

## Space Launch System Spacecraft and Payload Elements: Progress Toward Crewed Launch and Beyond

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While significant and substantial progress continues to be accomplished toward readying the Space Launch System (SLS) rocket for its first test flight, work is already underway on preparations for the second flight – using an upgraded version of the vehicle – and beyond. Designed to support human missions into deep space, SLS is the most powerful human-rated launch vehicle the United States has ever undertaken, and is one of three programs being managed by the National Aeronautics and Space Administration’s (NASA’s) Exploration Systems Development division. The Orion spacecraft program is developing a new crew vehicle that will support human missions beyond low Earth orbit (LEO), and the Ground Systems Development and Operations (GSDO) program is transforming Kennedy Space Center (KSC) into a next-generation spaceport capable of supporting not only SLS but also multiple commercial users. Together, these systems will support human exploration missions into the proving ground of cislunar space and ultimately to Mars. For its first flight, SLS will deliver a near-term heavy-lift capability for the nation with its 70-metric-ton (t) Block 1 configuration. Each element of the vehicle now has flight hardware in production in support of the initial flight of the SLS, which will propel Orion around the moon and back. Encompassing hardware qualification, structural testing to validate hardware compliance and analytical modeling, progress is on track to meet the initial targeted launch date. In Utah and Mississippi, booster and engine testing are verifying upgrades made to proven shuttle hardware. At Michoud Assembly Facility (MAF) in Louisiana, the world’s largest spacecraft welding tool is producing tanks for the SLS core stage. Providing the Orion crew capsule/launch vehicle interface and in-space propulsion via a cryogenic upper stage, the Spacecraft/Payload Integration and Evolution (SPIE) element serves a key role in achieving SLS goals and objectives. The SPIE element marked a major milestone in 2014 with the first flight of original SLS hardware, the Orion Stage Adapter (OSA) which was used on Exploration Flight Test-1 with a design that will be used again on the first flight of SLS. The element has overseen production of the Interim Cryogenic Propulsion Stage (ICPS), an in-space stage derived from the Delta Cryogenic Second Stage, which was manufactured at United Launch Alliance (ULA) in Decatur, Alabama, prior to being shipped to Florida for flight preparations. Manufacture of the OSA and the Launch Vehicle Stage Adapter (LVSA) took place at the Friction Stir Facility located at Marshall Space Flight Center (MSFC) in Huntsville, Alabama. Marshall is also home to the Integrated Structural Test of the ICPS, LVSA, and OSA, subjecting the stacked components to simulated stresses of launch. The SPIE Element is also overseeing integration of 13 “CubeSat” secondary payloads that will fly on the first flight of SLS, providing access to deep space regions in a way currently not available to the science community. At the same time as this preparation work is taking place toward the first launch of SLS, however, the Space Launch System Program is actively working toward its second launch. For its second flight, SLS will be upgraded to the more-capable Block 1B configuration. While the Block 1 configuration is capable of delivering more than 70 t to LEO, the Block 1B vehicle will increase that capability to 105 t. For that flight, the new configuration introduces two major new elements to the vehicle – an Exploration Upper Stage (EUS) that will be used for both ascent and in-space propulsion, and a Universal Stage Adapter (USA) that serves as a “payload bay” for the rocket, allowing the launch of large exploration systems along with the Orion spacecraft. Already, flight hardware is being prepared for the Block 1B vehicle. Welding is taking place on the second rocket’s core stage. Flight hardware production has begun on booster components. An RS-25 engine slated for that flight has been tested. Development work is taking place on the EUS, with contracts in place for both the stage and the RL10 engines which will power it. (The EUS will use four RL10 engines, an increase from one on the ICPS.) For the crew configuration of the Block 1B vehicle, the SLS SPIE element is managing the

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USA and accompanying Payload Adapter, which will accommodate both large payloads co-manifested with Orion and small-satellite secondary payloads. This co-manifested payload capacity will be instrumental for missions into the proving ground around the moon, where NASA will test new systems and demonstrate new capabilities needed for human exploration farther into deep space. Beyond the second flight, additional upgrades will be made to the vehicle. The Block 1B vehicle will also be able to launch 8.4-meter-diameter payload fairings, larger than any previously flown, and the SPIE Element will oversee development and production of those fairings. Ultimately, SLS will be evolved to a Block 2 configuration, which will replace the solid rocket boosters on the Block 1 and 1B vehicles with more powerful boosters, and will be capable of delivering at least 130 t to LEO. The Block 2 vehicle will be capable of launching even larger 10-meter diameter fairings, which will enable human missions to Mars. With these fairings, the Block 1B and 2 configurations of SLS will also be enabling for a wide variety of other payloads. For robotic science probes to the outer solar system, for example, SLS can cut transit times to less than half that of currently available vehicles, producing earlier data return, enhancing iterative exploration, and reducing mission cost and risk. In the field of astrophysics, SLS' high payload volume, in the form of payload fairings with a diameter of up to 10 meters, creates the opportunity for launch of large-aperture telescopes providing an unprecedented look at our universe, and offers the ability to conduct crewed servicing missions to observatories stationed at locations beyond LEO. This paper will provide a description of the SLS vehicle and an overview of the vehicle's capabilities and utilization potential. It will outline progress toward the first two flights, as well as future launches, with a focus on the work being done by the SPIE Element to prepare SLS for its early flights in beginning a new era of human exploration of space.

## I. Background

As NASA draws closer to the first integrated launch of its new deep space exploration systems, the agency continues to mature its plans for the missions those systems will enable. The Space Launch System (SLS) rocket, together with the the Orion crew vehicle and the Ground Systems Development and Operations program at Kennedy Space Center, mark the return of human spaceflight capability beyond low-earth orbit, enabling missions to the moon, Mars, and beyond.

Orion is designed to carry astronauts on exploration missions into deep space. GSDO is converting the facilities at NASA's Kennedy Space Center in Florida into a next-generation spaceport capable of supporting launches by multiple types of vehicles. Currently under construction, the initial configuration of SLS (Figure 1) will have the capability to deliver a minimum of 70 t into LEO and to launch a crew aboard the Orion spacecraft into cislunar space on its first flight. The vehicle will evolve to a full capability of greater than 130 t to LEO that will be instrumental to the first footsteps on Mars.

These capabilities are part of a larger NASA strategy of working with commercial partners that will support crew and cargo launches to the International Space Station, while the agency focuses its development efforts on an incremental approach to developing the systems necessary for human exploration beyond Earth orbit and eventually to Mars. SLS is being designed with performance margin and flexibility to support an evolvable human exploration approach, capabilities that will make it not only a foundational asset for human spaceflight but a game-changing resource for a variety of other missions.

Today, the Space Launch System Program is well into production of the hardware for the vehicle's first launch, and is already working on production for the second flight and beyond.



Figure 1 Artist's rendition of Space Launch System

## II. Vehicle Overview and Status

The initial Block 1 configuration of SLS was optimized for expediting an uncrewed test flight of the vehicle, allowing the program to demonstrate the primary propulsion elements of the vehicle and the new core stage while the human-rated upper stage needed for crewed flight is still in development. Those propulsion elements, the RS-25 liquid engines and the solid rocket boosters (SRBs), will also power the more-capable Block 1B configuration that will be used beginning with the second launch of SLS, and the core stage is designed for commonality in all SLS configurations, along with the RS-25 engines.

The SLS core stage, which stores the liquid oxygen (LOX) and liquid hydrogen (LH<sub>2</sub>) propellant for four RS-25 core stage engines, represents almost two-thirds of the vehicle's 97 m height, standing 61 m tall, and will have a diameter of 8.4 m. At MAF outside New Orleans, Louisiana, the world's largest space vehicle welding tool, the 52 m tall Vertical Assembly Center (VAC), is currently being used by The Boeing Company, core stage prime contractor, to weld barrel sections, rings, and domes together to form the test and flight articles of the propellant tanks for the stage. (Figure 2)

The forward skirt, intertank, and engine section are structurally complete and are all in various stages of equipment installation for flight. Welding of the LOX tank structural test article is complete and will be followed by the LOX flight tank and a second liquid hydrogen flight tank. A test article for the engine section has already arrived at MSFC to be tested. In the coming months, test articles for the hydrogen and oxygen tanks and intertank will be delivered from Michoud by the Pegasus barge.

The Core Stage will be powered by four RS-25 engines, which previously served as the Space Shuttle Main Engine (SSME). These human-rated engines support the SLS pursuit of safety, with a record of 100 percent mission success for the engines over 135 flights. At the end of the Space Shuttle Program, 16 RS-25 flight engines and two development engines were transferred to the SLS Program and placed in inventory at NASA's Stennis Space Center, providing enough engines for the first four flights of SLS.

Modifications to Stennis Test Stand A-1 to support RS-25 testing were completed in 2014, and testing has been underway since the beginning of 2015 in preparation for flight certification of the SLS configuration of the engine, including tests of flight hardware of the new engine controller unit that will be used on SLS. (Figure 3) The testing includes propellant pressure and temperature inlet conditions that will both be higher with SLS than with the shuttle, as well as other SLS-specific performance requirements such as 109 percent thrust versus the shuttle's 104.5 percent thrust. Stennis Test Stand B-2 is being refitted for the SLS "green run" – the test firing of the first Core Stage with four RS-25 engines beginning in 2018, which will be NASA's largest liquid engine ground firing since stage tests of the Saturn V in the 1960s.

The majority of the thrust for the first two minutes of flight will come from a pair of solid rocket boosters, also of Space Shuttle Program heritage. The SLS is upgrading the boosters from the four-segment version flown on the shuttle



*Figure 2 Test article of liquid hydrogen tank of the SLS core stage*



*Figure 3 July 2017 test of an RS-25 engine and engine controller unit flight hardware*

t o a more-powerful five-segment version. Each booster measures 54 m long and 3.7 m in diameter and is capable of generating up to 3.6 million pounds of thrust, the most powerful flight boosters in the world. Although largely similar to the SRBs used on the space shuttle, this upgraded five-segment SRB includes improvements such as a larger nozzle throat and an environmentally-benign insulation and liner material (asbestos-free). In June 2016, the SLS configuration of the booster successfully underwent the second of two Qualification Motor tests, and booster hardware is currently being prepared for first flight. Propellant has been cast for ten booster motor segments for the first flight, and multiple segments are fully complete and in storage, awaiting transfer to Kennedy Space Center for stacking.



Figure 4 Technicians applying photogrammetric markings on completed segments for the five-segment solid rocket booster motors for the first integrated mission of SLS.

### III. Spacecraft/Payload Element Development

The SLS Spacecraft/Payload Integration and Evolution (SPIE) element office serves a key role in the successful execution of the SLS mission, both for the initial launch capability represented by the 70 t Exploration Mission 1 (EM-1) configuration as well as formulation and evolvability of the capability in subsequent vehicle 105 t (Block 1B) and 130 t (Block 2) configurations.

In support of the EM-1 mission, three major hardware components are managed by the SPIE element with responsibility for design, development, test and evaluation (DDT&E). As represented in Figure 5, these components include the Orion Stage Adapter (OSA), Interim Cryogenic Propulsion Stage (ICPS), and the Launch Vehicle Stage Adapter (LVSA). The two adapters enable attachment of the launch vehicle propulsive elements (core stage with engines, solid rocket boosters) to the payload for the EM-1 mission, the Orion crew capsule, while the ICPS provides the in-space propulsion necessary to place the Orion spacecraft on a trans-lunar injection orbit trajectory. While the Orion spacecraft represents the primary objective of the EM-1 mission, an additional benefit is provided by the OSA in regards to its ability to host thirteen 6U CubeSats for deployment following successful separation of Orion. Comprising a broad spectrum of science and technology destinations/objectives as well as partners (academia, international, corporate, and private), this ability to manifest secondary payloads further extends the benefits offered by the SLS enterprise in terms of access to deep space science opportunities.

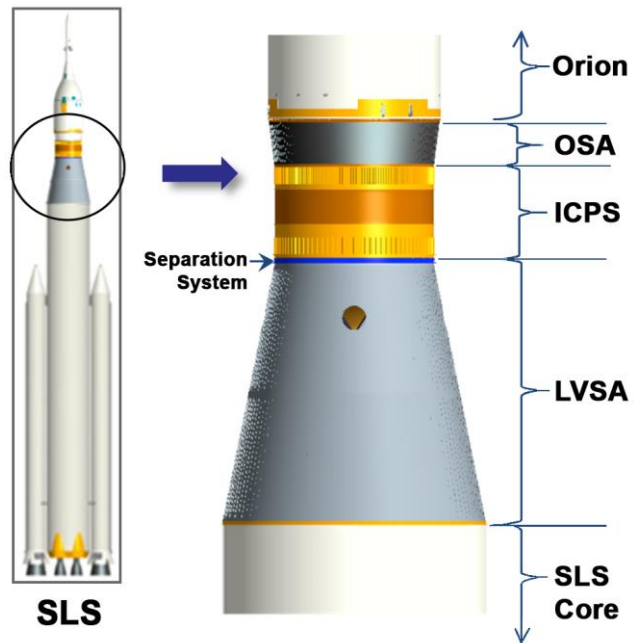


Figure 5 Spacecraft/Payload Elements

### A. Launch Vehicle Stage Adapter (LVSA)

Standing approximately 8.5 m (28 ft) in height, the LVSA structure is the largest non-propulsive component of the SLS launch vehicle. Tapering from approximately 8.4 m (~27.5 ft) to 5 m (~16.5 ft), both houses and enables attachment of the ICPS to the core stage while nesting the Aerojet Rocketdyne RL10B-2 engine which provides the in-space propulsion to put the Orion crew capsule on its trans-lunar injection orbit. The Prime contractor for the LVSA is Teledyne-Brown Engineering (TBE) while actual manufacture of the adapter utilizing Friction Stir Welding techniques is performed by NASA-MSFC under a Space Act Agreement.

A Structural Test Article (STA) required for incorporation into the Integrated Structural Test (IST) was completed in early 2016 and successfully qualified to predicted SLS structural loads. The specifics of the IST are covered in more detail in Section D. Following this activity, work was initiated to begin manufacture of the EM-1 flight article using the same materials, processes, and procedures as the STA while incorporating minor design enhancements to further structural capability of the hardware and to provide Development Flight Instrumentation (DFI) attach locations. As shown in Figure 6, the flight article has completed weldment and final machining and is currently undergoing activities relating to secondary hardware installation and priming of the weld land locations to both protect the metallic structure and provide a suitable surface for external foam application necessary to thermally protect the adapter during ascent through the atmosphere.



Figure 6 EM-1 LVSA undergoing final priming prior to foam application.

The application of external foam was not performed for the STA article as the foam served no role in the structural capability of the adapter. Application will be accomplished by technicians in a manual application process in a facility at MSFC and leverages from Space Shuttle experience in terms of material and technique. Practice simulation panels have been completed as well in support of the actual foam application currently scheduled for September 2017.

Finally, prior to transportation to KSC in Spring 2018, a separation system will be installed to allow separation and extraction of the ICPS hardware enclosed by the LVSA (LO<sub>2</sub> tank, RL10B engine). The Frangible Joint Assembly (FJA) is an “off-the-shelf” system procured from ULA that currently flies on the Delta IV launch vehicles and was the system utilized for the Orion demonstration test, Exploration Flight Test-1 (EFT-1), successfully launched in December 2014, which used the same OSA and ICPS hardware as SLS.

Pending successful completion of these and final close-out/acceptance activities, the hardware will be shipped to the launch site via barge down the Tennessee river to the Mississippi river, Gulf of Mexico, and around to KSC. Efforts are in-work to utilize the Pegasus barge, modified to deliver core stage tanks, engine section, and other components to KSC resulting in significant cost savings for that activity.

### B. Orion Stage Adapter (OSA)

Located between the ICPS and the Orion Service Module, the OSA serves dual roles for the SLS system, providing both a structural interface and hosting location for placement of the 6U CubeSat secondary payloads. Approximate dimensions of the lightweight aluminum cone are 5.1 m (~17 ft) and 5m (~16.5 ft) for the forward and aft circumferences respectively while standing approximately 1.5 m tall.

Designed for EFT-1 in December 2014 due to the common geometry provided by the geometric similarity of the ICPS to the



Figure 7 Diagram of the Orion Stage Adapter

Delta Cryogenic Second Stage (DCSS) used on the United Launch Alliance Delta IV launch vehicle, the design remains unchanged for SLS. However, owing to the increased loads imparted by the SLS mission, the OSA required upgrading in the qualification rating which was successfully accomplished as an integral component of the IST completed in May 2017.

Major welding of the Orion Stage Adapter EM-1 flight unit has been completed at Marshall Space Flight Center. Upon completion of brackets and wiring for secondary payload deployers, the diaphragm will be installed ahead of transfer to Kennedy Space Center, where final preparations will be made and secondary payloads will be integrated. (Figure 7)

### C. Interim Cryogenic Second Stage (ICPS)

The final primary hardware element managed by the SPIE element office is the ICPS, manufactured by ULA under contract to Boeing and then delivered to the government. It should be noted that the ICPS is a slightly modified version of the DCSS in use by the Delta IV launch vehicle including the FJA separation system. As a result, the FJA hardware installed on the LVSA prior to shipment to KSC was also employed and successfully demonstrated during the EFT-1 launch thus allowing an efficient use of resources and confidence in mission success. To date, all major components of the ICPS have been manufactured and assembled for the EM-1 flight article, functionally tested, transported, and prepared for storage at KSC prior to stacking into



Figure 8 The EM-1 Interim Cryogenic Propulsion Stage, prior to delivery to Kennedy Space Center

the LVSA in preparation for the EM-1 mission (Figure X). Previously, as with the other SPIE hardware elements, the STA article was successfully integrated and the primary structural load path tested to qualify the hardware for use on EM-1. One key difference between the flight and test articles was the incorporation of a mass simulator to represent the RL10B engine and nozzle boundary condition effects on the primary load path hardware. Other secondary structures such as cabling, wiring, and avionics components were not represented on the test unit as well.

Remaining work required prior to its use on EM-1 includes manufacturing completion and checkout of the flight avionics components in addition to final coding and baseline of the flight software code specific to the intended launch window.

### D. Integrated Structural Test (IST)

Each primary hardware element (LVSA, ICPS, OSA) was required to structurally test their hardware to certify/qualify the primary load paths to required SLS loads and environments. In order to most accurately determine hardware capability and anchor associated analytical models for future needs (discrepancies, Design Certification Review (DCR) certification, etc.), the three hardware components were integrated along with core stage and Orion simulators to represent interface geometry and stiffness versus testing each component individually and recombining analytically. Moreover, substantial cost savings were realized as a result of the integrated test which was planned, assembled, and executed by the Test Group at MSFC with each prime contractor providing a team of cognizant engineers to work with the test team to resolve any pre-test issues encountered as well as real-time test support and analysis.

The purposes of this testing were to: (1) verify the Integrated Spacecraft/Payload Elements (ISPE) can withstand SLS ultimate loads without rupture or collapse, (2) verify ICPS LH2 tank to ultimate cyclic pressure loads, (3) obtain dynamic and static data for validation of structural finite element models, and (4) obtain acoustic characterization data about the LVSA and OSA/Orion volumes.

The actual testing consisted of a series of dynamic characterization tests performed during and at the completion of test stack-up followed by a series of static load tests to provide stiffness data and exercise the STA of the ISPE up to qualification (ultimate) load levels. Upon completion of the static load testing, acoustic impulse tests were

conducted in the LVSA and OSA volumes to gather data for model development/improvement. The various ISPE test conditions were used to qualify multiple STA hardware, including the LVSA provided by TBE, the Separation System provided by Boeing/ULA to TBE as part of the LVSA STA, the ICPS STA, and the OSA provided by NASA. Simulators used to achieve the correct hardware interfaces for the ISPE test stack, such as the Orion simulator, the Core Stage simulator, and the LOX Adapter Ring simulator were manufactured and provided by NASA as well. (Figure 9)

Stacking of the test articles into the stand commenced in mid-August, with a test start in February 2017 and completion in May 2017 of 52 tests addressing unpressurized (17 of the 52) as well as cryogenic pressurized tests (the remaining 35) using liquid nitrogen to simulate the LH2 and LOX propellant conditions.

Subsequent to the successful completion of the test, a request was made by the Orion Program to provide the OSA article to support structural and acoustic testing planned for that hardware development/qualification effort. Once the IST had been completed, test case results reviewed and determination made that no retest were required, approval was granted to begin disassembly of the test configuration with priority placed on removing the OSA in a timely manner to meet the schedule needs of the Orion testing. Once removed, the OSA was prepared for shipping while transportation logistics were coordinated with the NASA Super Guppy cargo aircraft for delivery to the Lockheed-Martin facility in Littleton, Colorado. This activity was accomplished with loading and delivery of the OSA performed July 11, 2017, as shown in Figure 10 at Redstone Airfield. In total, the OSA STA will have effectively served three tests for the SLS/Orion Programs comprised of the STA for EFT-1, the IST for SLS noted here and the upcoming Orion tests representing a substantial savings to each program.

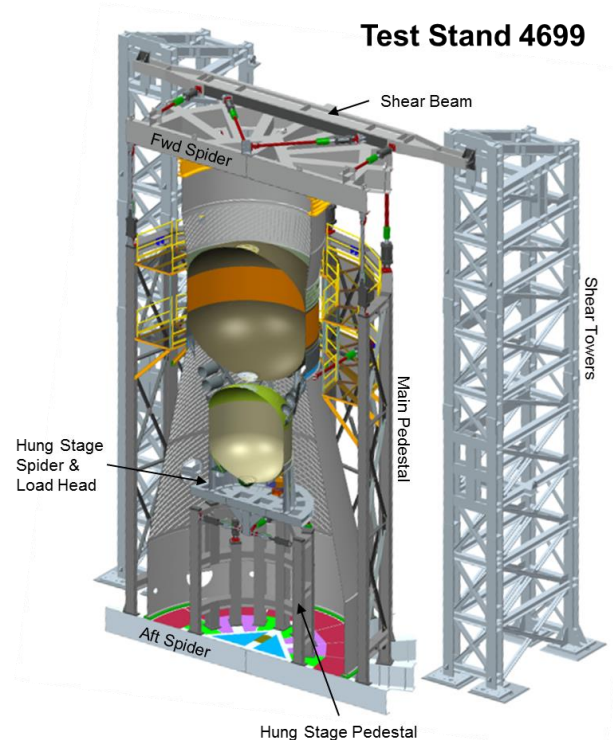


Figure 10 Arrangement of test articles for the IST

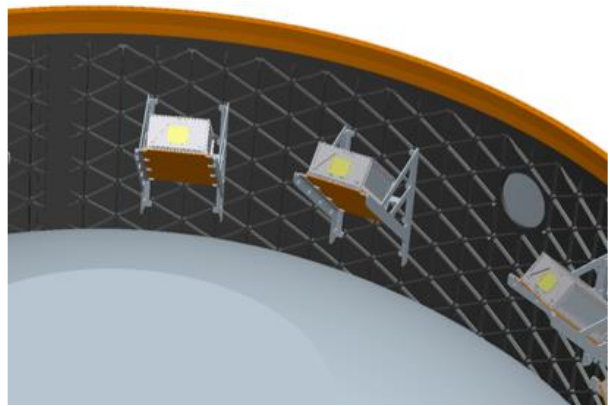


Figure 9 Loading of the OSA test article for delivery to Colorado

#### IV. Secondary Payloads

While the most obvious mission profiles to benefit from SLS are those with requirements beyond the performance of current launch vehicles, SLS will also offer unique opportunities for smaller experiments in the form of secondary payload berths. Thirteen secondary payload locations will be available in the Orion-to-Stage Adapter in the initial SLS configuration, allowing payload deployment following Orion separation. The deployment berths are sized for “6U” CubeSats (of 14 kg maximum mass), which will be deployed into cislunar space following Orion’s separate from the SLS Interim Cryogenic Propulsion Stage. (Figure 11)

CubeSat payloads on EM-1 will include both NASA research experiments and spacecraft developed by industry, international, and academia partners. The Human Exploration and Operations Mission Directorate (HEOMD) Advanced Exploration Systems (AES) Division was allocated five payload opportunities on the EM-1 mission. Near Earth Asteroid (NEA) Scout is a 6U CubeSat designed to rendezvous and characterize a candidate NEA, using a solar sail for propulsion. Lunar Flashlight will use a green propellant system and search for potential ice deposits in the moon's permanently shadowed craters. BioSentinel will carry a yeast radiation biosensor, planned to measure the effects of space radiation on Deoxyribonucleic Acid (DNA). Two additional payloads were selected for the EM-1 mission by AES from the Next Space Technologies for Exploration Partnerships (NextSTEP) Broad Agency Announcement (BAA). Lunar Icecube, a collaboration with Morehead State University, will prospect for water in ice, liquid, and vapor forms as well as other lunar volatiles from a low-perigee, highly inclined lunar orbit using a compact infrared spectrometer. Skyfire, a partnership with Lockheed Martin, is a technology-demonstration mission that will perform a lunar flyby, collecting spectroscopy and thermography data to address questions related to surface characterization, remote sensing, and site selection.



*Figure 11 Artist rendition of CubeSat deployers within the Orion Stage Adapter*

NASA's Space Technology Mission Directorate (STMD) was allocated three payload opportunities on the EM-1 mission. NASA's STMD is innovating, developing, testing, and flying hardware for use in NASA's future missions through the Centennial Challenges Program, NASA's flagship program for technology prize competitions. The three teams selected for flight through the competition are Cislunar Explorers, Cornell University, Ithaca, New York; CU<sup>3</sup>, University of Colorado in Boulder; and Team Miles, Fluid & Reason, LLC, Tampa, Florida.

The NASA Science Mission Directorate (SMD) was allocated two payload opportunities on the EM-1 mission. The CubeSat Mission to Study Solar Particles (CuSP) payload will study the sources and acceleration mechanisms of solar and interplanetary particles in near-Earth orbit, support space weather research by determining proton radiation levels during Solar Energetic Particle (SEP) events and identifying suprathermal properties that could help predict geomagnetic storms. The LunaH-Map payload's objectives are to understand the quantity of H-bearing materials in lunar cold traps (~10 km), determine the concentration of H-bearing materials with 1 m depth, and constrain the vertical distribution of H-bearing materials.

The final three payload opportunities for the EM-1 mission were allocated for NASA's international space agency counterparts. The flight opportunities are intended to benefit the international space agency and NASA as well as further the collective space exploration goals. A joint process with NASA and the international partners was employed to review, evaluate, and recommend the payloads to fly on EM-1. ArgoMoon is sponsored by ESA/ASI and will fly along with the ICPS on its disposal trajectory, perform proximity operations with the ICPS post-disposal, take external imagery of engineering and historical significance, and perform an optical communications demonstration. The EQUilibriUm Lunar-Earth point 6U Spacecraft (EQUULEUS) sponsored by the Japanese Aerospace Exploration Agency (JAXA) will fly to a libration orbit around the Earth-Moon L2 point and demonstrate trajectory control techniques within the Sun-Earth-Moon region for the first time by a nano spacecraft. The OMOTENASHI mission sponsored by JAXA will land the smallest lunar lander to date on the lunar surface to demonstrate the feasibility of the hardware for distributed cooperative exploration system and to observe the radiation and soil environments of the lunar surface by active radiation measurements and soil shear measurements.

Concepts are still being reviewed for secondary payload accommodations on the evolved configurations of SLS. Since the Orion Stage Adapter where the secondary payloads are berthed on EM-1 will not be part of future configurations, the payloads will be housed in either the larger Universal Stage Adapter or a payload fairing, providing greater potential volume. Plans currently call for the Block 1B configuration of the vehicle to offer accommodations for 6U, 12U and 27U CubeSats, mounted on a payload adapter in a modular format that would allow for the different sizes and potentially more payloads than the Block 1 configuration. Payloads could also be deployed either into



cislunar space with Orion or to another deep-space destination, depending on the requirements of a primary science payload.

## V. Future Evolution Of SLS

For the second launch of SLS, Exploration Mission 2, the vehicle will be augmented with a low-thrust dual-use Exploration Upper Stage (EUS), providing both ascent and in-space propulsion capabilities. This stage will upgrade SLS to a performance of 105 t to LEO, and create a configuration that will serve as a workhorse for the development of lunar-vicinity exploration systems in the early and mid-2020s. From there, additional upgrades, including upgraded boosters, will ultimately evolve SLS in the late 2020s to a configuration capable of delivering more than 130 t to LEO, the capability identified as necessary for human missions to Mars. (Figure 12)

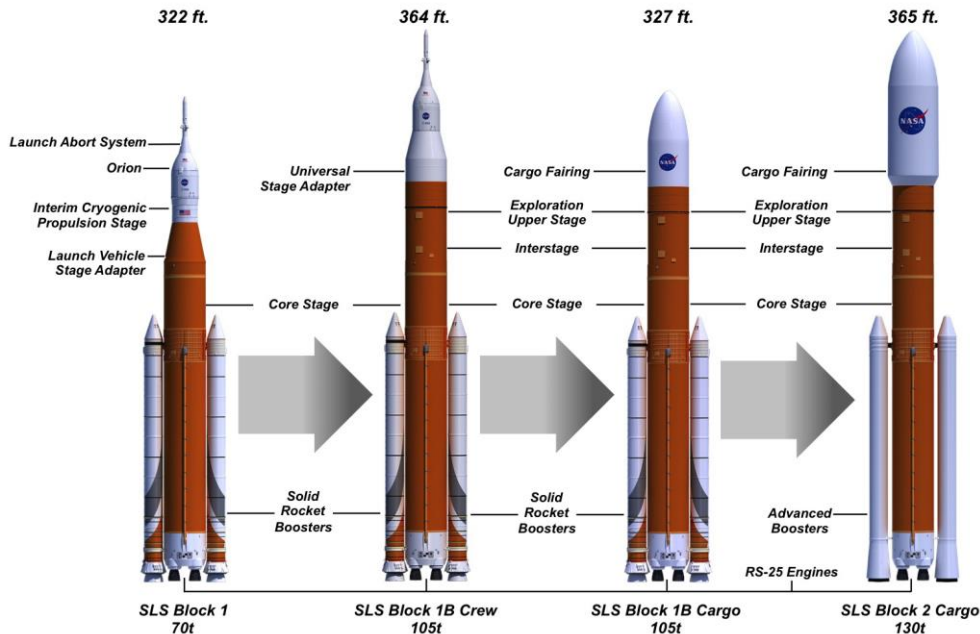


Figure 12 SLS evolutionary path

The Space Launch System offers additional unique payload capabilities, including launch of a co-manifested payload along with the Orion spacecraft or delivery of secondary payloads to lunar or planetary trajectories. A co-manifested payload, with a volume of up to 400 cubic meters, could be placed within the Universal Stage Adapter connecting the Exploration Upper Stage to the Orion stack. The Block 1B crew configuration will ultimately be capable of carrying a payload mass upwards of 9 t to the lunar vicinity with Orion. The initial crewed flights will be used to transport modules that will be assembled in order to create the Deep Space Gateway vehicle that will be used as a staging platform for exploration in the solar system.

Research has also been conducted into options for larger 8.4- and 10-m fairings, with which SLS will potentially offer payload volumes of 1,200 and 1,800 cubic meters, respectively. In a cargo configuration, the Block 1B vehicle will be capable of delivering to orbit 40 t of payload to translunar injection.

The payload accommodations of the SLS Block 1B vehicle are being designed to provide flexibility to meet the wide range of needs for future missions. The payload interfaces will build upon the already established and familiar interfaces offered by existing launch vehicles. This will allow the payload community to easily adapt to the payload interfaces offered by SLS Block 1B while taking advantage of the increased capabilities. The SLS Block 1B vehicle payload area is 1.7 times wider than existing vehicles. As such, new payload interfaces will be ultimately offered that will enable big payloads currently unavailable with the existing launch vehicles.

Work is already underway on future configurations of the vehicle. Boeing will be the contractor for the EUS, which has completed its preliminary design review, with Aerojet Rocketdyne providing the RL10C-3 engines.

NASA's Glenn Research Center will manage the USA, and a contract has been awarded to Dynetics, of Huntsville, AL, for its production. Early risk reduction and engineering demonstration work has also been conducted for concepts related to future booster upgrades. Development work is ongoing at MSFC on the payload adapter for the Block 1B vehicle. Aerojet Rocketdyne has been awarded a contract to restart production of the RS-25 engine, implementing changes to optimize the engine for expendability and increasing performance and affordability.

## VI. SLS Capabilities and Utilization

The capabilities of the Space Launch System provide not only the capability to conduct human exploration of deep space, but also game-changing benefits for a range of promising space science missions. Three major interrelated areas have been identified in which SLS offers unique benefits that make possible new missions or mission profiles – unrivaled mass-lift capability, payload volume capacity, and departure energy.

Taking advantage of these benefits allows spacecraft designers and mission planners to change fundamental assumptions about spacecraft and mission design, as these areas offer the potential for numerous benefits: less-complex payload design and miniaturization needed to fit in fairings, leading to increased design simplicity; decreased launches for in-space assembly, resulting in reduced risk; less folding/deployment complexity, leading to increased mission reliability and confidence; high-energy orbit and shorter trip times, leading too less expensive mission operations and reduced exposure to the space environment; and increased lift capacity and payload margin, resulting in less risk.

The high mass-lift capability of SLS is vital to NASA's plans for human deep-space exploration, allowing the launch of the Orion crew vehicle and other exploration systems to a staging location in the lunar vicinity, or directly into deep space. Current planning calls for the assembly of a facility in the lunar vicinity that would allow astronauts to gain experience living and working in deep space and serve as a departure platform providing access to the lunar surface or the solar system. (Figure 13) Assembly of that facility would begin with the second launch of SLS, which would see the first crewed Orion vehicle fly around the moon on a free-return trajectory while also deploying a power and propulsion element that would remain in lunar orbit. On the next mission, Orion would be accompanied by a comanifested habitat module; the two would dock with each other and then proceed toward a rendezvous with the power and propulsion element, docking with it to create the foundation of the deep space facility and enabling longer duration missions in cislunar space, followed by additional assembly missions to complete the facility. In the late 2020s, the focus would then shift to the assembly of a deep space transport vehicle, which would be able to depart from the lunar vicinity facility and embark into the solar system for exploration missions including crewed journeys to Mars.

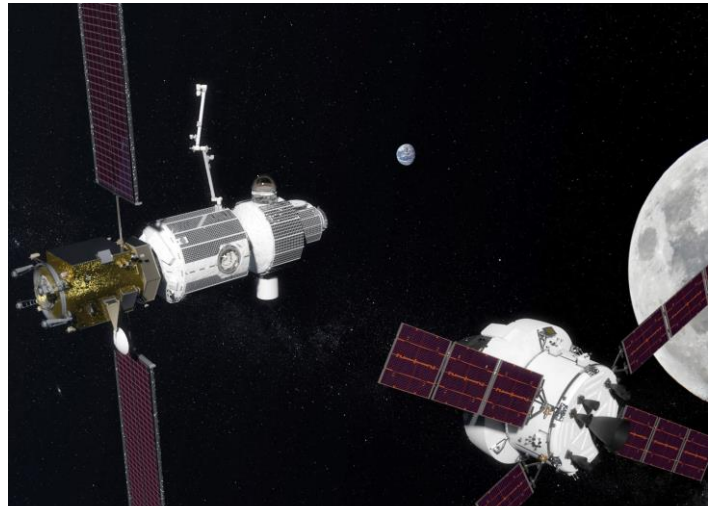


Figure 13 Artist's rendition of Orion docking with a habitate in lunar orbit

SLS' characteristic energy (C3) offers reduced mission transit time, thereby reducing power requirements as well as the amount of time that scientific instruments are exposed to space. While commercial launchers will continue to serve as the workhorse for many of NASA's science missions, those spacecraft often have to make multiple gravity-assist maneuvers around inner planets before reaching the velocity needed to reach the outer planets. These maneuvers increase mission times by years and increase risk to onboard instruments because of the extended time in the space environment and the range of conditions to which they require exposure.

SLS utilization is currently being considered for NASA's proposed Europa Clipper mission, which would provide an unprecedented look at the icy Jovian moon, believed to hold a subsurface ocean with more than twice the quantity of water on Earth, and investigate its potential habitability. While launch on Delta IV Heavy EELV-baseline vehicle could require a Venus-Earth-Earth gravitational assist trajectory requiring 7 to 8 years, launch on SLS would enable

a direct transit to the Jovian system in less than three years, providing far earlier science return and reduced operational costs, among other benefits. With consideration currently ongoing of a follow-up Europa lander mission, the earlier science return could allow use of data from the flyby mission to inform the lander mission, without a substantial delay to the latter. The lander mission, in turn, would use SLS' characteristic mission in a different way – enabling not a more rapid transit but a substantially higher launch mass, pushing more than 15 t toward Jupiter.

Europa mission analysis also serves as a test case for how SLS could benefit outer-planet exploration. One of the major benefits to the science community from the Mars Program has been the ability to learn from one mission and use that knowledge when formulating a near-term future investigation. The paradigm for outer-planet exploration has necessitated very long cruise times, which, among other things, make it impossible to have a rapid turnaround in penetrating the mysteries that the “ocean world” icy moons of the outer planets possess. The availability of the SLS breaks this model, and allows for significant transit-time reduction.

In the area of payload volume capacity, human exploration planning is seeing benefits of the large fairings the vehicle could carry. Current plans call for a dedicated SLS cargo flight in the late 2020s to begin assembly of the Deep Space Transport vehicle, allowing for the launch of a large-diameter habitat module for the system. In addition to human exploration planning, a large-aperture space telescope offers a good case study of utilization of SLS' volume.. Concept evaluation has demonstrated potential benefits of a large 8.4- or 10-m SLS payload fairing for the science community. Such a fairing would enable the launch of a large aperture (potentially 16-m class) telescope that would be able to make ultra-high-contrast spectroscopic observations of exoplanets. Such a capability would address a need identified in the 2013 NASA astrophysics roadmap, “Enduring Quests, Daring Visions.” Concept evaluations of such a project have also identified opportunities for further collaborations between science and human exploration systems in the form of assembly and servicing of an observatory in deep space.

In April 2017, the Space Launch System (SLS) Mission Planner's Guide (MPG) was released by NASA's Exploration Systems Development (ESD) division. Its purpose is to provide future payload developers/users with sufficient insight to support preliminary SLS mission planning. It organizes and details SLS interfaces/accommodations in a manner similar to that of current Expendable Launch Vehicle (ELV) user guides to support early payload feasibility assessment. It is being used to respond to queries by the potential SLS user community concerning SLS capabilities and their general availability to meet the different phases of the Human Exploration and Operations (HEO) Directorates Exploration Mission planning. It will be updated as needed as payload specific performance to destination, interfaces, and operational constraints mature.

SLS users requiring additional mission planning information or more detailed technical interchange concerning specific SLS accommodations should contact the SLS Spacecraft/Payload Integration and Evolution (SPIE) office. SPIE serves as the payload point of contact to SLS and can be reached by email at [NASA-slspayloads@mail.nasa.gov](mailto:NASA-slspayloads@mail.nasa.gov).

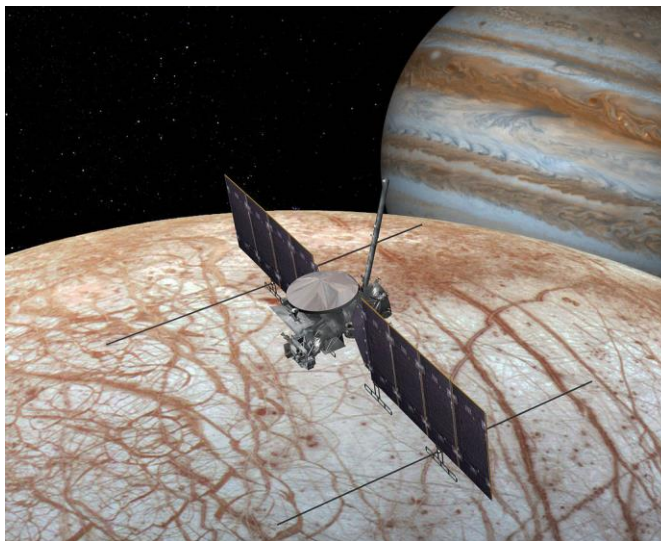


Figure 14 Aristo's rendition of Clipper spacecraft making a pass over Europa

## VII. Conclusion

Substantial progress has been made on the development and manufacture of the initial 70 t Block 1 configuration of SLS and its first launch will be a significant step in demonstrating the super-heavy-lift capability needed for human exploration of deep space. With the evolution of SLS beginning with its second launch, this vehicle will return humans to deep space for the first time in decades, beginning a series of exploration missions that will lead to Mars and other destinations that will reveal an unprecedented wealth of knowledge about our solar system and universe.