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**NASA'S SPACE LAUNCH SYSTEM:
PROGRESS TOWARD THE PROVING GROUND**

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Abstract: With significant and substantial progress being accomplished toward readying the Space Launch System (SLS) rocket for its first test flight, work is already also underway on preparations for the second flight – using an upgraded version of the vehicle – and beyond. SLS is the most powerful human-rated launch vehicle the United States has ever undertaken, and together with the Orion spacecraft will support human exploration missions into the proving ground of cislunar space and ultimately to Mars. This paper will provide a description of the SLS vehicle, and an overview of the vehicle's capabilities and utilization potential.

Keywords: Space Launch System, SLS, Orion, Mars, Payloads

1. INTRODUCTION

Conceived and designed to enable exploration and discovery in deep space, NASA's Space Launch System represents a transformative capability for a wide range of potential missions. The exploration-class launch vehicle's primary purpose is to provide the foundational launch capability for human exploration of deep space, propelling humans beyond low Earth orbit for the first time in almost half a century, and then supporting previously-impossible missions farther into space than ever before, demonstrating new capabilities and ultimately enabling crewed landings on Mars. In providing the performance required for those tasks, SLS offers capabilities that are paradigm-shifting for spacecraft designers and mission planners, enabling architectures and mission profiles not currently possible.

SLS is designed to evolve to deliver greater performance and to be configurable to support different types of missions, providing an affordable and sustainable path forward that delivers new vehicle capabilities as human exploration mission requirements demand them. The initial configuration of SLS, known as Block 1, was designed to support initial demonstration, and is making progress toward launch in two years. This configuration, which can deliver greater than 70 metric tons to low Earth orbit, will launch NASA's Orion crew vehicle into lunar orbit. (Fig 1.)

For its second flight, SLS will evolve into a more-capable configuration, the Block 1B vehicle, which will increase the vehicle's payload-to-LEO capability to 105 metric tons. The third configuration, Block 2, will be able to deliver 130 metric tons to LEO. The Block 1B and Block 2 vehicles can be configured to carry either the Orion

crew vehicle with an additional, co-manifested payload, or to carry a large primary payload in a fairing as large as 10 meters in diameter.

NASA is developing SLS in parallel with two other exploration systems development efforts – the Orion crew vehicle program, managed at NASA’s Johnson Space Center in Houston, Texas, and the Ground Systems Development and Operations (GSDO) program, which is converting the facilities at NASA’s Kennedy Space Center (KSC) in Florida into a next-generation spaceport capable of supporting launches by multiple types of vehicles.

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.

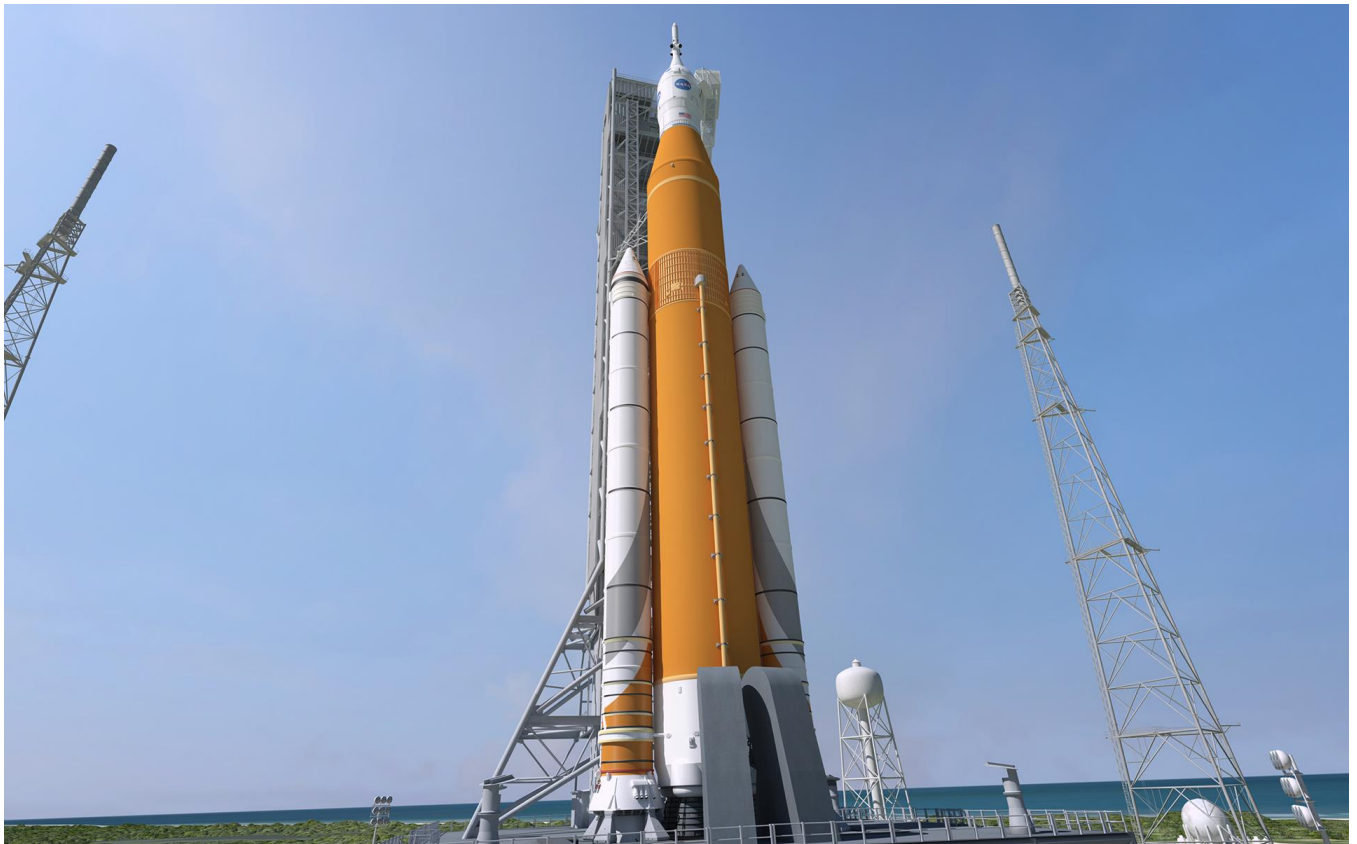


Fig. 1. Artist's rendition of Space Launch System

2. VEHICLE OVERVIEW AND STATUS

2.1. Background

The inception of NASA’s Space Launch System stems from requirements for a U.S. heavy-lift capability in the nation’s congressional NASA Authorization Act of 2010 (which have more recently been reiterated in the NASA Authorization Act of 2017). The architecture of the SLS initial Block 1 configuration reflects NASA’s desire to meet those mandates in a manner that is safe, affordable, and sustainable. After input was received from industry and numerous concepts were reviewed, the chosen design was found to enable the safest, most-capable transportation system in an expedient time frame within anticipated near-term and long-range budgets.

The SLS operational scheme takes advantage of extant NASA assets, including workforce, tooling, manufacturing processes, supply chains, transportation logistics, launch infrastructure, and liquid oxygen and hydrogen (LOX/LH₂) propellants and allows the initial configuration of the vehicle to be delivered with only one clean-sheet new development, the Core Stage. In October 2015, the SLS Program completed its Critical Design Review (CDR), the first time a NASA human-class launch vehicle has reached that milestone since the Shuttle Program almost 40 years ago and the first for an exploration-class vehicle since the Saturn V.

Today, substantial progress has been made toward the first integrated launch of the SLS rocket with the Orion spacecraft, Exploration Mission-1 (EM-1).

2.2. Core Stage

The SLS Core Stage, which stores the liquid oxygen and liquid hydrogen propellant for four liquid engines, represents almost two-thirds of the vehicle's 98-meter height, standing 64 m tall, and has a diameter of 8.4 m, sharing commonality with the space shuttle's external tank in order to enhance compatibility with equipment and facilities at KSC and elsewhere. At Michoud Assembly Facility (MAF), outside New Orleans, Louisiana, the world's largest space vehicle welding tool, the 52m-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.

Structural test and flight engine sections have completed welding. The test section is at MSFC for structural tests. Structural test and flight liquid hydrogen tanks and the flight forward skirt have also completed welding. Progress on the first example of the largest rocket stage in the world has been slowed by production issues and a tornado which struck MAF this spring. (Fig. 2)



Fig. 2. Technicians inside an SLS core stage hydrogen tank plug fusion weld holes.

2.3. RS-25 Engines

The Core Stage will be powered by four RS-25 engines, which previously served as the Space Shuttle Main Engine (SSME), taking advantage of 30 years of U.S. experience with liquid oxygen and liquid hydrogen, as well as an existing U.S. national infrastructure that includes specialized manufacturing and launching facilities. 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 in Mississippi, providing enough engines for the first four flights of SLS. The engines are managed under a contract with Aerojet Rocketdyne.

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 recent testing of the flight hardware of a new engine controller unit. 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 (as well as margin testing to 111 percent in anticipation of future performance increases). 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. The test will be the largest liquid-engine test since stage tests of the Saturn V in the 1960s.



Fig. 3. Drone footage of an RS-25 test on 22 February 2017.

2.4. Solid Rocket Boosters

The majority of the thrust for the first two minutes of flight will come from a pair of solid rocket boosters (SRB), also of Space Shuttle Program heritage. The SLS is upgrading the boosters from the four-segment version flown on the shuttle to 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. (Fig. 4.) The tests took place at the Promontory, Utah facility of Orbital ATK, the prime contractor for the boosters. Nine of ten booster motor segments have been cast with propellant at Orbital ATK facilities and two segments are complete and in storage, awaiting shipment to Kennedy Space Center.



Fig. 4. Qualification Motor-2 test of the SLS solid rocket booster.

2.5. In-Space Propulsion

In-space propulsion for the Block 1 vehicle will be provided by an Interim Cryogenic Propulsion Stage (ICPS). In order to expedite the initial launch of this new U.S. super-heavy-lift launch capability, the decision was made early in the vehicle's development to leverage the proven Delta Cryogenic Second Stage (DCSS) for SLS in-space propulsion for EM-1, delaying development of a larger upper stage until the vehicle's Core Stage, the largest clean-sheet development for the Block 1 vehicle, was more mature. To provide the necessary power to propel Orion on its EM-1 trajectory, the LH2 tank of the SLS ICPS will be stretched 46 centimeters longer than the standard DCSS. The ICPS is being produced by United Launch Alliance in Decatur, Alabama, under contract to Boeing. The flight unit of the ICPS has already been shipped to Cape Canaveral Air Force Station in Florida for final processing prior to delivery to adjacent Kennedy Space Center for stacking.

The Block 1 spacecraft/payload elements include not only the DCSS-derived ICPS but also two adapters, connecting that stage to the core stage and to the Orion spacecraft. The Launch Vehicle Stage Adapter (LVSA), which connects the Core Stage with the ICPS, is being produced by Teledyne Brown Engineering of Huntsville, Ala., and is in final welding on site at Marshall Space Flight Center. The Orion Stage Adapter (OSA), which connects the Orion spacecraft with the ICPS, is being produced by Marshall Space Flight Center. An OSA produced by the SLS Program flew successfully on the Exploration Flight Test-1 of Orion in December 2014; and the EM-1 flight unit has been welded at Marshall. A stack of test articles for all three elements recently underwent structural testing at Marshall Space Flight Center, qualifying them for flight. (Fig. 5.)



Fig. 5. A structural test article of the Interim Cryogenic Test Article is installed for testing.

3. EVOLUTION PLANS AND PROGRESS

While the Program's focus is very much on preparation for the first launch in two years, work is already well underway on development for future missions and evolved configurations of the vehicle.

Current plans are for the second flight of SLS with Orion to use the Block 1B configuration of the vehicle, capable of delivering 105 metric tons of payload to low Earth orbit. The Block 1B vehicle will replace the single-engine ICPS with a more-powerful, four-engine, dual-use Exploration Upper Stage (EUS), which will provide both ascent and in-space propulsion. The contract for the EUS has been awarded to Boeing and an agreement has been reached with Aerojet Rocketdyne to provide the stage's RL10-C3 engines. A Preliminary Design Review for the stage concluded in early 2017, and initial hardware production has begun.

The change from the 5-meter ICPS to the 8.4-meter EUS means that the LVSA and OSA will be supplanted by a Universal Stage Adapter (USA), which will provide room for a comanifested payload to fly on an SLS along with Orion. The Universal Stage Adapter (USA) will be managed by NASA's Glenn Research Center in Cleveland, Ohio. Plans currently call for the award of a contract for the USA in summer 2017. Within the USA will be a payload adapter, a demonstrator version of which is currently being built at Marshall.

Other work for Exploration Mission-2 (EM-2) is also currently taking place. Welding for the second core stage has been taking place at Michoud Assembly Facility, and in March 2016, a test-firing of an EM-2 RS-25 engine was performed at Stennis Space Center. Wind tunnel testing is maturing understanding of crew and cargo versions of the Block 1B vehicle.

Work is also currently underway toward making upgrades and affordability enhancements to the RS-25 engines and restarting the production line for the fifth flight of SLS and beyond, after the initial inventory of shuttle RS-25s is expended.

The SLS Program has also conducted initial engineering demonstration and risk reduction work on advanced booster technologies and concepts, preparing for a later upgrade from the shuttle-derived boosters to new boosters that will deliver greater performance. With that upgrade, SLS will reach the fully evolved Block 2 configuration. (Fig. 6.)

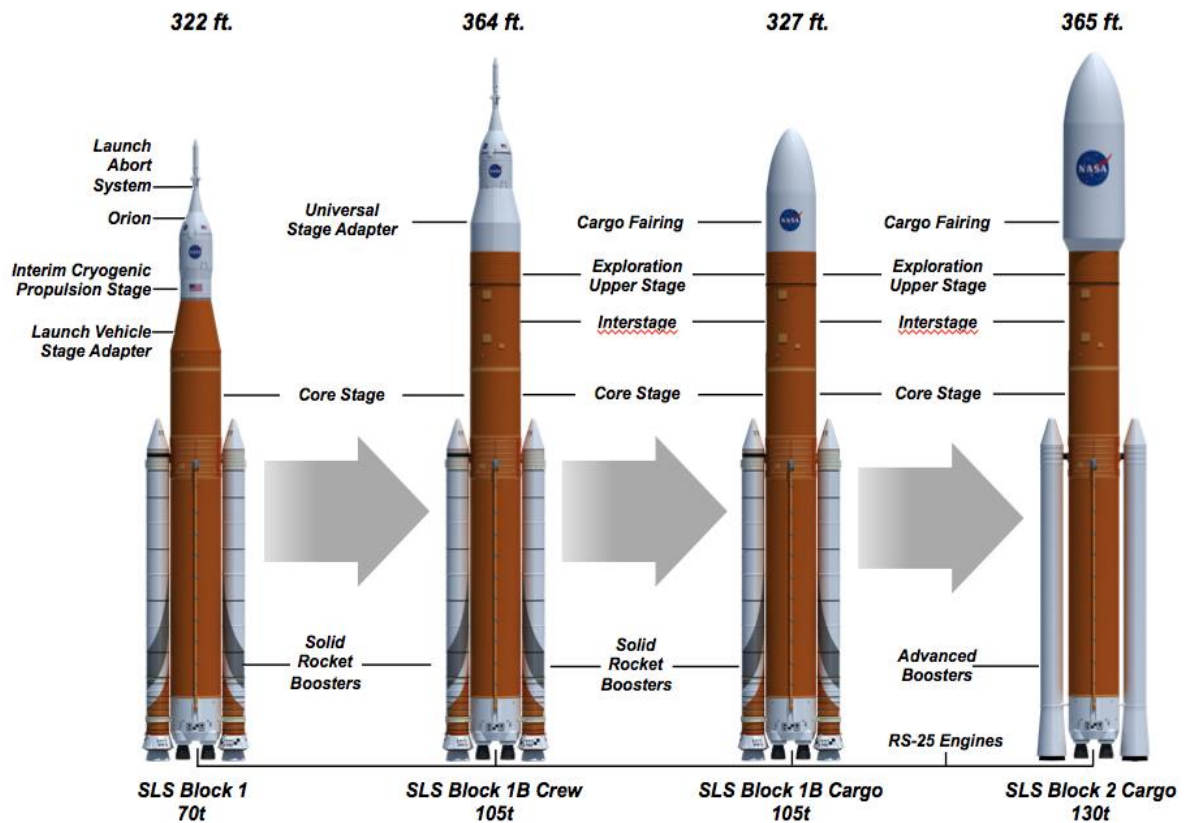


Fig. 6. Evolutionary path for SLS development.

4. CAPABILITIES

Space Launch System offers substantial benefits in three primary areas, which offer game-changing opportunities for spacecraft designers and mission planners – volume, mass and departure energy.

Space Launch System offers greater volume than any other launch vehicle. Beginning with EM-2, the Universal Stage Adapter will allow a payload to fly with Orion with as much accommodation volume as the current industry-high 5-meter fairing. The Block 1B configuration will also enable the use of an 8.4-m fairing for primary payloads, and the Block 2 vehicle will be able to carry 10m fairings with a volume of up to 1,800 cubic meters, several times greater than any currently available fairing. (Fig. 7.)

For missions to, or staging in, the Earth-moon vicinity, Space Launch System offers unrivaled mass lift capability. The Block 1B configuration of the vehicle, which will be the version available for payloads during most of the 2020s, will be able to lift more than 105 metric tons to low Earth orbit and will be able to deliver 41 metric tons to translunar injection (TLI). The crew configuration of the Block 1B vehicle can carry up to an additional 10 tons of payload along with the Orion spacecraft. The Block 2 configuration will increase that performance to more than 130 metric tons to LEO, and at least 45 t to TLI.

For missions beyond the Earth and moon, SLS offers substantially greater characteristic energy (C3) than contemporary evolved expendable launch vehicles (EELVs). For the missions to the outer planets, for example, this can enable a larger science package, reduced transit times, or both.

These primary benefits make possible a variety of secondary benefits. For example, greater payload volume can decrease the need for “origami” deployments, thus decreasing spacecraft complexity and risk. Reducing transit time by enabling a direct trajectory without gravitational assists reduces mission risk and operational cost, and can eliminate the need to design for inner-solar system conditions.



Fig. 7. Fairing options for evolved configurations of SLS.

The mass and volume capabilities of SLS also provide unique opportunities for use of smallsats in deep space. The first launch of SLS, using the Block 1 configuration, will deploy 13 6U CubeSats into deep space. Future configurations of the vehicle will provide opportunities for increasing the size and number of secondary payloads SLS carries. Current plans call for a flexible smallsat accommodation system that could carry up to seven 27U CubeSats or up to 21 6U CubeSats. Depending on the requirements of primary or comanifested payloads, it might also be possible to deploy larger “ring payloads,” similar to those currently flown on an EELV Secondary Payload Adapter (ESPA), to deep space.

5. HUMAN SPACEFLIGHT UTILIZATION

The primary purpose of SLS is to enable a new era of human space exploration unlike any before it, with missions that would previously have been impossible. As NASA continues to mature plans for the exploration of deep space, working toward a horizon goal of Mars, SLS and Orion are foundational assets in that journey. The first human beings to launch on Space Launch System will go farther into space than anyone currently has, and increasingly ambitious undertakings will follow.

Currently planning calls for a multi-phase approach to the exploration of deep space, development and demonstrating new capabilities during the 2020s in preparation for missions to Mars in the 2030s. NASA is currently in a “Phase 0” of the process, using the International Space Station for precursor research and demonstration prior to beginning crewed missions into deep space.

The first phase of exploration near the moon will use current technologies and allow us to gain experience with extended operations farther from Earth than previously completed. These missions enable NASA to develop new techniques and apply innovative approaches to solving problems in preparation for longer-duration missions far from Earth. In addition to demonstrating the safe operation of the integrated SLS rocket and Orion spacecraft, the agency is also looking to build a crew tended spaceport in lunar orbit within the first few missions that would serve as a gateway to deep space and the lunar surface.

This Deep Space Gateway would have a power bus, a small habitat to extend crew time, docking capability, an airlock, and serviced by logistics modules to enable research. The propulsion system on the gateway mainly uses

high power electric propulsion for station keeping and the ability to transfer among a family of orbits in the lunar vicinity. The three primary elements of the gateway, the power and propulsion bus and habitat module, and a small logistics module(s), would take advantage of the cargo capacity of SLS and crewed deep space capability of Orion. An airlock can further augment the capabilities of the gateway and can fly on a subsequent exploration mission, Building the deep space gateway will allow engineers to develop new skills and test new technologies that have evolved since the assembly of the International Space Station. The gateway will be developed, serviced, and utilized in collaboration with commercial and international partners. (Fig. 8.)

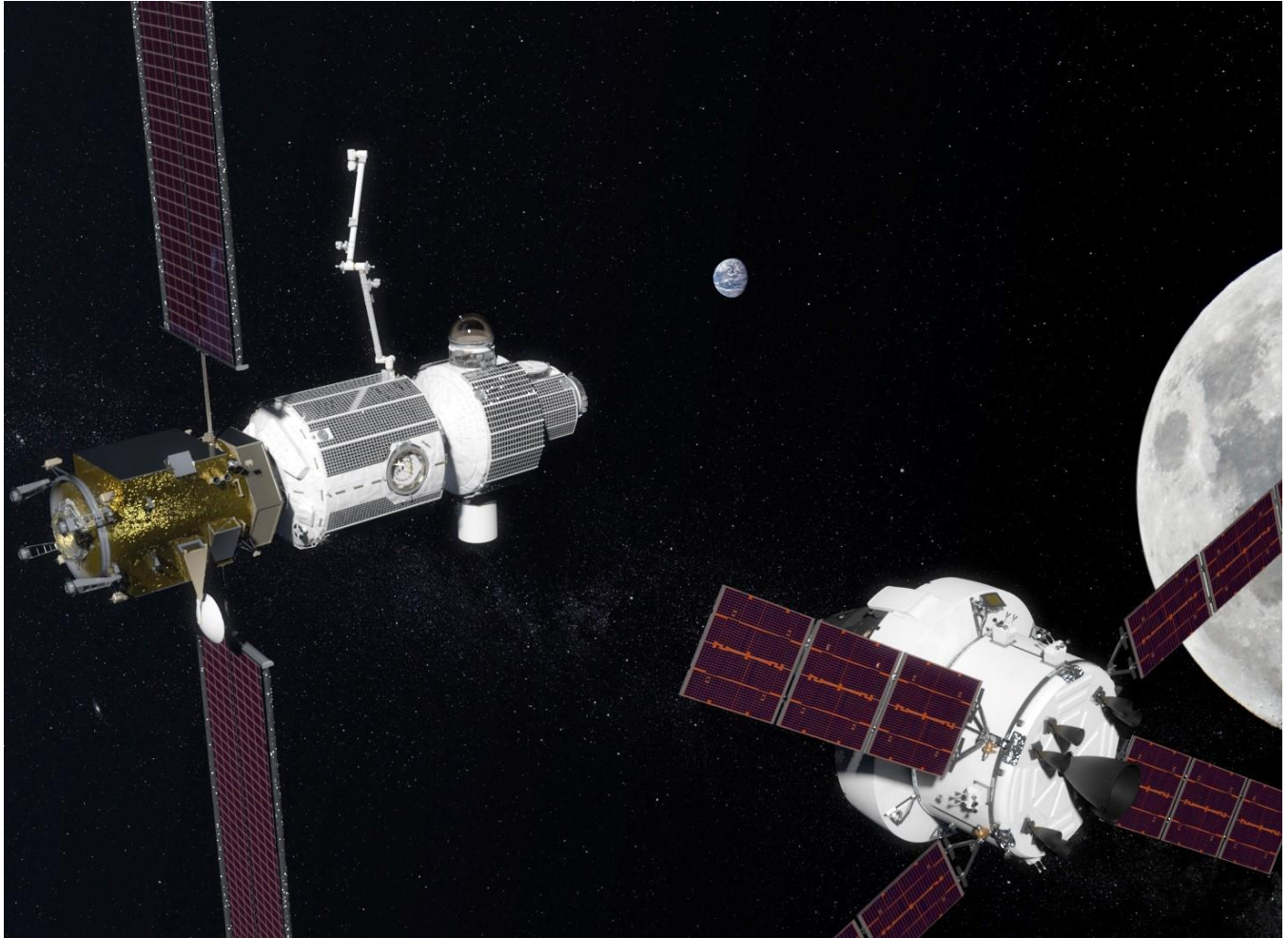


Fig. 8. Artist's rendition of the Deep Space Gateway.

The second phase of missions will confirm that the agency's capabilities built for humans can perform long-duration missions beyond the moon. For those destinations farther into the solar system, including Mars, NASA envisions a Deep Space Transport spacecraft. This spacecraft would be a reusable vehicle that uses electric and chemical propulsion and would be specifically designed for crewed missions to destinations such as Mars. The transport would take crew out to their destination, return them back to the Gateway, where it can be serviced and sent out again. The transport would take full advantage of the large volumes and mass that can be launched by the SLS rocket, as well as advanced exploration technologies being developed now and demonstrated on the ground and aboard the International Space Station.

This second phase will culminate at the end of the 2020s with a one-year crewed mission aboard the transport in the lunar vicinity to validate the readiness of the system to travel beyond the Earth-moon system to Mars and other destinations, and build confidence that long-duration, distant human missions can be safely conducted with

independence from Earth. Through the efforts to build this deep space infrastructure, this phase will enable explorers to identify and pioneer innovative solutions to technical and human challenges discovered or engineered in deep space.

NASA's vision for deep-space exploration is being matured as a capabilities-based framework focused on identifying and developing the systems needed for gaining ever-increasing operational experience in space, growing in duration from a few weeks to years in length, and moving from close proximity to Earth to Mars. The approach is consistent with the Global Exploration Roadmap, a Mars exploration partnership strategy developed by the International Space Exploration Coordination Group (ISECG), consisting of 14 space agencies, including NASA, from nations around the world. The Roadmap, which identifies Mars as "the driving goal of human exploration," is a living document updated via an ongoing series of meetings between partner agencies and interested stakeholders.

6. SCIENCE UTILIZATION

While Space Launch System was designed around the goal of enabling human exploration of the solar system, the capabilities of the vehicle to fulfill that charter will also provide game-changing benefits for a range of promising space science missions. The SLS team has participated in technical interchange meetings with members of the science community to further a dialogue on the vehicle's benefits for future missions and to better define how it could enable them. Taking advantage of the C3, mass and volume capacity that SLS offers will allow spacecraft designers and mission planners to change fundamental assumptions about spacecraft and mission design.

Two proposed missions to Europa serve as excellent case studies for the range of benefits the vehicle offers. SLS utilization is being considered for NASA's 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.

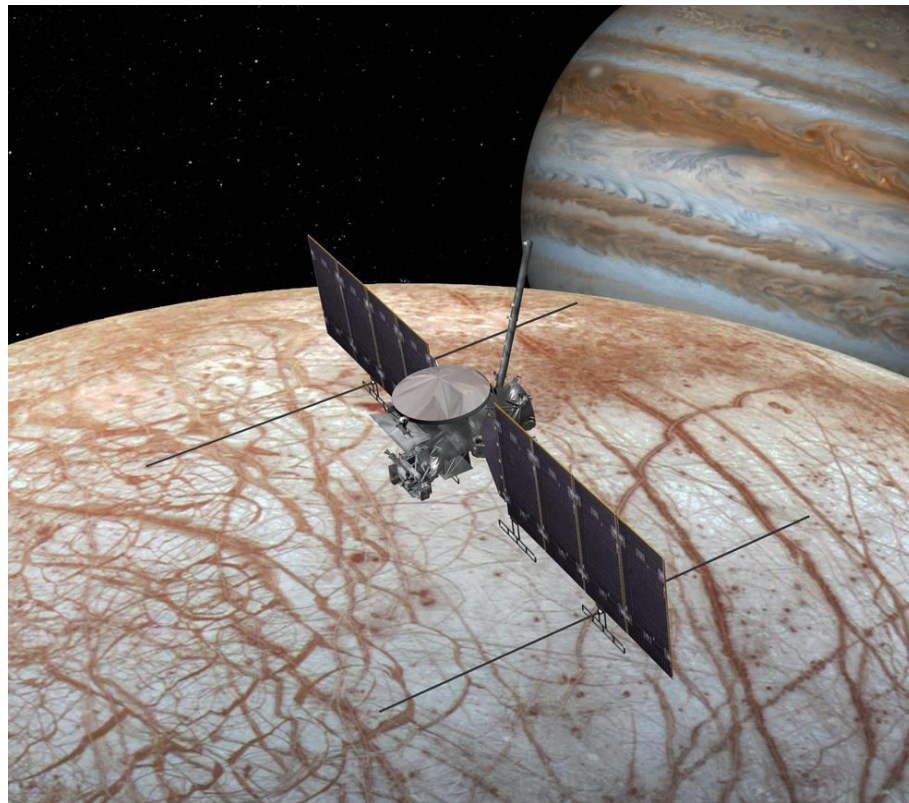


Fig. 9. Artist's rendition of the Europa Clipper spacecraft.

While launch on a Delta IV Heavy would involve a Venus-Earth-Earth gravitational assist trajectory requiring seven to eight years, launch on SLS would enable a direct transit to the Jovian system in less than three years, providing earlier science return and reduced operational costs, among other benefits. Consideration is also currently ongoing of a follow-up Europa lander mission, which would use the performance of SLS not for decreased transit time but for increased mass, using a gravitational-assist trajectory to deliver a large payload with a launch mass of 16 t. Not only does SLS provide benefits for each of the two missions, it also provides benefits to the missions as part of a larger robotic exploration effort – 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.

This demonstrates 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, a large-aperture space telescope offers a good case study. 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.

Interest in taking advantage of the mass-lift capability of SLS has been expressed by the Resource Prospector mission, which would land a rover in the lunar polar region to excavate volatiles such as hydrogen, oxygen, and water from the moon. Discussions between the SLS Program and the Resource Prospector team have focused on the possibility of launching the lander and rover as a co-manifested payload within the Universal Stage Adapter on a crewed flight of Orion, taking advantage of the launch of Orion as an opportunity to deploy the mission to the lunar surface, if an unallocated SLS comanifested payload opportunity were to arise during a timeframe consistent with the Resource Prospector timeline.

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 smallsats to operate in deep space. The diversity of the 13 CubeSat payloads that will fly within the Orion Stage Adapter on EM-1 demonstrates the broad potential this opportunity provides. CubeSat payloads on EM-1 will include both NASA research experiments and spacecraft developed by industry, international and potentially 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. The CubeSats’ research will range from search for potential ice deposits in the moon’s permanently shadowed craters to using a solar sail to rendezvous with a Near Earth Asteroid to landing on the lunar surface to measuring the effects of deep-space radiation on DNA to conduction heliophysics research and much more.

7. CONCLUSION

With unprecedented mass, volume and C3 capability, NASA’s Space Launch System offers unique opportunities for human space exploration, robotic science, and other missions. Currently making progress toward first launch in two years, the SLS Program is already working toward production of an evolvable vehicle that will be the workhorse of NASA’s Proving Ground missions in the 2020s and enable human missions to Mars in the 2030s.