

NASA's Space Launch System: Deep-Space Delivery for Smallsats

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ABSTRACT

Designed for human exploration missions into deep space, NASA's Space Launch System (SLS) represents a new spaceflight infrastructure asset, enabling a wide variety of unique utilization opportunities. While primarily focused on launching the large systems needed for crewed spaceflight beyond Earth orbit, SLS also offers a game-changing capability for the deployment of small satellites to deep-space destinations, beginning with its first flight. Currently, SLS is making rapid progress toward readiness for its first launch in two years, using the initial configuration of the vehicle, which is capable of delivering 70 metric tons (t) to Low Earth Orbit (LEO). On its first flight test of the Orion spacecraft around the moon, accompanying Orion on SLS will be small-satellite secondary payloads, which will deploy in cislunar space. The deployment berths are sized for "6U" CubeSats, and on EM-1 the spacecraft will be deployed into cislunar space following Orion separate from the SLS Interim Cryogenic Propulsion Stage. Payloads in 6U class will be limited to 14 kg maximum mass. Secondary payloads on EM-1 will be launched in the Orion Stage Adapter (OSA). Payload dispensers will be mounted on specially designed brackets, each attached to the interior wall of the OSA. For the EM-1 mission, a total of fourteen brackets will be installed, allowing for thirteen payload locations. The final location will be used for mounting an avionics unit, which will include a battery and sequencer for executing the mission deployment sequence. Following the launch of EM-1, deployments of the secondary payloads will commence after sufficient separation of the Orion spacecraft to the upper stage vehicle to minimize any possible contact of the deployed CubeSats to Orion. Currently this is estimated to require approximately 4 hours. The allowed deployment window for the CubeSats will be from the time the upper stage disposal maneuvers are complete to up to 10 days after launch. The upper stage will fly past the moon at a perigee of approximately 100km, and this closest approach will occur about 5 days after launch. The limiting factor for the latest deployment time is the available power in the sequencer system. Several NASA Mission Directorates were involved in the development of programs for the competition, selection, and development of EM-1 payloads that support directorate priorities. 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. Near Earth Asteroid (NEA) Scout is designed to rendezvous with and characterize a candidate NEA. A solar sail, an innovation the spacecraft will demonstrated for the CubeSat class, will provide propulsion. Lunar Flashlight will use a green propellant system and will search for potential ice deposits in the moon's permanently shadowed craters. BioSentinel is a yeast radiation biosensor, planned to measure the effects of space radiation on deoxyribonucleic acid (DNA). 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. NASA's Space Technology Mission Directorate (STMD) was allocated three payload opportunities on the EM-1 mission. These slots will be filled via the Centennial Challenges Program, NASA's flagship program for technology prize competitions, which directly engages the public, academia, and industry in open prize competitions to stimulate innovation. 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 suprathreshold properties that could help predict geomagnetic storms. The LunaH-Map payload will help scientists understand the quantity of H-bearing materials in lunar cold traps (~10 km), determine the concentration of H-bearing materials with 1m depth, and constrain the vertical distribution of H-bearing materials. The final three payload

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crewed landings on Mars. SLS' performance translates into capabilities that are paradigm-shifting for spacecraft designers and mission planners, enabling architectures and mission profiles not currently possible.

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 Exploration Ground Systems (EGS) 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.

SLS is designed to evolve to deliver greater mass and volume to support different types of missions as human exploration goals demand them. The initial configuration of SLS, known as Block 1, was designed to support initial demonstration of the vehicle's heavy-lift capability, and is making progress toward launch in two years. This configuration, which can deliver greater than 70 metric tons to LEO, will launch NASA's Orion crew vehicle into lunar orbit. 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.

The exploration systems development capabilities of SLS, Orion and ground systems at Kennedy Space Center 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.

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

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. At Michoud Assembly Facility (MAF), outside New Orleans, Louisiana, 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 Marshall Space Flight Center 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. (Fig. 2)

The core stage will be powered by four RS-25 engines – which previously served as the Space Shuttle Main Engine (SSME). 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. The engines, managed under a contract with Aerojet Rocketdyne, are currently undergoing testing with the new engine controller unit developed for SLS.

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. Qualification testing for the boosters is complete and nine of ten booster motor segments have been cast with propellant at Orbital ATK facilities and three segments are complete and in storage, awaiting shipment to Kennedy Space Center.

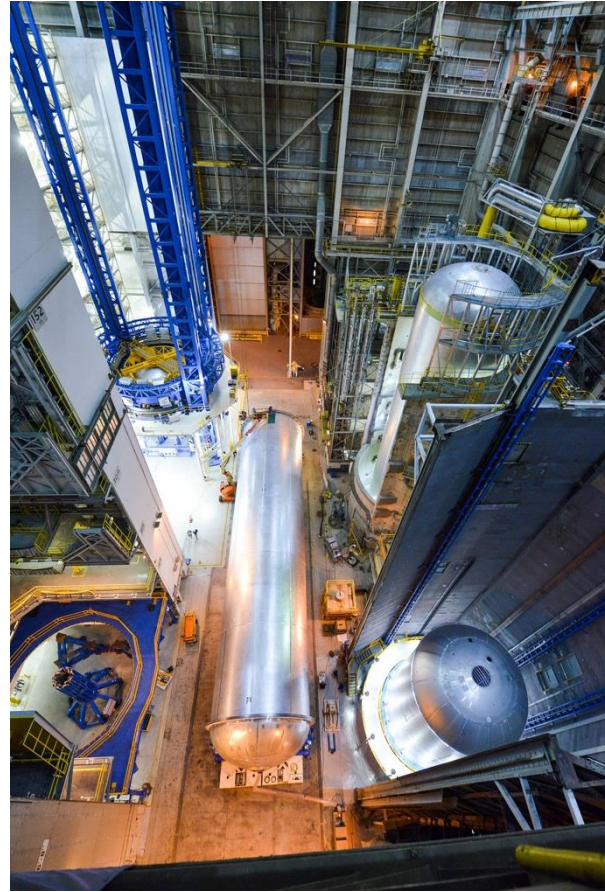


Figure 2 Core stage hardware, including test and flight articles for the oxygen tank and a hydrogen tank built for flight at Michoud Assembly Facility

In-space propulsion for the Block 1 vehicle will be provided by an Interim Cryogenic Propulsion Stage (ICPS), derived from the proven Delta Cryogenic Second Stage (DCSS). The ICPS is being produced by United Launch Alliance (ULA) in Decatur, Alabama, under contract to Boeing. The ICPS flight unit has already been delivered to Kennedy Space Center to await stacking. (Fig. 3)



Figure 3 The Interim Cryogenic Propulsion Stage is delivered to Kennedy Space Center

The Block 1 spacecraft/payload elements include not only the 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, Alabama, and is in final preparation on-site at Marshall. The Orion Stage Adapter (OSA), which connects the Orion spacecraft with the ICPS, is being produced by Marshall. 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.

III. 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 t of payload to LEO. This configuration will be the workhorse for much of the 2020s, prior to evolution to a full Block 2 configuration capable of delivering 130 t to LEO. (Fig. 4) 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 was concluded in early 2017, and initial hardware production has begun.

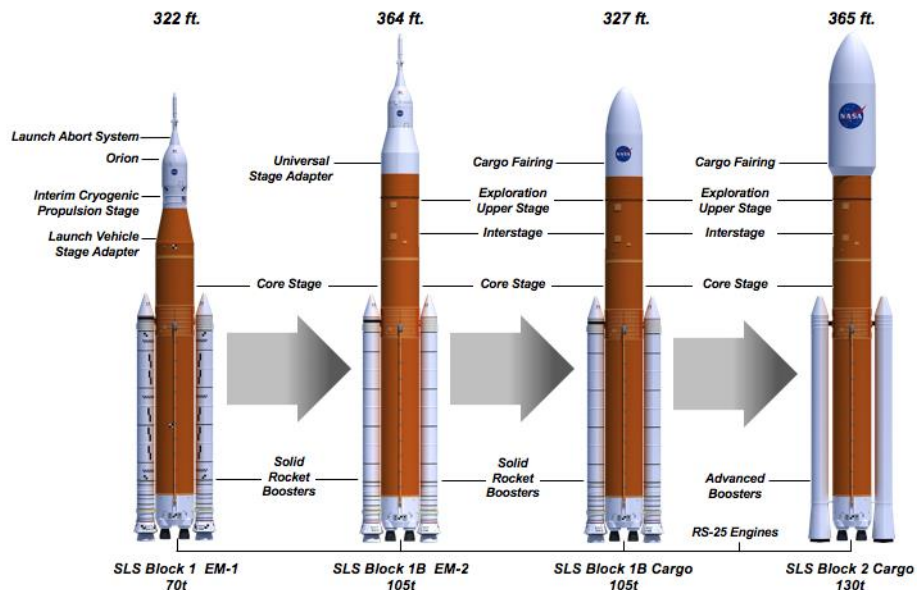


Figure 4 SLS evolutionary path

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 co-manifested payload to fly on an SLS along with Orion. The USA will be managed by NASA's Glenn Research Center in Cleveland, Ohio, and Dynetics, of Huntsville, Alabama, was named as the prime contractor for the USA in June 2017. Within the USA will be a payload adapter, a demonstrator version of which is currently being built at Marshall.

Other work for Block 1B 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 a Block 1B 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.

IV. 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.

SLS offers greater volume than any other launch vehicle. Beginning with the second flight of SLS with Orion, Exploration Mission-2 (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 10 m fairings with a volume of up to 1,800 cubic meters, several times greater than any currently available fairing.

For missions to, or staging in, the Earth-moon vicinity, SLS 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 LEO 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.



Figure 5 SLS Fairing options

V. SmallSat Utilization

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 have been allocated in the Orion-to-Stage Adapter in the initial SLS configuration, allowing payload deployment following Orion separation. (A total of fourteen brackets will be installed, allowing for thirteen payload locations. The final location will be used for mounting an avionics unit, which will include a battery and sequencer for executing the mission deployment sequence.) The deployment berths are sized for 6U CubeSats, and on EM-1 the spacecraft will be deployed into cislunar space following Orion separate from the SLS Interim Cryogenic Propulsion Stage. (Fig. 6) Secondary payloads in 6U class will be limited to 14 kg maximum mass.

The avionics unit will interface with each dispenser through cables mounted in the OSA. Secondary payloads will remain powered off until the sequencer transmits the deployment signal to each dispenser, and the payload is released. Secondary payloads will exit the dispenser at an approximate rate of 1.2 m/sec, with deployments separated by a minimum of 1 minute.

The SLS Program will perform all mission and payload integration for the baseline vehicle manifest. The mission integration process defined in this section has been developed to ensure safety and mission success, while reducing the amount of data required from the secondary payload developers.

The integration process is designed to support the payload requirements as well as the requirements of the launch vehicle and ground systems. The typical integration process encompasses the entire cycle of payload integration activities including analytical and physical integration.

Secondary payloads will be turned over to EGS fully integrated in their dispenser, ready for installation in the OSA at approximately L-6 months. EGS will install the integrated dispensers onto the OSA brackets and mate all required connections for deployment signals. Secondary payloads will not be accessible once stacking operations begin. For EM-1, additional tests and pad stay time is required to fully check out the vehicle configuration. Due to this “first flight” test activity, the vehicle will remain at the launch pad for up to two months, which will increase secondary payload exposure to documented natural environments.

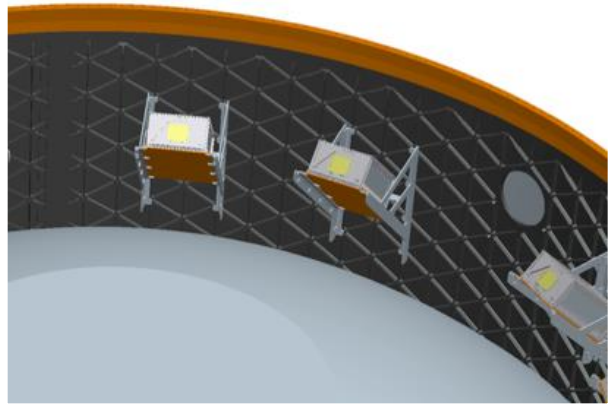


Figure 6 SLS Block 1 secondary payload accommodations

Secondary payloads on SLS will remain powered off during the ascent phase of the launch vehicle, through separation of the Orion spacecraft. Once separation is confirmed, the ICPS will send a discrete signal to the Secondary Payload Deployment System’s avionics unit to activate. The schedule for deployments will be loaded prior to vehicle stacking. No real-time commanding or telemetry is available; therefore, payloads will be deployed automatically through the pre-determined mission timeline sequence.

Secondary payloads will have opportunity to be deployed after the ICPS disposal sequence is complete (approximately T+4 hours) and up to 10 days from launch. (Fig. 7) All deployments will be completed before avionics batteries are expended.

Once deployed, secondary payloads will be required to wait 15 seconds before deploying antennas, solar panels, sails, etc. to ensure adequate clearance from ICPS. Payload communications following deployment will be the responsibility of the secondary payload project, with no resources being provided by SLS.

VI. EM-1 Secondary Payloads

CubeSat secondary 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. AES selected the first three payloads to fly on EM-1 at the same time the capability for accommodating secondary payloads on the SLS was being developed.

Near Earth Asteroid (NEA) Scout is a 6U CubeSat designed to rendezvous and characterize a candidate NEA. A solar sail, another innovation to be demonstrated in the CubeSat class, will provide propulsion.

Lunar Flashlight is the second AES payload planned for manifest on EM-1. It will use a green propellant system and will search for potential ice deposits in the Moon’s permanently shadowed craters. Pulsed lasers will be used to illuminate the surface. Surface reflection will be measured by a spectrometer to distinguish water ices from regolith.

The third payload being developed by AES is BioSentinel. The payload is a yeast radiation biosensor, planned to measure the effects of space radiation on deoxyribonucleic acid (DNA). This will be accomplished by entering into a heliocentric orbit, outside of the Van Allen belts to expose the payload to a deep space radiation environment.

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). The payloads selected are Lunar Icecube, a collaboration with Morehead State University, and Skyfire, a partnership with Lockheed Martin. Lunar Icecube 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 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.

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. The Centennial Challenges Program is NASA’s flagship program for technology prize competitions (www.nasa.gov/challenges). The program directly engages the public, academia and industry in open prize competitions to stimulate innovation in technologies that have benefit to NASA and the nation.

STMD has released the CubeSat Lunar Challenge to foster innovations in small spacecraft propulsion and communications.

There are two concurrent In-Space Competitions, the Lunar Derby and the Deep Space Derby. In the Lunar Derby, there are prizes awarded for successfully achieving lunar orbit, downlinking the largest volume of error-free data and surviving the longest. In the Deep Space Derby (> 4 million km), there are prizes awarded for farthest data transmission distance, largest volume of error-free data and longest duration of operability. Potential candidates for the three STMD opportunities on the EM-1 mission competed in a series of four Ground Tournaments before final selection is made.

The three STMD selectees were announced in June 2017. The three teams are Cislunar Explorers, from Cornell University, in Ithaca, New York; CU-E3, from the University of Colorado; and Team Miles, from Fluid & Reason, LLC, in Tampa, Florida. The Cislunar Explorers' CubeSat is focused around a water-electrolysis-based propulsion system, CU-E3 is designed for a communications demonstration mission, and Team Miles will demonstrate evolutionary plasma thrusters.

The NASA Science Mission Directorate (SMD) was allocated two payload opportunities on the EM-1 mission. The NASA SMD issued an amendment to its annual Announcement of Opportunity (AO) in the Research Opportunities in Space and Earth Sciences-2014 (ROSES-2014) Solicitation NNH14ZDA001N-HTIDS Heliophysics Technology and Instrument Development for Science. Within this Amendment was the request for CubeSat proposals specific to the Exploration Mission 1 launch opportunity focusing on the heliophysics science enabled through the unique deployment location and trajectory afforded through the planned EM-1 mission. The CubeSat Mission to Study Solar Particles (CuSP) payload was selected under this AO. CuSP 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. A Small Innovative Missions for Planetary Exploration (SIMPLEx) NASA Research Announcement (NRA) was also released as part

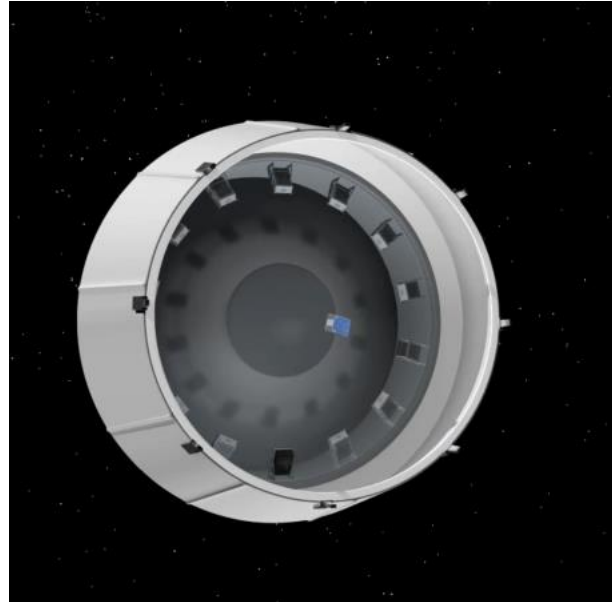


Figure 7 Deployment of CubeSat on EM-1

of the ROSES-2014 AO. The LunaH-Map payload was selected from this NRA. The LunaH-Map 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. From that joint process three payloads were chosen: Outstanding MOon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor (OMOTENASHI), EQUilibriUm Lunar-Earth point 6U Spacecraft (EQUULEUS) and ArgoMoon.

ArgoMoon is sponsored by the European Space Agency and the Italian Space Agency, ASI, and will fly-along with the ICPS on its disposal trajectory. The primary objectives are to perform proximity operations with the ICPS post-disposal, take external imagery of engineering and historical significance, and perform an optical communications demonstration.

The EQUULEUS spacecraft sponsored by the Japanese space agency, JAXA, will fly to a libration orbit around the Earth-Moon Lagrange Point 2 point and demonstrate trajectory control techniques within the Sun-Earth-Moon region for the first time by a CubeSat spacecraft. The mission will also contribute to the future human exploration scenario by understanding the radiation environment in geospace and deep space, characterizing the flux of impacting meteors on the far side of the moon, and demonstrating the future deep space exploration scenario using the "deep space port" at Lagrange points.

The OMOTENASHI mission, also 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. Small landers will enable multi-point exploration, which is complimentary with large-scale human exploration. Once on the lunar

surface, the OMOTENASHI spacecraft will observe the radiation and soil environments of the lunar surface by active radiation measurements and soil shear measurements.

Progress is being made in preparations for the launch of these secondary payloads on EM-1. The brackets for the CubeSat deployers have been mounted on the Orion Stage Adapter for the flight; the deployers and payloads will be integrated at Kennedy Space Center. The secondary payloads team within the Space Launch System Program is conducting ongoing safety reviews with the teams responsible for the payloads.

VII. Future Opportunities

After EM-1, SLS will evolve from the 70 t Block 1 configuration to the 105 t Block 1B configuration. That configuration of the rocket will replace the one-engine ICPS in-space stage with the four-engine EUS upper stage, and, as a result, replace both the LVSA and the OSA, where the EM-1 CubeSat payloads will be mounted, with the new Universal Stage Adapter. The USA will allow the rocket to carry large co-manifested payloads along with the Orion spacecraft, and these payloads will be mounted within the USA on a Payload Adapter. These hardware elements will also be part of the 130 t Block 2 configuration of the vehicle, so planning for secondary payload accommodations on the Block 1B vehicle will be relevant to Block 2 as well.

Current plans are for this Payload Adapter to carry CubeSat-class small satellite secondary payloads. In this arrangement, SLS would be able to carry larger CubeSats than EM-1 and more of them. The Payload Adapter would have eight areas for mounting secondary payload hardware. One of those areas would be used for an avionics unit. Each of the remaining areas could be used to carry either one 27U CubeSat, two 12U CubeSats, or three 6U CubeSats, in any combination. Depending on vehicle mass allocation, it could for example, carry seven 27U CubeSats or 21 6U CubeSats or two 27U, six 12U and six 6U payloads. (Fig. 8)

Possibilities are still being evaluated for enabling even larger smallsats or adding more berths for CubeSats in the future.

VIII. Conclusion

NASA's Space Launch System (SLS) will provide unprecedented capability to further advances in science and exploration. The capability to deploy small satellites allows SLS to utilize excess capability on the planned exploration missions. With the planned mission trajectories, small satellite payload developers will have an opportunity to operate in deep space, a capability not realized to this point. As the SLS vehicle evolves its configuration and becomes more capable, the opportunities for secondary payloads of different types and sizes will increase.

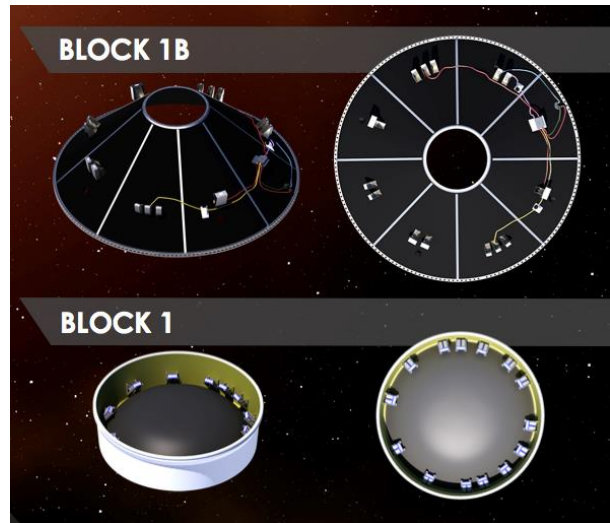


Figure 8 Block 1 and 1B accommodations