NASA's Space Launch System: Exceptional Opportunities for Secondary Payloads to Deep Space

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When NASA's Space Launch System (SLS) launches for the first time from Kennedy Space Center, it will send the Orion crew vehicle farther into space than a human-rated spacecraft has ever traveled. The primary objectives of this first uncrewed mission, Exploration Mission-1 (EM-1), focus on verifying and validating the new technologies and integrated systems developed for SLS, Orion and Exploration Ground Systems (EGS), which together comprise NASA's new deep space exploration system. EM-1 also provides the opportunity for 13 6U CubeSat secondary payloads to be deployed in deep space. As progress is being made toward that first launch, planning is also taking place for secondary payload opportunities on future missions. This paper will provide an overview of the status of the SLS Block 1 launch vehicle and an overview of the 6U payloads selected for EM-1. In addition, an overview of the EM-1 mission trajectories and the "bus stops" along the trajectory where the payloads will be deployed will be noted. Challenges and new workflows required in identifying and certifying potential payloads will be discussed. The paper will also discuss opportunities that will be presented by future evolutions of SLS.

I. Introduction

When NASA's Space Launch System rocket makes its maiden flight, it will propel an uncrewed Orion spacecraft on a trajectory toward the Moon on a mission that will mark a major step in an exploration program that will include a human-tended deep-space outpost, a return of astronauts to the lunar surface, and ultimately crewed missions to Mars. That first flight of SLS, Exploration Mission-1, will be historic on a smaller, but also groundbreaking, scale as well, as the first deployment of CubeSat secondary payloads into deep space. Following the success of the MarCO CubeSats that were launched to Mars as an integral part of NASA's InSight mission, EM-1 will see the deployment of 13 6U CubeSats, representing a variety of developers from within NASA, academia, industry, international partners and the public, and performing a variety of scientific and technology-demonstration missions.

The Space Launch System (SLS) rocket (Fig. 1), managed at Marshall Space Flight Center in Huntsville, Alabama, will be the world's most capable launch vehicle, with an initial Block 1 capability of at least 26 metric tons (t) to trans-lunar injection (TLI). A more powerful Block 1B, available in crew and cargo configurations, with have the power to loft more than 37 t to TLI; the ultimate Block 2 variant will lift more than 45 t to TLI. The initial Block 1 configuration will be able to launch in either a crewed variant with the Orion spacecraft, or in a cargo variant with a 5-meter (m) diameter payload fairing offering

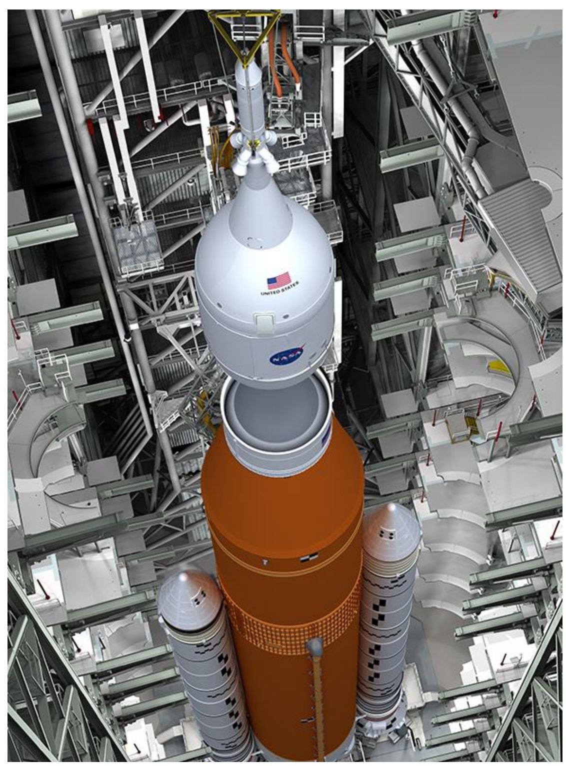

Fig. 1 Artist's rendition of Space Launch System

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accommodations compatible with those on a contemporary Evolved Expendable Launch Vehicle (EELV). The Block 1B and 2 vehicles will be able to carry larger 8.4-m fairings in their cargo variant, and their crew variants will also be able to carry large co-manifested payloads.

The first mission of SLS and Orion, launching no earlier than December 2019, will send Orion into lunar distant retrograde orbit on a 25.5-day shakedown cruise known as Exploration Mission-1 (EM-1), enabling NASA to verify and validate new systems before sending astronauts to deep space on the next exploration mission.

II. Exploration Mission-1 CubeSat Accommodations and Deployment

Secondary payloads on the initial Block 1 configuration of SLS will be housed in the Orion Stage Adapter (OSA), which connects the vehicle's Interim Cryogenic Propulsion Stage (ICPS) with the Orion crew vehicle (Fig. 2). Upon stacking of the vehicle, the ICPS in-space stage will be permanently integrated with the OSA and to the Orion spacecraft adapter, which mates to the service module of the Orion vehicle. In flight, these three pieces of hardware function as one element.

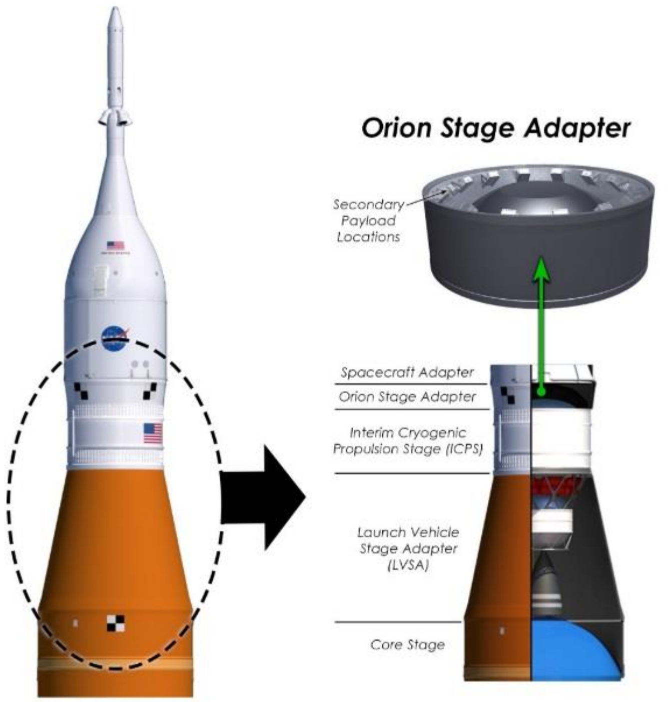

Fig. 2 At the top of the Block 1 configuration, the Orion Stage Adapter (OSA) has capacity for 13-17 smallsats.

For EM-1, a Secondary Payload Deployment System (SPDS) has been installed within the OSA capable of supporting 13 6U CubeSats. The system is composed of mounting brackets for the commercial off-the-shelf (COTS) dispensers, cable harnesses, and an avionics unit. The avionics unit is a standalone controller that controls the release of the secondary payloads. For EM-1, each payload developer is responsible for the payload, its dispenser, and the vibration isolation system. In partnership with the Launch Services Program (LSP) at Kennedy Space Center, the dispensers are being obtained from Planetary Systems Corporation.

Payloads were chosen for EM-1 with consideration given to their ability to 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 of the 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.

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 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, as well as all SLS adapters, fairings, and payload interfaces and integration.

Before the OSA is stacked on the ICPS in Kennedy's Vehicle Assembly Building, integration contractor Tyvak will install the payloads into their dispensers, and the EGS Program will install the dispensers onto the brackets. The avionics unit's battery 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 schedule, or "skit," for the mission based on trip time to the Moon and when the payloads need to be deployed to complete their missions.

Following launch, the ICPS and Orion will separate from the SLS core stage roughly eight minutes into flight. The ICPS will subsequently perform the TLI burn that will power it and the Orion spacecraft toward the moon. Orion will separate from the ICPS, which will continue its trajectory toward a heliocentric disposal orbit. The ICPS will put itself into a one-revolution-per-minute roll and be pointed at a 55-degree beta angle to the sun. It will 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 and its payloads will reach the first deployment opportunity. Early in mission planners the SLS Secondary Payload Team identified five representative "bus stop" locations for payload deployment (Fig. 3). While deployment can occur any time after the window opens, these "bus stops" reflect a range of possibilities available to the payloads. The first of those opportunities is between Earth's van Allen radiation belts, the second is once the stage clears the van Allen belts, the third is halfway between Earth and the Moon, the fourth is prior to reaching the moon and the fifth is after the stage completes its lunar flyby toward heliocentric disposal. The bus stops reflect trade space between early deployment, enabling earlier operations and greater trajectory control, and later deployment, taking longer advantage of the protection offered by the stage structure. On EM-1, seven payloads will deploy at the first bus stop, two will deploy between the first and second bus stops, one will deploy at the second bus stop, and three will remain with the stage until the final bus stop.

While most launches to low Earth orbit (LEO) restrict CubeSats from carrying propulsion systems, smallsats operating in deep space 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.

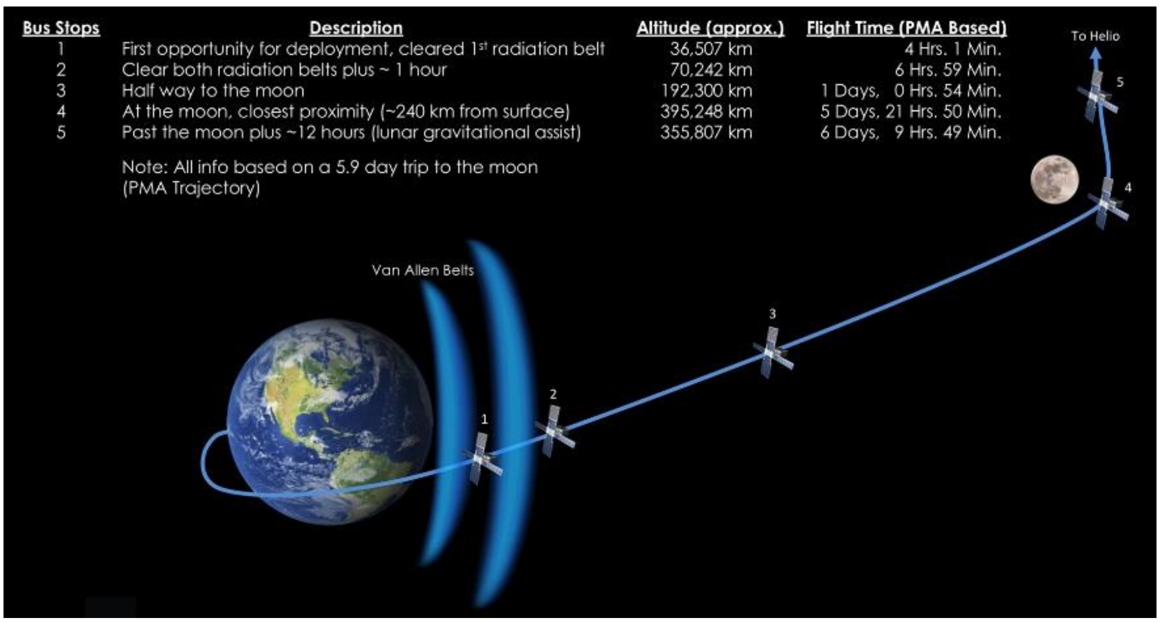

Fig. 3 Providing smallsats with extraordinary access to deep space, SLS presented several "bus stops," or deployment opportunities, for the first mission; similar opportunities are expected to be available on future missions.

III. Exploration Mission-1 CubeSat Manifest

The CubeSats manifested on EM-1 will undertake a diverse variety of experiments and technology demonstrations.

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.

BioSentinel, developed by NASA Ames Research Center, features a yeast radiation biosensor that will measure effects of space radiation on DNA.

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 assists with the moon, and then be captured into lunar orbit.

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.

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.

The EQUilibriUm Lunar-Earth point 6U Spacecraft (EQUULEUS), another Japan Aerospace Exploration Agency (JAXA) payload, 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.

The Lunar-Polar Hydrogen Mapper (LunaH-Map) payload from Arizona State University will 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.

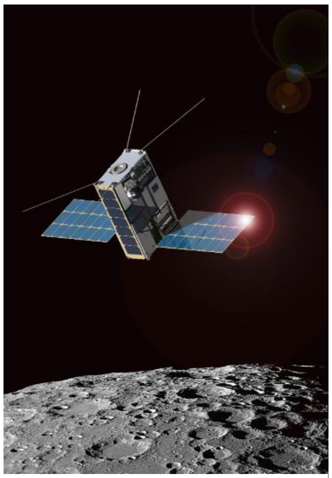

Fig. 4 Morehead State University and NASA's Goddard Space Flight Center are partnering to create the Lunar IceCube mission, one of 13 smallsats manifested on EM-1.

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.

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 (Fig. 4).

The LunIR spacecraft, developed by Lockheed Martin, is a technology demonstration mission that will perform a lunar flyby and use 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.

The Near Earth Asteroid (NEA) Scout, a NASA Marshall Space Flight Center mission equipped with a solar sail to rendezvous with an asteroid, will gather detailed imagery and observe the asteroid's position in space.

The Outstanding MOon exploration TEchnologies demonstrated by Nano Semi-Hard Impactor (OMOTENASHI) mission by JAXA will land the smallest lander to date on the lunar surface to demonstrate the feasibility of the hardware for distributed cooperative exploration systems.

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.

IV. Progress Toward Exploration Mission-1 and Beyond

A. Core Stage

The SLS core stage, the largest ever constructed in terms of both length and volume, consists of an engine section that houses four RS-25 engines, a liquid hydrogen (LH2) fuel tank, an intertank structure with forward attach points for the solid rocket boosters, the liquid oxygen (LOX) oxidizer tank, and the forward skirt, which holds most of the vehicle's avionics. Core stage prime contractor Boeing is manufacturing the stage at NASA's historic Michoud Assembly Facility near New Orleans, Louisiana, USA. Parts of NASA's Saturn V, the Space Shuttle and now SLS have all been manufactured at Michoud. The SLS Program modernized the factory by installing the world's largest spacecraft welding tool, the Vertical Assembly Center. That investment has paid off as weld confidence articles, structural test articles and flight hardware have all been manufactured for EM-1.

The EM-1 core stage engine section has completed welding; major subassembly and integration work is underway. Technicians are installing the Thrust Vector Control (TVC) system, boat tail assemblies, pumps, manifolds, ducts, cables, harnesses and instrumentation for flight. The EM-1 LH2 tank, which will hold 537,000 gallons of cryogenic fuel, has been constructed and proof-tested. At the time of writing, the LH2 tank had undergone a thorough cleaning process and was ready for priming. After priming, major work on the tank includes applying the thermal protection system, similar to the thermal protection used on the Space Shuttle external tank.

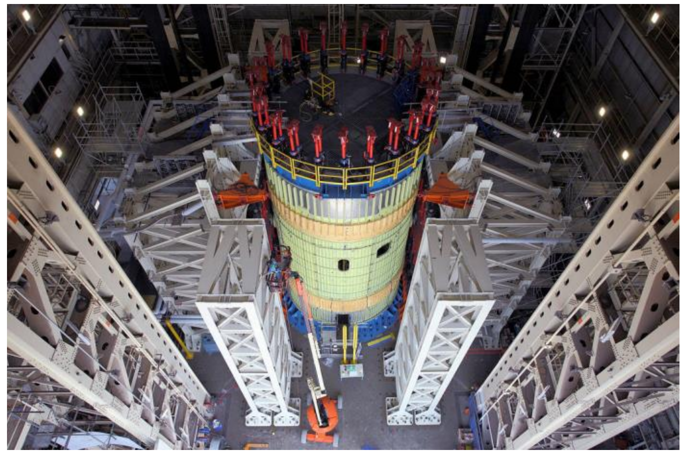

Fig. 5 Engineers installed structural test hardware for the SLS core stage intertank into a stand at Marshall Space Flight Center, where testing recently began.

The EM-1 intertank will measure 6.7 m (22 ft.) long, and will connect the LH2 tank below it to the LOX tank above it. The intertank serves as the forward attach point for the five-segment solid rocket boosters and contains the supporting thrust structure needed to handle the loads the boosters will impart. To handle the enormous booster- induced thrust loads plus the stresses of the rocket above and below it, the intertank is the thickest core stage structure and is bolted rather than welded. The intertank consists of eight panel sections and more than 7,500 high-strength bolts. Structural testing of the intertank recently began at Marshall Space Flight Center (Fig. 5)

The EM-1 LOX tank required thicker walls than the LH2. That tank was successfully manufactured and is currently being sprayed with thermal protection system. Robotic acreage sprays are possible on the barrel section, but manual spraying is required for the domes. Technicians are installing sensors and cable harnesses on the EM-1 forward skirt and testing is underway on the avionics system and harnesses.

The forward skirt recently became the first piece of core stage hardware to complete assembly, and is now fully ready for integration with the other core stage elements.

B. RS-25 Engines

The four RS-25 engines, manufactured by prime contractor Aerojet Rocketdyne, are of space shuttle heritage, and have been upgraded for the demanding requirements of SLS's mission. The engines for EM-1 are complete and ready for integration with the SLS core stage (Fig. 6). The RS-25 engines will generate 512,000 lbs. of thrust each and operate for about eight minutes. The RS-25 was selected for SLS based on its power and efficiency, its successful performance over 135 shuttle missions and its well-understood characteristics over more than a million seconds of ground and flight operating time.

Fig. 6 All four EM-1 RS-25 engines have been tested and verified; they are ready for integration into the core stage and flight.

The SLS Program is using flight-proven RS-25s and, in addition to the new, updated controllers and software, new nozzle insulation is necessary to meet greater thermal protection requirements due to the engines' location nearer the booster nozzles. For SLS, the engines will operate at 109 percent thrust versus the 104.5 percent that was standard for space shuttle missions to LEO.

The NASA-Aerojet Rocketdyne team continues to push the world's most proven rocket engine to new heights. During a recent hot-fire test at NASA's Stennis Space Center, a development engine achieved a record 113 percent thrust.

C. 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.

Fig. 7 Northrop Grumman has nearly completed the five-segment solid rocket boosters for EM-1.

To support qualification for flight, NASA and SLS have conducted demonstrating testing and two full-scale static firings of qualification motors. All ten EM-1 motor segments have been cast and being finalized before the motors are shipped to KSC for stacking and integration with the core stage (Fig. 7). In addition, EM-1 nozzle assemblies are complete. Already at KSC, the forward assemblies for the mission, also shuttle-era hardware, are in various stages of refurbishment. Stiffeners were added to the forward skirts to address increased buckling loads over Space Shuttle loads. Other changes from the shuttle-era boosters include moving the rear attach point farther aft to accommodate the core stage structure, new environmentally benign insulation and all-new state-of-art avionics. The boosters will have five avionics boxes, all of which have completed qualification testing at Marshall Space Flight Center (MSFC). The booster avionics will then be tested with the overall vehicle avionics. The aft skirts have been sprayed with a thermal protection system and technicians are currently installing the TVC system.

D. Upper Stage and Adapters

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 (Fig. 8). The dispenser brackets for the secondary payload and the SPDS cabling was installed prior to delivery to EGS, and engineers at Marshall Space Flight Center tested the avionics unit to ensure scripts for controlling bus stop deployments performed as expected.

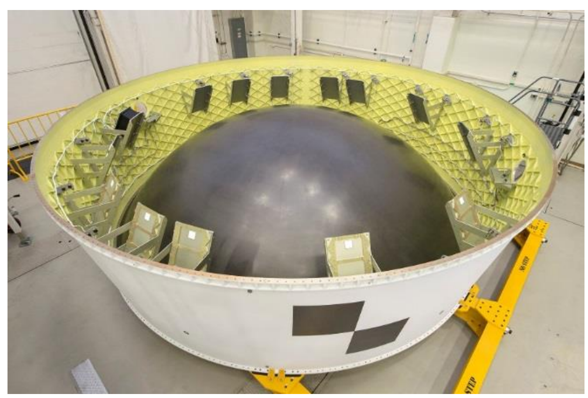

Fig. 8 The finished OSA for EM-1 before it was shipped to EGS; mounting brackets for smallsat COTS dispensers and an avionics box are visible just above the diaphragm.

The ICPS, a modified Delta Cryogenic Second Stage manufactured by United Launch Alliance in Decatur, Ala., supplies in-space propulsion for the Block 1 vehicle. The EM-1 ICPS has been completed and is currently at Kennedy Space Center awaiting stacking.

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 MSFC in Huntsville, Ala. 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 MSFC. The LVSA is scheduled for completion and shipping to the EGS Program at KSC later in 2018.

E. Future Missions

As Exploration Mission-1 draws nearer to launch, progress is also being made on future flights of SLS. Boeing has begun manufacture of the second flight core stage, and has begun development of the Exploration Upper Stage for the Block 1B configuration of SLS. Northrop Grumman has begun manufacturing the second flight's boosters, including casting the motor segments. The RS-25 engines for the first four flights of SLS are currently in inventory, and Aerojet Rocketdyne has performed hot-fire testing of the one of the engines for the second flight. In addition, NASA and Aerojet Rocketdyne have restarted production of the RS-25 engines for the fifth mission and beyond, working to make the engines more affordable and easier to manufacture. Part of this initiative to reduce costs and labor includes using additively manufactured rocket engine parts. In December 2017, a 3D- printed pogo accumulator was tested on a development engine. The additively manufactured parts and other process improvements aim to reduce the cost of future RS-25s by 30 percent. In the additive manufacturing process used to build the pogo accumulator, more than 100 welds were eliminated, reducing costs by nearly 35 percent and production time by more than 80 percent. Initial reports show the 3D-printed hardware performed as expected, opening the door for more additively manufactured components scheduled for future tests. Marshall Space Flight Center has conducted development work on the payload adapter for the Block 1B vehicle, and a contract has been awarded to Dynetics, of Huntsville, Ala., for production of the Universal Stage Adapter, the "payload bay" for co-manifested payloads on the crew variant of the Block 1B and 2 configurations of SLS.

V. Future Smallsat Opportunities on SLS

With funding allocated for a second mobile launcher to be constructed at KSC for SLS's Block 1B configuration, NASA expects to fly multiple Block 1 flights before transitioning to the more powerful Block 1B (Fig. 9). The Block 1B vehicle's crewed variant will accommodate co-manifested payloads in a Universal Stage Adapter, (USA) which contains as much cargo volume as the space shuttle payload bay or a contemporary EELV. Mission planners will consider opportunities for smallsats on future flights depending on the requirements of the launch's primary mission.

Fig. 9 The Block 1 configuration is the first in a series of iterations of the SLS family of vehicles that will provide the performance and payload capacity to lift Mars-class payloads.

A. Block 1

Similar to EM-1, the Program is prepared to accommodate secondary payloads in the OSA on future Block 1 flights. On future flights, the Block 1 vehicle could potentially provide up to 17 berths for a combination of 6U- and 12U-class smallsats. The key requirement to “do no harm” to the primary mission will remain in effect, as will phased safety reviews with Program managers. Deployment bus stops would vary depending on primary mission parameters, but for most missions would represent a similar range of opportunities as those on Exploration Mission-1.

B. Block 1B

Depending on capacity available, smallsats of up to 27U may be accommodated on SLS Block 1B flights in the 2020s. For Block 1B flights, CubeSats may be integrated onto a payload adapter. The Program would continue to provide mounting hardware integrated into the adapter hardware and an avionics unit to control deployment. Deployment would be available along the upper stage disposal trajectory. Rideshare opportunities for CubeSats as well as 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.

VI. Conclusion

NASA’s new deep space exploration system, including the SLS vehicle, will revitalize exploration of deep space by enabling the Agency to launch both humans and large payloads of multiple types (primary, co-manifested and secondary). EM-1 is an opportunity for thirteen secondary payloads (CubeSats) to explore space and advance science and technologies for the benefit of all humankind. Lessons learned from this first flight will be applied to future flights to enhance and improve exploration opportunities. SLS is well on its way to its first test flight with the Orion spacecraft launching from upgraded facilities at KSC with the Vertical Assembly Building configured to stack the SLS vehicle, the RS-25 engines tested and in storage ready for transportation to KSC and the ICPS and OSA hardware elements delivered and in storage at KSC. As the SLS is fielded and matured future flights will capitalize on the substantial mass and volume capability of SLS to enable international and commercial cooperation/exploration to build a new lunar outpost known as the Gateway. Along the way, multiple unique opportunities for smallsats of various sizes and configurations will likely be available for organizations to affordably reach deep space with groundbreaking science experiments and technology demonstrations.