time under expected budget projections.¹ Since the SLS Program was created in 2011, the results have validated that assessment.

The following section will discuss SLS Program background and vehicle architecture.

SLS PROGRAM BACKGROUND

SLS was established by the NASA Authorization Act of 2010 and scheduled for first launch in 2017, SLS is the basis for a new era of international human and robotic exploration of deep space for the United States. SLS will be the world's first exploration-class launch vehicle since the Saturn V, designed to carry human beings beyond LEO for the first time since 1972, when the crew of Apollo 17 returned from the Moon.

Along with SLS, NASA is developing the Orion crew vehicle and the Ground Systems Development and Operations (GSDO) Program. Orion is a four-person spacecraft designed to carry astronauts on exploration missions into deep space managed at NASA's Johnson Space Center (JSC). GSDO is converting the facilities at NASA's Kennedy Space Center (KSC) into a next-generation spaceport capable of supporting launches by multiple types of vehicles.

SLS will enable NASA to expand its human spaceflight operations across the solar system. SLS capability will evolve using a block upgrade approach, driven by exploration mission requirements. Human exploration beyond low Earth orbit will be simpler and safer by using SLS. In its earliest configuration, SLS will have a 70 t lift capability to low Earth orbit. General vehicle design consists of a four-engine LOX/LH2 first stage, two 5-segment solid propellant boosters, and a liquid propellant upper stage. (Fig. I)

Early SLS and Orion testing will support missions in cislunar space and the Agency's proposed mission to find, capture, redirect, and study a near-Earth asteroid. Follow-on upgrades will improve vehicle payload performance, with an ultimate evolutionary capability to 130 metric tons. (Fig. II)



Fig. II: Artist's concept of SLS Block 2 130 t vehicle at launch

The 70 t vehicle will have 10 percent more thrust than the Saturn V at liftoff and the 130 t vehicle will have 20 percent more thrust with the addition of advanced boosters and a cryogenic propulsion upper stage. As the vehicle is evolved to greater lift and larger payload fairing sizes, from 8.4 m to 10 m, the capability and flexibility that the SLS offers can be tailored to reduce payload design complexity, trip times, and potential on-orbit assembly, further reducing cost and risk to crews and missions.

Crewed missions will explore the solar system's mineral-rich asteroids, and, eventually, the mountains and canyons of Mars. Additionally the enhanced lift capability of SLS will enable robotic science missions in the decades ahead that were previously not possible, such as Mars sample returns, large monolithic space telescopes, and explorations of the moons of Jupiter and Saturn.²

SLS is designed to capitalize on the investments the United States has already made in space transportation. (Fig. III).

The most costly part of any rocket development is its propulsion systems. The SLS architecture was designed to be affordable and restore U.S. space exploration capability as rapidly as possible by using the national investments from previous projects.

As discussed below, SLS will use 16 existing Shuttle-heritage RS-25 engines that will be modified to support the specific requirements of the first four missions. The RS-25 benefits from 30 years of experience and continuous improvements, as well a track record of 100 percent mission success in 135 Shuttle missions. For future missions, the RS-25 will be modified for expendability and the production line re-started.



Fig. III: SLS Block I - Proven success, Greater Power

The expendable boosters will be based on the 4-segment Shuttle booster and the more powerful 5-segment booster in development for the Constellation Program's Ares Project. Upgrades include a larger nozzle throat, and an environmentally benign insulation and liner. Continuing the contract already in place proved a significant cost avoidance and allowed a quick start to the design of the world's most powerful boosters.

The sole new SLS hardware development is the massive core stage, which forms the vehicle's structural backbone and houses the LOX/LH2 tanks, as well as the instrument ring that contains vehicle-level avionics, based on commercially available software. The 8.4-meter (m) diameter stage is the same width as the Space Shuttle's external tank, taking advantage of the one-of-a-kind Michoud Assembly Facility (MAF) manufacturing infrastructure.

The initial upper stage propulsion will be provided by the Interim Cryogenic Propulsion Stage (ICPS), a modification of the current Delta IV Cryogenic Second Stage (DCSS), leveraging a valuable asset from the U.S. evolved expendable launch vehicle fleet. It will be capable of sending the Orion to missions in the vicinity of the Moon.

In addition to progress on the initial design for the 2017 launch, progress is also being made for the evolved design, including advanced booster, upper stage, and engine trade studies, as well as the application of technologies such as composites, additive manufacturing, and structured light scanning.

The program benefits from NASA's half-century of experience with liquid oxygen and liquid hydrogen heavy-lift vehicles, and from advances in technology and manufacturing practices. Further, by using common design elements, the SLS connections with the ground systems at KSC and with the spacecraft and payloads it carries will remain consistent over time, reducing complexity. The SLS operational scheme takes advantage of resources established for the Space Shuttle, including the workforce, tooling, manufacturing processes, supply chains, transportation logistics, launch infrastructure, and LOX/LH2 propellants.

The following sections will note key milestones and accomplishments of the various SLS Program elements.

LIQUID ENGINES

Four RS-25 main engines will power the SLS core stage during the first 8 minutes of ascent. Each engine will deliver more than 500,000 pounds of thrust at 109 percent rated power level. Produced by Aerojet Rocketdyne, the RS-25 is the first reusable rocket engine in history, as well as the most reliable and highly tested large rocket engine ever built.

The decision to use the RS-25 was part of the SLS affordability strategy during the program formulation stage. (Fig. IV) Two non-flight engines will be assigned to test the RS-25 under SLS operating conditions. The remaining inventory consists of 16 flight engines that will be assigned to one of four flight vehicles based on their remaining safe operable life and specific operating requirements for engine green run, stage testing, potential on-pad shutdowns, and the planned nominal 500-second mission.



Fig. IV: RS-25 engines at KSC

While the availability of the Shuttle engines and the proven design represent a major cost and risk reduction, the engine itself must accommodate the different SLS operating conditions and environments. The engine will be operated at 109 percent rated thrust versus 104.5 percent. Inlet pressures will be higher because of the height of the core stage tanks and greater acceleration during launch. LOX inlet temperatures will be lower due to core stage design and engine chill-down process prior to the engine start sequence as compared to the Shuttle. The ascent profile will require changes to the engine throttling profile, and the engine itself will face a more challenging heating environment due to its location in-plane with the boosters.

Much preliminary work was completed during 2013-2014 to ready the RS-25 for SLS use. The 16 Shuttle-heritage engines were moved from Kennedy Space Center to Stennis Space Center, where personnel began inspection and selective reconfiguring to support the specific objectives for the test and flight program. Assembly also began on an RS-25 “Pathfinder” engine that will be used for a variety of facility, transportation and stage fit checks. The Pathfinder engine is fully representative of the mass, center of gravity, mechanical interfaces, and major components of a flight RS-25 engine.

With J-2X testing on the A-1 Test Stand complete, work began on modifying the stand for RS-25 testing by removing the J-2X-specific thrust frame adapter and piping and beginning installation of a thrust frame adapter, liquid hydrogen piping, and hydraulic lines designed for RS-25 testing. (Fig. V) The RS-25 testing project was accelerated by a few months, shortening the time for preparation work on the A-1 test stand.³ The first RS-25 tests will involve a series of tests combining chill-down and hot-fire tests.



Fig. V: Renovating the SSC A-1 test stand (left) and RS-25 thrust frame adapter (right)

Last year, development continued on a new Engine Controller Unit (ECU) for the RS-25. The ECU allows communication between the engine and launch vehicle, sends commands, transmits data, regulates thrust and fuel mixture ratio, and monitors engine health. The original Shuttle-era engine was made in the early 1980s, and many of the parts are obsolete. As an affordability initiative, the Program is developing a common controller based on the new J-2X controller that is capable of serving the RS-25 and future engines. The team completed several milestones in developing the ECU software, power supply and single board computer. The ECU completed hardware Critical Design Review and Software Preliminary and Critical Design Reviews in 2013, and an operational demonstration at the Huntsville Hardware in the Loop Laboratory in late 2013. With a common physical design and component change-outs, ECU costs could be half those of the Shuttle controller.

At Stennis Space Center, J-2X Development Engine 10002 completed 13 tests totaling 5,201 seconds in 2013 – two times the require engine service life. Objectives included exploring the envelope of temperature, pressure, mixture ratio, combustion stability, high/low thrust, gimballing, nozzle extension thermal characterization, and more. Also among the objectives, the test team completed was the first test of selective laser melting (SLM) hardware. Development Engine 10003 began testing and completed 5 tests totaling 1,350 seconds in 2013.⁴

Testing on engine 10003 continued in calendar 2014 with seven tests totaling 2,408 seconds on the SSC A-2 stand.(Fig. VI) The last 2 tests of the series were designed to focus on the engine's low-thrust throttling capability to demonstrate requirements for future upper stage applications. At the end of testing, having served as an important tool for technologies such as structured light scanning and 3D printing, the four development J-2X engines will be stored for potential upper stage applications in the future.⁵



Fig.VI: J-2X engine test at SSC A-2 test stand

SOLID ROCKET BOOSTERS

The majority of SLS thrust during the early boost phase of flight will be generated by two 5-segment solid rocket boosters produced by Alliant Techsystems, Inc. The SLS boosters are based on the operational Shuttle 4-segment booster and research, development, and testing of a more powerful 5-segment booster conducted during the Constellation Program. Each booster motor will generate up to 3.5 million pounds of thrust.

Heritage hardware and design includes forward structures, metal cases, aft skirt, and thrust vector control. Although benefiting from that heritage design, the SLS booster will be modified for the SLS mission. In addition to the larger nozzle throat and new insulation and liner materials mentioned above, the propellant grain will be modified to meet the requirements of the SLS ascent profile, and avionics will be updated. Additionally, core stage attach interfaces will be modified to accommodate the different vehicle configuration and static loads, flight loads, and separation environments.

The SLS Booster Office completed its PDR in April 2013 and is scheduled for its CDR in 2014. The booster flight set is slated for delivery to KSC for processing in mid-2017. The Program also signed a contract modification with ATK Launch Systems, Inc., for the SLS Booster. This important modification aligned the contracted scope previously in place with ATK to be consistent with SLS requirements.

Following three successful developmental motor tests in 2012 and 2013 (Fig. VII), work is continuing on casting and preparing the first qualification Motor (QM-1). Following the QM-1 test in 2014, the instrumented motor will be disassembled and inspected prior to casting QM-2 segments. QM-2 testing is scheduled for 2015. Following disassembly, inspection, and analysis of QM-2, decision gates will lead to booster fabrication for Exploration Mission 1 (EM-1), the first SLS launch.



Fig. VII: SLS 5-segment Development Motor (DM-3) test firing

ATK completed two key avionics tests for the solid rocket boosters (SRBs) during 2013.⁶ The avionics tests operated the booster's thrust vector control (TVC) system as if the booster were operating during an actual mission. (Fig. VIII) The avionics system provides power distribution, communication with flight computers, ignition, command and control of the nozzle actuator system, and staging. The tests simulated SLS launch sequences in preflight and ascent profiles. The successful testing validated the new booster avionics subsystem and innovative electronic support equipment that replaced Shuttle-era equipment. It was also a chance to train and evaluate the test team during simulated countdowns and firings. Two additional tests are planned. In addition to contractor facilities, an avionics hardware-in-the-loop facility at MSFC allows end-to-end control system testing under simulated load conditions for development and certification testing.



Fig. VIII: SLS booster aft skirt avionics/thrust vector control system

STAGES

The core stage will be the tallest ever built, holding more than 800,000 gallons of propellant. The Stages Project completed installation of four of five core stage manufacturing tools at Michoud Assembly Facility in 2013, including the Segmented Ring Tool (SRT), Gore Weld Tool (GWT), Circumferential Dome Weld Tool (CDWT) and Vertical Weld Center (VWC). (Fig. IX) Confidence welding followed, resulting in completion of the first two 25-foot-tall core stage barrel sections on the VWC. The segments are considered “confidence” because they validate the tool is working correctly.^{7, 8}

Each barrel is 22 feet tall, weighs 9,100 pounds and is made of Al 2219. The first segment will be used for structural tests. A total of five similar barrels and two end domes make up the SLS core stage liquid hydrogen tank. The core stage will be more than 200 feet tall and 27.6 feet in diameter

The 3-story-tall, 150-ton VWC is a friction-stir-weld tool for wet and dry structures on the core stage. The VWC will be used to produce the barrels for the core stage’s two pressurized tanks, the forward skirt, and the aft engine section.

Additionally, the first SLS core stage forward LOX tank dome recently was completed on the CDWT. It is also considered a “confidence” article to ensure that the weld tool can produce the qualification and flight domes. The SLS core stage liquid hydrogen and liquid oxygen tanks will each have two domes similar to the confidence article. The dome will be used to develop inspection techniques for the flight articles. It also will be used for future confidence welding on the fifth and final core stage tool, the Vertical Assembly Center (VAC), one of the world’s largest welding tools. The VAC was acceptance tested in Sweden and shipped to Michoud in late 2013 and installed in 2014.



Fig. IX: SLS core stage confidence dome weld (left) and barrel section at MAF

SPACECRAFT AND PAYLOAD INTEGRATION (SPIO)

The Spacecraft and Payload Integration (SPIO) team had the distinction of delivering the first SLS flight hardware in 2013. The first Multi Purpose Crew Vehicle Stage Adapter (MSA) and composite diaphragm for Exploration Flight Test -1 (EFT-1), scheduled to launch in late 2014. The MSA completed machining, welding, painting, diaphragm pressure testing, and a fit-check with its Delta IV Heavy DCSS forward skirt, and was delivered to United Launch Alliance in April for integration with the launch vehicle.⁹ Structural loads testing on the prototype flight adapter was completed at MSFC's East Test Area in early 2014. Hydraulic actuators were used to simulate static and flight loads. Twenty-five loads cases were completed during testing.¹⁰ (Fig. X)

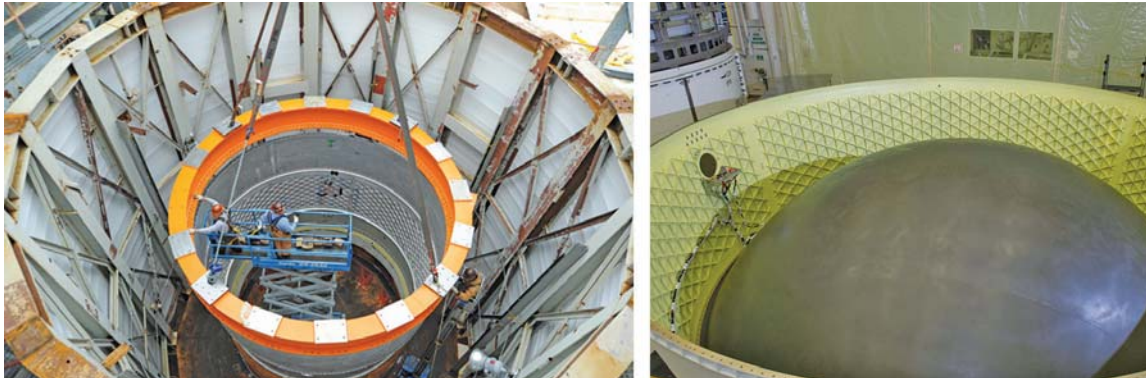


Fig. X: Orion stage adapter test article in stand (left) and flight stage adapter/diaphragm

This effort provided a valuable opportunity to engage/develop MSFC capabilities (in-house design and manufacturing) while supporting a critical cross-program and cross-center initiative. This milestone reflected a key point in the qualification and acceptance of this hardware for EFT-1 and enhanced the productive and successful cross-center partnership between Langley Research Center (LaRC) and MSFC.

Other milestones included award of the last major hardware contract for the Launch Vehicle Stage Adapter (LVSA) to Teledyne Brown Engineering, which will attach the mated upper stage and Orion to the rocket. The company will partner with MSFC to use its Advanced Welding Facility for assembly of LVSA components.

Work continued on refining the requirements for the Interim Cryogenic Propulsion Stage (ICPS) that will propel Orion to the far side of the Moon. It will be a modified Delta IV Cryogenic Second Stage (DCSS), leveraging a valuable asset from the U.S. evolved expendable launch vehicle fleet. The DCSS has successfully flown more than 20 times. For the SLS mission, the propellant tank will be stretched. Part of the analysis will include changes to the stage to accommodate SLS loads and environments such as winds at the launch pad and ascent loads.

SYSTEMS ENGINEERING & INTEGRATION (SE&I)

The Systems Engineering & Integration team worked numerous actions to understand vehicle performance, work out interface issues between vehicle elements, coordinate overall vehicle design issues, develop guidance and control hardware and software, refine performance, and complete numerous ground support hardware and process operations.

The team conducted more than 4,000 runs in the Transonic Dynamics (LaRC), Trisonic (MSFC), Polysonic (Boeing), and Unitary Plan (LaRC) wind tunnels.¹¹ Testing included liftoff transition data with four different payload configurations to improve the design and stability, examine buffet loads, and ensure vehicle control at low speeds. The Transonic tunnel evaluated performance with speeds ranging from Mach 0.7 to Mach 1.4, including low frequency buffet tests. The fastest acoustic speed simulated was

Mach 1.5 to Mach 2.5 conducted in the Unitary facility.(Fig. XI) It evaluated high-supersonic flow and focused more on local vibrations related to feed lines or the boosters. Tests were conducted over a range of configurations, Mach numbers, angles, and more than 4,000 data conditions.

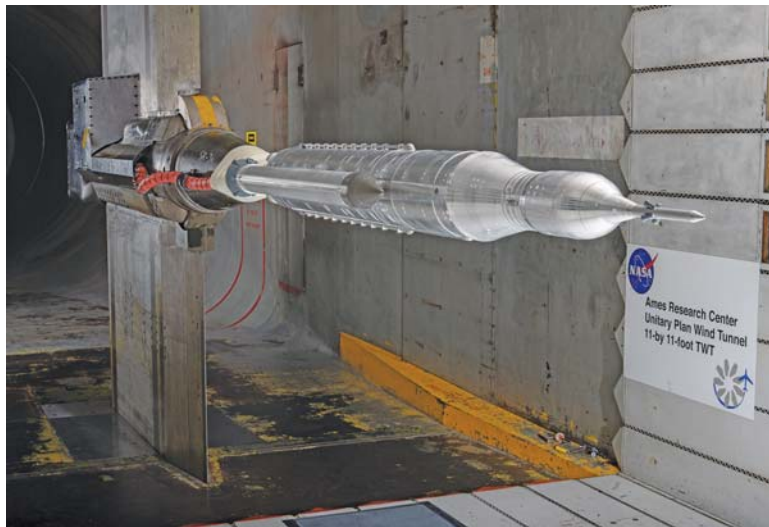


Fig. XI: SLS wind tunnel testing at Ames Research Center (ARC)

The Program used a new technique to add performance and robustness to SLS flight software. For the first time in a launch vehicle, the SLS team developed an adaptive control concept, adding the ability for an autonomous flight computer system to retune itself in flight. The system, called the Adaptive Augmenting Controller, learns and responds to unexpected differences in the actual flight versus preflight predictions. This ability to react to unknown scenarios that might occur during flight and make real-time adjustments to the autopilot system provides system performance and flexibility, as well as increased safety for the crew.¹²

Dryden Flight Research Center's (DFAC) F/A-18 aircraft was used for the five-flight series. (Fig. XII) More than a dozen tests simulating abnormal conditions such as wind gusts or higher thrust were conducted on each flight. Although the jet was in the air for 60 to 90 minutes, the algorithm was tested in different scenarios for up to 70 seconds at a time. Engineers were able to validate the control algorithm and modify it as necessary.



Fig. XII: SLS flight control testing using Dryden (DFAC) F/A-18 test plane

The SE&I team also began flight software development using core stage flight computer engineering development units, performed early integration of developmental hardware and software, delivered scheduled Integrated Avionics and Software (IAS) builds, completed construction of the core stage System Integration Test Facility (SITF) and incorporated developmental avionics hardware and flight software for planned 2014 tests.¹³

MSFC's Software Development Facility developed the avionics software that guides the vehicle and steers the engines and boosters using flight computers from The Boeing Company. The SLS flight computer has the highest processing capability available in a flight avionics computer and is being developed by upgrading existing component and board designs that have been used in communication satellites. (Fig. XIII)



Fig. XIII: NASA Administrator at SITF (left) and test engineer runs avionics flight simulation (right)

It was tested in MSFC's (SITF) a hardware in the Loop Lab, which was designed to functionally represent the forward skirt, intertank and engine section of the SLS core stage, where avionics components are located. The SITF structure supports the mounting of flight-equivalent avionics boxes and flight-length cables in addition to simulation and test system components. Simulations allow the computers and software to be tested to see how they perform together. In 2015, the avionics will be shipped to Michoud Assembly Facility, where the core stage is being manufactured and integrated onto the actual rocket.

Another important vehicle-level test series in 2013-2014 was the Scale Model Acoustic Test (SMAT) at MSFC. (Fig. XIV) Engineers used a 5-percent scale model of the SLS positioned on a like-scaled mobile launcher, tower and flame trench. Subscale liquid and solid motors simulated SLS firing while engineers collected acoustic data and tested the performance of water jets to acoustic waves that can affect the vehicle, crew, and payloads.¹⁴



Fig. XIV: Core stage SMAT testing at MSFC

Engineers also used a scale model to better understand the heating conditions at the base of the launch vehicle. (Fig. XV) Working 2-percent models of the RS-25 engines and solid rocket boosters were designed, built and scheduled for hotfire testing this year by MSFC in collaboration with Calspan-University of Buffalo Research Center, in Buffalo, N.Y. The tests provided data on convective heating environments that the bottom of the core stage and boosters will experience during ascent.¹⁵ Many new innovative design and manufacturing methodologies have been used in the development of these rocket engines/motors. This has enabled the Team to surpass the performance of previous base heating model propulsion systems, which will enable minimal data scaling and improved data fidelity. The development of these sub-scale propulsion systems for short-duration testing (~100 msec) has not been accomplished in 40 years. This test program also involved the technical collaboration of Marshall's Thermal Analyses Branch, Glenn Research Center's Propellant & Propulsion Branch, and Plasma Processes Inc. Test results will be used to establish specifications for the SLS base thermal protection system that protects, wiring, avionics, and pipes from extreme heating.

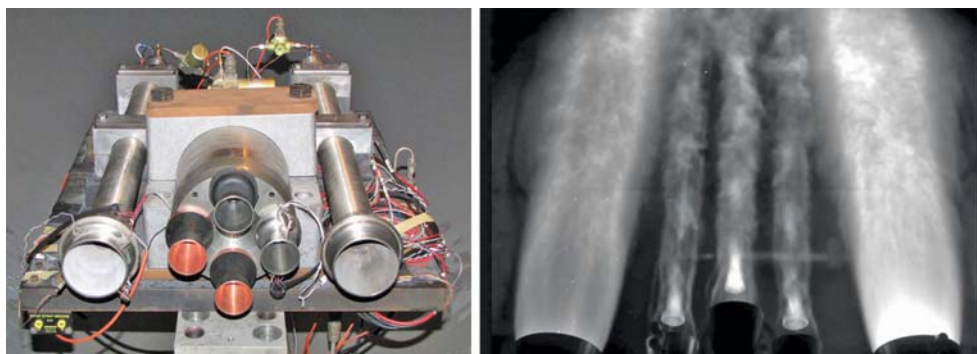


Fig. XV: Two-percent scale model of SLS core stage RS-25 engines and boosters for base heating tests

ADVANCED DEVELOPMENT

The SLS Advanced Development team continued to lay the groundwork for evolution of initial vehicle configuration, as well as future capabilities and missions. The Program partnered with Dynetics and Aerojet Rocketdyne to conclude hot-fire testing of a gas generator from an Apollo-era F-1 engine in the MSFC test area as part of research into development of a modernized F-1B version of the powerful engine.

Other efforts that support SLS evolution included support to research into an aerospike RP-1 rocket engine, testing of a new more environmentally-benign, spray-on insulation foam, maturation and utilization of additive manufacturing techniques, development of an Exploration Upper Stage, and studies on long-duration cryogenic propellant storage.

Members of the SLS evolvability team met with representatives of NASA's Jet Propulsion Laboratory (JPL) to discuss design reference missions for two planned JPL spacecraft. The discussions not only potentially lay groundwork for future utilization of SLS, but also provide beneficial real-world inputs to both sides that can inform design decisions.

The team also briefed members of the private Inspiration Mars, including Chairman Dennis Tito, entrepreneur and the world's first space tourist. Following several months of reviews with NASA field centers, industry and academia to validate an architecture for a human Mars flyby mission in 2018, Tito concluded that SLS was critical to achieving the Inspiration Mars goal of a flyby mission. The SLS/Orion system, he said, will enable humans to explore many deep space destinations.¹⁶

This validation by a member of the new entrepreneurial space community confirmed what numerous knowledgeable voices in the space industry and the payload community already concluded, that SLS truly is "the spaceship to everywhere."

2014-2015 PLANS

As discussed earlier, Orion's first test flight is scheduled for 2014. (Fig. XVI) A Delta IV Heavy rocket will launch an uncrewed Orion for a check of aerodynamic and thermal performance, structure, and systems during a four-hour, two-orbit flight, and 3,600 miles above the Earth. The complete SLS/Orion system will launch uncrewed in FY 2018 for EM-1, with SLS carrying an uncrewed Orion vehicle into space for a 25-day journey beyond the Moon and back to Earth. The first crewed mission is scheduled to launch in fiscal 2021-2022.



Fig. XVI: Artist's concept of Orion crew vehicle in Earth orbit

The SLS team continues to work toward those key milestones. All hardware elements (boosters, main engines, core stage/avionics, and spacecraft and payload integration) have completed their respective PDRs and made significant technical progress, including production and testing of test hardware and even flight hardware and software. In early 2014, SLS completed all requirements associated with Key Decision Point (KDP)-C. The decision memo will be finalized this year. In the meantime, NASA has cleared SLS to proceed to Critical Design Review in 2015.

Over 2014 and into 2015, SLS will complete element-level and vehicle-level Critical Design Reviews. The Program will complete a significant amount of hardware, including the core stage liquid hydrogen tank, liquid oxygen tank, intertank, forward skirt, and engine structure. This includes completing structural test article facilities at MSFC and qualification avionics integrated into the software integration test facility. The project will also begin qualification testing of the liquid hydrogen tank, liquid oxygen tank, engine structure, intertank, and forward skirt. In support of EM-1, the project will complete assembly and test of the first flight RS-25 engine, finish booster avionics fabrication and test, begin integration of core stage flight hardware at the Michoud Assembly Facility, and start the booster thrust vector control assembly.

SUMMARY AND CONCLUSIONS

With SLS, NASA is working to ensure that the United States remains the world leader in the human and scientific exploration of space. Exploring deep space requires the capability to transport crew and substantial masses and volumes of cargo beyond low Earth orbit. NASA is developing SLS, Orion, and supporting ground facilities for that purpose, leveraging existing NASA investments.

SLS is the critical enabling capability for a future exploration architecture. With a lift capability more than two and half times that of any launch vehicle currently in operation, SLS will carry American astronauts beyond low Earth orbit for the first time since the Apollo program and enable robotic science missions not possible today.

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REFERENCES

1. **"Preliminary Report Regarding NASA's Space Launch System and Multi-Purpose Crew Vehicle Pursuant to Section 309 of the NASA Authorization Act of 2010** (P.L. 111- 267), http://www.nasa.gov/pdf/510449main_SLS_MPCV_90-day_Report.pdf
2. **"Voyages: Charting the Course for Sustainable Human Space Exploration,"** June 2012, <http://www.nasa.gov/exploration/whyweexplore/voyages-report.html#.UhZwPOBcTh4>
3. **"Excitement Building As NASA Continues Preparations for RS-25 Engine Testing,"** nasa.gov, Jan. 16, 2014, <http://www.nasa.gov/exploration/systems/sls/rs25-testing-stennis.html>
4. **"NASA Sets Sights on Testing Space Launch System Engines,"** nasa.gov, Sept. 5, 2013, <http://www.nasa.gov/exploration/systems/sls/j2x/j2x-last-gimbal-test.html>
5. **"The Future of Exploration Starts With 3-D Printing,"** nasa.gov, Mar.19, 2013, http://www.nasa.gov/exploration/systems/sls/j2x/3d_print.html
6. **"NASA and ATK Complete Avionics and Control Testing for SLS Booster,"** AmericaSpace, Dec. 13, 2013, <http://www.americaspace.com/?p=46724>
7. **"First Liquid Hydrogen Tank Barrel Segment for the SLS Core Stage Completed at Michoud,"** nasa.gov, July 30, 2013, <http://www.nasa.gov/exploration/systems/sls/sls-barrel-at-michoud.html>
8. **"Tools Building SLS Progress at Michoud,"** The Marshall Star, Feb. 26, 2014, <http://www.nasa.gov/centers/marshall/about/star/star140226.html>
9. **"Marshall Team Celebrates Work on Orion's First Test Flight,"** The Marshall Star, Feb. 5, 2014, <http://www.nasa.gov/centers/marshall/about/star/star140205.html>
10. **"Orion Stage Adapter Aces Structural Loads Testing,"** Space News, Feb. 7, 2014, <http://www.dmn.org/media/2036037/snu-02072014.pdf>
11. **"Wind Tunnel Tests evaluating environmental conditions for SLS,"** NASASpaceflight.com, Sept. 23, 2013, <http://www.nasaspaceflight.com/2013/09/wind-tunnel-environmental-conditions-sls/>
12. **"LVAC: Advancing the Technology Readiness of SLS Adaptive Controls,"** Mar. 20, 2014, nasa.gov, http://www.nasa.gov/centers/armstrong/Features/SLS_Adaptive_Controls.html
13. **"SLS Avionics System Sees the (First) Light,"** Jan. 9, 2014, nasa.gov, <http://www.nasa.gov/exploration/systems/sls/testing-sls-avionics.html>
14. **"NASA Begins Acoustic Tests On The Space Launch System,"** Jan. 29, 2014, Popular Science, <http://www.popsci.com/article/science/nasa-begins-acoustic-tests-space-launch-system>
15. **"Mini Rocket Models to be Used in a Big Way for SLS Base Heating Test,"** The Marshall Star, Mar.12, 2014, <http://www.nasa.gov/centers/marshall/about/star/star140312.html>
16. **"The Spaceship to Everywhere,"** Huffington Post, Mar. 14, 2014, http://www.huffingtonpost.com/dennis-tito/the-space-ship-to-everywh_b_4966782.html