

NASA'S SPACE LAUNCH SYSTEM DEVELOPMENT STATUS

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ABSTRACT

Development of the National Aeronautics and Space Administration's (NASA's) Space Launch System (SLS) heavy lift rocket is shifting from the formulation phase into the implementation phase in 2014, a little more than 3 years after formal program establishment. Current development is focused on delivering a vehicle capable of launching 70 metric tons (t) into low Earth orbit. This "Block 1" configuration will launch the Orion Multi-Purpose Crew Vehicle (MPCV) on its first autonomous flight beyond the Moon and back in December 2017, followed by its first crewed flight in 2021. SLS can evolve to a130t 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. Benefits associated with its unprecedented mass and volume include reduced trip times and simplified payload design. Every SLS element achieved significant, tangible progress over the past year. Among the Program's many accomplishments are: manufacture of core stage test barrels and domes; testing of Solid Rocket Booster development hardware including thrust vector controls and avionics; planning for RS-25 core stage engine testing; and more than 4,000 wind tunnel runs to refine vehicle configuration, trajectory, and guidance. The Program shipped its first flight hardware – the Multi-Purpose Crew Vehicle Stage Adapter (MSA) – to the United Launch Alliance for integration with the Delta IV heavy rocket that will launch an Orion test article in 2014 from NASA's Kennedy Space Center. The Program successfully completed Preliminary Design Review in 2013 and will complete Key Decision Point C in 2014. NASA has authorized the Program to move forward to Critical Design Review, scheduled for 2015 and a December 2017 first launch. The Program's success to date is due to prudent use of proven technology, infrastructure, and workforce from the Saturn and Space Shuttle programs, a streamlined management approach, and

judicious use of new technologies. The result is a safe, affordable, sustainable, and evolutionary path to development of an unprecedented capability for future missions across the solar system. In an environment of economic challenges, the nationwide SLS team continues to meet ambitious budget and schedule targets. This paper will discuss SLS Program and technical accomplishments over the past year and provide a look at the milestones and challenges ahead.

INTRODUCTION

NASA's future exploration plans are based on three key, interrelated activities: continuing long-duration research and operations with the International Space Station, developing commercial crew and cargo services to lower access to space, and development of the SLS and Orion crew vehicle for deep space exploration.

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 analyses and thousands of configuration trades that were evaluated for safety, development and life cycle costs, mission objectives, utilization of critical industrial base capability, and transitioning the workforce effectively.

SLS is designed to capitalize on the investments the United States has already made in space transportation, such as liquid oxygen/liquid hydrogen (LOX/LH2) propulsion, common design elements, manufacturing, infrastructure, logistics, and workforce. 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.

SLS will be the world's first exploration-class launch vehicle since the Saturn V, designed to carry human beings beyond low Earth orbit (LEO) for the first time in more than 40 years. In its earliest configuration, SLS will have a 70t lift capability to low Earth orbit. Key design features are: a four-

engine LOX/LH2 core stage, two 5-segment solid propellant boosters, and a liquid propellant upper stage.

The SLS core stage will use the Space Shuttle-heritage RS-25 engine 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 restarted.

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, further than any humans have traveled before.

SLS is designed from the start to support a variety of evolutionary paths to a payload capability of 130t based on mission requirements (Fig. I).

Both human and robotic missions beyond low Earth orbit will be simpler, safer, and enable greater exploration by using SLS. The following section will discuss broadly the technical and management challenges the SLS Program faces and how they are successfully overcome.

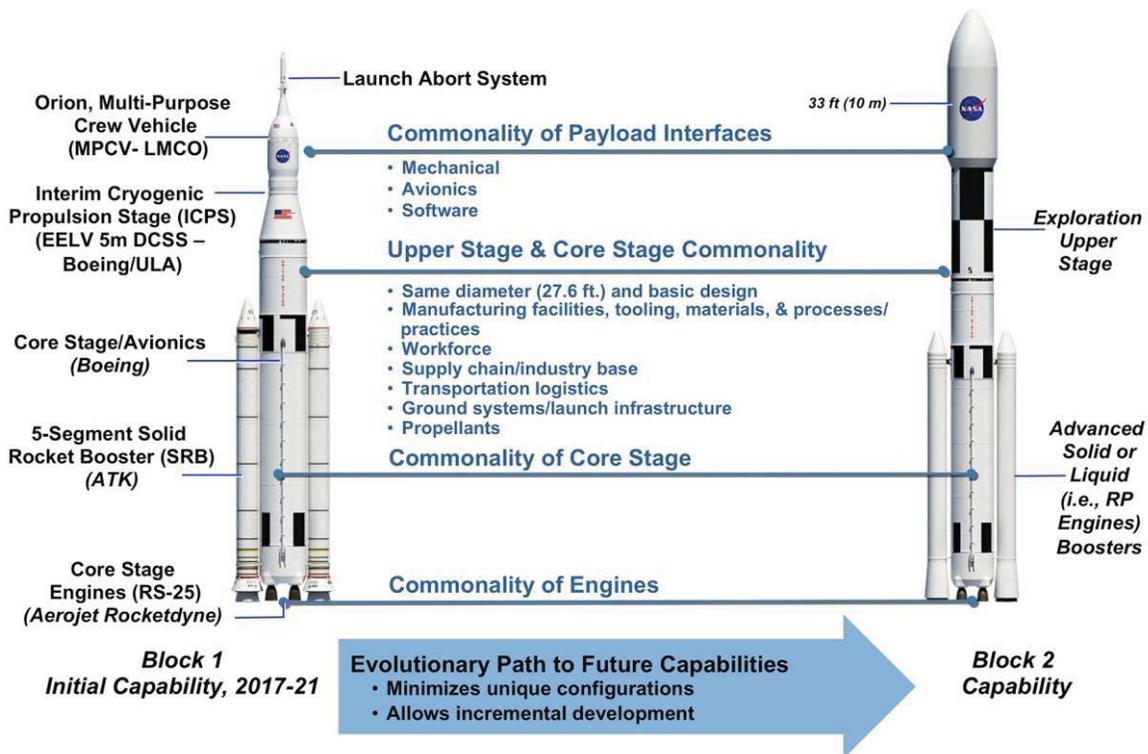


Fig. I: SLS evolutionary design path

PROGRAM CHALLENGES

Large, complex projects such as SLS come together in the Systems Engineering and Integration (SE&I) function. This job is even more critical when bringing together components that were originally designed for other applications, such as SLS. The SLS Program coordinates a nationwide program comprising both development and operations communities. It integrates a broad range of work by both government and private contractors. It operates in a resource-constrained environment that flattens the normal hardware development curve. The team strives to work smarter, not harder.

The core stage engines, boosters, and ICPS are based on hardware designed for other launch vehicles. The core stage itself is the only major new development hardware, but it is based on the Shuttle External Tank to take advantage of Shuttle infrastructure.

To perform the 70t SLS mission, the engines are required to operate at 109 percent vs. 104 percent. LOX entering the engine is colder and under higher pressure than the Shuttle. Booster fore and aft interface loads will be higher due to the core stage mass and acceleration. The ICPS will experience greater structural loads from the MPCV as well as SLS acceleration and thermal loads. And both engines and booster thermal curtain face higher heating due to the engine and booster exit planes being aligned.

Communication and integration are top challenges for SLS. To maintain accountability and responsibility, SLS maintains a strong focus on authority, accountability, and technical leadership. The number of oversight boards has been reduced. The SLS chief engineer serves as lead designer. He and his staff are focused on technical integration. The Program is organized to balance functional expertise and cross-functional integration. SLS uses a maxtrixed organization, where systems and discipline lead engineers communicate horizontally across the vehicle elements and report vertically within their own disciplines. This ensures that lead engineers are keeping each other informed of progress and changes while also ensuring consistency of practice in the line organizations.

SE&I involves process and management challenges as well as technical challenges. The program has successfully increased decision velocity and has been changed to reduce the number and structure of requirements. It continues to refine tabletop process and clarify expectations and requirements structure and models approach.

As a result, the Program is firmly on track to its Fiscal 2018 launch target. The initial SLS configuration achieves the 70t requirement while maintaining multiple evolutionary paths to the eventual 130t capability. Trajectory design has been established. The challenge remains to execute on schedule. The following sections will discuss highlights of SLS development and how the Program is resolving technical challenges.

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. Manufactured 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. SLS will utilize 16 flight-worthy RS-25 engines from the Shuttle program and re-start the RS-25 for future flights.

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 the 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.

Through the SE&I process, margin was built into overall vehicle performance to allow the engines to be throttled back during ascent to reduce inlet pressure. Heaters will be added to

the LOX line to provide oxidizer to the engine at the optimum temperature. Insulation may be added to the engines to reduce heating, much as it was on the Saturn F-1 first stage engines.

Much preliminary work was completed during 2013-2014 to ready the RS-25 for SLS use. RS-25s in inventory at Kennedy Space Center were moved to SSC (Fig. II), 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.



Fig. II: RS-25 engines at KSC

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. III). The RS-25 testing project was accelerated by a few months, shortening the time for preparation work on the A-1 test stand.

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.



Fig. III: RS-25 thrust frame adapter

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 upper stage engine 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 changeouts, ECU costs could be half those of the Shuttle controller.

NASA and industry engineers completed 13 tests of J-2X development engine 10002 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, gimbaling, 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 2013.¹

Testing on engine 10003 continued in calendar 2014 with seven tests totaling 2,408 seconds on the SSC A-2 stand (Fig. IV). 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.² At the end of testing, having served as an important tool for technologies such as structured light scanning and 3D printing³, the four development J-2X engines will be stored for potential upper stage applications in the future.



Fig. IV: 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. (ATK). 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, 30 percent more powerful than the 4-segment shuttle boosters.

Heritage hardware and design includes forward structures, metal cases, aft skirt, and thrust vector control. Although benefitting 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. Higher loads expected on the booster/core interface points are part of forward skirt structural test article program in 2014. Additional measures to mitigate loads include a design change to the separation bolt and throttling of the core stage engines.

ATK has successfully fired three heavily-instrumented, full-size, 5-segment development solid rocket motors at the high and low ranges of the booster's operating range and introduced deliberate insulation flaws to test new materials. Following those tests, 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.

ATK completed two key avionics tests for the solid rocket boosters (SRBs) during 2013.⁴ The avionics tests operated the booster's thrust vector control (TVC) system as if the booster were operating during an actual mission (Fig. V).



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

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. 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.

Structural tests planned for this year will ensure the integrity of the forward skirt ascent loads, including throttling the core stage engines before separation and strengthening the separation bolt as well as the core/booster interfaces.

STAGES

The core stage will be the tallest ever built, holding more than 800,000 gallons of propellant. As the only major new-design propulsion element, it has added structural capability to handle the higher loads expected for the 130t vehicle, as well as the initial 70t vehicle. And can support multiple paths to the 130t vehicle.

The Stages Element completed installation of four of five core stage manufacturing tools at Michoud Assembly Facility (MAF) in 2013, including the Segmented Ring Tool (SRT), Gore Weld Tool (GWT), Circumferential Dome Weld Tool (CDWT), and Vertical Weld Center (VWC) (Fig. VI). 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.^{5,6}



Fig. VI: SLS core stage barrel section at MAF

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.

SPACECRAFT AND PAYLOAD INTEGRATION (SPIO)

The Spacecraft and Payload Integration (SPIO) team delivered the first SLS flight hardware in 2013. Exploration Flight Test-1 (EFT-1) will be the first launch of the Multi Purpose Crew Vehicle Stage Adapter (MSA) and composite diaphragm (Fig. VII). 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 Kennedy Space Center for vehicle assembly in early 2014.⁷ Structural loads testing on the prototype flight adapter was completed at MSFC’s East Test Area in early 2014.⁸ Hydraulic actuators were used to simulate static and flight loads. Twenty-five loads cases were completed during testing. This MSA design will be used for the EM-2 mission and future Block 1 SLS missions.



Fig. VII: Orion stage adapter and diaphragm

Work continued on refining the requirements for the ICPS that will propel Orion to the far side of the Moon. It will be a modified Delta IV DCSS, which 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. To accommodate vehicle side loads on the launch pad, a vehicle stabilizer has been added to the launch tower.

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.

SYSTEMS ENGINEERING & INTEGRATION (SE&I)

The SE&I team worked numerous actions in 2013 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 (Langley Research Center), Trisonic (MSFC), Polysonic (Boeing), and Unitary Plan (Ames Research Center) wind tunnels.⁹ Testing included liftoff transition data with four different payload configurations to improve the design and stability, examine buffet and aero 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. VIII). 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. VIII: SLS wind tunnel testing at 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.¹⁰

Dryden Flight Research Center's (DFRC) F/A-18 aircraft was used for the five-flight series. More than a dozen tests simulating abnormal conditions such as wind gusts or higher thrust were conducted on each flight (Fig. IX).



Fig. IX: SLS flight control testing at DFRC

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.

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) (Fig. X) and incorporated developmental avionics hardware and flight software for planned 2014 tests.¹¹



Fig. X: NASA Administrator at SITF

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.

It was tested in MSFC's System Integration Test Facility, 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. XI). Engineers used a 5-percent scale model of the SLS positioned on a like-scaled mobile launcher, tower and exhaust duct. Subscale liquid and solid motors simulated SLS firing while engineers collected acoustic data and tested the performance of water jets designed to mitigate acoustic and overpressure loads that can affect the vehicle, crew, and payloads.¹²



Fig. XI: 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. XII). 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.¹³ 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 MSFC Space Flight Center'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.

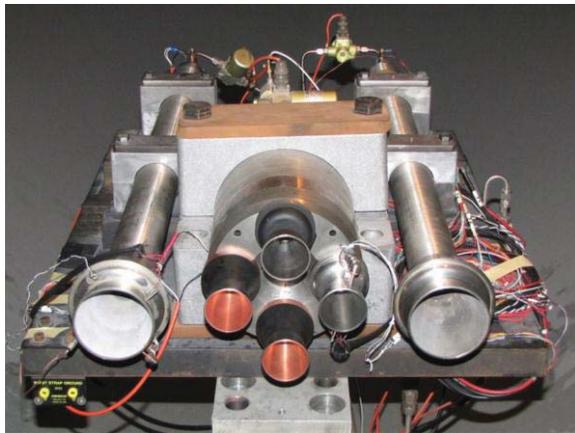


Fig. XII: Two-percent scale model of SLS core stage RS-25 engines and boosters for base heating tests

THE PATH TO LAUNCH

As discussed earlier, Orion's first test flight is scheduled for 2014 on Exploration Flight Test-1 (EFT-1). A Delta IV Heavy rocket will launch an uncrewed Orion for a check of aerodynamic and thermal performance, structure, and systems during a 4-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 years 2021-2022 (Fig. XIII).



Fig. XIII: Artist's concept of SLS launch

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 and made significant technical progress, including production and testing of development 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.

During 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

SLS is the enabling capability for continuing to advance national and international goals in both human and scientific space exploration and create incredible new possibilities for international cooperation and collaboration. Expanding humanity's reach beyond Earth orbit again, explore more fully our solar system, and see deeper into the universe requires the capability to put crews and large volumes and masses of cargo into space. NASA is developing SLS, Orion, and supporting ground facilities for that purpose, affordably building on more than 50 years of experience and investment. With a lift capability more than two and half times that of any other existing launch vehicle. 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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