NASA's Space Launch System: Progress Toward Launch

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The Space Launch System (SLS), NASA's cornerstone launch capability for a new generation of deep space exploration, has begun assembly at Kennedy Space Center (KSC) in preparation for launch in 2021. SLS will provide an unparalleled launch capability for human and robotic deep space exploration missions. Its proven propulsion system, upgrade path to more powerful vehicles, and high-volume payload fairings make it the foundation for ambitious and demanding as part of the Artemis program. Artemis is NASA's 21st-century plan to put boots on the Moon and to perform sustainable, long-term science in deep space, with eyes toward sending explorers to Mars. The initial SLS vehicle to fly, Block 1 in the crew configuration – with the new Orion spacecraft – is scheduled to lift off from revitalized launch facilities at KSC in 2021 for an uncrewed test flight known as Artemis I. Manufacturing is complete on the vehicle and all elements have been delivered to the Exploration Ground Systems (EGS) Program, except the core stage. The program's all-new development, the core stage is currently in the midst of a "Green Run" test campaign at Stennis Space Center (SSC). Eight progressively more challenging tests in the Green Run series will culminate in a hot-fire of four flight-proven liquid hydrogen/liquid oxygen (LH2/LOX) RS-25 engines. Following the Green Run hot-firing, the core stage will ship to KSC. Already at KSC, aft sections of the five-segment solid rocket boosters

Figure 1. Artist's rendering of SLS Block 1 in the crew configuration with Orion on the Mobile Launcher at Kennedy Space Center's (KSC's) Launch Complex 39B.

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are being assembled. Previously delivered elements, including the upper stage, are undergoing final checkouts in preparation for stacking. An exciting 2021 will include such milestones as stacking SLS and Orion in KSC's Vehicle Assembly Building (VAB), modal testing, roll out to Launch Pad 39B, Wet Dress Rehearsal (WDR), and launch. Teams across the country are preparing for launch by finalizing procedures, defining launch constraints and flight rules, training console operators, performing simulations, and more. With the SLS Block 1 vehicle for Artemis I nearing integration and launch, the second Block 1 vehicle in the crew configuration, which will carry astronauts on an Artemis II hybrid lunar flyby mission, has several elements manufactured. In fact, the solid rocket motor segments and RS-25 engines are complete. Those program elements are processing hardware for the third flight and working toward manufacturing the second SLS variant to fly, Block 1B, which will onramp a powerful new upper stage, the Exploration Upper Stage (EUS).

I. Introduction to SLS

Designed to launch NASA's most ambitious and challenging missions, SLS lifts more mass, provides more volume in wide-diameter payload fairings, and launches with more departure energy than commercial launch vehicles. With a block upgrade path planned that will increase lift capability and the flexibility to configure each block variant for crew or with large payload shrouds, SLS provides unique benefits for launching crewed and automated/robotic missions beyond Earth's orbit (see Figure 2). For interplanetary probes, SLS can launch high-energy missions to the outer solar system, such as directly to Jupiter or with additional stages in a high-volume payload fairing to enable missions to Europa, Enceladus, Neptune and Triton, Pluto, or interstellar space. [1, 2, 3, 4, 5] The wide-diameter payload fairings enable a new generation of wide-aperture space telescope missions, able to collect more light and see farther back in time than current missions. [6] Other applications for SLS include space-based solar power and

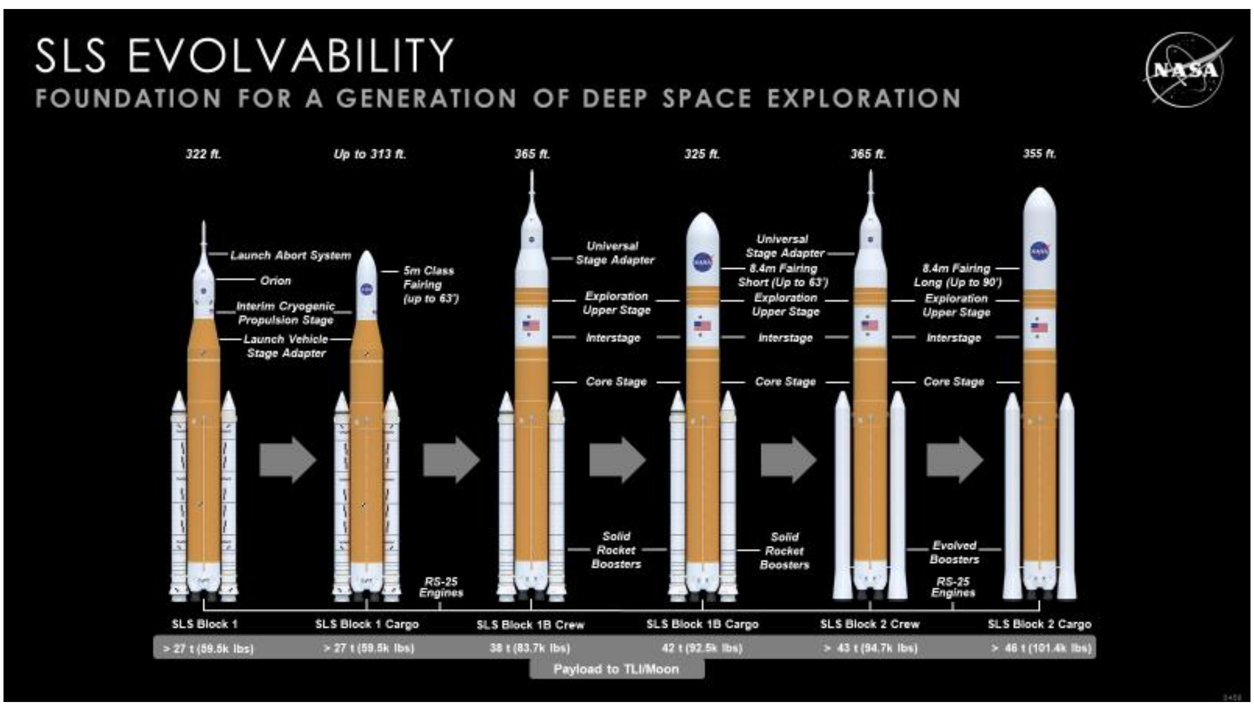


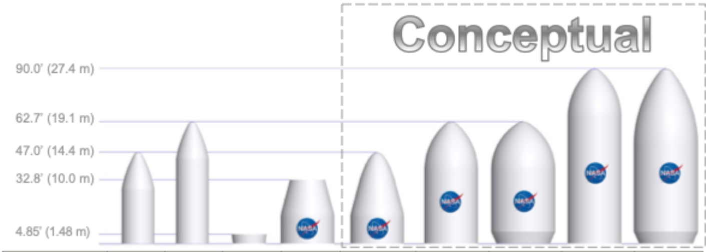
Figure 2. A series of block upgrades will increase SLS performance with each block variant having the flexibility to be configured for missions with Orion or with a large payload fairing.

harnessing its high C3 performance for mitigation of Potentially Hazardous Objects (PHOs) for planetary defense. [7, 8]

The evolutionary path of SLS includes three variants: Block 1, Block 1B, and Block 2, with each variant built on a reliable, proven propulsion system of solid rocket boosters and LH2/LOX RS-25 engines. A central core stage houses propellant tanks, engines, main propulsion system, and avionics, as well as the thrust takeouts for the solid rocket boosters. On top of this architecture, Block 1 uses a single-engine LH2/LOX modified United Launch Alliance (ULA) Interim Cryogenic Propulsion Stage (ICPS) as an in-space stage to provide a lift capability of at least 27 metric tons (t) to trans-lunar injection (TLI) for the Block 1 vehicle. Block 1B and Block 2 will replace the ICPS with a more powerful four-engine LH2/LOX EUS. Block 1B will lift at least 38-42 t to TLI, depending on crew or cargo configuration (with a payload fairing). Block 2 will use a new evolution of five-segment solid rocket boosters with composite cases, rather than steel cases, to increase vehicle lift to 34-46 t to TLI (see Figure 2).

As currently manifested, Block 1 rockets in the crew configuration will launch the first three Artemis missions to the Moon. At 322.4 feet tall and 5.7 million pounds fueled, SLS will generate up to 8.8 million pounds of thrust during ascent. In all variants, the center core stage supports four aft-mounted RS-25 liquid propellant engines and two side-mounted five-segment solid rocket boosters. Above the core stage is a Launch Vehicle Stage Adapter (LVSA) that partially encloses the ICPS in the Block 1 crew vehicle and allows access to the stage during ground processing. In the Block 1 crew vehicle, above the LVSA, the Orion Stage Adapter (OSA) connects SLS to the Orion spacecraft. The OSA also provides volume for CubeSats, with structural capability to accommodate 6U and 12U smallsats. For the Artemis I flight, 13 6U CubeSats are manifested. The Block 1 vehicle can also be outfitted with a 5 m-class payload fairing. Hardware interfaces are industry-standard on the fairing to streamline design.

Table 1. SLS offers unprecedented volume for co-manifested payloads in the Universal Stage Adapter (USA) and in large-diameter payload fairings.



Enclosure		5.1m PLF	5.1m PLF	OSA	8.4m USA	8.4m USA PLF	8.4m PLF, Short	10m PLF Short	8.4m PLF, Long	10m PLF Long
Payload Type		5m PPL	5m PPL	5m SPL	8.4m CPL	8.4m PPL	8.4m PPL	10m PPL	8.4m PPL	10m PPL
Length		47.0 ft	62.7 ft	4.85 ft	32.8 ft	47.2 ft	62.7 ft	62.7 ft	90 ft	90 ft
		14.3 m	19.1 m	1.48 m	10.0 m	14.4 m	19.1 m	19.1 m	27.4 m	27.4 m
Diameter		16.7 ft	16.7 ft	17.7 ft	27.6 ft	27.6 ft	27.6 ft	33.0 ft	27.6 ft	33.0 ft
		5.1 m	5.1 m	5.4 m	8.4 m	8.4 m	8.4 m	10.0 m	8.4 m	10.0 m
Internal Diameter		15.1 ft	15.1 ft	16.7 ft	24.6 ft	24.6 ft	24.6 ft	29.9 ft	24.6 ft	29.9 ft
		4.6 m	4.6 m	5.1 m	7.5 m	7.5 m	7.5 m	9.1 m	7.5 m	9.1 m
Available Volume		5,358 ft^3	8,118 ft^3	516 ft^3	10,100 ft^3	11,260 ft^3	21,930 ft^3	32,470 ft^3	34,910 ft^3	46,610 ft^3
		151.7 m^3	229.9 m^3	14.6 m^3	286.0 m^3	319 m^3	621 m^3	919 m^3	988 m^3	1,320 m^3
Potential Availability *(No Earlier Than)*		COTS	COTS	2021	2024	2025	2025	2029	2029	2029

COTS: Commercial Off-the-Shelf CPL: Co-manifested Payload OSA: Orion Stage Adapter PPL: Primary Payload SPL: Secondary Payload PLF: Payload Fairing

Figure 3. The aft sections of the Artemis I solid rocket boosters are currently being assembled at KSC.

Figure 4. The Artemis I core stage is currently at Stennis Space Center undergoing a Green Run test campaign, scheduled to conclude in late 2020.

The Block 1B vehicle will increase lift capability by on-ramping a new, more powerful upper stage, the EUS. The EUS is an LH2/LOX system that uses four Aerojet Rocketdyne RL10 engines. The more powerful stage, on the same reliable, high-energy propulsion system used to escape Earth's orbit – the five-segment solid rocket boosters and the four LH2/LOX RS-25s – will enable SLS to lift 38-42 t to TLI, depending on crew or cargo configuration. Because the program leveraged existing flight assets from the space shuttle program, including 14 RS-25 engines and enough steel cases for eight flight sets of boosters, the evolved boosters with composite cases will come online for the ninth SLS flight and the Block 2 variant. Those boosters, with a new propellant and electric thrust vector control system, will increase lift capacity of the Block 2 vehicle to 43-46 t, depending on crew or cargo configuration. For the Block 1B and Block 2 crew vehicles, SLS can accommodate a 10 t co-manifested payload in the Universal Stage Adapter (USA), which provides as much volume as a 5 m-class payload fairing (see Table 1). Both the Block 1B and Block 2 cargo vehicles can be outfitted with 8.4 m-diameter fairings, up to 27.4 m long, providing unprecedented volume for payloads (see Table 1). In addition to the 8. 4 m fairing, engineers are also preserving the option of a 10 m-diameter fairing for the vehicle. Designed and built from the ground up with human safety and mission success paramount, SLS is the cornerstone launch capability for the agency's Artemis initiative to land the first woman and the next man on the Moon.

II. Block 1 Progress to the Pad

The Artemis I SLS vehicle is fully manufactured and all elements have been delivered to the Exploration Ground Systems (EGS) Program at KSC with the exception of the core stage. The solid rocket booster motor segments were delivered from Northrop Grumman facilities in Utah to KSC in June 2020. Jacobs Engineering then began assembling the aft sections of the boosters, mating the aft segments to the aft skirts and exit cones (see Figure 3) shortly after delivery. The remaining segments are being inspected and stored in KSC's Rotation, Processing & Surge Facility (RPSF) until needed for stacking in the Vehicle Assembly Building (VAB). The Artemis I core stage is undergoing a battery of tests, known as "Green Run," at Stennis Space Center (SSC) in Mississippi (see Figure 4). Green Run includes eight progressively more challenging tests. At the time of writing, five tests have been successfully completed with all data collected so far validating designs and models and supporting moving forward toward a penultimate wet dress rehearsal (WDR) test and an ultimate hot-firing of the four RS-25s. Currently, the Green Run hot-firing of the Artemis I core stage is scheduled for early November 2020. Following WDR and hot-firing, the stage will be refurbished at shipped to KSC.

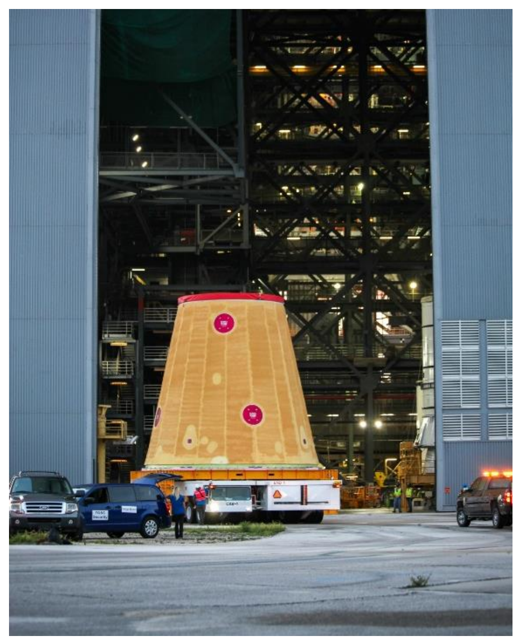


Figure 5. The Artemis I Launch Vehicle Stage Adapter (LVSA) was delivered to EGS in June 2020 and is in the Vehicle Assembly Building awaiting stacking operations.

Booster stacking in KSC's Vehicle Assembly Building (VAB) is tentatively scheduled to begin in November 2020, contingent upon a successful hot-fire of the core stage. When the core stage arrives at KSC, it will be transferred to the VAB and lowered by crane

Figure 6. The Artemis I Interim Cryogenic Propulsion Stage (ICPS) and Orion Stage Adapter (OSA) at KSC.

Figure 7. Technicians at United Launch Alliance (ULA) in Decatur, Alabama recently applied spray-on foam insulation (SOFI) to the Artemis II liquid hydrogen tank for the ICPS.

between the boosters onto the Mobile Launcher (ML) and stacking will continue. The ICPS will be stacked on the core stage, as well as the LVSA, which partially covers the ICPS. The Artemis I ICPS was delivered to EGS in 2017 (see Figure 6) and the LVSA was transported in June 2020 and is currently in the VAB in preparation for stacking operations (see Figure 5).

Artemis II will be the second flight of SLS and Orion. The first crewed deep space flight since 1972, Artemis II will be a hybrid lunar flyby mission. Several elements of the Artemis II vehicle – also an SLS Block 1 crew configuration – are complete. The 10 solid rocket motor segments are complete at Northrop Grumman facilities in Utah and the four RS-25 engines have also finished processing and are stored in place at SSC. All five major components of the Artemis II core stage have been manufactured by Boeing at Michoud Assembly Facility and are currently being prepped for stage integration (see Figure 9). ULA has manufactured much of the Artemis II ICPS at its Decatur, Alabama rocket factory and its RL10 engine was delivered in August 2020 (see Figure 7). Both adapters, the LVSA and the OSA, are currently being at Marshall Space Flight Center's Advanced Weld Facility (see Figure 8).

For the third flight, currently manifested as the final Block 1 vehicle in the crew configuration, booster motor segments and forward and aft assemblies are being processed, as are RS-25 engines. The RL10 engine for the ICPS is complete (see Figure 10). Panels have been formed for the adapters. This historic flight of SLS and Orion will carry astronauts to cislunar space, where they will rendezvous with a new-generation commercial human lunar landing system (HLS) and descend to the lunar surface.

III. Block 1B/2 Progress

SLS Block 1B and Block 2 will use the EUS to increase lift capacity. The SLS Program has Critical Design Review (CDR) for the EUS scheduled for December 2020. In addition, the RL10 engines for the first Block 1B flight are complete (see Figure 10)

Figure 8. The Launch Vehicle Stage Adapter (LVSA) for the Artemis II flight is currently being welded at Marshall Space Flight Center (MSFC).

and weld development articles have been manufactured at Michoud. For Block 2, which will use evolved solid rocket booster technology, subscale motor testing is being conducted to characterize new materials (see Figure 11). Recently, SLS and Northrop Grumman successfully tested the electric thrust vector control system for the evolved boosters.

Figure 9. For the Artemis II flight, core stage prime contractor Boeing has constructed all five primary components of the stage, including the LH2 tank shown here.

IV. The Artemis Missions

The first flight of SLS and Orion, Artemis I, will be an uncrewed test flight to thoroughly check out the system – from ground processing to launch to mission control to recovery of Orion, before crew flies on Artemis II. Artemis I is expected to be 26-45 day flight to a Distant Retrograde Orbit (DRO) about the Moon. Primary objectives for the Artemis I flight include testing Orion’s heat shield at lunar re-entry velocities, checking out all systems in deep space, and deploying CubeSats into deep space. As mentioned earlier, 13 CubeSats are manifested on the flight, all 6U form factor. Several missions are lunar-focused, with the south pole a key focus. Two of the missions will be searching for hydrogen and other volatiles that may inform future in-situ resource utilization. Another mission aims to land the smallest lunar lander yet on the Moon. Still other missions will be testing green propellant, other innovative propulsion techniques, monitoring space weather, and studying the effects of deep space radiation on a living organism (yeast). Three of the CubeSats are competing for prize money in the Cube Quest Challenge, part of NASA’s Centennial Challenges program [9].

Figure 10. Engines prime contractor Aerojet Rocketdyne has completed processing of RL10 engines for Artemis II, Artemis III, and the first SLS Block 1B flight.

Following Artemis I, astronauts will return to cislunar space for the first time since Apollo 17 aboard the Artemis II flight. Artemis III will enable astronauts to once again walk on another world. In addition to SLS and Orion, NASA is working with a number of industry and international partners to build a full deep space ecosystem, including the aforementioned HLS, as well as an orbiting

Figure 11. The SLS Program and boosters prime contractor Northrop Grumman have performed subscale motor testing for the Block 2 evolved boosters.

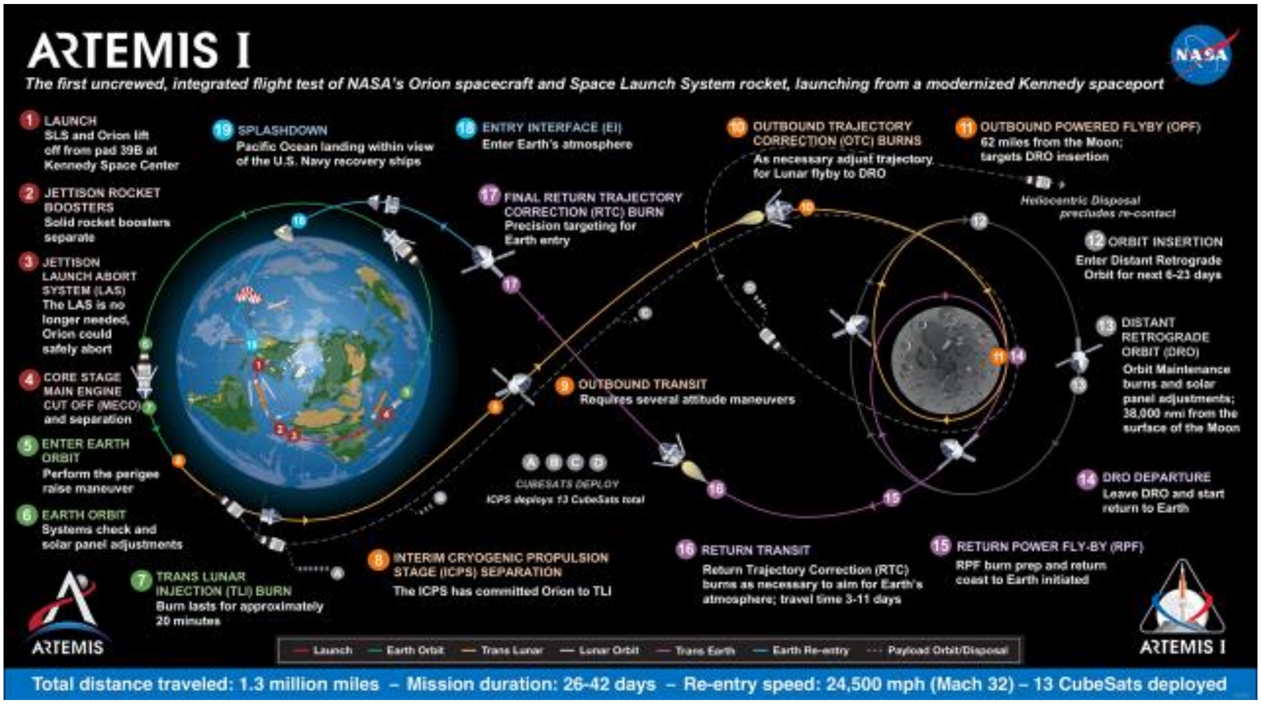


Figure 12. Mission map of the uncrewed Artemis I test flight of SLS and Orion, which includes sending Orion on a Distant Retrograde Orbit about the Moon and deployment of 13 6U CubeSats.

lunar science outpost, the Gateway. To pave the way for the Artemis generation of Moonwalkers, NASA is sending numerous robotic payloads to the lunar surface. As a stepping stone to Mars, NASA's Artemis initiative will further develop the knowledge and technologies humanity needs to expand human exploration farther into the solar system, including Mars.

V. Conclusion

An exciting new generation of deep space exploration is dawning: the Artemis generation. The uncrewed Artemis I test flight will be a key event in 2021, kick-starting NASA's return to the Moon. The Artemis I vehicle, an SLS Block 1 in the crew configuration, has completed manufacturing. All components, with the exception of the core stage, are already at KSC. The aft sections of the powerhouse five-segment solid rocket boosters are being assembled at KSC's RPSF prior to transfer to the VAB. The Artemis I core stage is currently at NASA's SSC for a battery of Green Run tests that will culminate in a hot-fire that will confirm its readiness to be shipped to KSC and integrated for flight.

The core stage tanks, engines and booster motor segments for Artemis II are all manufactured with the core stage structures undergoing additional processing. The LVSA and OSA are being manufactured at

Figure 13. To support a new generation of deep space exploration, the SLS Engineering Support Center (SESC) in the Huntsville Operations and Service Center (HOSC) has been upgraded with new computer systems. Operator console training and simulations with the Launch Control Center (LCC) at KSC and the Mission Control Center (MCC) at Johnson Space Center (JSC) are in progress.

MSFC and ULA is manufacturing the ICPS. Early work on the Artemis III vehicle has begun.

Initial work is under way on the more powerful Block 1B configuration. Based on Block 1, it will also use the same core stages engines and boosters. But it will gain performance through a host of improvements, the most significant of which is replacing the initial single-engine upper stage with a larger four-engine EUS. With the new stage, Block 1B will send at least 42 t of payload to TLI and will be the workhorse transportation for the Artemis missions. In addition to all the hardware being manufactured for the SLS Program, a newly outfitted launch monitoring center, called the SLS Engineering Support Center (SESC), has been built in MSFC's Huntsville Operations & Support Center (HOSC). The SESC is connected to the Launch Control Center (LCC) at KSC as well as to the Mission Control Center (MCC) at Johnson Space Center (JSC) and numerous contractor locations. Console operators, who will monitor vehicle health once the vehicle is assembled at KSC, are currently being trained. Nearly all the pieces are ready for the Artemis I flight and 2021 promises to be a pivotal year for human spaceflight.

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