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Space Launch System Artemis I CubeSats: SmallSat Vanguards of Exploration, Science and Technology

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ABSTRACT

When NASA's Space Launch System (SLS) rocket launches in 2021 with the Orion crew vehicle, it will lay the foundation for NASA's goal of landing the first woman and the next man on the Moon as part of the Artemis program. This first flight — Artemis I — will also mark a milestone for smallsats. Thirteen 6U CubeSats are manifested on the Artemis I flight, the first fleet of CubeSats carried as a rideshare opportunity to deep space. (NASA's first CubeSats to deep space, the twin Mars Cube One [MarCO] spacecraft, were an integral part of the InSight Mars lander mission). The Artemis I CubeSat manifest represents a diverse collection of smallsats performing an array of science missions and technology demonstrations. Payloads from NASA, international partners, academia and industry will execute a variety of experiments. Several smallsats will perform lunar-focused missions that may return data that addresses Strategic Knowledge Gaps (SKGs) in the agency's lunar exploration program. Indeed, the Artemis I CubeSats will be in the vanguard of the agency's 21st-century lunar program. The Artemis I missions will produce data to support space radiation awareness, crewed landings and *in-situ* resource utilization, helping to support a sustained human lunar presence. Several of the Artemis I CubeSats are demonstrating new technologies, including propulsion capabilities. Among the Artemis I CubeSats are three selected through NASA's Cube Quest Challenge, part of the Centennial Challenges program. These three missions will compete for prize money while meeting specific technical development goals. Payloads from the Japanese and Italian space agencies provide an early opportunity for international involvement in the Artemis program. Student involvement in almost half of the payloads allow STEM engagement with NASA's Artemis program. The SLS Block 1 vehicle for the Artemis I flight is manufactured with several elements delivered to Kennedy Space Center (KSC) and being prepared for stacking and integration. The new-development of the program, the 212-foot core stage with its four RS-25 engines installed is currently at Stennis Space Center (SSC) for "green run" testing. Following the green run test campaign, the stage will ship to KSC, where it will be integrated with the rest of the vehicle, including the upper stage adapter, where the Artemis I smallsats will be housed.

SLS OVERVIEW

NASA's Space Launch System (SLS) is the agency's new super heavy-lift vehicle for crewed and cargo missions to deep space. Designed to return NASA's human spaceflight program to the Moon by launching the Orion crew spacecraft as well as large mass and volume infrastructure to lunar orbit, the vehicle can also accommodate CubeSat payloads for rideshare flights, depending on mission parameters. The vehicle is a 2.5-stage inline design, with propulsion provided by two five-segment solid rocket boosters and four liquid hydrogen/liquid oxygen (LH2/LOX)-fed RS-25 engines. To minimize new developments, the SLS Program chose a proven, reliable propulsion system that leverages existing structures, technology and industrial base from the Space Shuttle Program.

The vehicle has a planned evolutionary path with each block upgrade increasing mass-to-destination capability over the previous variant. SLS is designed in its crew configuration to carry Orion and also has the flexibility to be outfitted with payload fairings in varying diameters and lengths to accommodate large interplanetary science probe, astrophysics missions and may others.

The initial vehicle configuration, Block 1, uses a modified commercial upper stage, the Interim Cryogenic Propulsion Stage (ICPS), based on the Delta Cryogenic Second Stage (DCSS) from United Launch Alliance (ULA). An adapter known as the Launch Vehicle Stage Adapter (LVSA) changes the vehicle's diameter from 8.4 m to 5 m and partially encloses the ICPS on the Block 1 crew vehicle. The LVSA attaches the ICPS to the core stage. Another adapter, the Orion Stage Adapter (OSA), connects SLS ICPS to the Orion spacecraft and provides volume for 6U and 12U CubeSats. For the cargo configuration, the Block 1 vehicle can be outfitted with a 5-m class payload fairing. The Block 1 vehicle will lift at least 27 metric tons (t) to trans-lunar injection (TLI).

The intermediate variant to come online, Block 1B, will onramp propulsion upgrades, mass reductions and a more powerful upper stage to

Figure 1. Rendering of NASA's Space Launch System (SLS) and Orion crew spacecraft ready for launch on the Mobile Launcher (ML) at Kennedy Space Center (KSC) for the Artemis I flight, which has 13 6U CubeSats manifested.

increase performance. Block 1B will increase payload mass to TLI to 38-42 t depending on whether configured for crew or outfitted with an 8.4-m diameter payload fairing. The new upper stage, known as Exploration Upper Stage (EUS), is a four-engine LH2/LOX system that provides unparalleled departure energy to make previously impossible science mission profiles to the outer solar system possible. In addition, the 8.4 m payload fairing, available in 19.1 m and 27.4 m lengths, provides unparalleled volume for payloads.

The ultimate variant, Block 2, will deliver 43-46 t to TLI depending on crew or cargo configuration. Block 2 will incorporate evolved solid rocket boosters and other upgrades to achieve this performance. The Block 2 performance, coupled with 8.4-m diameter fairings, can make many new deep space missions possible, such as crewed missions to Mars, habitation modules to Martian orbit, a lander on Europa, a mission to Neptune and its moon Triton, a solar-system escape mission to the very local interstellar medium (VLIM), and more.

Although designed to usher in a new generation of deep space exploration of crew and large cargo missions, SLS will also offer rideshare opportunities to CubeSats when mission parameters allow, giving CubeSats access to deep space. CubeSats in 6U or 12U sizes may be accommodated on future flights of the Block 1 vehicle. In addition, in the evolved versions of SLS (Block 1B and Block 2), it may be possible to house a combination of 6U, 12U, 27U and potentially larger smallsats on a payload adapter. Also in Block 1B and Block 2, volume is available for CubeSats in a propulsive ring-type structure. Mission planners continue to develop concepts for smallsat accommodations on the various configurations of SLS.

ARTEMIS I OVERVIEW

Artemis I will be an uncrewed launch of SLS with 13 CubeSats, delivering the Orion spacecraft to a lunar distant retrograde orbit (DRO). The launch will serve as a rigorous checkout of SLS, Orion and new ground processing and launch facilities at Kennedy Space Center (KSC) before crew fly

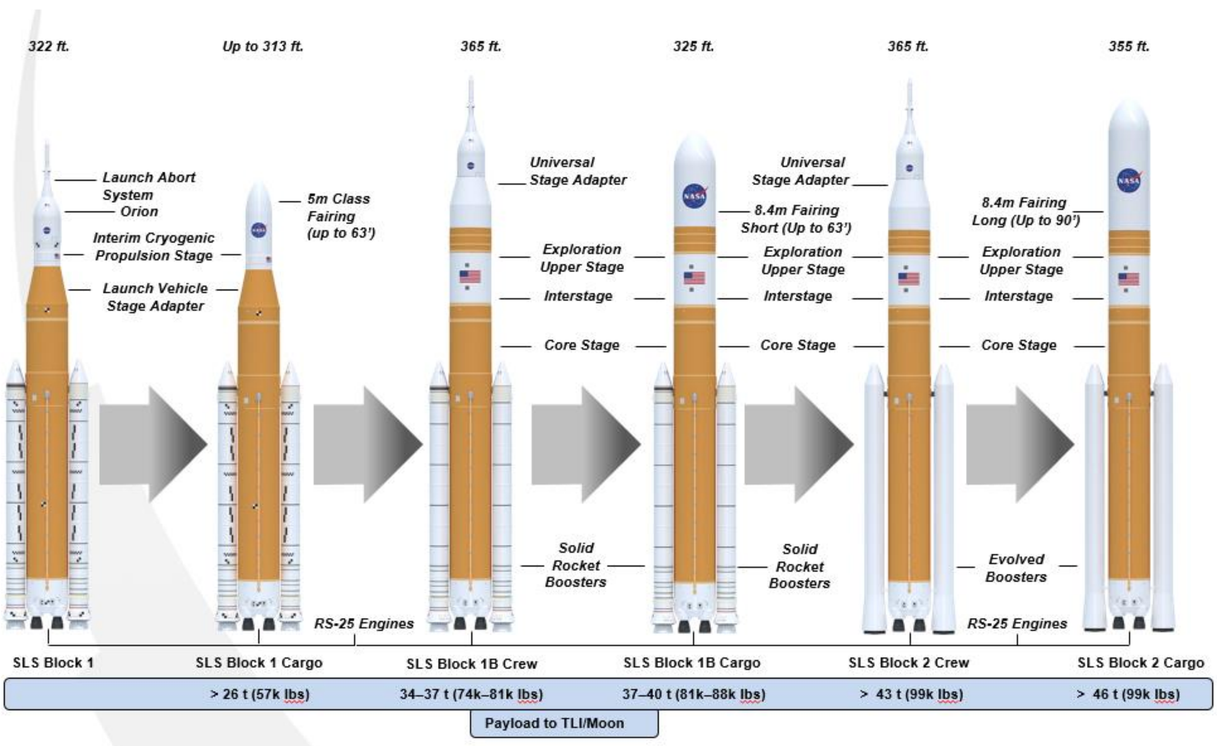

Figure 2. SLS Block 1 will be first variant to launch, with Block 1B and Block 2 providing more mass to deep space destinations for crewed and cargo flights.

on Artemis II, the second flight of SLS and Orion. Technicians will assemble the SLS-Orion stack in KSC's iconic Vehicle Assembly Building (VAB), where the Saturn V Moon rockets and space shuttles were also integrated. The stack will be built up on the Mobile Launcher (ML); the Crawler-Transporter will move the 322-foot vehicle to Launch Complex 39B. Launch countdown and monitoring will occur at KSC's Launch Control Center (LCC) and distributed NASA and industry partner sites throughout the U. S., including the SLS Engineering Support Center (SESC) at Marshall Space Flight Center (MSFC) in Huntsville, Alabama, which also manages the program.

On launch day, after polling is complete and the countdown reaches zero, the four RS-25 engines will light milliseconds prior to the solid rocket booster ignition sequence commencing. After the 5.75 million lb. vehicle clears the ML tower, the Mission Control Center (MCC) at Johnson Space Center (JSC) in Houston takes control of the Artemis I mission.

The SLS solid rocket boosters — the largest ever built for flight — burn for about two minutes, then are jettisoned into the Atlantic Ocean. The RS-25 engines burn for approximately another six minutes to place the vehicle in a high arc. Next, the ICPS will make its first burn to place Orion in an Earth orbit. From this parking orbit at 100 x 1,450 nmi, engineers will perform various system checks before committing to trans-lunar injection (TLI). When engineers give the "go" for TLI, the ICPS will perform the TLI burn to send Orion toward the Moon, followed by ICPS disposal. Orion's outbound transit to the Moon will take five to six days. At about six days and 62 miles from the Moon, Orion's service module will perform the burn to insert the spacecraft into DRO for the next six to 23 days. Orion will perform a free-return to Earth after a lunar return power flyby.

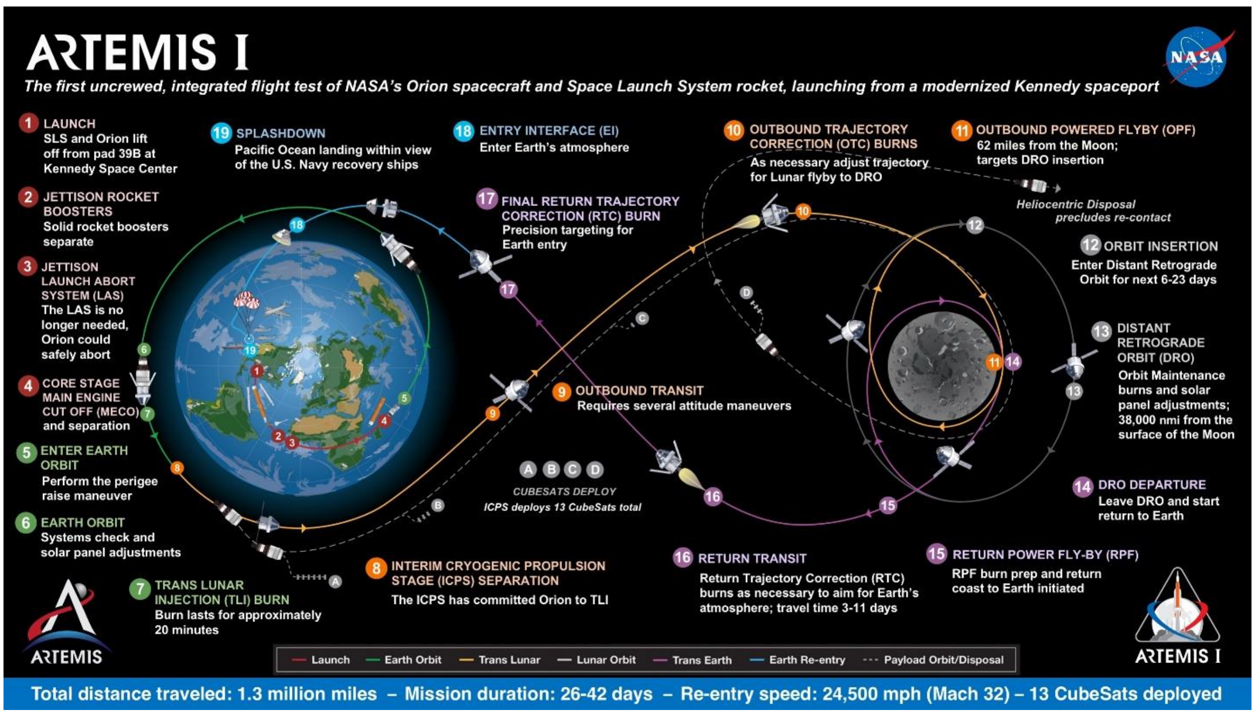

Figure 3. Artemis I mission map showing major events, including CubeSat deployment.

After the ICPS has performed the TLI burn and separated from Orion, it will perform some final maneuvers to insert into a heliocentric disposal trajectory. Once the ICPS and OSA have cleared the first Van Allen Belt, CubeSat deployment will begin. Over the next two days, the CubeSats will be released at designated intervals, with enough time elapsing between deployments to minimize the chance of recontact, until the final smallsat is headed for its deep space destination.

ARTEMIS I SMALLSATS

The manifested 6U CubeSats for the Artemis I flight represent a diverse array of missions from international space agencies, industry, NASA projects, universities and small businesses (see Table 1). Three of the spacecraft are competing in the Cube Quest Challenge, part of NASA's Centennial Challenges, which are ongoing competitions that provide prizes to solve technical challenges. The three Cube Quest Challenge spacecraft — Team Miles, Cislunar Explorers and CU-E^3 — are now competing for a multimillion-dollar prize, having earned the "ride of a lifetime" on SLS by placing high in qualifying ground tournaments.

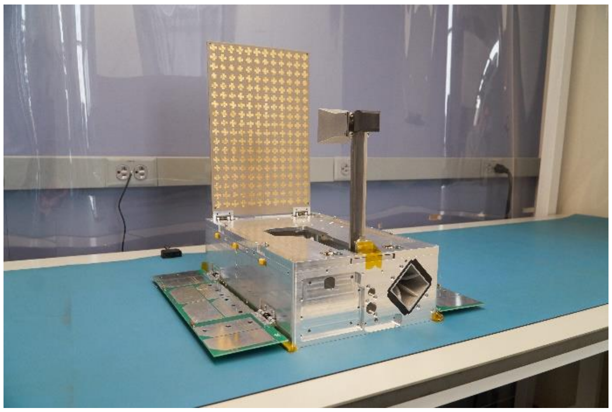

Figure 4. The assembled CU-E^3 spacecraft from the University of Colorado-Boulder, one of the missions competing in the Cube Quest challenge.

The CubeSat from Team Miles, a small business that includes team members from several states, will attempt to communicate with Earth from a minimum of four million kilometers in space. The mission also includes a propulsion technology demonstration using plasma thrusters. Cislunar Explorers, from Cornell University, is a flight experiment that uses water as an environmentally friendly, dense, high-efficiency propellant. The 6U CubeSat will split into two 3U spacecraft that spin continuously around the thrusters' axes, flinging the water outward, similar to a centrifuge, and separating inert from electrolyzed propellant. Their mission is to orbit the moon and meet the challenges goals. Finally, the University of Colorado Earth Escape Explorer (CU-E^3) from the University of Colorado-Boulder, will compete in the Deep Space Derby for best data burst rate, largest aggregate volume data sustained over time and farthest communication from Earth. The mission is targeting a distance of more than 10 times the distance between the Earth and Moon.

From industry, Lockheed Martin is providing the LunIR mission. LunIR will use a miniature high-temperature mid-wave infrared sensor to collect imagery of the lunar surface. The mission hopes to return thousands of images of the lunar surface. Payloads from international space agencies include two from JAXA, the Japanese space agency. EQUilibriUm Lunar-Earth point 6U Spacecraft (EQUULEUS) will use one instrument to image the Earth's plasmasphere from an Earth-Moon L2 point. Another instrument will characterize the size and distribution of lunar dust particles. JAXA's other Artemis I spacecraft, Outstanding Moon exploration TEchnologies demonstrated by NAno Semi-Hard Impactor (OMOTENASHI), will observe the lunar radiation environment and demonstrate extremely small technologies useful for a lunar landing. In fact, OMOTENASHI will be the smallest spacecraft ever to land on the Moon, if successful. The Italian Space Agency, ASI, will provide the ArgoMoon mission. ArgoMoon will use a new "green" propellant

Figure 5. Testing the thrusters on the CubeSat from Team Miles, which is also competing in Centennial Challenges' Cube Quest Challenge.

Figure 6. Team members assemble the BioSentinel spacecraft, which will study the effects of radiation on yeast in deep space.

propulsion system to perform proximity operations near the ICPS and the Moon. ArgoMoon's imaging system with an advanced software algorithm will locate the ICPS and collect imagery of the upper stage as well as take pictures of the Earth and Moon. The mission will also take high-resolution images of potential lunar landing locations.

In addition to the two university-supplied CubeSats competing in the Cube Quest Challenge, other universities have partnered with NASA on Artemis I CubeSats. Morehead State University will supply the Lunar IceCube mission. Lunar IceCube will search for water (ice, liquid and vapor) and other volatiles using a broadband infrared compact high-resolution exploration spectrometer. Lunar IceCube will fly over the lunar surface in a low-perilune highly inclined orbit and may return valuable data to inform future Artemis missions. Likewise, a mission from Arizona State University, LunaH-Map will enter a low-perilune, polar orbit and use a miniaturized neutron spectrometer to measure the count rates of neutrons leaking from the lunar surface at low altitude over the south pole. LunaH-Map will determine the spatial distribution of hydrogen within permanently shadowed regions at unprecedented spatial resolution. Another CubeSat mission with the potential to pave the way for future Artemis missions is Lunar Flashlight, developed by NASA's Jet Propulsion Laboratory (JPL). Lunar Flashlight will scour the lunar surface for ice deposits using near-infrared-band lasers. Lasers will shine light into the shaded polar regions, while the onboard spectrometer measures surface reflection and composition.

Missions not focused on lunar science include the Southwest Research Institute's CubeSat to Study Solar Particles (CuSP). This experiment will study the sources and acceleration mechanisms of solar and interplanetary particles in near-Earth solar orbit. The mission will help scientists gain insight into space weather as well as advance the technology readiness level (TRL) of the spacecraft's suprathermal ion spectrograph. BioSentinel, from NASA's Ames Research

Figure 6. The Lunar IceCube spacecraft's solar array undergoing electromagnetic testing at Morehead State University.

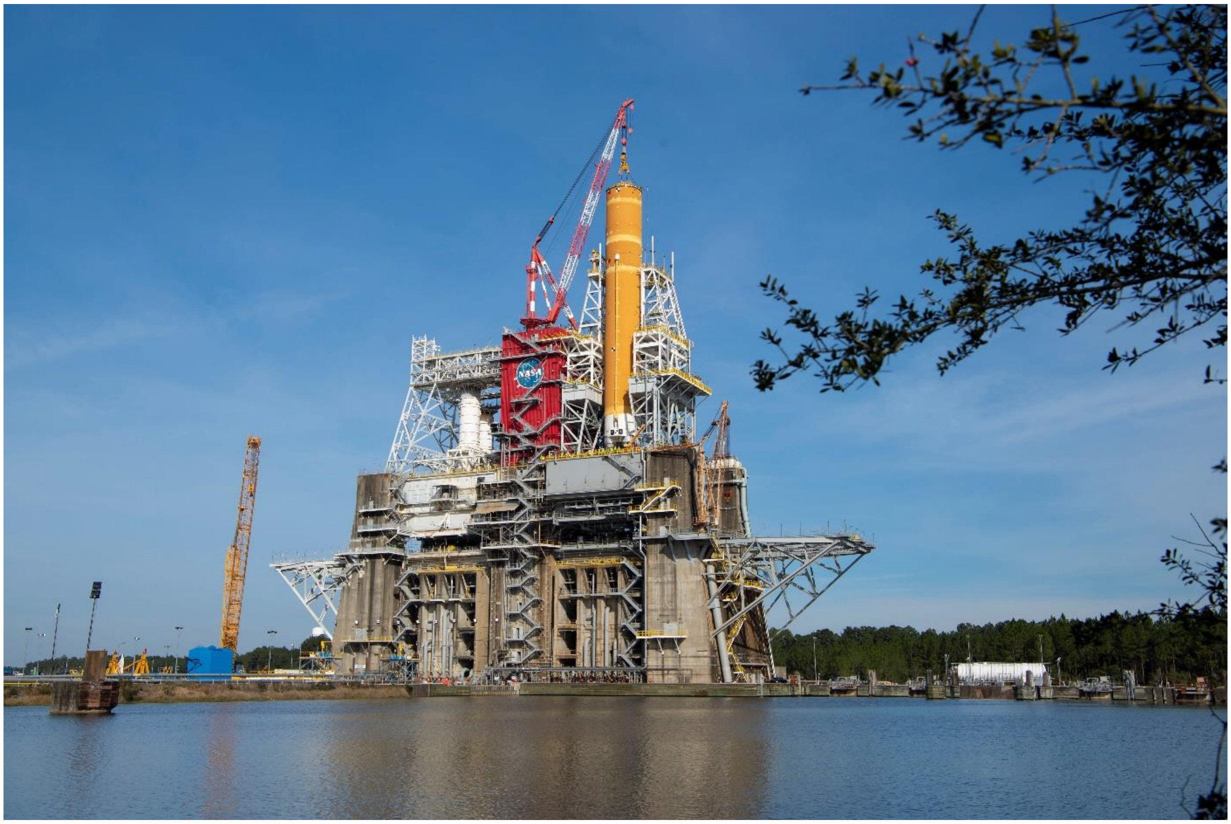

Figure 8. The SLS core stage is currently undergoing "green run" testing at Stennis Space Center (SSC) in preparation for the Artemis I flight.

Center, is developing a biosensor using yeast to detect, measure and correlate with other measurements the impact of space radiation to living organisms over long durations beyond low Earth orbit (LEO). The Near Earth Asteroid Scout (NEA Scout), from MSFC, will map a target near-Earth asteroid for imaging. The spacecraft will observe the asteroid's position in space, its shape, rotational properties, spectral class, local dust and debris field, regional morphology and regolith properties. NEA Scout will use a 38' x 38' solar sail for propulsion.

The Artemis I CubeSat developers are continuing final testing and assembly of their spacecraft, with several smallsats now having completed final assembly. The fully assembled spacecraft will ship to the dispenser vendor site for integration with the commercial off-the-shelf (COTS) dispensers. From there, the dispensers with integrated spacecraft will ship to KSC for integration with the Secondary Payload Deployment System (SPDS) in the OSA. The SPDS provided by the SLS Program includes an avionics unit, brackets for holding the dispensers, a vibration mitigation system and cable harnesses.

Figure 9. The completed Orion Stage Adapter (OSA) with brackets to hold the 13 6U CubeSats in dispensers (and avionics unit) that are manifested on the Artemis I flight.

Figure 10. NEA Scout team members at NASA's Jet Propulsion Laboratory (JPL) paused for a picture with their spacecraft's avionics unit before it shipped to Marshall Space Flight Center (MSFC) for integration and testing.

ARTEMIS I VEHICLE'S PROGRESS TOWARD LAUNCH

The Artemis I vehicle has completed fabrication. All elements are either at KSC, *en route* at the time of writing, or expected at the end of 2020. The Orion crew vehicle, as well as preparations in the Vehicle Assembly Building (VAB) necessary to assemble the SLS and Orion stack, are likewise complete. The ML and Launch Complex 39B have been upgraded and stand ready for the Artemis I launch.

Below the Orion crew vehicle and its launch abort system (LAS), sits the OSA. The OSA was completed, with the SPDS tested, before shipping to KSC in 2018. The OSA is currently housed in the Space Station Processing Facility (SSPF) at KSC. All Artemis I CubeSat payloads are scheduled to be integrated into their COTS dispensers and installed in the OSA in the SSPF with the exception of OMOTENASHI. That solid-rocket-motor, lunar-lander mission will complete its assembly and be installed in its dispenser in KSC's Multi-Payload Processing Facility (MPPF) prior to installation on the OSA in the SSPF.

Below the OSA in the stacked SLS vehicle are the ICPS and the LVSA. The ICPS was complete and delivered to KSC in 2017. The LVSA is preparing to ship to KSC in summer 2020, having been delayed due to a work stoppage related to the COVID-19 pandemic. The LVSA changes the diameter of the vehicle and provides protection for the ICPS during launch as well as access to the ICPS during ground processing.

Below the ICPS and LVSA is the core stage, the program's all-new development. The core stage contains the avionics and propellant tanks, as well as an engine section and boattail assembly to house the four RS-25 engines. Currently located at Stennis Space Center (SSC), the Artemis I core stage is undergoing "green run" testing. The green run test campaign includes nine major tests, including avionics power-on, filling the LOX and LH2 tanks with cryogenic propellant, de-tanking the propellant as part of a "wet dress rehearsal," then refilling the tanks again. Finally, the four RS-25 engines will be simultaneously hot-fired. Plans are for the engines to fire in a full-duration 500-second test, the same length of time they will

Figure 11. After completing safety reviews for their two Artemis I CubeSats, team members from JAXA received a tour of KSC's Vehicle Assembly Building, where SLS and Orion will be integrated for the Artemis I flight.

fire during Artemis I in order to place the vehicle in a parking orbit. This thorough testing and analysis of the SLS core stage reduces risk not only for the first flight but also reduces the risks of anomalies that would delay future flights. At the completion of the green run test campaign the stage will ship to KSC.

Two solid rocket boosters will provide more than 75 percent of the vehicle's thrust during the first two minutes of flight. The SLS solid rocket boosters leverage the space shuttle booster technology, but are 20 percent more powerful due to an extra propellant segment. The SLS solid rocket motor segments for the Artemis I flight are complete and preparing to ship to KSC. Forward and aft structures, including the thrust vector control system in the booster aft skirts, are also finished.

After the booster motor segments are received at KSC and inspected, assembly will begin at the Rotation, Processing & Surge Facility (RPSF). Aft segments are mated to the aft skirt assemblies and aft exit cones. Once the aft parts of the boosters are assembled, stacking the boosters on the ML in the VAB can begin. Stacking the booster aft structures and segments on the ML in the VAB is scheduled to start about nine months prior to launch. Once the boosters are stacked, the core stage, with four RS-25 engines integrated, will be lifted out of the transfer aisle in the VAB, carefully lowered between the boosters, and mated. The ICPS and LVSA will then be stacked on the core. Finally, the OSA, with the CubeSats integrated into their dispensers, will be stacked on the ICPS and LVSA. Orion's spacecraft adapter will attach to the OSA. The European service module will sit on the spacecraft adapter, followed by the Orion crew vehicle. Orion's LAS will complete the stack.

FUTURE SLS MISSIONS

Additional flights using the Block 1 vehicle with its ICPS and OSA are planned. The OSA can accommodate a combination of 6U and 12U CubeSats, total of up to 17. As the program moves toward Block 1B availability in the next few years, engineers are evaluating accommodations for CubeSats on a payload adapter in the Block 1B crew and cargo configurations. Propulsive ring-type deployment systems for CubeSats are also being considered for future flights, if mission parameters allow. These increased capabilities will provide greater opportunities for smallsat missions.

CONCLUSION

As an entirely new capability for crewed lunar missions as well as missions to send science probes deep into the solar system and beyond, SLS is ushering in a new generation of space exploration. SLS will provide a reliable launch asset for crew as well as large-volume and -mass cargo payloads, such as deep space infrastructure. The Artemis I CubeSat missions will have the rare opportunity to be deployed in deep space, with the first missions targeted to be released between the Van Allen Belts. With several missions destined for cislunar space, the Artemis I CubeSats are poised to be in the vanguard of NASA's Artemis program, testing new technologies and helping pinpoint lunar resources that can be utilized on future missions. As SLS evolves to increased performance and capacity for ever-larger payloads, vehicle planners continue to develop concepts for integrating CubeSats into future missions. As SLS opens the solar system for exploration, CubeSats to deep space can help make exciting new discoveries and test key technologies.

Table 1. Artemis I CubeSat Manifest.

Payload	Developer(s)	Sponsor	Destination	Mission
ArgoMoon	Argotec	Agenzia Spaziale Italiana (ASI)	After proximity operations with the ICPS, will transit to lunar orbit for additional imaging	Photograph the ICPS, CubeSat deployment, the Earth and Moon using HD cameras and advanced imaging software
Biosentinel	NASA Ames, NASA Johnson, Loma Linda University Medical Center, University of Saskatchewan	NASA Advanced Exploration Systems (AES)	Heliocentric orbit via lunar flyby	Use yeast as a biosensor to evaluate the effects of ambient space radiation on DNA
Cislunar Explorers	Cornell University	NASA Cube Quest Challenge, sponsored by NASA's Science Technology Mission Directorate (STMD) Centennial Challenges	Lunar orbit	Demonstrate use of an inert water-based propulsion system for lunar gravity assists and capture in lunar orbit; compete in NASA's Lunar Derby
CubeSat to Study Solar Particles (CuSP)	Southwest Research Institute, NASA Goddard	NASA Science Mission Directorate (SMD)	Deep space	Study the sources and acceleration mechanisms of solar and interplanetary particles in near-Earth orbit
EQUilibriUm Lunar-Earth point 6U Spacecraft (EQUULEUS)	University of Tokyo	Japanese Aerospace Exploration Agency (JAXA)	Earth-Moon L2 point	Demonstrate trajectory control techniques within the Sun-Earth-Moon region and image Earth's plasmasphere
Lunar IceCube	Morehead State University, NASA JPL, NASA Goddard, BUSEK	NASA Next Space Technologies for Exploration Partnerships (NextSTEP)	Lunar orbit	Search for water (and other volatiles) in ice, liquid and vapor states using infrared spectrometer
Lunar Flashlight	NASA JPL	NASA AES	Lunar orbit	Search for ice deposits using near-infrared band lasers
Lunar-Polar Hydrogen Mapper (LunaH-Map)	Arizona State University	NASA SMD	Lunar orbit	Perform neutron spectroscopy to characterize abundance of hydrogen in permanently shaded craters
LunIR	Lockheed Martin Space Systems	NASA NextSTEP	Heliocentric orbit via lunar flyby	Use a miniature high-temperature Mid-Wave Infrared (MWIR) sensor to characterize the lunar surface
Near Earth Asteroid (NEA) Scout	NASA Marshall	NASA AES	NEA within ~1.0 AU of Earth	Detect target NEA, perform reconnaissance and close proximity imaging
Outstanding MOon exploration Tech-nologies demonstrated by Nano Semi-Hard	Institute of Space and Astronautical Science (ISAS)/JAXA	JAXA	Lunar surface	Develop world's smallest lunar lander and observe lunar radiation environment

Payload	Developer(s)	Sponsor	Destination	Mission
Impactor (OMOTENASHI)				
Team Miles	Miles Space, LLC	NASA Cube Quest Challenge, sponsored by STMD Centennial Challenges	Deep space	Demonstrate propulsion using plasma thrusters; compete in NASA's Deep Space Derby
University of Colorado-Earth Escape Explorer (CU-E^3)	University of Colorado Boulder	NASA Cube Quest Challenge, sponsored by STMD Centennial Challenges	Deep space	Demonstrate use of solar radiation pressure for propulsion; compete in NASA's Deep Space Derby