SSC18-IX-02

NASA's Space Launch System: Opportunities for Small Satellites to Deep Space Destinations

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ABSTRACT

The first flight of NASA's new exploration-class launch vehicle, the Space Launch System (SLS), will test a myriad of systems designed to enable the next generation of deep space human spaceflight, while also providing the rare opportunity for 13 6U CubeSat-class payloads to be deployed in several locations along the flight path. The first mission of SLS and NASA's new Orion crew vehicle, Exploration Mission-1 (EM-1), will launch from upgraded facilities at Kennedy Space Center no earlier than fiscal year 2020. The initial Block 1 configuration for EM-1 will be capable of lofting at least 26 metric tons (t) of payload to the moon, with propulsion supplied by twin five-segment solid rocket boosters, four RS-25 engines and an Interim Cryogenic Propulsion Stage (ICPS). SLS will send Orion into a distant retrograde lunar orbit, paving the way for future missions to cislunar space and eventually Mars. The multidisciplinary small satellites for EM-1 derive from NASA research, as well as from international partners, industry and academia. Research subjects for the various smallsats include the moon, sun and an asteroid. Science objectives vary from characterizing the effects of radiation on living organisms (yeast) to landing the smallest spacecraft yet on the moon to supporting space weather research. Some of the payloads are technology demonstrations that will pave the way for more ambitious future missions that will be deployed by the more powerful SLS Block 1B configuration.

NASA'S SPACE LAUNCH SYSTEM: NATIONAL SPACE ASSET

Among the world's spacefaring nations, the United States has traditionally taken the lead in charting exploration goals and funding a robust national space program, transferring technology to the private sector and working with international, commercial and academic partners. By conquering the challenges related to operating in the extreme environment of space, NASA and its partners continue to expand human innovation and discovery.

Built to return astronauts to the moon in the Orion crew vehicle and to launch into deep space the largest space infrastructure and robotic payloads scientists and engineers can conceive of, SLS is a key asset of the American space program. The vehicle's flexible architecture and block configurations make available a progressively more powerful and capable family of super heavy-lift launchers for the most demanding missions. The vehicle can accommodate industry-standard 5 m-class or larger 8.4 m fairings in a variety of lengths, providing unparalleled payload volume.

The industrial base and supply chain, tooling, test facilities, certification procedures and launch infrastructure at Kennedy Space Center in Florida have been updated to facilitate a new generation of human spaceflight. Designs, production capabilities, experience and lessons learned will translate into future

Figure 1. In addition to sending the Orion crew vehicle and co-manifested payloads on lunar trajectories, SLS opens deep space to smallsats.

manufacturing and testing efficiencies. With steadfast support from the U. S. administration and Congress, the SLS Program ensures continued regular access to deep space for the world's most ambitious and exciting payloads, including CubeSat science and technology investigations to complement human operations.

SUSTAINED LUNAR OPERATIONS

After nearly two decades of continuous human presence aboard the International Space Station (ISS) and plans to commercialize low-Earth orbit (LEO) crystallizing, NASA is once again focusing on human deep space exploration. Working with commercial, academic and international partners, NASA plans to construct an astronaut-tended outpost in cislunar space to anchor an ongoing sustainable lunar presence. Minimally, the lunar Gateway will include power-propulsion, airlock and logistics elements, as well as a habitat module; additional elements are being evaluated. The Gateway will serve as a jumping-off point for lunar landings. The power-propulsion element will put the Gateway in a stable Near-Rectilinear Halo Orbit (NRHO) around the moon's poles, with orbital changes possible.

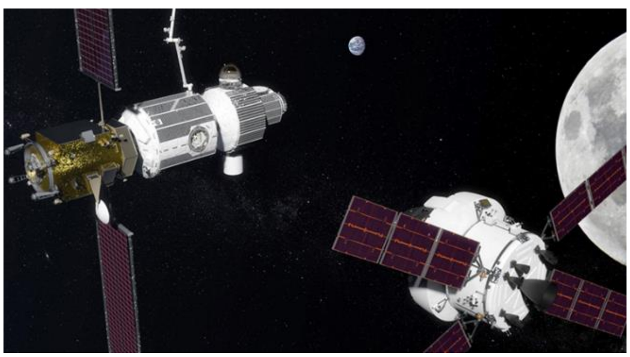

Figure 2. NASA plans to build an astronaut-tended lunar outpost in a Near-Rectilinear Halo Orbit (NRHO) about the moon, from which CubeSats could deploy on missions to the lunar surface.

With its unparalleled volume for payloads, SLS will play a key role in construction of the lunar outpost. The vehicle can loft habitats as co-manifested payloads in the Block 1B variant, along with the Orion spacecraft. Secondary payloads can also be a part of these missions to the Gateway, with SLS enabling access to the lunar surface where prospecting for volatiles will be one of the first objectives of the Gateway missions.

EXPLORATION MISSION-1 (EM-1): VERIFYING AND VALIDATING NASA's NEW DEEP SPACE EXPLORATION SYSTEM

EM-1, the first integrated mission for NASA's new deep space exploration system, will focus on verifying and checking out new spacecraft and ground systems — and sending 13 smallsats beyond LEO for exciting scientific investigations and technology demonstrations. Launching from upgraded and modernized facilities at Kennedy Space Center, SLS will send Orion on a 25.5-day mission to a distant retrograde lunar orbit. Key mission objectives include validating thermal, control and data systems; testing deep space maneuvers, communications and tracking; demonstrating landing and recovery operations; testing motion imagery systems; and deploying secondary payloads into deep space after the TLI burn.

For EM-1, mission planners chose the 13 smallsat payloads from a range of industry, academic and international partners as well as from within NASA. Preference was given to missions that will return data and results that may address Strategic Knowledge Gaps (SKGs) — information NASA needs to reduce risk and increase design and effectiveness of future robotic and human space exploration missions. Three additional payloads were selected as part of the Cube Quest competition, administered by NASA's Centennial Challenge Program. The competition offers a total of $5 million in prizes to teams that meet the challenge objectives of designing, building and delivering flight-qualified, small satellites capable of advanced operations near and beyond the moon.

Figure 3. Exploration Mission-1 (EM-1), the first mission of NASA's new deep space exploration system, has 13 smallsats on the manifest that will perform a variety of scientific investigations and technology demonstrations.

A key requirement imposed on the EM-1 secondary payload developers is that the smallsats do not interfere with Orion, SLS or the primary mission objectives. To meet this requirement, payload developers must take part in a series of safety reviews with the SLS Program's Spacecraft Payload Integration & Evolution (SPIE) organization, which is responsible for the Block 1 upper stage, adapters and payload integration. In addition to working with payload developers to ensure

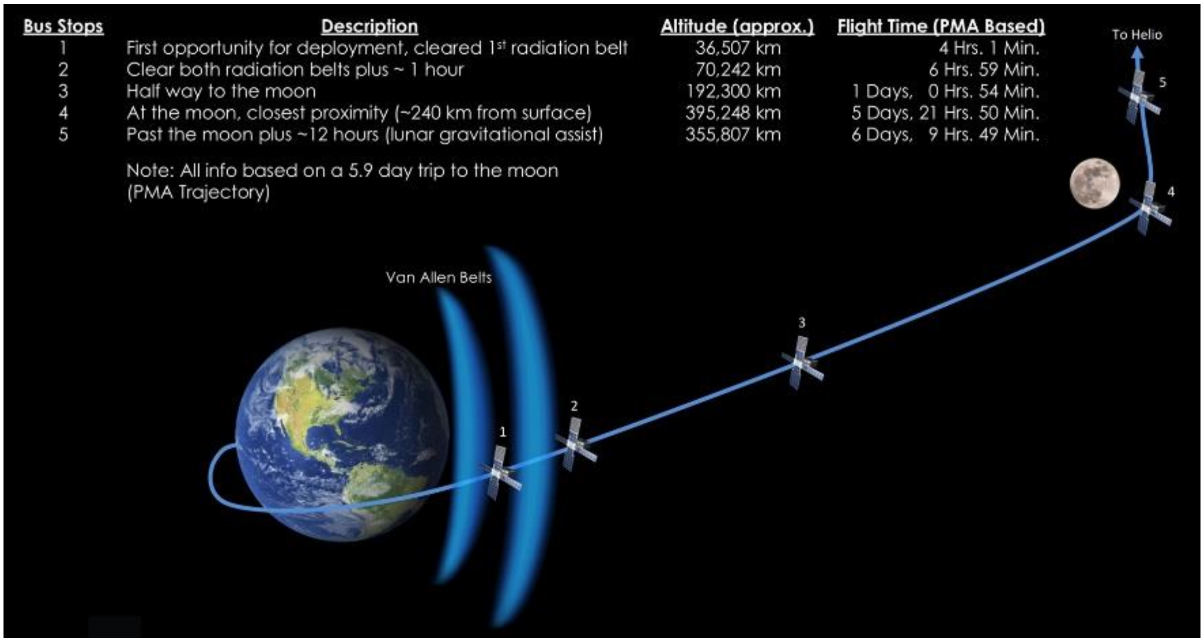

Figure 4. Providing smallsats with extraordinary access to deep space, SLS presented payload developers with several "bus stops," or deployment opportunities, for the first mission; similar opportunities are expected to be available on future missions.

mission safety, the SLS Program also provides a secondary payload deployment system in the OSA (see Block 1 Smallsat Accommodations). The deployment window for the CubeSats will be from the time ICPS disposal maneuver is complete (currently estimated to require about four hours post-launch) to up to 10 days after launch.

EM-1 SECONDARY PAYLOAD MANIFEST

The smallsats manifested on EM-1 will undertake a diverse variety of experiments and technology demonstrations. Seven payloads will be deployed after the ICPS has cleared the first Van Allen Radiation Belt (bus stop 1, Figure 4). JAXA, the Japanese Space Agency, will have two smallsats deploy at the first stop. The *Outstanding MOon exploration TEchnologies demonstrated by Nano Semi-Hard Impactor (OMOTENASHI)* mission will land the smallest lander to date on the lunar surface to demonstrate the feasibility of the hardware for distributed cooperative exploration systems. If this mission is successful, Japan will be the fourth nation to successfully land a mission on the Earth's moon. The other JAXA payload, the *EQUilibriUm Lunar-Earth point 6U Spacecraft (EQUULEUS)*, 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 smallsat. *Lunar Flashlight* is a NASA Jet Propulsion Laboratory mission that will look for ice deposits and identify locations where resources may be extracted from the lunar surface. The NASA Ames Research Center-developed *BioSentinel* mission is a yeast radiation biosensor that will measure effects of space radiation on DNA. *ArgoMoon,* sponsored by the Agenzia Spaziale Italiana (ASI), will perform proximity operations with the ICPS post-disposal and record imagery of engineering and historical significance — as well as of the Earth and moon — by testing an advanced software imaging recognition system using high-definition cameras. Cislunar Explorers, a team from Cornell University in Ithaca, New York, competing in NASA's Cube Quest Centennial Challenge competition, has designed a 6U CubeSat that will split into two smaller spacecraft that will orbit the moon using a novel propulsion system of inert water to carry out gravity

Figure 5. Morehead State University and NASA's Goddard Space Flight Center are partnering to create the Lunar IceCube mission, one of 13 smallsats manifested on EM-1.

assists with the moon, and then be captured into lunar orbit. Finally, *Lunar Icecube*, developed by Morehead State University in Kentucky, will search 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.

About 90 minutes after the ICPS clears the first Van Allen Belt, the *Near Earth Asteroid (NEA) Scout*, a NASA Marshall Space Flight Center mission equipped with a solar sail to rendezvous with an asteroid, will be deployed. NEA Scout will gather detailed imagery and observe the asteroid's position in space. After the ICPS has cleared both radiation belts, the *Lunar-Polar Hydrogen Mapper (LunaH-Map)* payload from Arizona State University will be released. LunaH-Map will help scientists understand the quantity of hydrogen-bearing materials in cold traps in permanently shaded lunar craters via low-altitude flybys of the moon's south pole. About one hour after clearing the radiation belts (bus stop 2, Figure 4), Lockheed Martin's *LunIR* spacecraft, a technology demonstration mission that will perform a lunar flyby, will be deployed. Using a miniature high-temperature Mid-Wave Infrared (MWIR) sensor to collect spectroscopy and thermography data, LunIR will provide data related to surface characterization, remote sensing and site selection for lunar future missions.

About 12 hours after the ICPS passes the moon (bus stop 5, Figure 4) and uses its gravity to enter heliocentric orbit, the final three smallsats will be released. The *CubeSat Mission to Study Solar Particles (CuSP)* from Southwest Research Institute in San Antonio, Texas, 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. Team Miles, of Miles Space, LLC, of Tampa, Florida, another Cube Quest competitor, has a mission that will fly autonomously using a sophisticated onboard computer system. The spacecraft will be propelled by evolutionary plasma thrusters. The final Cube Quest entrant, the *University of Colorado-Earth Escape Explorer (CU-E^3)*, is a CubeSat from the University of Colorado in Boulder, Colorado, that will be use solar radiation pressure rather than an onboard propulsion system.

Prior to ICPS propellant depletion, the stage will place itself in an attitude pointing toward the sun and having a 1 rpm roll in order to give the stowed small payloads the best thermal conditions. Unfortunately, once the ICPS depletes its propellant, it will no longer be able to maintain its attitude and it will eventually decay into a flat spin. Because EM-1 is the first flight of a new vehicle, it's unknown how long the ICPS will remain in its initial attitude post-shutdown. Thermal conditions are one of several factors each payload developer needed to consider when determining which bus stop to use for payload deployment. In addition to thermal environments, payload developers needed to consider flight time to the moon, which affects propellant usage; radiation conditions, mission goals, ICPS attitude stability and more. After considering these factors, each payload developer selected its final bus stop, or deployment location.

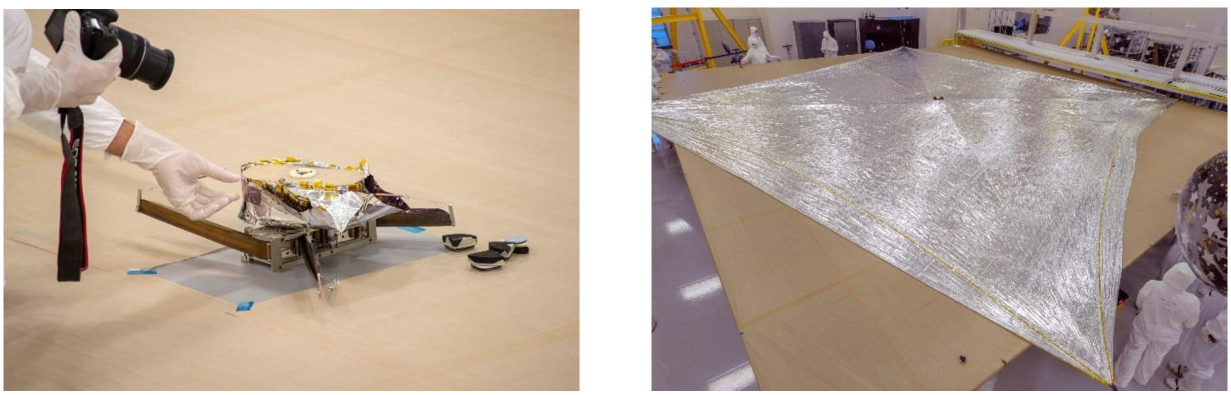

Figure 6. One of 13 6U-class secondary payloads manifested for EM-1, the NEA Scout spacecraft utilizes a solar sail the size of school bus on each side when unfurled.

BLOCK 1 SMALLSAT ACCOMMODATIONS

To release the payloads, the SLS Program installed a secondary payload deployment system in the OSA that includes mounting brackets for the commercial off-the-shelf (COTS) dispensers, cable harnesses and an avionics unit. Prior to shipping the completed OSA to the Exploration Ground Systems (EGS) Program at Kennedy, engineers at Marshall Space Flight Center tested the avionics unit to ensure possible scripts for controlling bus stop deployments performed as expected based on the flight time to the moon. For EM-1, each payload developer is responsible for the payload, the specified dispenser, vibration isolation system and thermal protection.

Before the OSA is stacked on the ICPS in Kennedy's Vehicle Assembly Building, the EGS Program will install the payloads previously integrated in their COTS dispensers onto the brackets. Then the payloads and the deployment avionics unit's batteries will be charged. EGS technicians will connect the electrical ground support equipment to the secondary payload deployment system via the OSA. The electrical ground support equipment will be removed and no further interaction with the payloads will be performed. On launch day, ICPS contractor United Launch Alliance (ULA) will load the upper stage operational parameters for the flight, including data needed for the secondary payload deployment system avionics unit to perform the correct skit for the mission based on trip time to the moon and when the payloads need to be deployed to complete their missions.

After the TLI burn and separation of Orion from the ICPS/OSA, and conclusion of most of the ICPS disposal maneuvers, the ICPS will power on the secondary payload deployment system. The ICPS will put itself into a one revolution per minute (rpm) roll and be pointed at a 55-degree beta angle to the sun and proceed with hydrazine depletion as part of stage disposal. Once the propellant is spent, the ICPS will take one more set of readings, downlink those readings and shut down. Soon after, the ICPS/OSA and secondary payload deployment system arrive at the first bus stop where seven payloads will be released into deep space.

Another noteworthy benefit SLS provides to the EM-1 smallsats is the ability to incorporate propulsion systems on the payloads. In most smallsat missions to LEO, CubeSats are restricted from having propulsion systems. Smallsats operating in deep space, on the other hand, require propulsion systems in many mission scenarios. The EM-1 CubeSats employ several types of propulsion systems, including ion, solid, green propellant, solar, pressure, etc., providing mission developers with the rare opportunity to utilize these small propulsion systems in deep space.

A prime example of both extraordinary deep space exploration opportunities and cooperation among numerous organizations, the 13 EM-1 6U-class payloads present the opportunity for science and technology advancement on what is otherwise a demonstration flight, paving the way for additional opportunities for CubeSats on future SLS missions.

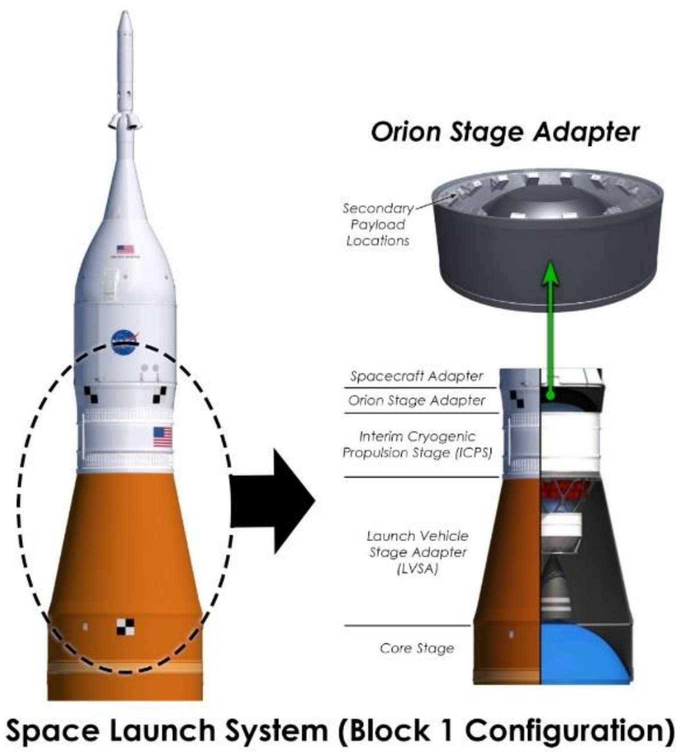

Figure 7. At the top of the Block 1 configuration, the Orion Stage Adapter (OSA) has capacity for 13-17 smallsats; the SLS Program provides an integrated deployment system for the payloads.

PROGRESS TOWARD FIRST FLIGHT

Upper Stage and Adapters

At the forward section of the rocket, just below the Orion crew vehicle, is the OSA, which holds the secondary payload accommodations. For EM-1, the OSA is complete and was delivered to EGS in February 2018. Made of a lightweight aluminum alloy, the OSA measures 18 feet (5.4 m) in diameter by 5 feet (1.5 m) high. A diaphragm just below the mounting brackets prevents launch gases from entering the Orion spacecraft.

Sitting just below the OSA, the ICPS, a modified Delta Cryogenic Second Stage manufactured by ULA in Decatur, Ala. through a contract with Boeing, supplies in-space propulsion for the Block 1 vehicle. The ICPS will provide the TLI burn to send Orion toward the moon during the EM-1 mission. After entering its disposal trajectory with the OSA attached, the ICPS will release the first seven CubeSats (see Block 1 Smallsat Accommodations above).

Partially covering the ICPS and providing the diameter adjustment from the 27.6-foot (8.4 m) core to the 17-foot (5 m) ICPS, the Launch Vehicle Stage Adapter (LVSA) is being built by Teledyne Brown Engineering at Marshall Space Flight Center in Huntsville, Ala. The LVSA will provide access to the ICPS during stacking and integration at Kennedy Space Center. The LVSA is nearing completion with instrumentation and cabling installed and thermal protection applied. The LVSA is the largest spaceflight hardware to receive a manually applied thermal protection system at Marshall. The LVSA is scheduled for completion and shipping to the EGS Program at Kennedy Space Center later in 2018.

Core Stage

Core stage prime contractor Boeing is building the world's largest rocket stage at Michoud Assembly Facility near New Orleans. The 212-foot (64 m) stage is comprised of five primary components, from forward to aft – the forward skirt, containing avionics; the liquid oxygen tank; an intertank structure where the forward attach points for the solid rocket boosters are located; the liquid hydrogen tank and an engine section that houses the four RS-25 engines. All five structures are structurally complete, with the world's largest spacecraft welding tool, the Vertical Assembly Center, having performed some of the welds on all the structures except the intertank, which is bolted (due to its thickness). All the EM-1 flight hardware is now being outfitted for flight with the installation of cables,

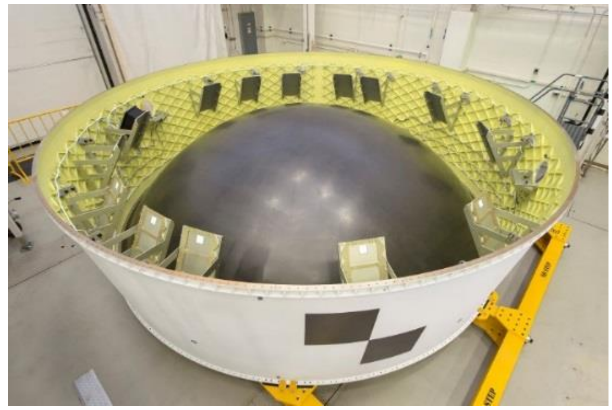

Figure 8. The finished OSA for EM-1 before it was shipped to EGS; mounting brackets for smallsat COTS dispensers and an avionics box are visible just above the diaphragm.

instrumentation, piping and other hardware. Avionics are currently being tested at Marshall Space Flight Center's Software Integration Lab.

In addition to the manufacture and outfitting of flight hardware, Boeing has also built full-scale structural test articles for each core stage component except the forward skirt. Those test articles, which include not only the vehicle structure but also simulators representing mass loads on top of and below the hardware, are being shipped to Marshall, where they will undergo rigorous structural testing to verify computer models and provide engineers with real-world data. The first core stage test article to undergo structural testing was the engine section. Engineers used 3,200 sensors to measure forces and stress. Fifty-five load lines applied up to 4.5 million pounds of vertical force and 900,000 pounds of side force to the

Figure 9. The ICPS, which will provide in-space propulsion for the first integrated flight of SLS and Orion, is complete.

engine section test article. Engineers ran 59 test cases similar to launch loads, testing the hardware to its limit. The next series of tests to be performed will be on the intertank test article. The article has been installed in

Figure 10. The SLS Program elected to build a "pathfinder" of the same dimensions as the core stage to give ground support and transportation crews experience in transporting and handling full-size spaceflight hardware.

the test stand, which is currently being built up around the test hardware. Structural testing on the intertank test article is scheduled to commence in summer of 2018 and last the rest of the year. Test versions of the liquid hydrogen and liquid oxygen tanks are scheduled to arrive at Marshall at a later date. The testing will use new test stands designed to apply compression, tension, bending, torsion and shear loads to those test articles.

RS-25 Engines

The SLS Program chose to use the world's most proven and reliable rocket engine in SLS: the RS-25, built by Aerojet Rocketdyne. Four RS-25s will be housed in the

Figure 11. All four EM-1 RS-25 engines have been tested and verified; they are ready for integration into the core stage and flight.

engine section of the core stage and provide 512,000 pounds of thrust each, operating until main engine cut-off (MECO) at about eight minutes into the flight. The four RS-25 engines for EM-1 have been assembled,

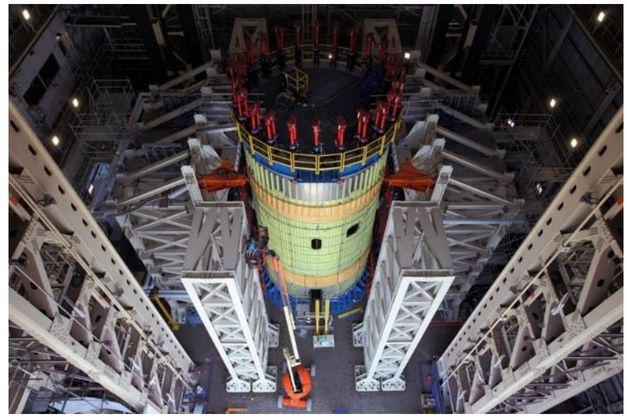

Figure 12. The next core stage component to undergo structural testing is the intertank structural test article, consisting of a full-size replica of the intertank and simulators for the liquid oxygen and liquid hydrogen tanks.

tested, checked out and stand ready for integration with the core stage. A series of hot-fire tests of development RS-25 engines at NASA's Stennis Space Center contributed to full qualification of the new, state-of-the-art engine controllers for EM-1.

The Program has four flight sets of RS-25 engines remaining from the Space Shuttle Program and has contracted with Aerojet Rocketdyne to restart engine production. The new series of engines incorporates numerous improvements to streamline production, reduce costs and compress manufacturing schedules. Several of the parts on the new engine series use technological innovations such as additive manufacturing. Some of those 3D-printed parts will be tested in upcoming hot-fire tests at Stennis Space Center in 2018 and used on future SLS flights.

Solid Rocket Boosters

The SLS solid rocket boosters, built by prime contractor Northrop Grumman, are the largest ever built for flight. The five-segment solid-fuel motors provide more than 7.2 million pounds of thrust — more than 75 percent of total vehicle thrust at liftoff. With 25 percent more propellant than the space shuttle-era booster on which it is based, the SLS boosters burn through more than six tons of polybutadiene acrylonitrile (PBAN) each second during their approximately two-minute flight. With several sets of flight hardware remaining from the shuttle program, including forward assemblies (nose caps, frustums, forward skirts), motor cases and nozzles, and aft skirts, the SLS Program and Northrop Grumman have nearly completed the EM-1 boosters and are working on the boosters for the second flight.

FUTURE SMALLSAT PAYLOAD ACCOMMODATIONS

With funding allocated for a second mobile launcher to be constructed at Kennedy Space Center for Block 1B flights, NASA expects to fly multiple Block 1 flights before transitioning to the more powerful Block 1B variant. Crew and cargo configurations are notionally planned for each block upgrade of the vehicle. The Block 1B vehicle's crewed variant will accommodate co-manifested payloads in a Universal Stage Adapter (USA) that contains as much cargo volume as the space shuttle payload bay. For lifting Mars-class payloads, the vehicle will evolve to its most powerful configuration, Block 2. This configuration will lift at least 45 t to TLI.

Mission planners will consider opportunities for smallsats on all future flights. Rideshare opportunities as well as propulsive Evolved Expendable Launch Vehicle (EELV) Secondary Payload Adapters (ESPA)-class payloads may be accommodated, depending on mission parameters. User demand for propulsive ESPA-class accommodations is currently being evaluated. Larger payloads, in the 200-300 kg class, and constellations of smallsats are within the realm of possibility. Payload developers can expect the Program to provide COTS deployers and other larger COTS payload carrier systems.

Figure 13. Northrop Grumman has nearly completed the five-segment solid rocket boosters for EM-1; motor segments will be shipped to Kennedy Space Center, where they will be stacked to assemble the final boosters.

Block 1

Similar to EM-1, the Program is prepared to accommodate secondary payloads in the OSA on future

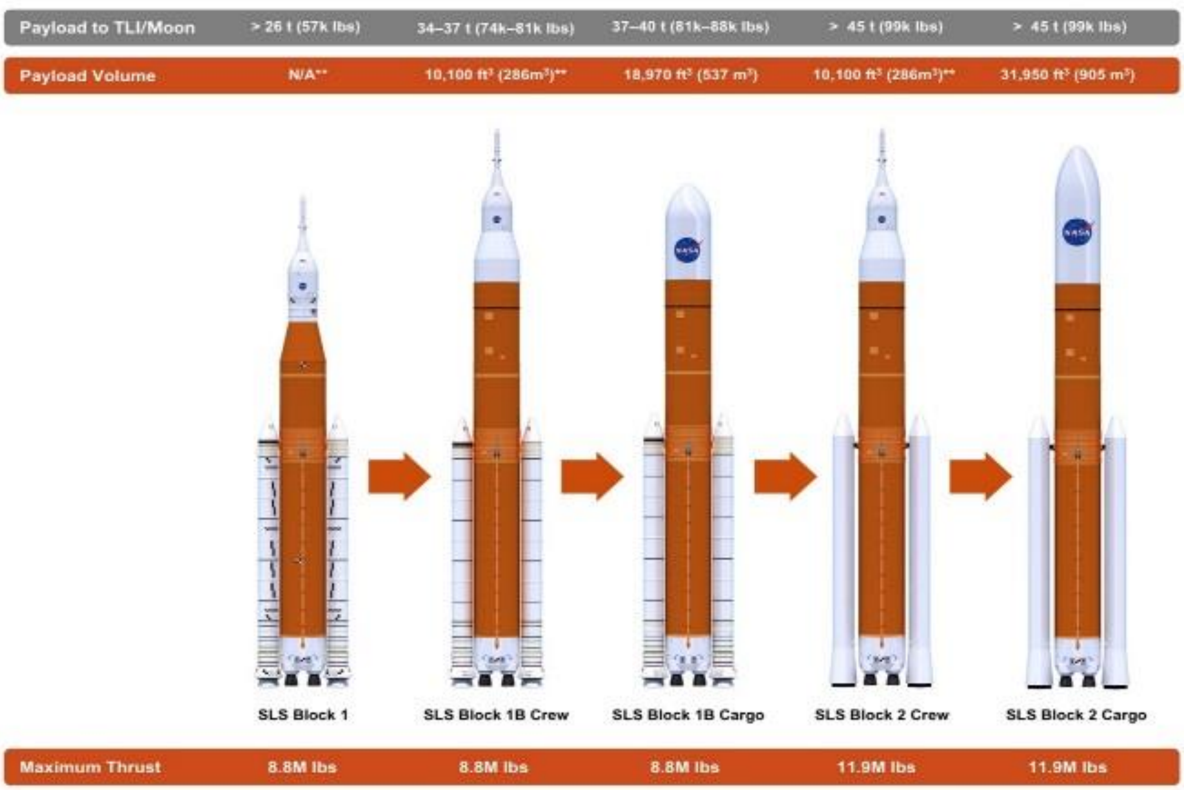

Figure 14. The Block 1 configuration is the first variant of the SLS family of vehicles that will provide the performance and payload capacity to lift Mars-class payloads.

Block 1 flights. The key requirement to "do no harm" to the primary mission will remain in effect, as will phased safety reviews with Program managers. The first crewed flight, Exploration Mission-2 (EM-2), could potentially provide up to 17 berths for a combination of 6U- and 12U-class smallsats. For that mission, the Program would offer smallsats the opportunity to deploy after clearing the Van Allen Belts, halfway to the moon and one-half day past the moon.

Table 1. Notional deployment opportunities, or "bus stops," for the first crewed flight of SLS, EM-2.

Deployment Opportunity	General Description
1	Beyond Van Allen Belts
2	Halfway to the moon
3	One-half day past the moon

Block 1B

Depending on capacity available, smallsats in 12U or even larger sizes may be accommodated on Block 1B flights in the 2020s. For Block 1B flights, CubeSats may be integrated onto a payload adapter in a variety of 6U and 12U configurations. The Program would continue to provide mounting hardware integrated into the adapter hardware and an avionics unit to control deployment. Deployment would be available at any point along the upper stage disposal trajectory.

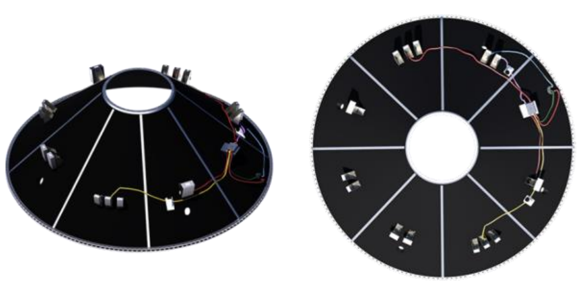

Figure 15. Block 1B and Block 2 flights may include accommodations for secondary payloads on a payload adapter.

SUMMARY

Now that commercial launch companies regularly provide cargo servicees to LEO — and are approaching the first test flights of ISS crew transportation – NASA has renewed its focus on deep space exploration. Working with private industry, academia and international partners, NASA plans to return to the moon with a sustainable, long-term presence. The SLS, Orion and EGS programs are the cornerstone of this plan, giving the nation — and the world — the ability to take astronauts and large space infrastructure to the moon in a single launch. With a regular cadence of launches to cislunar space, smallsats have an unparalleled opportunity to contribute to exploration of deep space. Plans will continue to mature in the next few years, but SLS will give smallsats exceptional opportunities for game-changing missions in deep space.

Figure 16. NASA's Exploration Ground Systems (EGS) Program at Kennedy Space Center has upgraded stacking and launch facilities in preparation for EM-1.