NASA's SPACE LAUNCH SYSTEM; MOMENTUM BUILDS TOWARDS FIRST LAUNCH

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NASA's Space Launch System (SLS) is gaining momentum programmatically and technically toward the first launch of a new exploration-class heavy lift launch vehicle for international exploration and science initiatives. The SLS comprises an architecture that begins with a vehicle capable of launching 70 metric tons (t) into low Earth orbit. Its first mission will be the launch of the Orion Multi-Purpose Crew Vehicle (MPCV) on its first autonomous flight beyond the Moon and back. SLS will also launch the first Orion crewed flight in 2021. SLS can evolve to a 130-t lift capability and serve as a baseline for numerous robotic and human missions ranging from a Mars sample return to delivering the first astronauts to explore another planet. Managed by NASA's Marshall Space Flight Center, the SLS Program formally transitioned from the formulation phase to implementation with the successful completion of the rigorous Key Decision Point C review in 2014. At KDP-C, the Agency Planning Management Council determines the readiness of a program to go to the next life-cycle phase and makes technical, cost, and schedule commitments to its external stakeholders. As a result, the Agency authorized the Program to move forward to Critical Design Review, scheduled for 2015, and a launch readiness date of November 2018. Every SLS element is currently in testing or test preparations. The Program shipped its first flight hardware in 2014 in preparation for Orion's Exploration Flight Test-1 (EFT-1) launch on a Delta IV Heavy rocket in December, a significant first step toward human journeys into deep space. Accomplishments during 2014 included manufacture of Core Stage test articles and preparations for qualification testing the Solid Rocket Boosters and the RS-25 Core Stage engines. SLS was conceived with the goals of safety, affordability, and sustainability, while also providing unprecedented capability for human exploration and scientific discovery beyond Earth orbit. In an environment of economic challenges, the nationwide SLS team continues to meet ambitious budget and schedule targets through the studied use of hardware, infrastructure, and workforce investments the United States has already made in the last half century, while selectively using new technologies for design, manufacturing, and testing, as well as streamlined management approaches that have increased decision velocity and reduced associated costs. This paper will summarize recent SLS Program technical accomplishments, as well as the challenges and opportunities ahead for the most powerful and capable launch vehicle in history.

I. BACKGROUND

NASA is developing the capabilities needed to send humans to an asteroid by 2025 and Mars in the 2030s – goals outlined in the bipartisan NASA Authorization Act of 2010 and in the U.S. National Space Policy, also issued in 2010. That plan is reinforced, validated, and expanded on in several reports and studies since then.[1,2,3,4,5]

NASA is developing the necessary tools to enable that exploration. While the Apollo Program model is the most familiar to the space community, current economic realities and historic precedent have changed. NASA has developed a stepping stone path to exploration (Fig. I) that prudently lays out the challenges and the capabilities needed to meet them on an extended timeline.

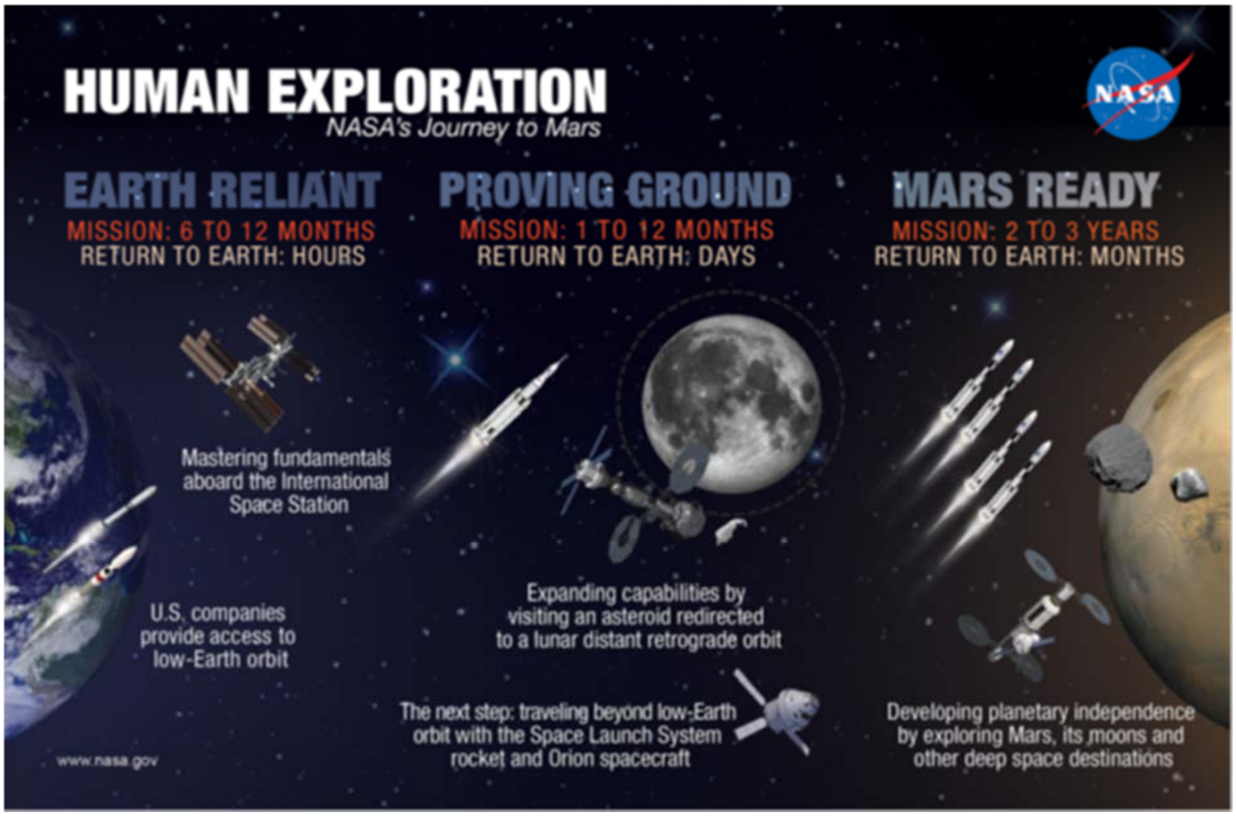

Fig. I: NASA's human exploration path to Mars.

The path for human exploration begins in low-Earth orbit, where NASA is proving many of the technologies and advancing its understanding of human health and long-term space operations. It is also an early proving ground for developing commercial cargo and crew transportation, with cargo carriers already in operation. In this "Earth-reliant" region, communications are almost instantaneous, and crews are only hours away from Earth in an emergency. Resupply is relatively easy. The next step for human exploration is deep space in the vicinity of the Moon, a proving ground where NASA can test advanced propulsion and life support, crew systems, operations, and other capabilities that will be needed for a Mars mission. Crews could be away from home for months. The time between asking a question and hearing the answer is seconds. Crews are days away from the safety of Earth and must be able to operate more independently.

Once NASA has demonstrated the capabilities needed to venture further, missions under consideration could take explorers to the Mars surface, its moons, and other destinations that will require missions lasting years, communications that require 4 to 24 minutes to reach Earth, and return times measured in months.

A key capability required to send crews and payloads to deep space is a heavy lift vehicle. The need for heavy lift has been validated in numerous NASA and external studies for more than a decade – the Space Transportation Architecture Study in 1986 and the Exploration Systems Architecture Study in 2005. NASA studied hundreds of vehicle configurations for their ability to meet a variety of design reference missions, minimize life-cycle costs, and maintain critical industry base skills. The result is SLS. It is designed to provide a safe, human-rated launch capability that can be developed under today's fiscally constrained environment and evolve to a progressively more capable vehicle as the nation's goals expand.

The SLS initial Block 1 vehicle stands 322 feet (97m) tall, including the Orion crew vehicle. It is capable of placing 70 t of payload in low Earth orbit, greater than any existing rocket. The configuration consists of four liquid hydrogen/liquid oxygen (LOX/LH_2) engines at the base of a core stage measuring 27.6 feet in diameter and more than 200 feet tall, along with two solid propellant boosters, together generating a combined liftoff thrust of 5.5 million pounds. (Fig. II)

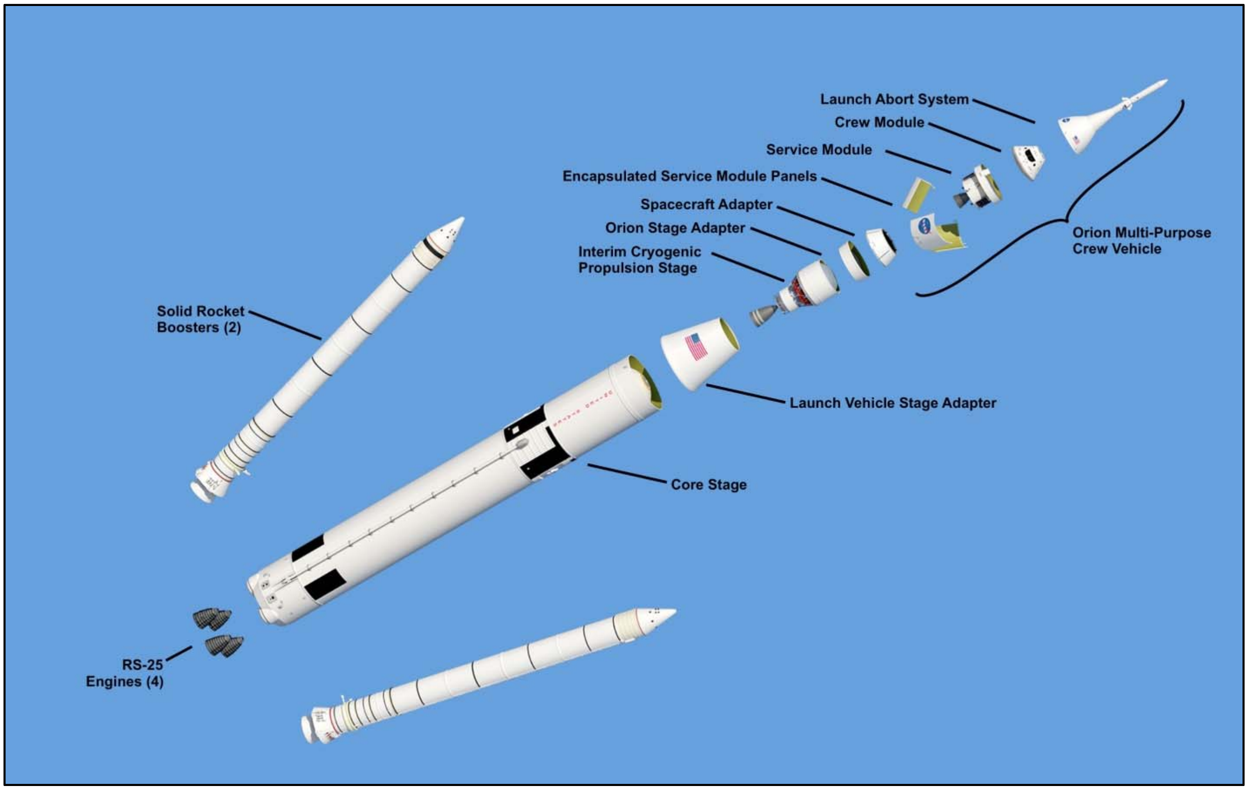

Fig. II: Expanded view of the SLS 70t elements.

Affordability is a key tenant of SLS development. As a result, SLS is based on the nation's investment in the technologies and infrastructure from the Apollo and Space Shuttle programs, including workforce, tooling, manufacturing processes, supply chains, and launch infrastructure. The initial SLS configuration employs the proven, reliable RS-25 main engine first developed for the Space Shuttle and the powerful Shuttle-based 5-segment solid rocket motor developed for the Ares Project. SLS will rely on the existing space industrial base, with assembly at NASA's Michoud Assembly Facility, testing at NASA's Stennis Space Center and other NASA facilities, and launched from NASA's Kennedy Space Center.

Despite the Program's use of heritage investments, it is also making wise use of new technologies and management approaches. The Core Stage is a new design that can readily support constraints of the heritage engines and boosters, as well as a variety of upper stages and payloads. Both the engine and the booster will be controlled by modern avionics. Contemporary manufacturing tools are being used to reduce assembly steps and improve quality. New modeling and simulation tools allow the design to be tested and flown "virtually" hundreds of times before putting physical hardware at risk, as well as reducing costs.

In addition, the Program has successfully applied a streamlined management approach, and its major contractors have used value stream mapping to implement efficiencies.

SLS has made significant progress since the Agency formally announced its architecture in September 2011. The Program formally transitioned from the formulation phase to implementation with the successful completion of two major life-cycle milestones in 2013 and 2014. SLS successfully passed its Preliminary Design Review in July 2013[6] and then completed the rigorous Key Decision Point C (KDP-C) review in January 2014. At KDP-C, the Agency Planning Management Council determines the readiness of a program to go to the next life-cycle phase and makes technical, cost, and schedule commitments to its external stakeholders.

Today, SLS is more than halfway through design and development and is consistently meeting its milestones. Every major element has hardware in manufacturing or testing, and critical vehicle software is in the ninth of 12 planned development builds. Vehicle Critical Design Review (CDR) is planned for mid-2015, and the Program is on schedule to meet Program internal commitment to deliver the first launch vehicle to Kennedy Space Center as early as December 2017.

The following sections will highlight key technical progress of the SLS major elements in the past year and the remaining challenges.

II. PAYLOAD ADAPTER, STAGES, AND AVIONICS

The first SLS flight hardware was shipped to Kennedy Space Center in early 2014 for launch. The Multi-Purpose Crew Vehicle (MPCV) Stage Adapter (MSA) is a structural ring that will mate an Orion test article to a Delta IV rocket for a test flight in late 2014. This same design will be used for future SLS missions also, reflecting the Program's affordability emphasis. While hardware development proceeded in several areas, the Core Stage project successfully passed its Critical Design Review in July 2014.[7] More than 3,000 artifacts were reviewed by 700 aerospace experts in the process of completing CDR ahead of schedule. As of mid-August, more than 70 percent of 4,682 Core Stage drawings were complete. Completion of the initial release drawing set is planned for January 2015.

At NASA's Michoud Assembly Facility, the last of five major welding tools for the Core Stage was installed. The 170-foot-tall Vertical Assembly Center, the world's largest spacecraft welding tool, is nearing completion. The Boeing Company, Core Stage prime contractor, will use it to weld propellant tank barrel sections together to form the Core Stage. Several "confidence" barrel sections and domes have been completed (Fig. III), and work is underway on completing development LOX and LH2 tanks for structural testing at Marshall Space Flight Center. Simultaneously, development and integration of vehicle flight computers and software continues at Marshall.

Fig. III: SLS core stage 'confidence' barrel section at Michoud Assembly Facility.

Also at Marshall, NASA awarded a $45.3 million contract this year for construction of the test stands (Fig. IV) to support Core Stage propellant tank testing to ensure they can withstand launch and ascent.[8]

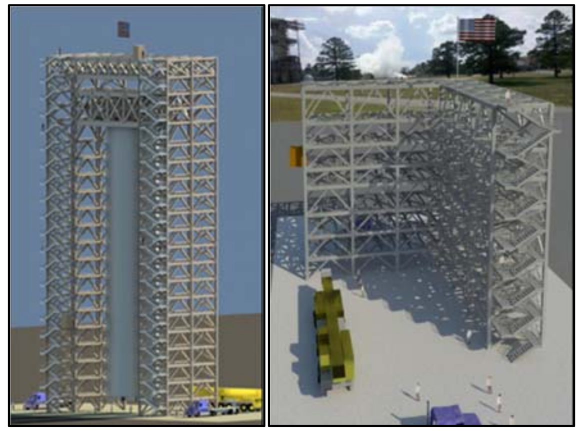

Fig. IV: Artist concepts of NASA's LH_2 test stand (left) and LOX test stand (right).

The Core Stage is made up of the engine section, liquid hydrogen tank, intertank, liquid oxygen tank, and forward skirt. Testing will subject the tanks to loads as great as 9 million pounds. The 215-foot-tall Test Stand 4693 will use 2,150 tons of steel. It will be used to test the liquid hydrogen tank, which will be 185 feet tall. The stand is being built on the foundation of the stand where Saturn V F-1 engine was tested. Test Stand 4697 is a 692-ton steel structure about 85 feet high. It will be used to test the liquid oxygen tank and forward skirt.

NASA is working to complete the renovation of the B-2 Test Stand at Stennis Space Center (Fig. V) for integrated Core Stage green run testing in 2016.[9] After testing is complete in 2017, the Core Stage will be used for Exploration Mission 1 (EM-1), the maiden, unmanned flight of the SLS.

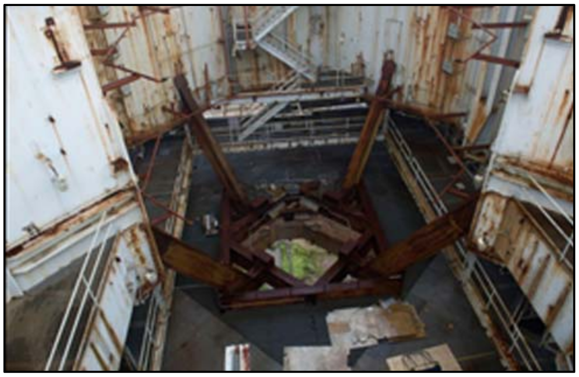

Fig. V: B-2 stand renovation showing before (top) and after (bottom) images.

The work includes restoration and upgrading of the main derrick crane, which sits atop the stand to lift the Core Stage into place. The Core Stage is nearly 50 percent longer than the Saturn stages previously tested on the stand, so the main derrick has to be significantly upgraded. Work is also ongoing to replace fixed and movable platforms on the engine servicing deck, restore the booster support frame, replace mechanical piping, electrical wiring, add a new 100-foot superstructure, and install a new pump to supply an additional 25,000 gallons of water per minute to the stand to attenuate the vibro-acoustic impact on the stage. Set for activation in early 2016, the stand will host modal tests to assess structural vibration, tanking tests to verify pre-launch sequences for pressurizing stage systems and filling and draining propellants, and hot-fire tests to operate the stage and engines as they will operate in an actual mission.

Marshall recently began anti-geyser testing in support of Core Stage development. (Fig. VI) A full-scale replica of the SLS liquid oxygen tank feed system was set up on a Marshall test stand to validate the process for keeping the tank's thousands of gallons of oxidizer from geysering.[10]

Fig. VI: Full-scale replica of SLS LOX tank feed system at MSFC for anti-geyser test.

The phenomenon occurs when heat enters the system and forms gas bubbles. The bubbles displace the liquid and allow it to come crashing down, potentially causing hardware damage. To prevent heat buildup and the resulting bubbles, helium is injected into different points along two feed lines that deliver the propellant to the tank. The helium induces circulation to keep propellant temperature uniform.

III. CORE STAGE ENGINE

SLS will be powered by a cluster of four RS-25 engines made by Aerojet Rocketdyne. The Program has 16 flight engines from the Shuttle Program available for the first four SLS flights, as well as two engines for development tests and a pathfinder engine for various facility, transportation, and stage fit-checks.

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 for Shuttle missions. 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.

Modifications to Stennis Test Stand A-1 to support RS-25 testing were completed in 2014, including are complete and engine #0525 is currently installed (Fig. VII) in preparation for developmental and flight certification of the engine.[11]

Fig. VII: RS-25 engine #0525 ready for installation on the A-1 test stand.

Development of the new engine controller is pacing the first test series to test propellant pressure and temperature inlet conditions that will both be higher with SLS than with the Shuttle. The controller regulates engine start, shutdown, and propellant flow under normal and emergency conditions. The Program is developing a common controller based on the J-2X engine controller that is capable of serving the RS- 25 and future engines. The team completed several milestones in developing the Engine Control Unit (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 and provide an affordable asset for other rocket engines, as well.

Renovation of the A-1 Test Stand at Stennis has been under way since last fall with installation of new equipment and components needed to accommodate RS-25 engines, including the cryogenic piping system tested May 1. The piping system is an intricate network that must handle rocket propellants flowing at extremely cold temperatures. Liquid oxygen flows at almost -300 degrees Fahrenheit (F), while liquid hydrogen is colder than -400 degrees F. RS-25 engines burn a mixture of the two to generate thrust.

The piping must be able to "move" as it expands and contracts due to the extreme temperature changes caused by the propellant flows. The temperature change can be as much as 500 degrees F during a hot-fire test. To ensure the piping system design allows the necessary movement, NASA engineers flowed liquid nitrogen through it at -320 degrees F and monitored the effects. Engineers also conducted a calibration run of the new thrust measurement system, which is particularly critical so engineers can obtain accurate measurements of engine thrust during tests.

IV. SOLID ROCKET BOOSTER

A pair of 5-segment solid rocket boosters made by Alliant Techsystems, Inc. (ATK) will provide most of the vehicle thrust during the early boost phase. Each booster measures 177 feet long and 12 feet in diameter and will generate up to 3.5 million pounds of thrust, the most powerful in the world.

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 booster recently completed its CDR after a review of about 1,200 documents confirming that the design is well-understood and clearing the way for verification and qualification testing.[11]

Several additional booster tests were conducted over the past year. The booster forward skirt, which houses the electronics responsible for igniting, steering, and jettisoning the two 5-segment boosters and serves as the forward attach point to the Core Stage, was subjected to structural loads simulating launch and ascent. (Fig. VIII)

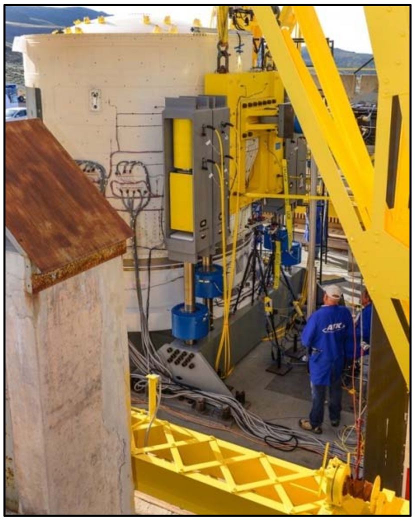

Fig. VIII: ATK engineers prepare booster forward skirt for testing.

Engineers used increments of force – about 200,000 pounds per minute – to prove the design meets strength requirements with sufficient margin.[12]

The new avionics system responsible for igniting, steering, and jettison of the boosters successfully completed a pair of hotfire tests in late 2013.[13] The tests operated the booster's thrust vector control system as if the booster were actually steering the SLS into orbit. Full-scale hardware, software, and ground systems for the booster avionics were tested again in early 2014 to stress the system beyond what it will experience during flight. (Fig. IX) The system and associated test equipment will be integrated into the SLS Core Stage avionics system for flight simulations leading to flight system certification in 2015.

Fig. IX: Engineers inspect booster avionics hardware.

A ground static test firing of the full-scale booster is tentatively scheduled for late 2014 or early 2015. Following on the three earlier successful test firings of full-scale 5-segment development solid rocket motors in 2009, 2010, and 2011, the upcoming SLS Qualification Motor 1 test will verify new materials and manufacturing methods for the new booster.

V. SYSTEMS ENGINEERING AND INTEGRATION

The Systems Engineering and Integration (SE&I) team performed numerous tests 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.

Engineers have completed eleven Scale Model Acoustic Tests (SMAT) in 2013 and 2014 designed to measure and develop attenuation methods for low- and high-frequency sound waves that will affect the rocket on the launch pad.[14] If not addressed, the noise of the engines and boosters could affect the rocket, payload, and crew during liftoff. For the test series, a 5-percent scale model of SLS outfitted with working liquid and solid engines and motors and instrumented with more than 200 sensors was fired at different elevation and drift positions on a scaled mobile launcher, tower, and flame trench. (Fig. X) Engineers collected acoustic data and tested the ability of water jets to dampen the sound waves.

Fig. X: Subscale Motor Acoustic Testing at MSFC.

The new SLS avionics system, including hardware, software, and operating system, were integrated and powered up for the first time in early 2014 at Marshall's Systems Integration and Test Facility.[15] The ongoing series of flight simulations replicates the environments the avionics will experience in flight, so engineers can find and fix any problems and make sure all the components communicate as designed. (Fig. XI) The avionics and the flight computer will be housed in the SLS Core Stage.

Fig. XI: SLS avionics setup (top) and Systems Integration and Test Facility (bottom).

In addition to traditional wind tunnel testing to understand vehicle design, stability, buffet loads, and control, the Program used a new technique called Adaptive Augmenting Control to make sure the rocket can adjust to different launch environments.[16] SLS employed the technique for the first time in a launch vehicle, adding the ability for an autonomous flight computer system to retune itself in flight. The system 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.

Armstrong Flight Research Center's F/A-18 aircraft was used for a six-flight series in late 2013 to simulate abnormal conditions such as wind gusts that could affect SLS. (Fig. XII) During these flights, almost 100 SLS trajectories and over a dozen straight-and-level airframe structural amplification tests were successfully executed, many of which were to collect additional data regarding the interaction of the pilot, the simulated SLS vehicle dynamics, and the adaptive augmenting control algorithm. In one of the innovative tests, the plane was intentionally placed in structural resonance, which causes the aircraft to vibrate while in flight. The adaptive augmenting control system then responded to these vibrations, suppressing them when they exceeded a pre-determined threshold, meeting one of the major objectives of the adaptive controller.

Fig. XII: Dryden F/A-18 test plane simulates SLS flight responses.

VI. CONCLUSION

Exploration is critical to prosperity and human progress. NASA and the nation have embarked on a bold new path for future human exploration that leads to Mars and beyond. This direction is articulated in U.S. Space and Transportation Policies, NASA's 2014 Strategic Plan, and the Global Exploration Roadmap.

Exploration of deep space involves unprecedented challenges and requires unprecedented capability to send crews and large masses and volumes of cargo into and beyond low Earth orbit. NASA is developing those capabilities in a stepwise approach, including launch vehicle, crew vehicle, and ground systems.

SLS was conceived with those challenges and opportunities in mind, as well as the economic challenges facing the nation. The Program is making significant progress toward developing that launch capability with unsurpassed mass and volume capability with the potential to lower overall mission cost and complexity and increases the odds of mission success. Every major element of SLS has hardware and software in testing. Two elements have completed their CDR requirements on the way to Program CDR in mid-2015. The Program is currently on budget and on schedule to support a November 2018 launch readiness state and the beginning of a new era of exploration. (Fig. XIII)

Fig. XIII: Artist's concept of SLS aboard the Mobile Launcher moving to the launch pad.

REFERENCES

[1]NASA, 2012, “Voyages: Charting the Course for Sustainable Human Exploration”, http://www.nasa.gov/exploration/whyweexplore/voyages-report.html

[2]The International Space Exploration Coordination Group, 2013, “Global Exploration Roadmap”, http://www.nasa.gov/sites/default/files/files/GER-2013_Small.pdf

[3]NASA Human Exploration and Operations Mission Directorate, 2014, “Pioneering Space: NASA’s Next Steps on the Path to Mars”, http://www.nasa.gov/sites/default/files/files/Pioneering-space-final-052914b.pdf

[4]National Research Council, 2014, “Pathways to Exploration: Rationales and Approaches for a U.S. Program of Human Space Exploration”, ISBN 978-0-309-30507-5 http://www.nap.edu/catalog.php?record_id=18801

[5]NASA, “2014 Strategic Plan”, http://www.nasa.gov/sites/default/files/files/FY2014_NASA_SP_508c.pdf

[6]Space.com, Aug. 1, 2013, “NASA’s Next Mega-Rocket Passes Key Design Review”, http://www.space.com/22211-nasa-space-launch-system-rocket-milestone.html

[7]Space-travel.com, July 4, 2014, “Space Launch System Core Stage Passes Critical Design Review”, http://www.space-travel.com/reports/NASAs_Space_Launch_System_Marks_Progress_as_Core_Stage_Passes_Critical_Design_Review_999.html

[8]AL.com, May 6, 2014, “Brasfield & Gorrie gets $45M to build new NASA test stands in Huntsville,” http://www.al.com/business/index.ssf/2014/05/brasfield_gorrie_gets_43m_to_b.html

[9]NASA.gov, May 15, 2014, “NASA Moving Forward on Test Stand Upgrades for SLS Core Stage Testing”, http://www.nasa.gov/press/2014/may/nasa-moving-forward-on-test-stand-upgrades-for-sls-core-stage-testing/

[10]Space-travel.com, August 12, 2014, “NASA Engineers Begin Testing for SLS Liquid Oxygen Feed System”, http://www.space-travel.com/reports/No_Geysers_Allowed_NASA_Engineers_Begin_Testing_for_SLS_Liquid_Oxygen_Feed_System_999.html

[11]Americaspace.com, Aug. 17, 2014, “ATK Completes Critical Design Review for Five-Segment SLS Rocket Booster.” http://www.americaspace.com/?p=65643

[12]NASASPACEFLIGHT.com, July 17, 2014, “RSASA.gov, May 21, 2014, “Engineers Test NASA’s SLS Booster Forward Skirt to the Limits,” http://www.nasa.gov/sls/forward-skirt-tests-limits.html

[13]ATK.com, Dec. 11, 2013, “NASA and ATK Complete Avionics and Controls Testing for NASA’s SLS Booster,” http://atk.mediaroom.com/2013-12-11-NASA-and-ATK-Complete-Avionics-and-Controls-Testing-for-NASAs-SLS-Booster

[14]NASAspaceflight.com, June 18, 2014, “SMAT firings ramp up for SLS acoustic testing” http://www.nasaspaceflight.com/2014/06/smat-firings-ramp-sls-acoustic-testing/[15]

[15]NASA.gov, Jan. 9, 2014, “SLS Avionics System Sees the (First) Light”, http://www.nasa.gov/exploration/systems/sls/testing-sls-avionics.htm

[16]Dailynews.com, March 25, 2014, "Advancing the technology readiness of SLS adaptive controls," http://www.dailynewsen.com/science/advancing-the-technology-readiness-of-sls-adaptive-controls-h2456716.html