National Aeronautics and Space Administration

ARTEMIS

Reference Guide

v. 1.0

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Contents

Image credit: NASA

Image credit: NASA

◀ A sunrise view of the low bay entrance to the Vehicle Assembly Building (VAB) at NASA's Kennedy Space Center in Florida on Jan. 19, 2022.

Foreword

Jim Free, Associate Administrator
Exploration Systems Development Mission Directorate (ESDMD)

The launch of Artemis I marks a proud and powerful moment in NASA's and the nation's history. This flight test is the result of an unparalleled workforce, tireless engineering, advances in modern fabrication and computing, strong industry and international partnerships, and vital support from Congress and multiple administrations. The path to Artemis I has continued through historic events, including the global pandemic and devastating storms that broke records in both number and magnitude. Yet here we are, ready to launch!

We are at the culmination of thousands of tests and analyses conducted across the country and beyond. Like many firsts in engineering on this scale, particularly for human space exploration vehicles, the rigors of analysis and testing cannot be fast-tracked or minimized. It is humbling that even our best modeling and simulations need operational validation. We learn something, at some level, every time we test.

We will launch the world's only spacecraft designed to carry humans to deep space, atop the most powerful rocket, with our dedicated ground systems team and launch and mission control personnel. We'll take what we learn from Artemis I and apply these lessons as we move further on the path of human exploration.

We have so many to thank for reaching this tremendous milestone, not only our tireless industry and international partners, but—perhaps most importantly—we thank our families, who have supported us on this quest to explore the cosmos that will begin at Launch Pad 39B.

In addition to the contributions from our primary industry contractors and international partners, thousands of companies across all 50 states have contributed to building these systems. Their contributions strengthen our national aerospace capabilities and return economic benefits to their communities.

To the Artemis I team: Please take in every moment of the mission, from rollout and launch to splashdown, and all the moments in between. Pause to reflect on all that we've achieved together. Acknowledge your individual and team contributions to this great mission.

This Artemis Reference Guide is a look into all the parts that have come together to reach Artemis I, the mission that signals the beginning of our human return to the Moon. I hope you will take time to peruse this document along with all the other resources available online and appreciate the immense energy and effort that brought us to this moment.

It's time to fly!

Jim

Purpose

Under Artemis, the new era of lunar exploration, NASA and its partners will lead humanity forward to the Moon and prepare us for the next giant leap, human exploration of Mars. This Artemis Reference Guide provides detailed descriptions of the systems and subsystems pertaining to the Artemis I mission, including program overviews; technical elements; testing; and management roles and facilities for the Space Launch System (SLS) rocket, Orion spacecraft, and associated ground systems.

Introduction

▲ Astronauts Stephanie Wilson, Karen Nyberg, and Rick Mastracchio (left to right) assist in testing the docking hatch on a representative model of the Orion spacecraft at Johnson Space Center. *Image credit: NASA*

Artemis Overview

We're going back to the Moon for the benefit of all humanity—scientific discovery, economic benefits, and inspiration for a new generation of explorers: the Artemis Generation. While maintaining American leadership in exploration, we will build a global alliance and explore deep space as one. With Artemis missions, NASA will land the first woman and first person of color on the Moon, using innovative technologies to explore more of the lunar surface than ever before. We will collaborate with commercial and international partners and establish the first long-term presence on the Moon. Then, we will use what we learn on and around the Moon to take the next giant leap: sending the first astronauts to Mars.

Artemis I

Artemis I will be the first integrated flight test of NASA's deep space exploration systems: the Orion spacecraft, the Space Launch System (SLS) rocket, and the supporting ground systems at NASA's Kennedy Space Center in Florida. The first in a series of increasingly complex missions, Artemis I will provide a foundation for human deep space exploration and demonstrate our commitment and capability to extend human presence to the Moon and beyond. The primary goal of Artemis I is to thoroughly test the integrated systems before crewed missions by launching Orion atop the SLS rocket, operating the spacecraft in a deep space environment, testing Orion's heat shield, and recovering the crew module after reentry, descent, and splashdown.

The SLS rocket will launch an uncrewed Orion spacecraft from Launch Complex 39B at NASA's modernized spaceport at Kennedy. As the Orion spacecraft orbits Earth, it will deploy its solar arrays, and the interim cryogenic propulsion stage (ICPS) will give Orion the big push—called a trans-lunar injection—needed to leave Earth's orbit and travel toward the Moon. From there, Orion will separate from the ICPS about two hours after launch. After Orion separates from the ICPS, 10 small satellites known as CubeSats will be deployed to perform experiments and technology demonstrations. The CubeSats will conduct a range of investigations and technology demonstrations from studying the Moon or an asteroid to the deep space radiation environment. Each CubeSat provides its own propulsion and navigation to get to various deep space destinations.

Orion will continue on a path toward a lunar distant retrograde orbit, where it will travel about 40,000 miles beyond the Moon, or a total of about 280,000 miles from Earth, before returning home. This flight test will demonstrate the performance of the SLS rocket on its maiden flight and gather engineering data throughout the journey before Orion returns on a high-speed Earth reentry at speeds of more than 25,000 mph. The high-speed lunar velocity reentry is the top mission priority and a necessary test of Orion's heat shield performance as it enters Earth's atmosphere, heating to nearly 5,000 degrees Fahrenheit (2,760 degrees Celsius)—about half as hot as the surface of the Sun—before splashing down in the Pacific Ocean for retrieval and post-flight engineering assessment.

▼ Illustration of the Orion spacecraft returning to Earth. *Image credit: NASA*

▲ NASA astronaut Nicole Mann gives a thumbs-up from inside the Orion mockup. *Image credit: NASA/Bill Ingalls*

Artemis II and Beyond

The Artemis II flight test will be NASA's first mission with crew aboard Orion and will confirm that all the spacecraft's systems operate as designed with humans aboard in the deep space environment. The initial launch will be similar to that of Artemis I as SLS lofts Orion into space. With a crew of four astronauts aboard this mission, Orion and the ICPS will orbit Earth twice before committing to the trip to the Moon to ensure that Orion's systems are working as expected while still close to home.

After Orion separates from the ICPS, the crew will use it as a target for a proximity operations demonstration. The crew will use Orion's onboard cameras and the view from the spacecraft's windows to line up with the ICPS as they approach and back away from the stage to assess Orion's handling qualities and related hardware and software. This demonstration will provide performance data and operational experience that cannot be readily gained on the ground in preparation for rendezvous, proximity operations, and docking, as well as undocking operations in lunar orbit beginning on Artemis III.

Following Artemis I and II, Artemis III will see Orion and a crew of four once again travel to the Moon, this time to make history by landing the first 21st-century astronauts on the lunar surface. Beginning with Artemis III, NASA intends to launch crewed missions about once per year, with initial missions focused on establishing surface capabilities and building Gateway, an outpost in orbit around the Moon that will provide access to more of the lunar surface than ever before.

Space Launch System

Introduction

SLS is a super-heavy-lift rocket that provides the foundation for human exploration beyond Earth's orbit. NASA evaluated thousands of combinations of attributes such as propulsion systems, stages, boosters, performance, development and operations cost, mission complexity, reliability and risks, and the ability to maintain industry base skills. The result was an evolvable rocket, available in crew or cargo configurations, with a proven propulsion system, that provides a safe launch capability for human exploration to deep space—the SLS rocket.

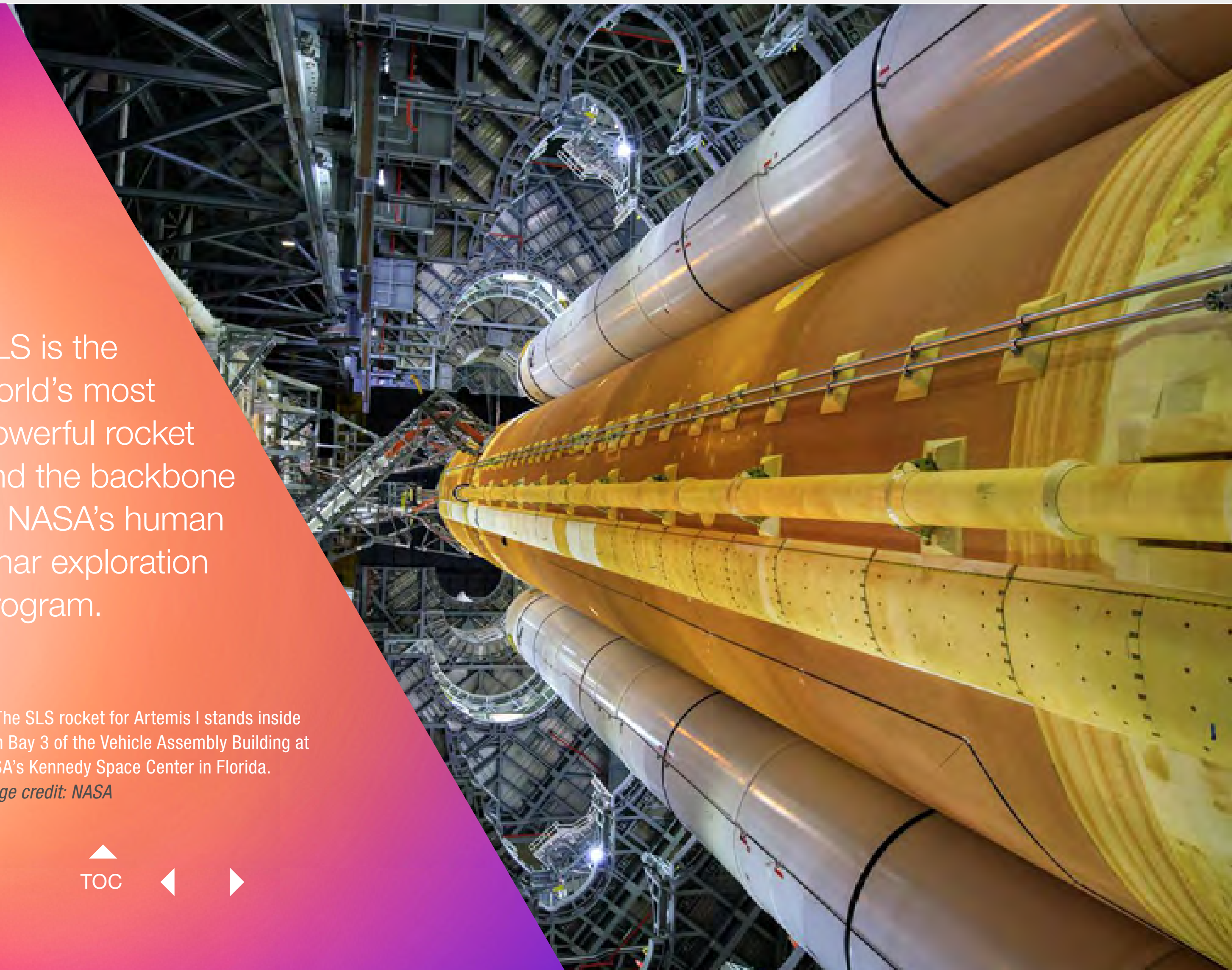
HELPFUL RESOURCES

For more information about SLS, visit https://www.nasa.gov/sls

SOCIAL MEDIA
Twitter: https://www.twitter.com/NASA_SLS
Facebook: https://www.facebook.com/NASASLS
Instagram: https://www.instagram.com/NASAArtemis

SLS was designed for the most challenging deep space missions involving strategic commitments of national resources, national prestige, and human life. SLS represents the best balance of mission performance, safety, cost, affordability, and risk. SLS is also designed to be flexible and evolvable, opening new possibilities for payloads,

SLS is the world's most powerful rocket and the backbone of NASA's human lunar exploration program.



▶ The SLS rocket for Artemis I stands inside High Bay 3 of the Vehicle Assembly Building at NASA's Kennedy Space Center in Florida. *Image credit: NASA* including robotic scientific missions to places like the Moon, Mars, and beyond. With its unprecedented power and capabilities, SLS has the largest payload mass and volume of any existing rocket and is the only rocket that can safely send Orion, astronauts, and cargo to the Moon on a single mission. More mass and volume translate into fewer launches of fewer pieces, requiring less assembly time in space and less overall risk.

Overview

SLS is designed for deep space missions and will send the Orion spacecraft and cargo to the Moon, which is nearly 1,000 times farther than where the International Space Station resides in low-Earth orbit. The rocket will provide the power to help Orion reach a speed of 22,600 mph, the speed needed to send it to the Moon.

SLS benefits from over 50 years of NASA experience with liquid oxygen and liquid hydrogen propellants, along with advances in technology and manufacturing practices. SLS development and manufacturing operations take advantage of resources established for the space shuttle, including the workforce, manufacturing processes, tooling and facilities, transportation logistics, launch infrastructure, and liquid oxygen and liquid hydrogen propellants.

SLS evolvability supports robust human exploration beyond low-Earth orbit as exploration missions become more complex and demanding. All planned variants of the basic SLS design are based on common propulsion components:

- A central core stage housing propellant tanks, engines, avionics, and attach points for a pair of solid rocket boosters.
- Four liquid propellant RS-25 engines powered by cryogenic, or supercold, liquid hydrogen and cryogenic liquid oxygen from the core stage.
- Two solid-fuel, side-mounted booster motors that provide the majority of thrust and steering for the rocket during the first two minutes of flight, after which they are jettisoned.
- An upper stage fueled by liquid hydrogen and liquid oxygen for in-space propulsion after separation from the core stage.

Future Missions and Configurations

To fulfill America's future needs for deep space missions, SLS will evolve into increasingly more powerful configurations. Each succeeding SLS block variant grows more capable through upgrades to the engines, boosters, and upper stage, providing a flexible platform for a variety of human and robotic deep space missions, rather than requiring the development of entirely new rockets to increase performance. SLS uses common design elements that can interface with the ground systems at Kennedy, the Orion spacecraft, and future payloads, reducing the complexity of deep space missions over time. In addition to flying Orion, SLS can also be outfitted with wide-diameter payload fairings in varying lengths for cargo and robotic science missions.

The Artemis I mission will use the first configuration of the SLS rocket, known as Block 1, capable of lifting more than 59,500 pounds (27 metric tons) to orbits beyond the Moon. The Block 1B variant will follow the Block 1 configuration beginning with Artemis IV and will be able to lift more than 83,000 pounds (38 metric tons) to deep space, including Orion and its crew. The Block 1B variant incorporates several upgrades to improve SLS performance, allowing the rocket to launch larger and heavier payloads to deep space destinations. SLS Block 1B uses the same core stage and twin five-segment solid rocket boosters as the Block 1 rocket. New-production RS-25 engines will provide slightly more thrust than the shuttle-era engines and cost 30 percent less to manufacture. Most of the increase in performance for the Block 1B rocket will come from replacing the single-engine ICPS with a more powerful four-engine exploration upper stage and a universal stage adapter to carry Orion along with large cargos for exploration systems needed to support a long-term presence at the Moon.

The Block 2 variant retains the core stage, RS-25 engines, and the new upper stage, but replaces the Block 1 steel case booster motor design with a lighter composite case, new propellant formulation, and other upgrades that increase overall performance. It will provide 9.5 million pounds of thrust and lift more than 101,000 pounds to the Moon and more than 80,000 pounds to Mars.

Elements

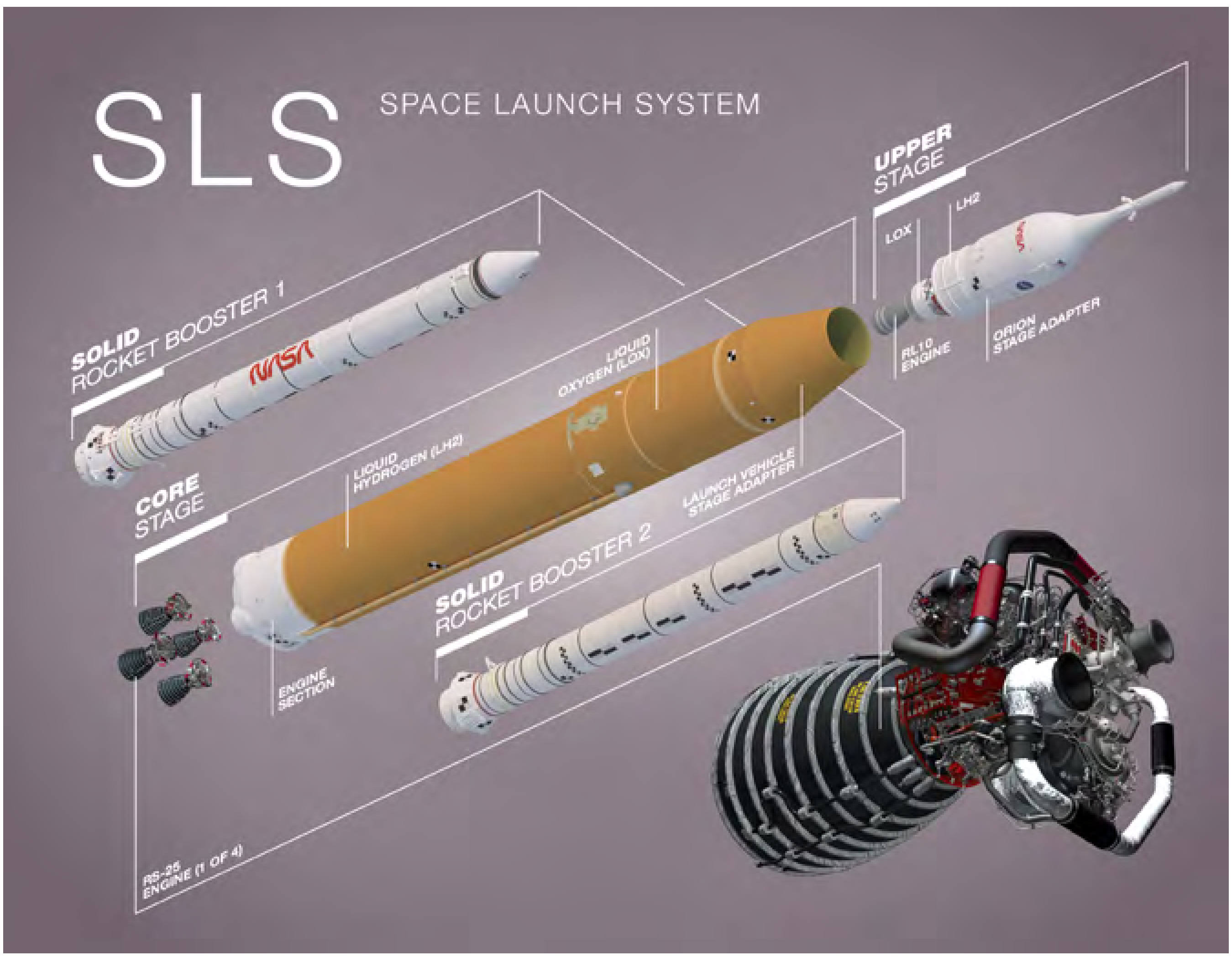
Core Stage

The SLS core stage is the tallest and most powerful rocket stage NASA has ever built. It measures approximately 212 feet tall and 27.6 feet in diameter (excluding thermal protection system foam and flanges). The stage is the largest ever built by length and volume, and its fully fueled weight, excluding engines, is 2.4 million pounds. It was manufactured by the lead contractor for the core stage, Boeing, at NASA's Michoud Assembly Facility in New Orleans using state-of-the-art manufacturing equipment. Michoud is a unique advanced manufacturing facility where NASA has built spacecraft components for decades, including the space shuttle's external tanks and Saturn rockets.

The SLS core stage is designed to operate for the roughly eight-minute Artemis I launch from ground and ascent to Earth orbit, reaching speeds of faster than 17,500 mph, or nearly 23 times the speed of sound (Mach 23), and more than 530,000 feet in altitude before it separates from the ICPS, Orion stage adapter, and Orion spacecraft.

The core stage was a major new development effort for the SLS Program, while other key elements, such as the RS-25 engines, solid rocket booster structures, and ICPS,

Diagram of the main components of the Space Launch System. *Image credit: NASA*



▲ The SLS core stage is shown atop the mobile launcher inside High Bay 3 of the VAB at NASA's Kennedy Space Center on June 12, 2021.
Image credit: NASA

have a rich, reliable spaceflight history. Like other SLS components, the SLS core stage leverages design experience from the space shuttle and has the same diameter as the shuttle external tank, and the propellant feedlines and fill and drain ducts were sized around heritage joints and existing valves.

As the literal core of SLS, the core stage supports other stages, spacecraft, and payloads atop its uppermost section and serves as the attach point for the two solid rocket boosters. It also includes the four RS-25 main engines, their liquid hydrogen and liquid oxygen propellant supply, and the avionics and software that control SLS operation and flight until the core stage separates from the ICPS.

The core stage is made up of 10 major barrel sections, four dome sections, and seven rings. Each cylindrical barrel section consists of eight aluminum panels that vary in length and height depending on the section. Those panels are friction stir welded or bolted vertically and horizontally to form the five major sections of the core stage:

- Engine section
- Liquid hydrogen tank
- Intertank
- Liquid oxygen tank
- Forward skirt

Friction stir welding transforms the metals from a solid state into a "plastic-like" state and then mechanically stirs the materials together under pressure to form a welded joint, producing high-strength bonds virtually free of defects. The intertank is the lone bolted section; it provides added strength to carry booster loads.

Beginning at the bottom, or aft end, of the stage, the engine section houses four RS-25 main engines, the engine thrust structure, propellant ducts, various avionics systems, and engine thrust vector control systems; it also serves as the lower attach point for the two solid rocket boosters.

The engine section consists of a single barrel section with welded aluminum isogrid panels and is 27.6 feet in diameter and 22.5 feet long. Isogrid is a pattern milled into the barrel section panels that reduces weight while retaining structural strength. An aerodynamic boat tail fairing at the bottom channels airflow and protects the engines from extreme temperatures during launch.

The liquid hydrogen fuel tank is 27.6 feet in diameter and 130.8 feet tall. It consists of five welded barrel sections, each 22 feet tall, and two end domes. The lower end of the liquid hydrogen tank includes four liquid hydrogen feedlines to the RS-25 engines. The tank has a capacity of 537,000 gallons of liquid hydrogen at minus 423 degrees Fahrenheit (minus 253 degrees Celsius).

The intertank separates the upper dome of the liquid hydrogen tank from the lower dome of the liquid oxygen tank and serves as the forward attach point for the boosters. The intertank contains one barrel section and measures 27.6 feet in diameter and 21.8 feet tall. It contains a thrust structure to carry loads imparted from the solid rocket boosters during ascent. The intertank also contains several avionics components, including two rear-facing cameras and interfaces to the liquid hydrogen and liquid oxygen tanks.

The liquid oxygen tank is 27.6 feet in diameter and 51.6 feet tall. It consists of two barrel sections of isogrid aluminum panels and two domes. Liquid oxygen is fed to the engine section and engines through a pair of "downcomer" ducts that exit the intertank on opposite sides and run down the core stage. The liquid oxygen tank has a capacity of 196,000 gallons of liquid oxygen at minus 297 degrees Fahrenheit (147 degrees Celsius).

The forward skirt is located at the top of the core stage. It contains one barrel section and connects the core stage to the launch vehicle stage adapter. The aluminum isogrid structure is 27.6 feet in diameter and 10.4 feet tall. It houses the majority of the rocket's avionics and has connections to launch pad utility umbilicals, the vehicle stabilization system that helps secure SLS to the mobile launcher, access doors, vent system, pressurant lines, and communications antennas.

The main propulsion system in the core stage consists of the ducts, valves, and other equipment that supply and control the flow of liquid hydrogen and liquid oxygen propellants, as well as gaseous helium and nitrogen pressurants for valve actuation and line or volume purges. To accomplish those functions, the main propulsion system has four subsystems:

- Liquid oxygen
- Liquid hydrogen
- Pressurization
- Pneumatics supplied by ground systems prior to launch

Major drivers in the design of the main propulsion system included the main propellant tank configuration, main engine configuration, reliability and affordability, mission requirements, and component mounting. For instance, the main propulsion system flow rates and interfaces were designed around the RS-25 configuration and the need to supply propellants to the engines under temperature and pressure conditions required by the engines. The orientation of the engine hydrogen and oxygen feed lines in the engine section determined the feed system layout for the main propulsion system.

▼ Teams with Exploration Ground Systems (EGS) and lead contractor Jacobs transport the massive SLS core stage to Kennedy Space Center's Vehicle Assembly Building in Florida on April 29, 2021, after its journey from NASA's Stennis Space Center in Mississippi aboard the Pegasus barge. *Image credit: NASA*

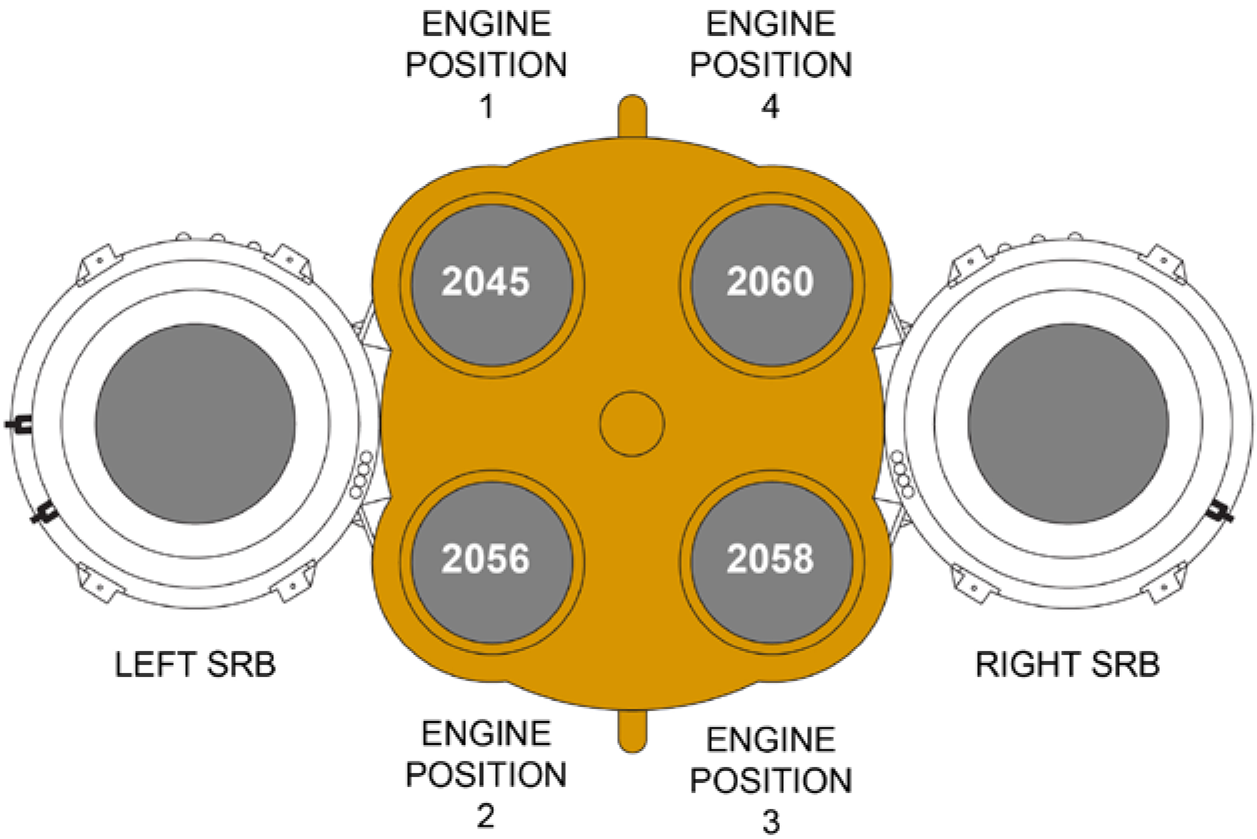


Image credit: NASA

HOW IT WORKS Combustion occurs when a fuel is combined with oxygen to produce energy to propel a vehicle. In automobiles, oxygen from the atmosphere combines with gasoline and an ignition source to run a combustion engine. In rocket science, propellants may include both fuel and a chemical oxidizer that releases oxygen. When the fuel and oxidizer combine, they ignite through a chemical reaction, and the hot, rapidly expanding gases look for a way out and move the rocket or spacecraft in the opposite direction.

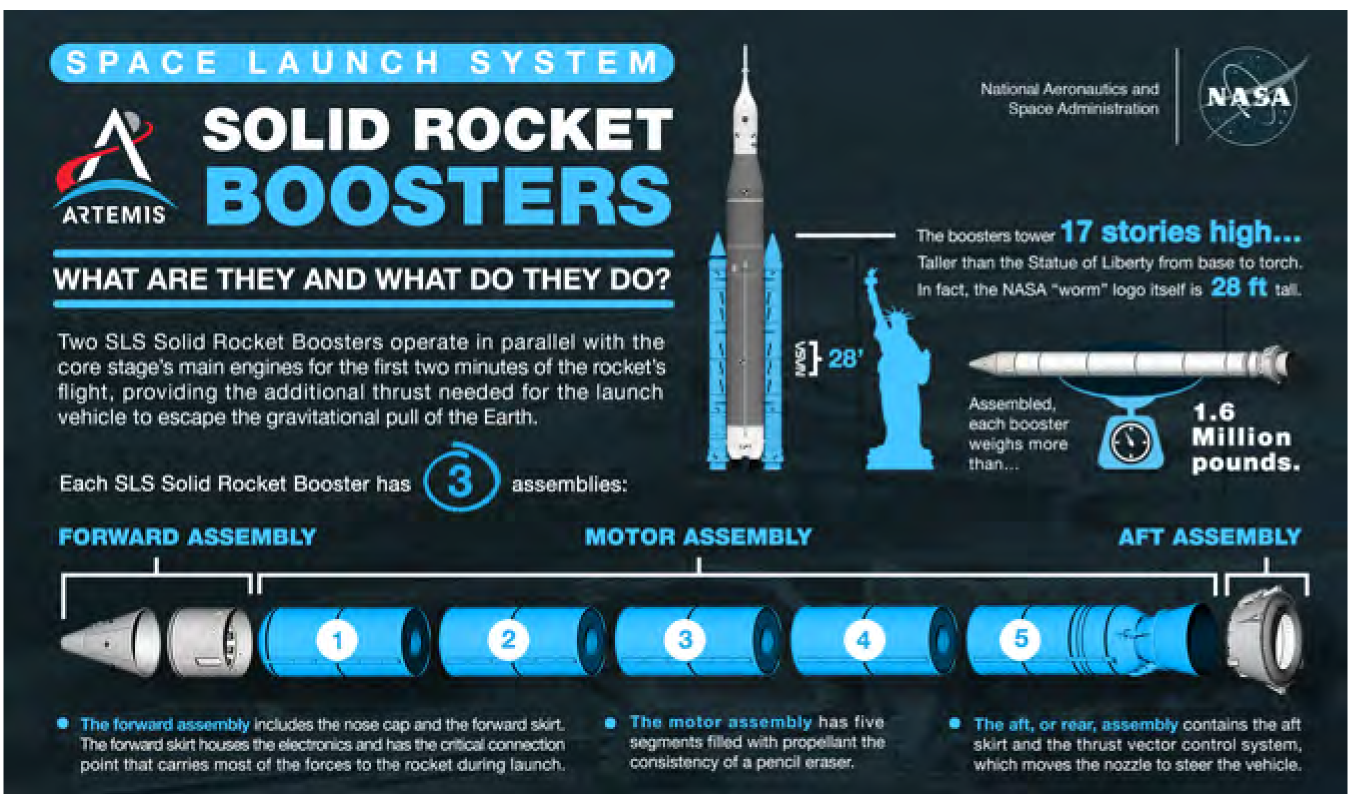
Thermal Protection System

The orange color of the core stage is actually the thermal protection system, or spray-on foam insulation. This insulation, along with other materials such as cork, provides thermal protection for every part of the rocket, although it is most visible on the core stage. The insulation is flexible enough to move with the rocket but rigid enough to take the aerodynamic pressures as SLS accelerates from 0 to 17,500 mph and soars to more than 100 miles above Earth in just 8 minutes.

Materials engineers qualified the third-generation, orange-colored spray-on foam insulation to meet the harsh environments that SLS will experience. At the same time, they made the foam more environmentally friendly. When the foam is applied, it gives the rocket a light-yellow color that the Sun's ultraviolet rays eventually "tan," giving the SLS core stage its signature orange color.

The thermal protection system provides the insulation to keep the cryogenic propellant that powers the RS-25 engines extremely cold to remain liquid. If temperatures rise too high, the propellant will become a gas. Hydrogen must remain at minus 423 degrees Fahrenheit (minus 253 degrees Celsius) and oxygen at minus 297 degrees Fahrenheit (minus 183 degrees Celsius).

All four RS-25 engines attached to the SLS core stage inside NASA's Michoud Assembly Facility in New Orleans. *Image credit: NASA*



RS-25 Engines

Four Aerojet Rocketdyne RS-25 engines are part of the engine section of the core stage and power the core stage of SLS. Formerly known as the Space Shuttle Main Engine, the RS-25 has successfully flown on 135 shuttle missions. It was selected for SLS for its power, efficiency, and reliability—as well as the knowledge and experience base. The liquid hydrogen and liquid oxygen-powered engines are compact and highly efficient and provide high performance.

The RS-25 is a type of engine known as a staged-combustion cycle engine that burns liquid hydrogen and liquid oxygen propellants at very high pressure. At full throttle, the four engines will give SLS about two million of its 8.8 million pounds of maximum thrust. The SLS engines start in a staggered fashion: engine 1, engine 3, engine 4, then engine 2, approximately six seconds before booster ignition. During ascent, the engines are gimballed, or pivoted, to direct thrust and steer the rocket.

Although SLS uses RS-25 engines that flew on the space shuttle, engineers made several physical and operational changes related to tailoring them to SLS operating requirements and environments. For SLS, the engines received new engine controllers with contemporary avionics, software changes to accommodate higher propellant inlet pressures and lower temperatures, and new exhaust nozzle insulation for the higher heating environment. The engines will operate in temperature extremes from -423 degrees Fahrenheit (-253 degrees Celsius) to 6,000 degrees Fahrenheit (3,316 degrees Celsius) and at pressures exceeding 7,000 psi (48,263 kPa). For SLS missions, the modified RS-25s can deliver thrust ranging from 65% to 109% of their original operational profile, a 5% gain in maximum thrust from the end of the Space Shuttle Program.

The modified RS-25s can operate at 109% of their original operational thrust level for SLS missions, a 5% gain from the end of the Space Shuttle Program. As new RS-25s are built for future missions, they will produce 111% operational thrust levels and incorporate advanced manufacturing methods that will streamline cost and production.

▼ The Artemis II RS-25 engines are designated as backups for the Artemis I engines. Engines 2047, 2059, 2062, and 2063 have completed modification and are ready for flight if needed.

RS-25 Engine Flight Histories for Artemis I

FLIGHT	DATE	ORBITER
ENGINE 1—2045		
STS-089	01/22/98	Endeavour
STS-092	10/11/00	Discovery
STS-095	10/29/98	Discovery
STS-102	03/08/01	Discovery
STS-105	08/10/01	Discovery
STS-110	04/08/02	Atlantis
STS-113	11/23/02	Endeavour
STS-118	08/08/07	Endeavour
STS-121	07/04/06	Discovery
STS-127	07/15/09	Endeavour
STS-131	04/05/10	Discovery
STS-135	07/08/11	Atlantis
ENGINE 2—2056		
STS-104	07/12/01	Atlantis
STS-109	03/01/02	Columbia
STS-114	07/26/05	Discovery
STS-121	07/04/06	Discovery
ENGINE 3—2058		
STS-116	12/09/06	Discovery
STS-119	03/15/09	Discovery
STS-120	10/23/07	Discovery
STS-124	05/31/08	Discovery
STS-129	11/16/09	Atlantis
STS-133	02/24/11	Discovery
ENGINE 4—2060		
STS-127	07/15/09	Endeavour
STS-131	04/05/10	Discovery
STS-135	07/08/11	Atlantis

Solid Rocket Boosters

The SLS twin solid rocket boosters, manufactured by lead booster contractor Northrop Grumman, provide more than 75% of the total SLS thrust at launch and for the first two minutes of flight. The SLS booster design is based on the space shuttle boosters, with an additional propellant segment to provide more power, as well as several other upgrades. Standing 177 feet tall, the SLS booster is the largest, most powerful solid propellant booster ever built for flight, with more than three million pounds of thrust generated by each booster. While the boosters are using metal casings and parts that were flown on space shuttle missions, they have many new upgrades and parts, including a new case insulation-liner configuration, new exhaust nozzle design, and new avionics systems to control flight. In addition, the SLS boosters undergo an improved, nondestructive evaluation process to confirm each motor's readiness for launch.

Engineers are designing next-generation boosters that will power SLS flights after all available shuttle-era hardware is expended. Teams are testing small-scale solid rocket motors to evaluate new components, including propellant, insulation materials, and nozzle materials for future SLS Block 2 flights before proceeding into full-scale testing.

Interim Cryogenic Propulsion Stage

Measuring 45 feet (13.7 meters) tall and 16.7 feet (5.1 meters) in diameter, the ICPS is a single-engine liquid hydrogen and liquid oxygen-based system that provides propulsion in space after the solid rocket boosters and core stage are jettisoned. The ICPS is based on the Delta Cryogenic Second Stage, which uses the RL10 engine, both of which have completed extensive testing and served on numerous flights of the United Launch Alliance (ULA) Delta IV rocket, with the RL10 completing its 500th flight in 2020. Modifications to the Delta Cryogenic Second

▼ Teams with NASA's Exploration Ground Systems and contractor Jacobs integrate the ICPS with LVSA atop the rocket's core stage in the agency's VAB at Kennedy on July 5, 2021. *Image credit: NASA*

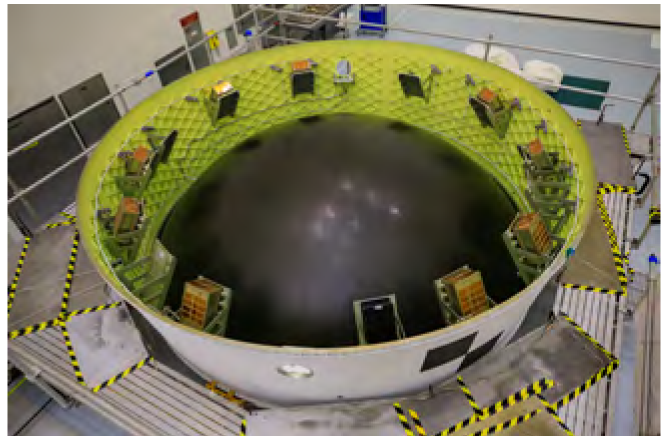
▼ Technicians with Exploration Ground Systems move the LVSA for the SLS rocket into the VAB at Kennedy on July 30, 2020, for processing. *Image credit: NASA*

▲ In High Bay 4 of the VAB at Kennedy Space Center, pathfinders, or full-scale replicas of SLS solid rocket booster segments, are stacked during a training exercise on Jan. 8, 2020. *Image credit: NASA*

Stage for SLS included lengthening the liquid hydrogen tank, adding hydrazine bottles for attitude control, and making minor avionics changes. The ICPS is powered by one RL10 engine manufactured by Aerojet Rocketdyne and generates 24,750 pounds of maximum thrust.

Launch Vehicle Stage Adapter

The SLS adapters connect parts of the rocket, change its diameter, and protect electronics during ascent. The cone-shaped launch vehicle stage adapter, also known as the LVSA, partially encloses the ICPS and connects to the SLS core stage below and the Orion stage adapter above. In addition to providing structural support for launch and a separation system, the LVSA also protects avionics and electrical devices in the ICPS from vibration and acoustic conditions during launch and ascent. The LVSA is 27.5 feet tall and measures 27.5 feet in diameter at the base and tapers to 16.5 feet in diameter at the top. Once the core stage propellant is expended and the rocket is in Earth orbit, a component at the top of the adapter that is designed to break apart, a pneumatically actuated frangible joint assembly, separates the core stage and the LVSA from the ICPS, Orion stage adapter, and Orion.



▲ Small satellites, called CubeSats, are shown secured inside NASA's Orion stage adapter at Kennedy Space Center on Aug. 5, 2021. *Image credit: NASA*

Orion Stage Adapter

The Orion stage adapter connects the ICPS to the Orion spacecraft. The adapter measures 18 feet in diameter and 5 feet tall and is made of lightweight aluminum. The adapter contains a diaphragm that provides a barrier to prevent gases, such as hydrogen, generated during launch from entering Orion.

For Artemis I, the Orion stage adapter will also carry small satellites, called CubeSats, as secondary payloads for research or technology demonstrations. The CubeSats are no more than 30 pounds each, about the size of a large shoebox, and do not require any extra power from the rocket to function. The adapter contains a comprehensive secondary payload deployment system for the CubeSats, including mounting brackets for commercial-off-the-shelf dispensers, cable harnesses, a vibration isolation system, and an avionics unit.

Following separation from Orion and after the spacecraft is a safe distance away, the avionics unit in the secondary payload deployment system will begin sending signals to release the payloads at pre-scheduled times. Following secondary payload deployment, the Orion stage adapter remains attached to the ICPS as the ICPS continues on its disposal trajectory.

Avionics and Software

The SLS core stage, boosters, and ICPS have computers and software that monitor and control their functions.

Avionics are the electrical systems necessary for flight and are driven by software to tell the rocket where it should go and how it should steer the engines to keep on the right trajectory. The core stage contains avionics in the forward skirt, intertank, and engine section, as well as the engines themselves. The avionics in the boosters and ICPS are connected to the flight avionics in the core stage. The core stage flight computers use data from the distributed avionics systems and its own flight computers to control the rocket and carry out its mission, transmitting performance data to controllers on the ground and Orion crew on future missions.

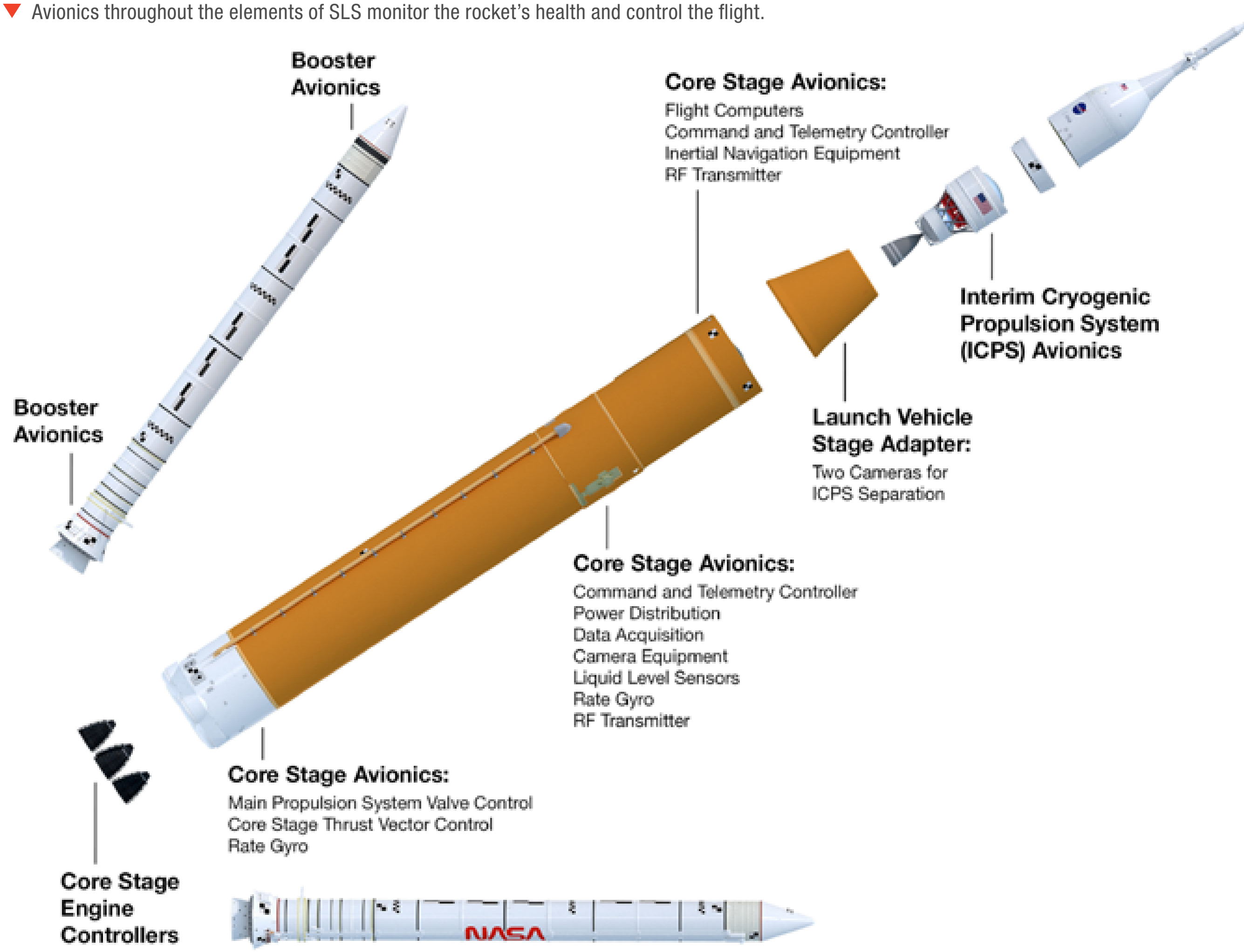
Core stage avionics and flight software serve as the "brains" of the rocket. They execute the commands to prepare and launch SLS, route data and commands to the stage, distribute power, produce navigation and flight control data, produce range safety tracking data, execute flight termination commands, produce motion imagery, provide telemetry to ground systems, synchronize and process data, monitor stage conditions, and receive and execute flight safety commands.

Core stage avionics consist of four main subsystems:

- Flight control
- Telemetry
- Flight safety
- Electrical power

Three flight computers and four power, data, telemetry, and navigation systems are located in the forward skirt.

Avionics throughout the elements of SLS monitor the rocket's health and control the flight.



Each of the three flight computers uses three microprocessors. Each flight computer runs the same software for redundancy. The intertank houses 26 avionics systems for power, power distribution, data receiving and handling, telemetry, and camera control. The engine section contains 10 avionics systems related to navigation and engine monitoring.

SLS flight software was developed at Marshall and provides the flight and pre-flight software functions necessary for pre-launch procedures on the pad, as well as launch and ascent up to ICPS separation.

Flight Control System

The flight control system, led by three redundant flight computers, monitors the rocket's condition, senses vehicle motion, generates navigation and control data, actuates main propulsion system valves, monitors the main propulsion system and engine controls, and routes commands to engine thrust vector control systems and controllers.

Core Stage Telemetry System

The core stage telemetry system includes radio and ethernet communications with the ground, telemetry control, engineering and development flight instrumentation, and a motion imagery system.

Flight Safety System

The flight safety system provides range tracking data and controls the rocket's flight termination system located in the core stage and boosters. For safety, all rockets are required to have a flight termination system that can remotely destroy the rocket to end the flight if it were to go off-course.

Avionics Power System

The avionics power system distributes ground power, stores ground power for flight, and provides data to ground control centers.

Testing

The SLS Program conducted extensive testing on the rocket, ranging from basic structural materials testing to element-level testing of the engines, boosters, core stage, and upper stage elements, as well as full integrated testing of the entire Artemis I SLS rocket.

RS-25 Engine Testing

The RS-25 has successfully flown on 135 space shuttle missions and has accumulated more than 3,000 starts and one million seconds of ground and flight hot fire experience. NASA conducted a series of development engine ground tests to adapt the former shuttle engine design to SLS performance requirements and operating environments. The 14 flown shuttle engines required no further testing. Two new engines assembled from shuttle-era spares were hot fire tested. New engine controllers for all 16 engines were hot fire tested as part of the development engine adaptation series. The agency continues development engine ground testing as part of an ongoing program to develop new RS-25 engines and components for future Artemis missions.

▼ The core stage for the first flight of NASA's SLS rocket is shown in the B-2 Test Stand during a hot fire test at Stennis on Jan. 16, 2021, as part of the Green Run testing series. *Image credit: NASA*

Following a successful Green Run hot fire test at Stennis on March 18, 2021, teams lift the first core stage of the agency's SLS rocket from the B-2 Test Stand. *Image credit: NASA*

Booster Testing

The SLS solid rocket boosters completed five test firings and qualification motor testing in a horizontal position at Northrop Grumman's facility in Promontory, Utah. The first qualification motor test in March 2015 tested booster operation under high-temperature launch conditions, and the second and final qualification test in June 2016 chilled the motor to test it under cold-weather conditions. Qualification testing also validated major motor upgrades, such as new insulation, updated avionics, and a redesigned larger nozzle.

Core Stage Green Run Testing

The Artemis I core stage with its four RS-25 engines underwent a series of eight "Green Run" tests in 2020 and early 2021 to thoroughly check out the new, or "green," rocket stage before its first flight. After manufacture at Michoud, the stage was transported by barge to Stennis and installed in the B-2 test stand.

1. **Modal Test:** For the modal test, engineers applied forces to the stage mimicking the stresses the rocket will endure during launch and flight to validate computer models of structural vibration "modes" and establish a baseline for Green Run testing.
2. **Avionics:** The second test was a checkout of the avionics and flight computers, which control the rocket's first eight minutes of flight.
3. **Fail-Safes:** The third test simulated potential issues to check out all the safety systems that shut down the stage in case of an issue.
4. **Propulsion:** The fourth test of the series flowed propellants through the core stage lines, ducts, and valves supplying the engines.
5. **Thrust Vector Controls:** During the fifth test, engineers operated the actuators in the thrust vector control system that steer the four engines and checked all the related hydraulic systems.
6. **Countdown:** The sixth test simulated the launch countdown, including step-by-step fueling procedures, and the test team exercised and validated the countdown timeline and sequence of events.
7. **"Wet" Dress Rehearsal:** During the seventh test, known as the wet dress rehearsal, engineers demonstrated loading, controlling, and draining more than 700,000 gallons of cryogenic propellants into and out of the core stage and then returning the stage to a safe condition.
8. **Hot Fire Test:** The final Green Run test culminated with firing all four engines together in early 2021 for eight minutes—the same amount of time it will take to send Orion and the upper stage to space. After an initial test that was shut down after 61 seconds by conservative test parameters to ensure the safety of the flight stage, the test team modified the software and the stage and successfully completed a full-duration hot fire test.

Structural Testing

Structural testing of the core stage and the ICPS took place at Marshall from 2017 through 2020. These tests helped verify computer models showing that the structural

▲ The SLS liquid hydrogen tank is pushed to its limits on Dec. 5, 2020, to see how much force it would take to cause the tank's structure to fail. This image shows the resultant buckling of the structure when the tank failed after exposure to more than 260% of expected flight loads over 5 hours. *Image credit: NASA*

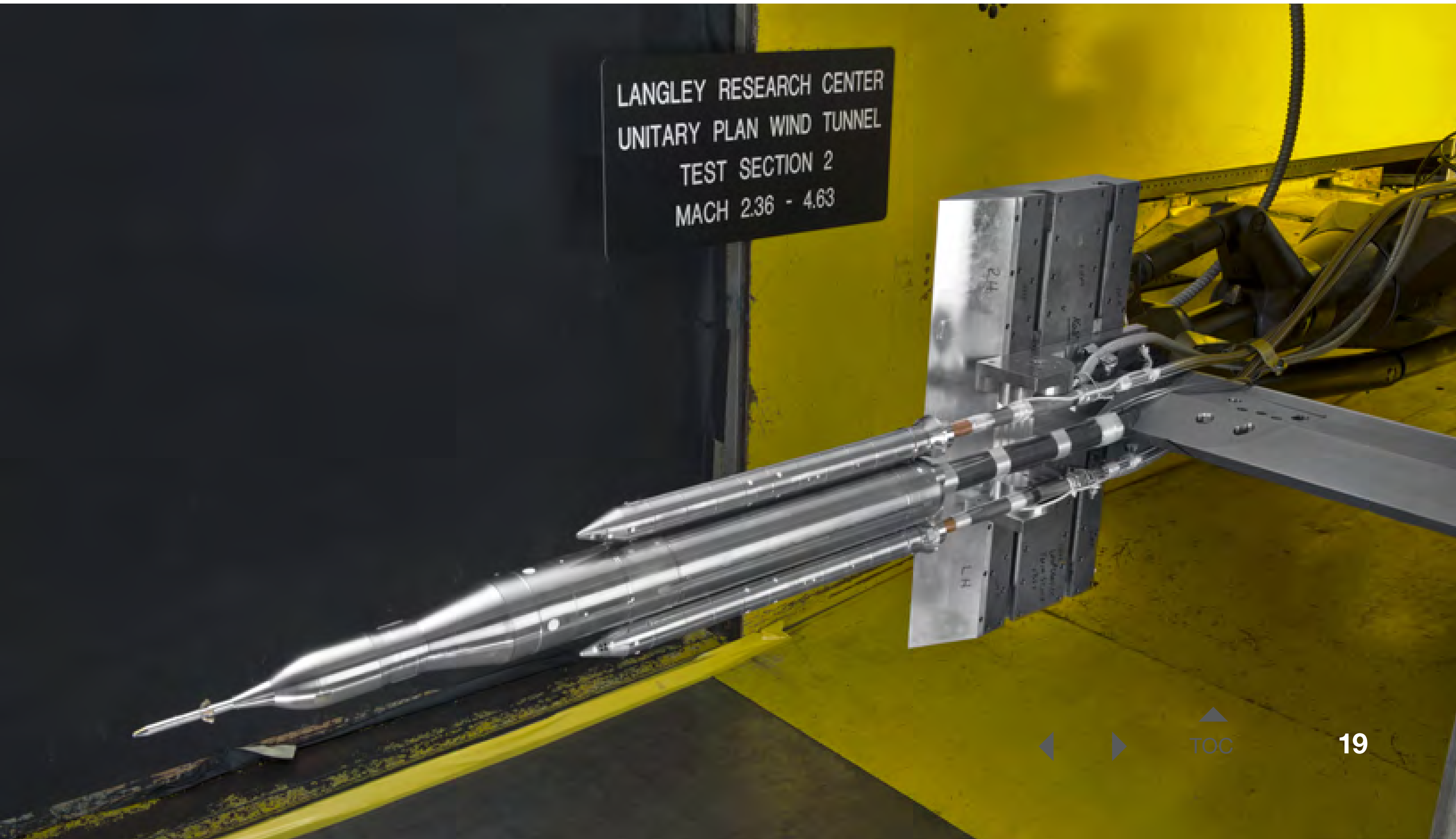
design can survive flight. Special test stands subjected test articles for the core stage engine section, liquid hydrogen tank, intertank, and liquid oxygen tank to millions of pounds of flight-like pushing, pulling, bending, and twisting stresses. This testing also included deliberately pushing the propellant tanks beyond their design limits to understand their breaking points. The tanks failed in the relative locations as engineers predicted and at the approximate load levels expected, proving flight readiness and providing data for designers.

In a separate test program completed in 2017, the SLS team performed similar structural testing for the ICPS and payload sections, including the LVSA, the Orion stage adapter, and a frangible joint assembly.

Wind Tunnel Testing

The SLS team completed numerous tests that simulated launch and flight conditions. Engineers conducted extensive wind tunnel testing at NASA's Ames Research Center in Moffett Field, California; Langley Research Center in Hampton, Virginia; and Marshall. Wind tunnel tests

▼ A model of SLS is tested in the Unitary Plan Wind Tunnel at Langley using high-pressure air blown through the solid rocket boosters to simulate the booster separation motors' firing. *Image credit: George Homich*



used smaller-scale rocket models to refine designs and smooth airflow in flight and to determine the effects of wind before the rocket clears the launch tower, how SLS heats up as it pushes through the atmosphere, and how it vibrates and responds at or near the speed of sound. During hundreds of test runs at Langley and Ames, engineers worked on measuring the forces and loads that air induces on the rocket during every phase of its mission.

Management Roles and Facilities

Marshall Space Flight Center

Marshall is home to the SLS Program Office and manages all areas of the program, including planning, procurement, development, testing, evaluation, production, and operation of the integrated rocket. Marshall also developed and tested the flight software in-house.

Michoud Assembly Facility

The hardware welded at Michoud included confidence, qualification, and flight components of the SLS core stage. Confidence articles verified that weld procedures worked as planned and tooling-to-hardware interfaces were correct. It also gave the weld team experience in bringing all aspects of hardware, tooling, and software together. Qualification articles closely replicated flight hardware and processing procedures. Engineers later used the qualification articles in structural testing to ensure that the rocket design was sound.

Engineers and technicians used six state-of-the-art welding tools for the core stage, including the world's largest spacecraft welding tool, the Vertical Assembly Center. At 170 feet tall, the Vertical Assembly Center is the last stop in welding the primary structure and is used to join domes, rings, and barrels to make a completed section of the core stage.

Katherine Johnson Independent Verification and Validation Facility

The Katherine Johnson Independent Verification and Validation (IV&V) facility assures the safety and success of software on NASA's highest-profile missions. IV&V has supported the development of SLS software for more than a decade, providing significant value in improving the software products as well as the reliability, safety, and success of the Artemis mission. Collaboration with the development and test teams resulted in the resolution of more than 3,000 identified higher-severity issues that were found in phase with the software development life cycle—ultimately contributing to the SLS Program's flight readiness for Artemis I.

Stennis Space Center

The SLS Program includes a Resident Management Office at Stennis Space Center, which conducts SLS engine and stage Green Run testing. Stennis provides propulsion testing and engineering services and is the nation's premier rocket propulsion test facility and largest rocket engine test site.

Kennedy Space Center

The SLS Program includes a Resident Management Office at Kennedy, responsible for receiving and integrating SLS hardware, as well as overall integration with Orion and launch operations in coordination with the Exploration Ground Systems Program.

Ames Research Center

Engineers conducted wind tunnel tests on smaller-scale rocket models of SLS at Ames to enhance the design and stability of the rocket.

Langley Research Center

Engineers at Langley completed testing for the SLS rocket in a low-speed wind tunnel.

Industry Partners

Boeing is the lead contractor for the SLS core stage and ICPS, as well as the exploration upper stage for future missions beginning with Artemis IV. Boeing manufactures the core stage at Michoud and works with ULA in Decatur, Alabama, to modify the Delta Cryogenic Second Stage for use as the ICPS on Artemis I through III.

Northrop Grumman is the lead contractor for the five-segment solid rocket boosters, which are the largest ever built for spaceflight. Northrop Grumman manufactures the booster motors in Utah and then transports them by rail to Kennedy to be stacked with the aft and forward assemblies in the Rotation, Processing and Surge Facility.

Aerojet Rocketdyne is the lead contractor for adapting 16 existing RS-25 engines that were upgraded from the Space Shuttle Program to SLS operating conditions and requirements, as well as restarting production of the RS-25 engines for flight at a higher thrust level. Assembly and testing occur at the company's facility located at Stennis. Aerojet Rocketdyne also provides the single RL10 engine, manufactured in its West Palm Beach, Florida, facility, that will power the ICPS.

Teledyne Brown Engineering is the lead contractor for the launch vehicle stage adapter, providing engineering, technical support, and hardware for the Artemis I adapter and structural test article. Teledyne Brown manufactures the adapter using the friction stir welding tools in the Advanced Weld Facility at Marshall.

At NASA's Michoud Assembly Facility in New Orleans, Orion's newly completed pressure vessel for the Artemis III mission is lifted out of the welding tool. *Image credit: NASA*

Quick Facts

SLS Rocket

Design	Evolvable super heavy-lift
Height	322 ft (98.3 m)
Weight	5.74 million lb (2,603 metric tons [t]) fueled; 3.5 million lb (1,588 t) unfueled
Main propulsion	Four RS-25 liquid propellant engines and two five-segment solid rocket boosters
Maximum thrust	8.8 million lb (39,144 kN)
Maximum speed	22,600 mph (36,371 km per hour [kph]) at ICPS trans-lunar injection (TLI) main engine cutoff
Payload to low-Earth orbit	209,439 lb (95 t)
Payload to TLI	> 59,525 lb (27 t)

Core Stage

Contractor	Boeing
Height	212 ft (64.6 m) from forward skirt to engine exhaust exit plane
Diameter	27.6 ft (8.4 m)
Weight	2.4 million lb (1,088 t) fueled without engines and 188,000 lb (85.3 t) unfueled without engines
Capacities	537,000 gal (2 million L), 317,000 lb (143.8 t) liquid hydrogen fuel; 196,000 gal (741,941 L), 1.86 million lb (843.7 t) liquid oxygen oxidizer
Maximum thrust	Approximately 2 million lb (8,896 kN)
Burn Time	8 minutes

Additional Facts

- There are:
  - 562 cables in the core stage; The largest number—231—are located in the engine section;
  - 45 miles of cabling in the core stage, and more than 18 miles in the engine section alone;
  - 775 independent sensors that have wire routing to them; and
  - approximately 100,000 clamps and ties securing wires and cables throughout the core stage.
- The liquid hydrogen tank shrinks about 6 in (152 mm) in length and 1 in (25.4 mm) in diameter when filled with cryogenic propellant.
- The liquid oxygen tank shrinks approximately 1.5 in (38.1 mm) in length and 0.5 in (12.7 mm) in diameter when filled with cryogenic propellant.
- To compensate for those changes, everything that attaches to them—ducts, vent lines, systems tunnel, brackets, etc.—must be connected by accordion-like bellows sections, slotted joints, telescoping sections, or ball joint hinges.
- Roughly 14,500 fasteners need to be drilled and filled in the intertank.
- Each flight computer is rated to operate over a temperature range of minus 11 degrees to 97.7 degrees Fahrenheit (minus 24 degrees to 36.5 degrees Celsius).

RS-25 Engines

Contractor	Aerojet Rocketdyne
Height	14 ft (4.3 m)
Diameter	8 ft (2.4 m)
Weight (each)	7,750 lb (3.5 t)
Propellants	Liquid hydrogen, liquid oxygen
Maximum thrust	418,000 lb (1,852 kN) at sea level; 512,300 lb (2,279 kN) in a vacuum at 109% power level
Burn time	8 minutes

Additional Facts

- The RS-25 exhaust is clean, superheated water vapor.
- Each turbine blade powering the RS-25's high-pressure fuel turbopump produces more horsepower than a Corvette ZR1's 638 horsepower, and its airfoil is the size of a quarter.
- Pressure within the RS-25 is equivalent to that found at an ocean depth of 3 mi—about the same distance as Titanic's resting place below the surface of the Atlantic Ocean.
- Hot gases exit the RS-25's nozzle at 9,600 mph (15,450 kph)—13 times the speed of sound, or fast enough to go from Los Angeles to New York City in 15 minutes.
- Four RS-25 engines push the SLS rocket 73 times faster than an Indianapolis 500 race car travels.
- The RS-25 is so powerful that it could power 846,591 mi of residential streetlights—a street long enough to go to the Moon and back, then circle Earth 15 times.
- SLS' four RS-25 engines consume propellant at the rate of 1,500 gal (5,678 L) per second during their 8 minutes of operation—more than enough to drain an Olympic-size swimming pool in that time.
- The RS-25 generates about 20% more thrust at sea level than comparable kerosene engines using the same amount of fuel.
- While the RS-25 is about the same size and weight as the two turbojet engines on an F-15 fighter, it generates eight times more thrust, which it achieves in less than 5 seconds, operating between minus 400 degrees Fahrenheit (minus 240 degrees Celsius) and 6,000 degrees Fahrenheit (3,316 degrees Celsius).
- In the RS-25, coolant travels through the main combustion chamber in 2 milliseconds, increasing its temperature by 400 degrees Fahrenheit (204 degrees Celsius).

Solid Rocket Boosters

Contractor	Northrop Grumman
Height	177 ft (54 m)
Diameter	12 ft (3.7 m)
Weight (each)	1.6 million lb (726 t) loaded; 219,000 lb (99.3 t) empty
Solid rocket motor	Five propellant segments
Propellants	Polybutadiene acrylonitrile (PBAN)
Maximum thrust	3.6 million lb (16,014 kN) each (vacuum)
Burn time	2 minutes, 6 seconds

Interim Cryogenic Propulsion Stage (Upper Stage)

Contractor	Boeing and United Launch Alliance
Designation	Interim Cryogenic Propulsion Stage (modified Delta IV Cryogenic Second Stage)
Height	45 ft (13.7 m)
Diameter	16.7 ft (5.1 m)
Weight	72,197 lb (32.7 t) fueled
Engine	Aerojet Rocketdyne RL10B-2
Propellants	Liquid hydrogen, liquid oxygen
Maximum thrust	24,750 lb (110 kN)
Reaction Control System	Hydrazine

Launch Vehicle Stage Adapter

Contractor	Teledyne Brown Engineering
Height	27.5 ft (8.4 m)
Diameter	27.5 ft (8.4 m) bottom; 16.5 ft (5 m) top
Weight	10,000 lb (4.5 t)

Orion Stage Adapter

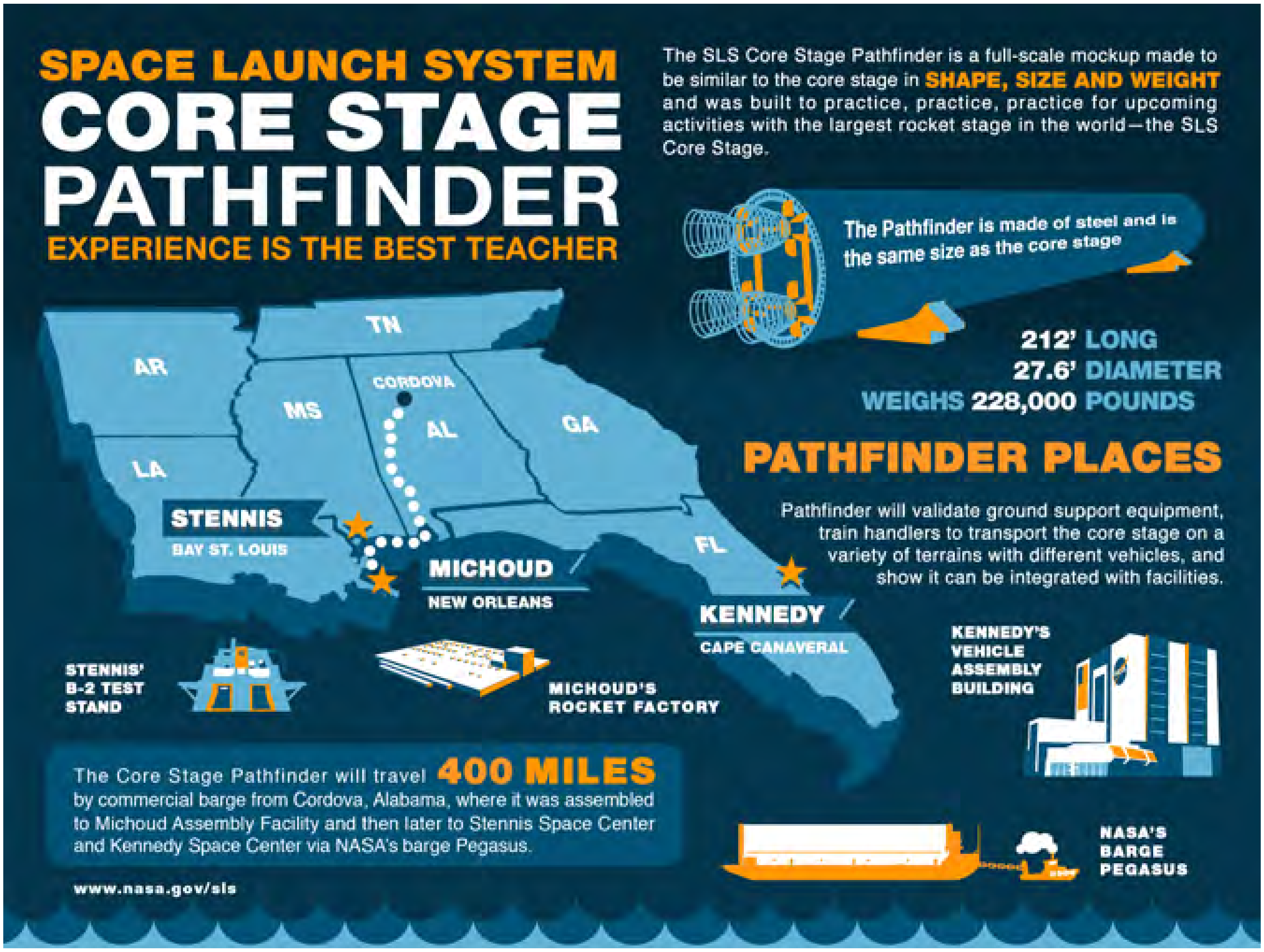
Manufacturer	NASA's Marshall Space Flight Center
Height	5 ft (1.5 m)
Diameter	18 ft (5.5 m)
Weight	1,800 lb (0.8 t)
Available payload volume	516 ft^3 (14.6 m^3)

Super Heavy Lifting on the Ground: Transportation, Logistics, and Pathfinders

The SLS Program provided several full-scale "pathfinders" to give transportation and ground handling crews the opportunity to rehearse and perfect logistics and handling procedures prior to receiving Artemis I hardware and pave the way for smooth shipping, handling, and lifting operations.

The core stage pathfinder is a full-scale mockup structurally similar to the core stage in shape, size, weight, center of gravity, and handling interfaces. Lacking the internal tanks and equipment of the flight hardware, the pathfinder was used to practice transport, handling, and lifting operations at NASA's Michoud Assembly Facility in New Orleans, Louisiana; NASA's Stennis Space Center near Bay St. Louis, Mississippi; and Kennedy.

Infographic with details of the Space Launch System core stage pathfinder. *Image credit: NASA*



▲ NASA's Pegasus Barge arrives at the Launch Complex 39 turn basin wharf at Kennedy Space Center in Florida on Sept. 27, 2019, to make its first delivery to Kennedy in support of the agency's Artemis missions. *Image credit: NASA*

Moving flight hardware during manufacturing and testing within facilities and onto rail cars, barges, and aircraft requires care and specialized equipment. While the RS-25 engines move by truck and the booster motor segments travel by rail, the core stage and launch vehicle stage adapter require their own transportation and handling equipment.

NASA's Super Guppy aircraft has a cargo compartment that is 25 feet tall, 25 feet wide, and 111 feet long; it can carry more than 26 tons. The aircraft has a unique hinged nose that can open more than 200 degrees, allowing large pieces of cargo to be loaded and unloaded from the front. The Super Guppy has been responsible for the transportation of both SLS fight hardware and the Orion spacecraft.

NASA's Pegasus barge is the largest vehicle used to transport SLS elements. Pegasus ferried the Artemis I core stage from Michoud, where it was manufactured, to Stennis for Green Run testing. After Green Run, Pegasus carried the core stage to Kennedy. Pegasus also transported the launch vehicle stage adapter from Marshall Space Flight Center in Huntsville, Alabama, to Kennedy.

Pegasus was designed and built in 1999 to transport space shuttle external tanks from Michoud to Kennedy. It replaced the Poseidon and Orion barges that were used to carry Saturn rocket stages and hardware for the Apollo Program. Pegasus was modified in 2014 to carry the longer SLS core stage. A 115-foot section was removed and replaced with a 165-foot section capable of carrying more weight and lengthening Pegasus from 260 feet to 310 feet. Pegasus has no engines and is moved by tugboats and towing vessels.

For surface transportation, SLS relies on specialized ground support equipment. This is a set of modular equipment including smaller brackets, shackles, and pins that secure the giant rocket hardware to the slow-moving motorized transports that transfer rocket components between buildings, barge, and test stands.

Like the flight hardware that depends on it, the ground support equipment was designed and built to exact specifications; furthermore, every move is carefully choreographed by the operations teams.

A full Moon is in view from Launch Complex 39B at NASA's Kennedy Space Center in Florida on June 14, 2022. The Artemis I Space Launch System (SLS) and Orion spacecraft, atop the mobile launcher, were being prepared for a wet dress rehearsal to practice timelines and procedures for launch. *Image credit: NASA*

Orion Spacecraft

Introduction

NASA's new spacecraft for human missions to deep space will usher in the next era of space exploration. Orion is composed of three main elements and supporting subsystems. The main elements are 1) the crew module, where astronauts live and work; 2) the service module, which provides power, propulsion, and critical supplies; and 3) the launch abort system, which can pull the spacecraft and crew to safety in the event of an emergency during launch or ascent to orbit.

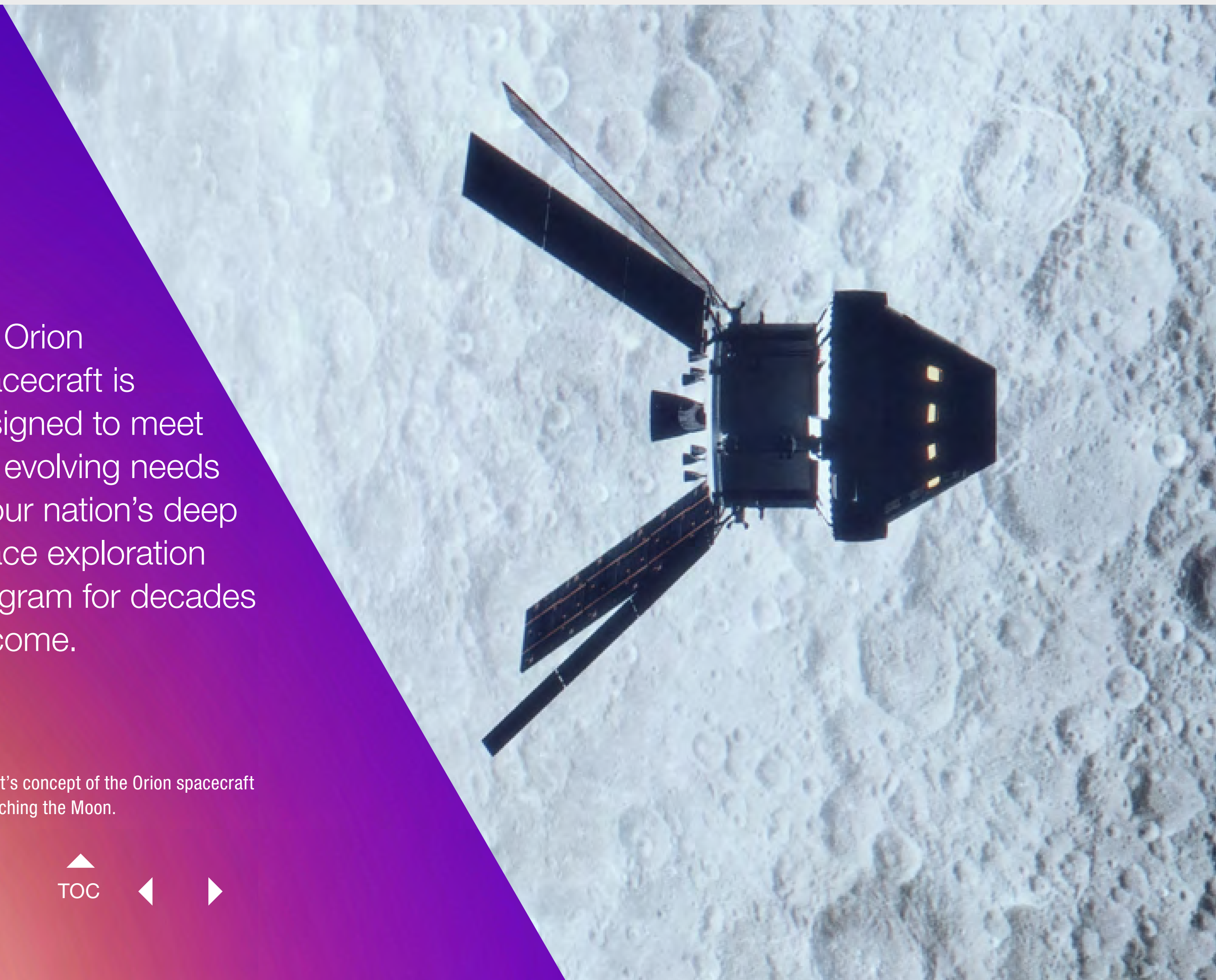
Drawing from more than 50 years of spaceflight research and development, the Orion spacecraft is designed to meet the evolving needs of our nation's deep space exploration program for decades to come. A series of increasingly challenging missions awaits as Orion embarks on deep space expeditions to take humans farther than ever before, including to the vicinity of the Moon and beyond.

HELPFUL RESOURCES

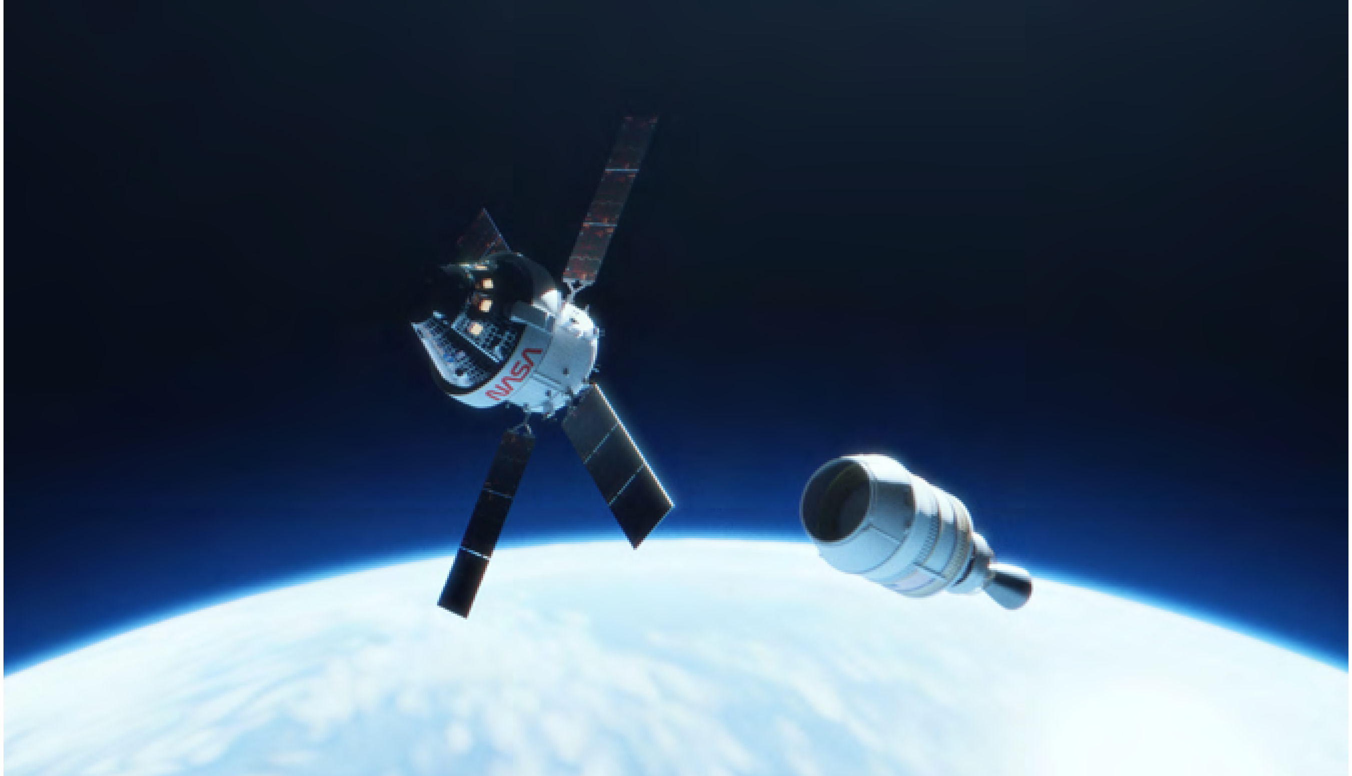
For more information about the Orion program, visit https://www.nasa.gov/orion

SOCIAL MEDIA
Twitter: https://www.twitter.com/NASA_Orion
Facebook: https://www.facebook.com/NASAOrion
Instagram: https://www.instagram.com/NASAArtemis

…the Orion spacecraft is designed to meet the evolving needs of our nation's deep space exploration program for decades to come.



▶ Artist's concept of the Orion spacecraft approaching the Moon.



▲ Artist's concept of the separation of the Orion spacecraft from the Interim Cryogenic Propulsion System.

Overview

The Orion spacecraft, built by lead contractor Lockheed Martin for NASA, is specifically designed to carry astronauts on deep space exploration missions farther than ever before and requires an array of features to keep the spacecraft and its crew safe. On deep space missions, both distance and duration dictate the capabilities and advanced technologies needed. No other spacecraft has the technology to endure the extremes of deep space, such as advanced environmental and life support, navigation, communications, radiation shielding, and the world's largest heat shield to protect astronauts and return them safely home.

Artemis I will send Orion on an uncrewed flight test around the Moon and back to test the spacecraft's systems and performance in a deep space environment before carrying astronauts beginning with Artemis II. Artemis I will test Orion's navigation and communications systems beyond the range of GPS and above communication satellites in Earth orbit; test the radiation sensors and shielding outside the protection of Earth's magnetic field; and test the world's largest heat shield during a high-speed return from the Moon. Future missions with crew will also include advanced systems for life support designed for the demands of a deep space mission.

Future Missions and Configurations

Artemis II will be the first flight with astronauts aboard Orion. The spacecraft will be equipped with advanced environmental control and life-support systems designed to be highly reliable while taking up minimal mass and volume for deep space missions. Additional crew systems will include advanced display and control panels, a compact toilet, exercise equipment to help prevent muscle and bone atrophy, and spacesuits capable of keeping the astronauts alive for six days in the event of cabin depressurization to support a multi-day return from the Moon.

Deep space missions require highly reliable systems because astronauts at the Moon will not have the benefit of frequent resupply shipments to bring spare parts from Earth, like those to the International Space Station. Distance and duration for deep space missions have shaped the design of Orion's compact systems, not only to maximize available space for crew comfort, but also to accommodate the volume needed to carry consumables, such as food and water for the entirety of a mission lasting days, weeks, or even months. Missions beyond Artemis II will also include a rendezvous and docking system for docking to a human landing system that will take astronauts to the surface of the Moon or to the lunar-orbiting Gateway outpost.

Elements

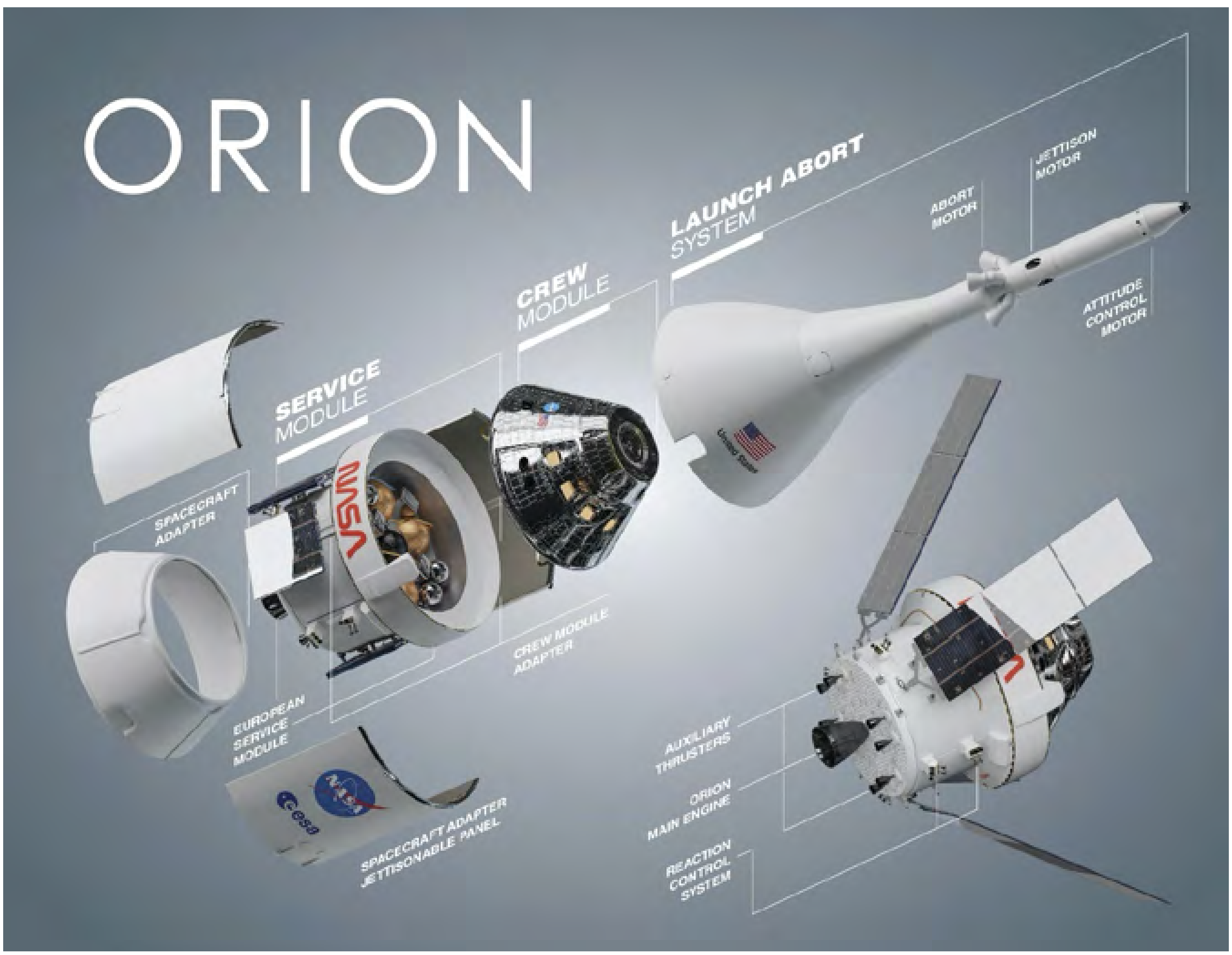
Crew Module

The crew module is the pressurized part of the Orion spacecraft, sometimes referred to as the capsule, where crew members on future missions will live and work on their journey to the Moon and back to Earth; it is the only portion of Orion that returns to Earth at the end of the mission. Although Artemis I is an uncrewed mission, the crew module can accommodate four crew members on future missions for up to 21 days without docking with another spacecraft, and it will provide a safe habitat through launch, in-orbit operations, landing, and recovery.

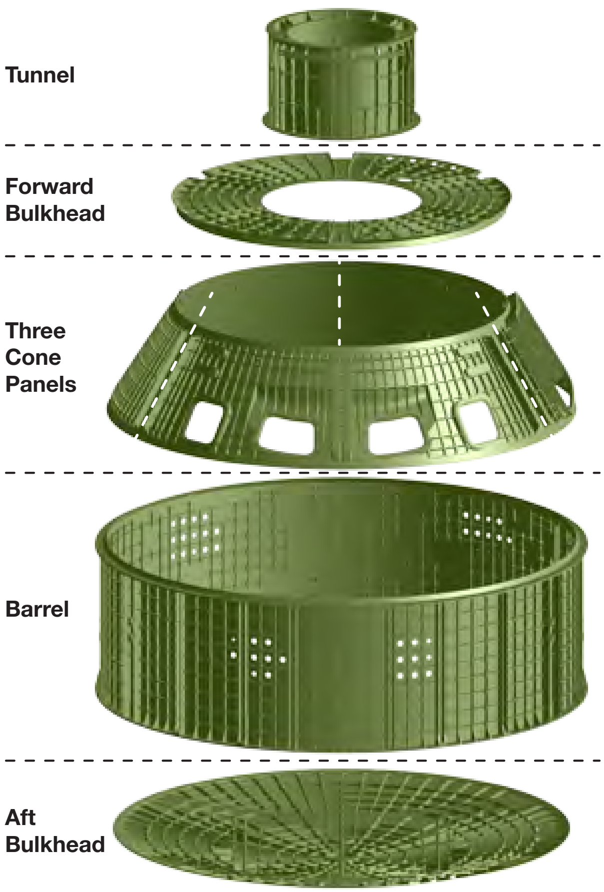
Pressure Vessel

The underlying structure of the crew module is called the pressure vessel. The pressure vessel consists of seven large aluminum alloy pieces that are joined together using friction stir welding to produce a strong, yet lightweight, airtight capsule. The seven major structural pieces include the barrel, the tunnel, the forward and aft bulkheads, and three cone panels. Orion's original designs required 33 welds to create the pressure vessel. Engineers refined the design to reduce the number of welds to seven on Artemis I, saving 700 pounds of mass on the spacecraft.

Illustration showing the major components of the Orion spacecraft.



7 Welds of Orion's Pressure Vessel



▲ Illustration of the seven aluminum alloy pieces that were welded together to create the Orion pressure vessel.

Back Shell

Covering the pressure vessel, on the sides of the crew module, is the back shell, made up of 1,300 thermal protection system tiles. These tiles are made of a silica fiber material similar to the tiles used for more than 30 years on the space shuttle, and they incorporate a stronger coating called "toughened uni-piece fibrous insulation," or TUFI coating, which was used toward the end of the Space Shuttle Program. The tiles protect the spacecraft from in-space micrometeoroid debris as well as the extreme temperature variances from the –350-degree-Fahrenheit coldness of space to the 5,000-degree heat when entering Earth's atmosphere at lunar return velocities. Spacecraft returning from the Moon reenter Earth's atmosphere faster and hotter than spacecraft from low-Earth orbit.

Forward Bay Cover

At the top of the crew module, the forward bay cover protects the top portion of the capsule, as well as the parachutes, during launch, orbital flight, and reentry; it is covered with the same thermal protection tiles as the back shell. After the spacecraft reenters Earth's atmosphere, it is jettisoned at an altitude of approximately 23,000 feet to allow for deployment of the parachute system. The parachute system includes a series of 11 parachutes that are deployed in a sequence to slow down the module from about 325 mph to 20 mph or less and provide a safe speed for splashdown into the ocean.

Heat Shield

The bottom of the Orion capsule is covered by the world's largest ablative heat shield, measuring 16.5 feet in diameter. The heat shield sheds intense heat away from the crew module as Orion returns to Earth, traveling about 25,000 mph and enduring temperatures about half as hot as the surface of the Sun at nearly 5,000 degrees Fahrenheit (2,760 degrees Celsius). The outer surface of the heat shield is made of 186 billets, or blocks, of an ablative material called Avcoat, a reformulated version of the material used on the Apollo capsules. The Avcoat is bonded to a titanium skeleton and composite skin that gives the shield its shape and provides structural support for the crew module during descent and splashdown. During descent, the Avcoat ablates, or burns off in a controlled fashion, transporting heat away from Orion.

The Avcoat is first made into large blocks at NASA's Michoud Assembly Facility in New Orleans, then shipped to NASA's Kennedy Space Center in Florida and machined into 186 unique shapes before application onto the heat shield. Engineers look for voids in the bond lines and also measure the steps and gaps between the blocks. The gaps are filled with an adhesive material and then reassessed. After the thermal protection system has been applied and inspected, engineers and technicians put the heat shield through a thermal cycle test. This testing ensures that the thermal protection blocks are properly bonded and will perform as expected when they are exposed to the extreme temperatures during the mission. The heat shield is then given a coat of white epoxy paint. Aluminized tape is applied after the painted surface dries to dissipate electrical surface charges and maintain acceptable temperatures.

Once all testing has been completed, the heat shield is bolted to the crew module.

Propulsion System

The crew module has a propulsion system composed of 12 small engines, called reaction control system thrusters, provided by Aerojet Rocketdyne, that provide full control of crew module translation and rotation. When the crew module separates from the service module for reentry into Earth's atmosphere, the 12 thrusters control the spacecraft's return by firing bursts of propellant in varying sequences.

Interior

Inside the crew module, the floor structure where the crew seats will be attached and where the crew stowage lockers will be located is called the backbone assembly, which is a nine-piece bolted structure of crisscrossing beams. The backbone, made of aluminum, also provides additional structural support for the crew module.

The seats in the crew module are designed to accommodate nearly 99% of the human population—from a 4′10″ woman to a 6′5″ man. Seats also include adjustable seat pans, foot plates, and arm rests, as well as adjustable hand controller mounts to ensure that astronauts can reach all the controls while in their pressure suits. Most of the equipment the crew will need to live in space on future missions, such as food, medical kits, emergency equipment (including masks and fire extinguishers), sleeping bags, and the pressure suits worn for launch and return to Earth will be stored in lockers located under the seats.

On crewed missions, the crew module will be configured with four seats. For the uncrewed Artemis I mission, only the commander's seat will be flown. Sitting in that seat (designated seat number 1) will be a male-bodied manikin equipped with a spacesuit and two sensors to test radiation impacts that could affect a human body. Sensors under the headrest and behind the seat will record acceleration and vibration data throughout the mission. The space under

▼ During NASA's Artemis I mission, two identical "phantom" torsos named Helga and Zohar will be equipped with radiation detectors while flying aboard Orion to measure the effects of radiation in space and to test for protection with Zohar wearing a vest, while Helga will not. *Image credit: NASA*

▲ Interior of the Orion Medium Fidelity Mockup at Johnson Space Center in Houston. *Image credit: NASA*

the commander's seat will be used to store lockers for the "official flight kit," which will carry various mementos during the trip around the Moon and back to Earth.

In what would be the pilot seat location (designated seat number 2) will be mass simulator plates that work with accelerometer sensors to test seat vibration. In the space where the two rear, or lower, seats will be located on future missions will be two manikin torsos, called phantoms, that simulate human tissue and organs. The phantoms are part of an investigation to measure radiation levels during the mission and evaluate a radiation protection vest worn by one of the phantoms. Two accelerometers also will be attached on the lower seat back simulator where the phantom without the vest will be located, which is closest to the hatch. The accelerometers will provide a comparison of vibration in the upper and lower seats. During splashdown, all accelerometers will measure impact accelerations on these seat locations. The team will compare those accelerations to the measurements taken during water impact testing at NASA's Langley Research Center in Virginia.

Environmental control systems will maintain cabin temperature, pressure, and humidity inside the capsule. The crew module also contains systems for avionics and power, and the sealed capsule provides the protection needed to safeguard spacecraft systems, and crew on future missions, from cosmic and solar radiation in deep space.

On future missions with astronauts, a life-support system will maintain oxygen and carbon dioxide levels, keeping crew healthy and comfortable. A cockpit with glass displays and control panels will allow the crew full control of Orion. Water tanks and a dispenser will provide drinking water and a simple way to rehydrate and warm food. The crew module's waste management system, or lavatory, is designed for multi-week missions and will privately accommodate personal hygiene needs for both men and women. Astronauts will use Orion's built-in exercise device, which supports both aerobic and strength training. The environmental control system will remove excess heat, humidity, and odor generated during exercise.

European Service Module

Orion's European Service Module is provided by ESA (European Space Agency) and built by lead contractor Airbus. It is the powerhouse that fuels and propels the Orion spacecraft in space. The service module is located below the crew module and is designed for long-duration missions to deep space destinations. It provides critical

▼ Engineers work to fit three spacecraft adapter jettison fairing panels onto Orion's service module inside Kennedy's Neil Armstrong Operations and Checkout Building on Oct. 13, 2020. *Image credit: NASA*

An artist's impression of the Orion spacecraft with ESA's service module. The module sits directly below Orion's crew capsule and provides propulsion, power, thermal control, and water and air for four astronauts. The solar array spans 19 m and provides enough power for two households. *Image credit: NASA*

functions for Orion, including propulsion, thermal control, and electrical power generated by the solar arrays.

The consumable storage system of the service module will provide potable water, nitrogen, and oxygen to the crew module on crewed missions. Potable water will be provided by the water delivery system and stored in four tanks with metal bellows, covering usable water needs of the crew for the duration of the mission. Oxygen and nitrogen will be provided by the gas delivery system and stored in four tanks.

The cylindrical module is unpressurized and about 13 feet high, including the main engine and tanks for gas and propellant. During launch, the service module fits into a 17-foot-diameter housing, surrounded by three fairing panels that protect it from the harsh environments of launch, such as heat, wind, and acoustic vibrations. Once Orion is above the atmosphere, the fairing panels surrounding the service module will be jettisoned and its four solar arrays will unfurl. After the spacecraft separates from the upper stage of the SLS rocket, the service module will propel Orion on its mission and help it return to Earth, detaching before the crew module enters Earth's atmosphere.

The farther into space a spacecraft ventures, the more capable its propulsion systems need to be to maintain its course with precision and ensure its return home. In addition to its function as the main propulsion system for Orion, the service module is responsible for orbital maneuvering and position control. It's equipped with a total of 33 engines: one main engine, eight auxiliary engines, and 24 reaction control thrusters.

The main engine is an orbital maneuvering system engine previously flown on space shuttle missions, provided by NASA and made by Aerojet Rocketdyne. The auxiliary engines are R4D-11 engines, also made by Aerojet Rocketdyne and provided by NASA. The reaction control thrusters are provided by ESA and are the same model as those used on the Automated Transfer Vehicles built by

ESA that carried cargo and resupply goods from Earth to the International Space Station between 2008 and 2015.

The main engine will provide major in-space maneuvering capabilities throughout the mission, including inserting Orion into a distant retrograde orbit around the Moon and also firing powerfully enough to depart the Moon's orbit to return to Earth. The eight auxiliary engines are also used for translational maneuvers, essentially backing up the main engine. The 24 reaction control thrusters are used to steer and control Orion in orbit, but usually only 12 are used and the other 12 are mostly backup. The propulsion system can also be used, during some late phases of the launch, for potential abort scenarios.

Orbital Maneuvering System Engine
Flight History for Artemis I

FLIGHT	DATE	ORBITER
STS-41G	10/05/84	Challenger
STS-51J	10/03/85	Atlantis
STS-61B	11/26/85	Atlantis
STS-27	12/02/88	Atlantis
STS-30	05/04/89	Atlantis
STS-33	11/22/89	Discovery
STS-31	04/24/90	Discovery
STS-41	10/06/90	Discovery
STS-37	04/05/91	Atlantis
STS-43	08/02/91	Atlantis
STS-44	11/24/91	Atlantis
STS-45	03/24/92	Atlantis
STS-46	07/31/92	Atlantis
STS-101	05/19/00	Atlantis
STS-106	09/08/00	Atlantis
STS-98	02/07/01	Atlantis
STS-104	07/12/01	Atlantis
STS-110	04/08/02	Atlantis
STS-112	10/07/02	Atlantis

The service module's structure is covered with Kevlar to absorb shocks from micrometeorites and debris impacts. During launch, the service module is held in place between the Orion crew module adapter—which connects the service module to the spacecraft's crew module—and the spacecraft adapter, which attaches to the Orion stage adapter, Orion/service module's connection to the SLS rocket. The crew module adapter houses electronic equipment for communications, power, and control, and it includes an umbilical connector that bridges the electrical, data, and fluid systems between the modules.

Computers control all aspects of the service module. The service module's avionics manage the powered equipment of the module and the data-exchange services, which are based on instructions received from Orion's flight computers in the crew module. Nearly seven miles of cables send commands and receive information from sensors.

The service module's electrical power system provides power for the Orion spacecraft, manages the power generated by the four solar-array wings of the service module, and charges the main batteries on the crew module. Each solar array wing consists of three panel sections, and each panel is approximately 6.5 by 6.5 feet (2 by 2 meters). The total length of each wing is nearly 23 feet (7 meters). There are a total of 15,000 gallium arsenide cells on the four arrays used to convert light into electricity, and the arrays can turn on two axes to remain aligned with the Sun for maximum power. A power control and distribution unit provides the power interface between the service module and the crew module adapter, distributes electrical power to service module's electrical equipment, and protects the power lines.

The service module's thermal control system includes radiators and heat exchangers to keep the equipment and future astronauts at a comfortable temperature. The thermal control system includes an active portion, which transfers the heat of the entire spacecraft to the service module's radiators, and a passive portion, which protects the service module from internal and external thermal environments.

▲ Inside the Launch Abort System Facility (LASF) at NASA's Kennedy Space Center, the fully assembled Orion spacecraft for the agency's Artemis I mission is prepared for transport. *Image credit: NASA*

Launch Abort System

Orion's launch abort system, also known as the LAS, is designed to carry the crew to safety in the event of an emergency during launch or ascent atop NASA's SLS rocket. It can activate within milliseconds to pull the spacecraft away from the rocket and position the module for a safe landing.

The LAS is divided into two parts: the fairing assembly and the launch abort tower. The fairing assembly is a shell composed of a lightweight composite material that protects the capsule from the heat, wind, and acoustics of the launch, ascent, and abort environments. The launch abort tower includes the system's three motors.

The three solid rocket motors work together to propel Orion's crew module to safety in an emergency: the abort motor pulls the crew module away from the rocket; the attitude control motor steers and orients the capsule; then the jettison motor ignites to separate the LAS from the crew module prior to parachute deployment.

The 17-foot-long, 3-foot-diameter abort motor, built by Northrop Grumman, has a manifold with four exhaust nozzles and provides thrust to quickly pull the crew module to safety if problems develop during launch. The high-impulse motor is designed to burn most of the propellant within the first three seconds and burns three times faster than a typical motor of this size to immediately deliver the thrust needed to pull the crew module to safety. If needed during a launch emergency, the crew module would accelerate from zero to 400–500 mph in just two seconds.

The attitude control motor, also built by Northrop Grumman, consists of a solid propellant gas generator and eight equally spaced valves capable of providing 7,000 pounds of thrust in any direction. The unique valve control system enables each valve to open and close, directing the flow of gas. The motor operates to keep the crew module on a controlled flight path after it is pulled away from the rocket by the abort motor, and then it reorients the module for parachute deployment and landing.

The jettison motor was built by Aerojet Rocketdyne and is the only LAS motor that fires on every mission. During a normal launch, once SLS successfully clears most of the atmosphere and the LAS is no longer needed, the jettison motor fires to separate the LAS from the spacecraft. From this point, abort scenarios are handled by the engines in the service module. In a pad abort or launch abort scenario with crew, the jettison motor ignites to separate the LAS from Orion after the attitude control motor has reoriented the spacecraft and prior to parachute deployment and landing.

There will not be astronauts inside the spacecraft for the Artemis I mission, so the abort and attitude control motors will not be active. The jettison motor will still fire once Orion has reached orbit to enable the spacecraft to continue on the remainder of its journey. The full abort system has been thoroughly tested and certified for flights with astronauts beginning with Artemis II.

The tower-like abort structure is specifically built for deep space missions and to ride on a high-powered rocket. It is designed with its motors above the Orion crew module that *pull* the capsule away from the rocket, rather than *push* it away with motors at the base, as some other escape systems designed for other destinations are built to do. This design is ideal for deep space missions because it minimizes the mass that aborts in an emergency by leaving the service module behind and avoids carrying thousands of pounds of unwanted mass to deep space by fully jettisoning the entire LAS once it is no longer needed.

The Orion LAS also offers the highest thrust and acceleration escape system ever tested, generating 400,000 pounds of thrust. In the event of an abort during ascent to orbit, the LAS can outrun the SLS rocket, which generates 8.8 million pounds of thrust. The puller-style system with the tower above the spacecraft is the first of its kind capable of controlling the spacecraft's orientation after separating from the rocket.

Avionics and Software

The Orion primary flight computers have over 750,000 lines of code that operate all the spacecraft systems, including power, communications, guidance, navigation, control, thermal management, instrumentation, and propulsion. For Artemis I, the software is fully automated and is able to execute the mission and handle numerous potential faults, including upsets due to radiation, without ground support. In addition, the software has a robust command and telemetry system that provides NASA's Mission Control Center, or MCC, with the insight and ability to handle unforeseen circumstances and adjust software operation.

In the event of a complete failure of all flight computers during reentry, Orion has a backup flight computer with independently developed software that will take over control and safely land the spacecraft. This capability will

▼ Engineers at NASA's Johnson Space Center in Houston are evaluating how crews inside a mockup of the Orion spacecraft interact with the rotational hand controller and cursor control device while inside their Modified Advanced Crew Escape spacesuits. *Image credit: NASA*

be expanded to cover all phases of the flight for future missions. Software in computers other than the primary flight computers handles various other tasks, such as video processing and optical navigation. All of the software has been extensively tested in multiple laboratories and in nominal and off-nominal conditions to ensure that all the various subsystems are working together to execute the planned mission.

The Orion spacecraft also houses a number of state-of-the-art avionics units to handle data generated by onboard systems, control the various functions of the spacecraft, carry out commands sent from the MCC (or by the crew on future missions), and return systems telemetry for insight into systems status.

The avionics and other electronics used in Orion are almost entirely driven by software and commercial processor technologies that have been ruggedized to endure extreme radiation and temperature fluctuations. Orion's updated avionics also can handle the severe acoustic and vibration environments associated with launch, orbit, a fiery entry into Earth's atmosphere, and a saltwater landing.

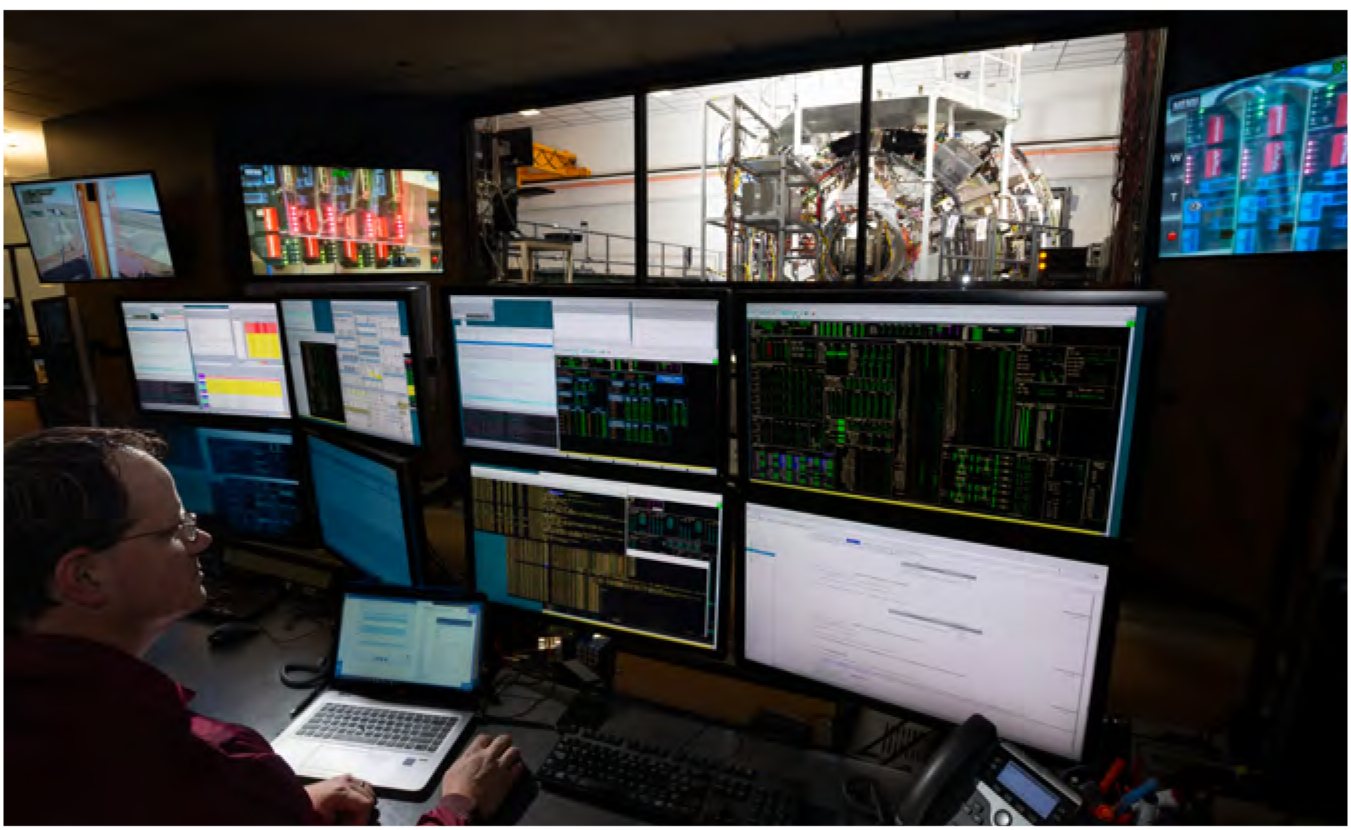
Orion's avionics system consists of the following subsystems:

- Command and data handling
- Guidance, navigation, control, and propulsion
- Communications and tracking
- Power
- Instrumentation
- Displays and controls

Command and Data Handling

The brains of the Orion spacecraft consist of two vehicle management computers that deliver more computing power to the Orion spacecraft than any previous spacecraft designed for humans.

▼ The Integrated Test Laboratory (ITL) has a full set of avionics, harnessing, sensors, and flight software identical to that on Orion. Using this real flight-like hardware and software, the lab is used to simulate and test every aspect of the EM-1 mission from launch to splashdown. *Image credit: NASA*



Each of the vehicle management computers is made up of two flight computer modules (FCMs), which are in charge of flight control and other software; a communication control module that allows commands and data to flow between Orion and the MCC; and a display control module for astronaut displays that will be installed on future crewed Artemis missions. The FCMs provide a high-integrity platform to house software applications and have sufficient processing power to perform command and control of Orion. Each of the four FCMs is internally redundant and continually checks all operations to be sure they match. If the FCMs ever detect a difference between them due to a hardware failure or a radiation upset, the different FCM "fails silent" by stopping all outputs so that a potentially corrupted FCM doesn't issue critical commands to the spacecraft. The FCM then resets itself, listens to the other FCMs to relearn where the spacecraft is and what is happening, and then rejoins the other FCMs in controlling the spacecraft—all within 22 seconds. Having four FCMs on the spacecraft allows the flight software to continue firing thrusters and flying as Orion transitions through the challenging radiation environment of the Van Allen belts, as the probability of all four FCMs being upset in the same 22 seconds is extremely low.

The four redundant FCMs greatly improve system reliability, yet Orion includes another measure of backup capability with the addition of a completely different computer, capable of running different code should it ever be needed. This capability is called the backup flight software. In the unlikely event that something goes wrong with the primary flight computers on Orion, a dissimilar processing platform with dissimilar flight software is hosted on a system called the vision processing unit. This dissimilar computer and software provide a backup function to the redundant FCMs during critical phases of flight, with a focus on crew survival and return functions in the highly unlikely scenario in which anything renders all the FCMs ineffective. The vision processing unit also provides a place to store data during times when Orion can't communicate with the ground.

Eight power and data units (PDU) connect the flight computers and the software to the rest of Orion. These PDUs, each of which has two cards with two redundant channels on each card, control the power to every component on the spacecraft, and they control effectors such as valves, thrusters, and heaters. All sensor data, such as temperature and pressure, is routed through the PDUs as well. The PDUs also communicate with SLS as it launches Orion and puts it on its trajectory to the Moon.

▲ Teams conduct power-up and docking operations for the Sensor Test for Orion Relative Navigation Risk Mitigation (STORRM) in a payload support room at Johnson Space Center's Mission Control Center in Houston.
Image credit: NASA

Orion's onboard data network is a triple-redundant network that allows the FCMs to communicate with all of the other avionic components on Orion. It uses a networking technology called Time-Triggered Gigabit Ethernet that is capable of moving data at a rate 1,000 times faster than systems used on the space shuttle and space station. This networking technology allows NASA engineers to categorize different types of data and prioritize how it should travel through the onboard network. Time-critical data relating to vital systems like navigation and life support, called time-triggered data, has guaranteed bandwidth and message timing to ensure it is always delivered exactly on time. Data that is critical for delivery but not timing, such as file transfers, is called rate-constrained data and is sent immediately whenever time-triggered data is not present. Data used for non-critical tasks such as crew videoconferencing is delivered over the remaining bandwidth. The technology means that critical data and non-essential data can travel safely over a single network on board a spacecraft for the first time. It is built upon a reliable commercial data bus that has been hardened to be resilient to space radiation and proven on Orion's Exploration Flight Test-1. The data system interfaces with all components, including the service module, through radiation-hardened network switches.

Guidance, Navigation, Control, and Propulsion

The Guidance, Navigation, Control, and Propulsion (GNC&P) system is responsible for always knowing where the spacecraft is and where it is going, and it controls the propulsion system to keep Orion pointed in the proper direction and on the correct trajectory.

At the center of this system is the GNC&P flight software that runs on the vehicle management computers. This software receives inputs from navigation sensors and pilot controls and commands the appropriate effectors on the crew module, service module, and LAS to accomplish mission objectives. The Orion GNC&P software operates across a variety of mission phases, including pre-launch, ascent, Earth orbit, transit to and from the Moon, and various abort scenarios, as well as loiter, rendezvous, docking, and entry on future missions. The software must operate in both manual and automated modes and must handle commands from the ground and the crew on future missions. The software must also run complex guidance and navigation algorithms while controlling highly dynamic configurations during reentry, ascent aborts, and orbital maneuvers.

The onboard navigation system for Orion is composed of a number of redundant sensors for measuring Orion's position, which refers to where Orion is in space, and attitude, which refers to the direction the spacecraft is pointing. Like most systems on the spacecraft, there are usually at least two of each sensor to increase reliability of the overall system. Several different types of sensors are needed, as the spacecraft operates in the atmosphere during ascent and reentry, in low-Earth orbit, and near the Moon. These include the following:

- **Orion Inertial Measurement Units:** Each unit contains three devices, called gyros, that measure spacecraft body rotation rates and three accelerometers to measure spacecraft body accelerations. This inertial data is used by the vehicle management computers for onboard navigation to compute spacecraft position, velocity, and attitude.
- **GPS Receivers:** The GPS receivers on Orion are similar to ground-based receivers, except that these are capable of operating at the very high velocities of spaceflight. The GPS sensor system provides position and velocity updates during low-Earth orbit operations, ascent, and reentry. GPS-based altitude values are the primary triggers for entry events. Outside the range of GPS in deep space, Orion will rely on NASA's Deep Space Network to determine the spacecraft's location using sensitive measurements of communication signals that pass between Orion and large tracking dishes on the ground.
- **Barometric Altimeter Assembly:** By sensing the atmospheric air pressure outside the spacecraft during ascent and reentry, these assemblies can measure Orion's altitude. They provide a backup altitude value for parachute and other deployments during entry.
- **Star Trackers:** The star tracker operates like a camera but is much more sensitive and takes pictures only of stars. By comparing the pictures to a known star catalog, the sensor determines spacecraft attitude during orbital operations.
- **Optical Navigation Camera:** The optical navigation camera takes images of the Moon and Earth. By looking at the size and position of these objects in the picture, the camera can determine Orion's range and bearing relative to that object. The optical navigation camera is part of the Orion emergency return system to autonomously operate the spacecraft in the event of lost communication with Earth.
- **Sun Sensors:** The Sun sensors are located on the service module and are used to determine the direction of the Sun during emergency safe mode. Knowing where the Sun is ensures that Orion can point its solar arrays in the right direction to keep power flowing to the spacecraft.

Communications and Tracking

Orion uses a high-speed communications system, employing four phased array antennas on the crew module and two phased array antennas on the service module. Phased array antennas allow signals to be controlled and directed without requiring any physical movement of the antenna. These will be used for video, data, and voice communications with the spacecraft, along with command uplink and telemetry downlink to ground stations, NASA's Tracking

▲ Goddard's Networks Integration Center, pictured here, coordinated the communications support for both the Orion vehicle and the Delta IV rocket, ensuring complete communications coverage through NASA's Space Network and Tracking and Data Relay Satellites. *Image credit: NASA*

and Data Relay Satellite systems, and NASA's Deep Space Network after leaving Earth's orbit.

On future missions with crew, an emergency radio system will allow voice communications anytime during a mission if the main communications system fails, and search and rescue radios and satellite phones will be available after landing for communication with the recovery team. An audio system on board will enable astronauts to speak with each other and with the MCC while they are wearing spacesuits.

Power

The Orion power system is capable of generating and supplying all of the power that is required for its in-orbit operations. The four solar arrays, which are located on the service module, generate about 11 kilowatts of power. Power is transferred between the solar arrays and batteries and to the end systems via the power and data units. Orion's four main batteries are located on the crew module and use small-cell packaging technology to ensure crew safety while providing 120 volts of power to the many systems on Orion. The batteries are fully charged before launch to operate the spacecraft until the solar arrays can be deployed once in orbit. The batteries also operate the spacecraft when the solar arrays cannot be pointed at the Sun or when Orion is in the shadow of Earth or the Moon. The solar arrays are jettisoned with the service module right before entering Earth's atmosphere, so the batteries also provide all the power needed to keep the astronauts safe for return to Earth and up to 24 hours after splashdown.

Instrumentation

Accomplishing flight test objectives requires a dedicated instrumentation system that will measure the dynamic response of all Orion subsystem performance during critical phases of the Artemis missions.

The developmental flight instrumentation (DFI) data system measures unique subsystem performance, such as spacecraft temperature and vibration, during all phases of the mission from launch, to flight in space, to return to Earth. The system is required to measure the response of newly designed components and structures to verify and validate engineering models that will be used to predict their future performance.

The architecture of the DFI system is robust and relies on proven hardware and software to deliver high reliability. The central components are data acquisition units that have two interfaces: one for the sensor interface and one for the control interface. The sensor interface communicates with the temperature, strain, accelerometers, and

▲ Orion descends to Earth under three massive red-and-white main parachutes after its first flight test on Dec. 5, 2014. *Image credit: NASA*

acoustic sensors. The control interface communicates with the power, control, recording, telemetry, and time-sync hardware. The sensors can be changed between flights to allow engineers to make adjustments based on what is learned about a previous flight.

Displays and Controls

On future missions, displays and control equipment inside the capsule will be the crew interface to the Orion systems. Without astronauts aboard Artemis I to test the displays and controls during the mission, Orion will carry mass simulators in place of the display and control panels as well as a technology demonstration payload for a digital crew interface that can respond to voice commands. Beginning with Artemis II, the displays and controls will consist of three display units, seven switch interface panels, two rotational hand controllers, two translational hand controllers, and two cursor control devices. Orion's "glass cockpit" provides fully redundant crew controls and displays, with over 60 graphical user interface formats and interactive electronic procedures—a first in spacecraft history.

Parachutes

Also contained within the crew module are systems to support Orion's safe return to Earth. Orion's parachute system is designed to ensure a safe landing for astronauts returning from deep space missions to Earth in the crew module at speeds exceeding 25,000 mph, as well as during abort scenarios. While Earth's atmosphere will initially slow the spacecraft down to 325 mph, the parachutes will slow Orion to a safe speed of 20 mph or less for landing in the Pacific Ocean.

The parachute system includes 11 parachutes made of 36,000 square feet of parachute canopy material and attached to the top of the spacecraft with more than 13 miles of Kevlar lines. Parachute deployment begins at about five miles in altitude with three forward bay cover parachutes used in conjunction with pyrotechnic linear thrusters to ensure separation of the forward bay cover, which protects Orion and its parachutes during the heat of reentry. The forward bay cover parachutes are packed using a hydraulic press, with forces as high as 3,000 pounds.

Two drogue parachutes are deployed to slow and stabilize the crew module during descent and establish proper conditions for main parachute deployment to follow. The drogues are deployed by cannon-like mortars from the crew module forward bay at 100 feet per second (68 mph). The drogues are packed using a hydraulic press, with forces as high as 10,000 pounds.

Three pilot parachutes will lift and deploy the main parachutes from the crew module forward bay. They are mortar-deployed from the crew module forward bay at 112 feet per second (76 mph). The pilots are packed using a hydraulic press for convenience but are much lower density and can be "hand packed" if required.

The three main parachutes will then slow the crew module to a speed that ensures astronaut safety during landing. Each of Orion's main parachutes weighs 270 pounds and is packed to the density of oak wood to fit in the top part of the spacecraft, but once fully inflated, the three mains would cover almost an entire football field. The mains are packed using a hydraulic press, with forces as high as 50,000 pounds. They are autoclaved with a vacuum applied to the parachute at 190 degrees Fahrenheit (88 degrees Celsius) for 48 hours to help "set" the packing and remove atmospheric moisture.

Embedded in several parachutes are pyrotechnic riser cutters, which use fuses set to ignite at specific times and push blades through bulletproof materials to sever the lines at precise moments and allow the parachutes to unfurl to complete the deployment sequence. Within 10 minutes of descent through Earth's atmosphere, everything must deploy and assemble itself in a precise sequence to slow Orion and its crew for a safe splashdown in the ocean. The parachute system also must be able to keep the crew safe in several failure scenarios, such as mortar failures that could prevent a single parachute from deploying, launch aborts, or other conditions that produce loads close to or exceeding the maximum material capability.

Crew Module Uprighting System

When Orion splashes down in the Pacific Ocean off the coast of San Diego, it will stabilize in one of two positions: the top of the capsule pointed up or top pointed down. The crew module uprighting system, known as CMUS, deploys a series of five bright-orange helium-filled bags on the top of the capsule to flip Orion right side up in the event it stabilizes upside down.

The five bags that make up the CMUS are packed in hard containers and installed atop the capsule inside the structural gussets between the parachutes and other equipment. The bags are inflated with helium gas that is stored in pressure vessels located close by the bags. Each bag has an independent inflation system. The CMUS system initiates after landing and opens a valve for helium to flow into the uprighting bags. As the gas fills the bags, they deploy from their containers and inflate to their full volume.

The CMUS will deploy regardless of the landing position of the capsule. It takes less than four minutes for the CMUS to upright the capsule, and the system will keep Orion upright and stable after splashdown in the ocean and for at least 24 hours, if necessary. The capsule must be upright for crew module communication systems to operate correctly and to help protect the health of the crew members inside on future missions from health impacts due to extended time hanging upside down in seat harnesses.

▲ The Orion Crew Module Uprighting System (CMUS) and Neutral Buoyancy Laboratory team completed two successful sea tests off the coast of Galveston, Texas. CMUS is designed to inflate five bags after the Orion spacecraft and its crew splash down after returning from deep space missions, enabling the capsule to right itself. *Image credit: NASA*

Testing

The Orion Program conducted rigorous testing of the spacecraft, from element-level testing with test articles for the crew module, service module, LAS, parachute system, and other supporting systems—including both flight tests

▲ Lockheed Martin technicians test the fitting of the Orion spacecraft's heat shield back shell panels inside the Neil Armstrong Operations and Checkout Building high bay at NASA's Kennedy Space Center in Florida. The back shell panels serve as the outer layer of the spacecraft and will protect it against the extreme temperatures of re-entry from deep space. *Image credit: NASA*

and ground tests—to integrated testing of the full spacecraft that will fly on Artemis I.

Exploration Flight Test-1

Orion's first uncrewed test flight, known as Exploration Flight Test-1, or EFT-1, demonstrated and validated the Orion crew module's systems that are critical to crew safety, such as heat shield performance, separation events, avionics and software performance, attitude control and guidance, parachute deployment, and recovery operations.

The EFT-1 test flight launched a high-fidelity crew module and a mock service module on a ULA Delta IV Heavy rocket from Space Launch Complex 37 at Cape Canaveral Air Force Station in Florida. During the nearly four-and-a-half-hour test flight, Orion orbited Earth twice, reaching an altitude of approximately 3,600 miles—about 15 times farther into space than the International Space Station—before returning to Earth. At the end of the flight test, Orion landed in the Pacific Ocean and was recovered by NASA and the U.S. Navy.

Sending Orion to such a high altitude allowed the spacecraft to return to Earth at speeds near 20,000 mph. Returning at this speed, as fast as any spacecraft built for humans had endured since the Apollo program, exposed the heat shield to temperatures close to 4,000 degrees Fahrenheit, 80% of what the crew module would endure returning from the vicinity of the Moon. EFT-1 collected data to help NASA lower risks to the astronauts who will fly on Orion beginning with the Artemis II mission. This first flight also gave NASA the chance to continue refining its production and coordination processes, and Orion's teams gained important experience and training in preparation for launching Orion on its first integrated flight with the SLS rocket.

Heat Shield Testing

Following Exploration Flight Test-1, the Orion heat shield was redesigned from a single-piece system to individual blocks of material. Before the time-saving block system was used, a fiberglass-phenolic honeycomb structure was bonded to the structure's skin. Then each of the 320,000 tiny honeycomb cells were individually filled with Avcoat by hand, inspected by X-ray, cured in a large oven, and robotically machined to meet precise thickness requirements.

The new design introduced several considerations that prompted further testing for risk reduction. Engineers performed more than 30 tests across the United States on the new design to investigate the effects of the block structure that could disrupt the smooth airflow and cause localized heating spots. Understanding both effects confirmed that the heat shield will thermally protect the astronauts during entry into Earth's atmosphere.

Teams tested the Avcoat material at NASA's Ames Research Center's Arc Jet Complex and at NASA's Johnson Space Center's Atmospheric Reentry Materials and Structures Evaluation Facility. Teams also performed thermal testing at Johnson's Radiant Heat Test Facility. During these tests, the Avcoat surface reached temperatures of over 3,000 degrees Fahrenheit (1,649 degrees Celsius). Heat shield testing also took place at NASA's Langley Research Center with a 6-inch Orion heat shield model in the 20-inch Mach 6 wind tunnel. The model was machined to represent small-scale features, including the patterns expected as the heat shield ablates during return to Earth.

European Service Module Propulsion Testing

Engineers used a replica of the service module's propulsion subsystem, called the propulsion qualification module (PQM), for testing at NASA's White Sands Test Facility. The data from these tests helped to certify the service module propulsion system for the Artemis I and II missions and beyond. The PQM was designed to verify the performance of the service module engines, propellant feed systems, and various other propulsion operations during expected and unexpected conditions. Testing of the PQM ensured that all engines and thrusters fired safely and accurately to prove that they would be reliable in getting the spacecraft where it needs to go during deep space exploration missions.

The PQM was equipped with a total of 21 engines: one U.S. Space Shuttle Orbital Maneuvering System (OMS) engine, eight auxiliary thrusters, and 12 smaller reaction control system thrusters produced by Airbus in Germany. The service module that will fly on Artemis missions has 33 engines in total, with double the amount of reaction control system thrusters included in the PQM. The full module was a roughly 15-foot cube made of stainless steel that provided the full components for testing the thrusters, fuel lines, and firing of Orion's engines.

Teams from NASA and ESA completed 48 hot fire tests and three discrete pressurization tests conducted in two phases at White Sands. The focus of these firing tests was the interaction between the engines and the propulsion subsystem, as well as the performance of the pressurization control assembly. Engineers conducted five additional hot fire tests with the auxiliary engines on the PQM, as well as tests on the pressure control assembly valves that involved chilling the valves and performing multiple cycles to recreate anomalies.

Teams successfully conducted a 12-minute propulsion test fire to simulate an abort-to-orbit scenario in which the spacecraft's service module must place Orion in a safe orbit if a problem were to arise after the LAS has been jettisoned. The test, which was the longest-ever continuous burn conducted on an OMS engine to date at White Sands, used the PQM to fire the OMS engine, eight auxiliary thrusters, and six reaction control system thrusters.

Acceptance Testing

At Kennedy, the Artemis I Orion crew and service modules underwent functional and performance testing in the high bay of the Neil Armstrong Operations and Checkout building, knowns as the O&C, to ensure its workmanship before ground processing and integration with the SLS rocket in the Vehicle Assembly Building.

Proof Pressure Testing

To certify that Orion could withstand the rigors of spaceflight, engineers completed a series of tests on the pressure vessel. In a test stand inside the proof pressure cell, technicians attached hundreds of strain gauges to the interior and exterior surfaces of the structure. The strain gauges measured the strength of the welds as the pressure vessel was pressurized at incremental steps over two days to reach the maximum pressure it is expected to encounter during flight. The tests confirmed that the weld points would endure the extreme forces during the launch, in-space, entry into Earth's atmosphere, and landing phases on Artemis missions.

Crew Module and Service Module Functional and Performance Testing

The Artemis I Orion crew module underwent initial power-on events, which was the first time the vehicle management computers and the power and data units were installed on the crew module, loaded with flight software, and tested. These tests verified the health and status of Orion's core computers and power and data units; they also ensured that the systems were able to communicate precisely with one another to accurately route power and commands throughout the spacecraft.

The Artemis I Orion service module also separately underwent initial power-on tests. The tests allowed technicians to check that all cables were connected and data was transferred at the speeds required by Orion, as well as the power distribution across the module.

After initial power-on, the Orion crew module and service module underwent separate functional testing, which ensured that each of the module's systems powered on and functioned as designed. After engineers completed functional testing, teams conducted separate performance testing of the crew module and service module. This testing verified that each module's systems not only powered on but functioned within the correct parameters. Performance testing also took place after the two modules were joined.

Environmental Testing

Environmental testing simulates environments the spacecraft will experience through launch, travel in deep space, and recovery; it also evaluates the spacecraft's structure and systems in those conditions. Before joining the crew module and service module for the Artemis I mission at Kennedy, engineers conducted acoustic and thermal cycle testing for each module separately in the high bay of the O&C.

- **Direct Field Acoustic Testing:** During this testing, the crew module or service module was surrounded with speakers and exposed to maximum acoustic levels that Orion will experience in space. Engineers secured the module inside a test cell and then attached microphones, strain gauges, and accelerometers. The module was blasted with extreme vibrations and acoustic levels up to 141 decibels—as loud as a jet engine during takeoff—to ensure that the spacecraft and its systems could withstand the noise expected during launch.
- **Module Thermal Cycle Testing:** Inside a specially constructed thermal cycle chamber, teams rapidly cycled the crew module or service module between hot and cold temperatures over several days to thermally stress the hardware and ensure the workmanship of the module's hardware and its subsystem operations. The cycle of temperatures for the initial thermal test ranged from 29 to 129 degrees Fahrenheit during 105 hours of testing.

After engineers at Kennedy completed testing on the Artemis I crew module and service module individually, they were moved to the Final Assembly and System Testing (FAST) cell, where they were integrated and put through their final system tests prior to shipping to NASA's Neil A. Armstrong Test Facility near Sandusky, Ohio, for three months of rigorous simulated in-space environmental testing at the world's largest and most powerful space environment simulation test facility.

An international team of engineers and technicians completed environmental testing in two phases inside the Space Simulation Chamber:

- **Integrated Spacecraft Thermal Balance and Thermal Vacuum Testing:** The first phase of testing was a thermal vacuum test lasting 47 days while Orion's systems were powered on under vacuum conditions that simulate the space environment. The spacecraft was subjected to extreme temperatures, ranging from minus 250 degrees to 300 degrees Fahrenheit (minus 157 to 149 degrees Celsius), to replicate flying in and out of sunlight and shadow in space. To simulate these conditions, a specially designed piece of hardware, known as the Heat Flux System, was used to heat specific parts of the spacecraft at any given time. It was also surrounded on all sides by a set of large panels called a cryoshroud that provided the cold background temperatures of space. The testing ensured that Orion's systems performed correctly in extreme flight conditions.

- **Integrated Spacecraft Electromagnetic Interference/ Compatibility Testing:** The second phase of testing was a 14-day electromagnetic interference and compatibility test. All electronic components have an electromagnetic field that can affect other electronics nearby. This testing ensured that the spacecraft's electronics worked properly when operated at the same time, as well as when bombarded by external sources. The test campaign confirmed that the spacecraft's systems performed as designed.

After testing in Ohio for several months, Orion was flown back to Florida and returned to the FAST cell at Kennedy's O&C Building for a final round of testing and assembly that included end-to-end performance verification of the spacecraft's subsystems, checking for leaks in the spacecraft's propulsion systems, installing its solar array wings, performing spacecraft closeouts, and pressurizing a subset of its tanks in preparation for flight prior to rolling to the Multi-Payload Processing Facility (MPPF) for commodity servicing before integration with the rocket.

Structural Testing

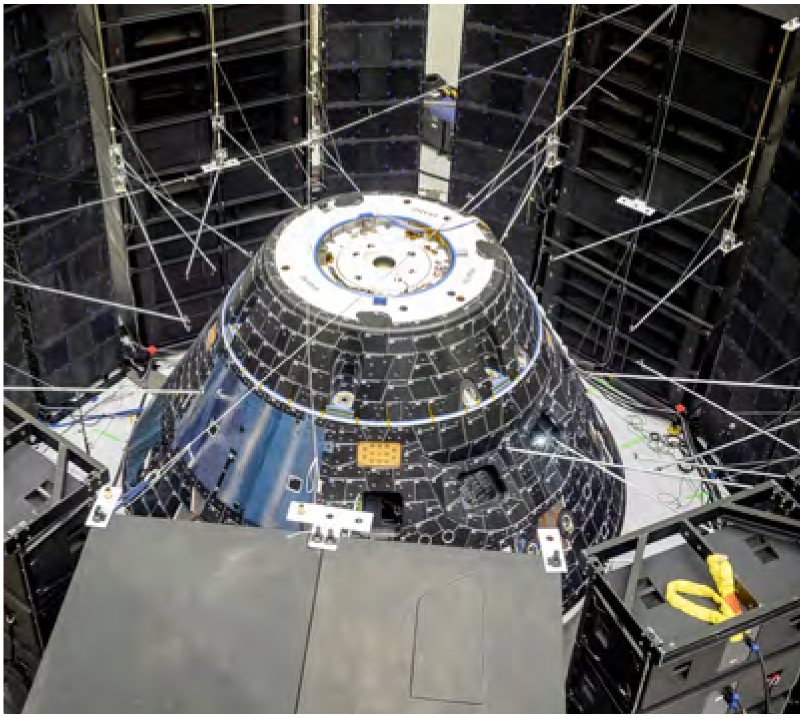
Testing with Orion's "structural twin" at Lockheed Martin's facility in Colorado validated Orion's structure and enabled engineers to push the structure past design standards, simulating the harsh environments that will physically affect the Orion spacecraft. NASA and Lockheed Martin built the structural test article to be identical to Orion's main structural elements: the crew module, service module, and LAS. It did not include the non-structural items, such as the spacecraft computers, propulsion, and seats, for these tests.

Testing involved a series of 21 tests using six different configurations—from a single element to the full stack—and various combinations in between. The different configurations simulated the different flight conditions—such as launch, return to Earth, parachute deployment, and water landing—that Orion will go through during a mission. During some test phases, engineers pushed expected pressures, mechanical loads, vibration, and shock conditions up to 40% beyond the most severe conditions anticipated during the mission, analyzing data to confirm that the spacecraft structures could withstand the extreme environments of space.

These tests helped to verify Orion's design and structural durability for Artemis missions to the Moon.

- **Pressure Testing:** Pushing and pulling with pressure that equates to 140% of the maximum expected loads during missions ensured that the spacecraft structures could withstand intense loads at launch and reentry.
- **Modal Testing:** During modal testing, dynamic loads of pressure were applied to the spacecraft structures. With more than 20,000 parts making up Orion's service module alone, modal tests evaluated how the spacecraft

▼ The Orion crew module for Exploration Mission-1 recently underwent Direct Field Acoustics Test, where it was exposed to maximum acoustics levels that the vehicle will experience in space. Spacecraft response and sound pressure data were collected with microphones, strain gauges, and accelerometers. The max decibel level was -12 dB. *Image credit: NASA*



▲ A fully functional launch abort system with a test version of Orion attached launches on NASA's Ascent Abort-2 atop a booster provided by Northrop Grumman on July 2, 2019, from Launch Pad 46 at Cape Canaveral Air Force Station in Florida. *Image credit: NASA*

components held up to vibration, especially at connection points.

- **Stiffness Testing:** Stiffness testing applied pressure steadily and continuously to the spacecraft's structures. This tested how the structures would respond to the static loads that the spacecraft will experience on missions.
- **Acoustic Testing:** Acoustic testing blasted the structures with sound waves that simulated the vibrating rumble of launch, reaching more than 160 decibels.
- **Pyrotechnic Shock Testing:** Shock tests recreated the powerful pyrotechnic blasts needed for separation events during flight, such as the LAS separating from the crew module after a successful launch.
- **Jettison Testing:** Jettison tests mimicked deployment mechanisms required to jettison the forward bay cover and ensured that components could endure the shock levels expected during flight.
- **Lightning Testing:** Lightning tests evaluated potential flight hardware damage that could occur if the rocket and spacecraft are exposed to a lightning strike prior to launch.

Launch Abort System Testing

Testing for Orion's launch abort system included two major flight tests, along with hot fire testing for the individual motors.

Pad Abort-1

NASA's Pad Abort-1 test was Orion's first major flight test and the first fully integrated test of the LAS. The agency successfully launched a test version of the crew module and its launch abort stack on May 6, 2010, at the U.S. Army's White Sands Missile Range near Las Cruces, New Mexico. The flight test demonstrated the capability of the LAS to propel the crew module to a safe distance during a ground-initiated abort on the launch pad.

The test lasted about 2.5 minutes from launch until the test version of the crew module touched down about a mile north of the launch pad. The crew module reached a speed of approximately 445 mph in the first three seconds, with a maximum velocity of 539 mph in its upward trajectory to about 1.2 miles high. The parachutes guided the crew module to touchdown at 16.2 mph.

Ascent Abort-2

NASA conducted the second major flight test for the launch abort system, known as Ascent Abort-2, on July 2, 2019, to test the Orion LAS during ascent, which is when the spacecraft is expected to experience the greatest aerodynamic stress. Combined with subsystem qualification tests and the successful Pad Abort-1 test, this test resulted in a LAS that is certified to fly on the Artemis missions with astronauts aboard.

During the test, which lasted approximately three minutes, a booster provided by Northrop Grumman launched from Space Launch Complex 46 at Cape Canaveral Air Force Station in Florida. It carried a fully functional LAS and a test version of Orion to an altitude of nearly six miles at over 1,000 mph. At that point, the LAS' powerful reverse-flow abort motor fired 400,000 pounds of thrust, propelling the Orion test article to a safe distance away from the rocket to splash down in the Atlantic Ocean. For cost-saving purposes, the test article was not equipped with parachutes, nor was the test capsule recovered from the ocean.

Motor Testing

Engineers have completed final qualification testing for each of the LAS motors—the attitude control motor, jettison motor, and abort motor. These tests looked at the maximum high- and low-temperature conditions that a motor might see during a launch in Florida to provide the data on how the motor reacts under hot or cold stressing conditions.

Aerodynamic, Aerothermal, and Aeroacoustics Testing

Engineers used wind tunnel testing and simulations to understand Orion's flight behavior in Earth's atmosphere and develop the aerodynamic, aerothermal, and aeroacoustics databases for Orion. The databases help to verify the performance, controllability, thermal protection system, structure, and safety during all phases of atmospheric flight, including launch aborts, by allowing accurate flight simulations and informing the design for the spacecraft.

Defining the crew module aerodynamics, both static and dynamic, helped to ensure stable and controllable flight from entry into Earth's atmosphere to parachute deployment and descent. Similarly, defining the aerodynamics for the LAS helped to ensure successful launch aborts during ascent from the launch pad to orbit. Defining the aerothermal environments for the crew module and LAS ensured that the thermal protection systems will protect them from heat during atmospheric entry, ascent, and ascent aborts. Characterizing the aeroacoustics was also important in designing and testing the Orion and LAS structures for the vibrations and loads they will experience during ascent and reentry.

Teams completed more than 120 tests as part of developing the aerodynamic, aerothermal, and aeroacoustic databases for Orion. Teams have conducted tests in 25 different wind tunnels, four ballistic ranges, two shock tunnels, and three research laboratories across the United States at NASA facilities in Virginia, California, and Ohio; Department of Defense facilities in Tennessee, Maryland, and Florida; and universities such as the University of Buffalo in New York. The tests have covered speeds from 38 mph to about 15,000 mph.

Parachute Testing

NASA has fully qualified the parachute system for flights with crew through an extensive series of 17 developmental tests and eight qualification tests at the U.S. Army's Yuma Proving Ground in Arizona.

During the development series, engineers tested different types of failure scenarios and extreme descent conditions to refine Orion's parachute design and ensure that the parachutes will work in a variety of circumstances. During the qualification testing, engineers evaluated the performance of the parachute system during normal landing sequences as well as several failure scenarios and a variety of potential aerodynamic conditions to ensure that astronauts can return safely from deep space missions.

While airdrop testing was a vital, and very visible, component to the development of Orion's parachutes, ground testing and analysis were equally important to ensuring success. Airdrop testing cannot physically reach all possible spaceflight deployment conditions, but its data helped generate computer models of parachute performance and allowed the team to evaluate the parachutes in altitude and airspeed regimes that could not be thoroughly drop tested. Repeated simulation of the parachutes with varied parameters, called the Monte Carlo method, allowed the team to estimate the bounds of what parachute loads and performance should be expected throughout the life of the program. Ground testing of material capabilities, coupled with the parachute simulations, determined how much structural margin exists in the system. This combination of ground tests, airdrop tests, and analysis qualified the system for Artemis flights with astronauts.

Crew Module Uprighting System Testing

Engineers tested the crew module uprighting system, or CMUS, as part of Orion's first flight test and implemented a series of design changes to improve its performance. During EFT-1, three of the system's five bags did not properly inflate. The spacecraft landed and remained upright in the water; however, had the capsule landed upside down, the two functioning CMUS bags would likely not have been able to fully upright the capsule. Design improvements included thickening the inner bladder of each bag to make it more durable, changing how the bags are packed, developing a hard enclosure for

▼ Workers check the pressure of the bright orange stabilizers that will keep Orion upright in the water if needed. NASA, Lockheed Martin, and the U.S. Navy are conducting the test in the Pacific Ocean off the coast of San Diego. *Image credit: NASA*

with the U.S. Coast Guard Cutter Cypress, Air Force personnel, and Texas A&M Galveston. Teams completed an additional four tests in the Atlantic Ocean, off the coast of Atlantic Beach, North Carolina, in cooperation with the U.S. Coast Guard Station Fort Macon and the U.S. Coast Guard Cutter Maple. These tests demonstrated performance in a natural wave environment and were instrumental in the certification of the CMUS.

Water Impact Testing

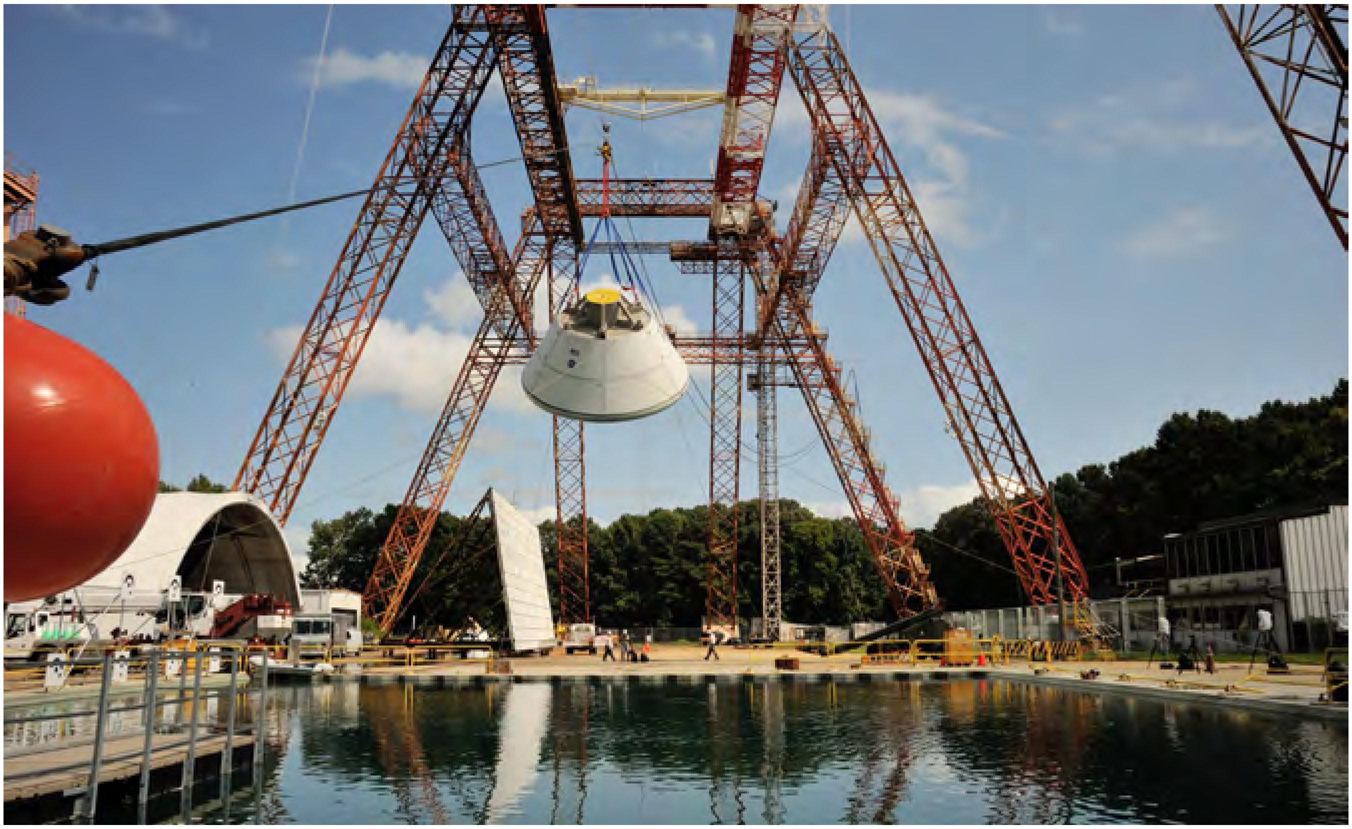
Teams conducted water-impact testing at NASA's Langley Research Center in the center's Hydro Impact Basin at the Landing and Impact Research Facility to provide high-fidelity data of the forces that the Orion spacecraft structure and its astronaut crew would experience during landing, helping to protect the crew and informing future designs. Water-impact testing evaluates how the spacecraft may behave in parachute-assisted landings in different wind conditions and wave heights.

Engineers used three different test versions of Orion as the spacecraft's design was refined over the course of the test series. The final series of drop tests used the test article previously used for structural testing at Lockheed Martin's facility in Colorado, which was based on the final design for the configuration that will fly on Artemis II. Teams will use data from the drop tests as well as from the upcoming Artemis I flight test in final computer modeling for loads and structures prior to Artemis II.

Avionics and Software Testing

The Orion program uses a network of integrated test labs designed to reduce cost and schedule risk by providing an early opportunity in the development phase of the program to perform systems-level avionics and software testing for Orion in a realistic environment.

Engineers used Lockheed Martin's state-of-the-art facility called the Exploration Development Laboratory in Houston for this testing, including avionics system testing to reduce risk prior to the Pad Abort-1 test and Exploration Flight Test-1. Initial testing of systems also included the guidance, navigation, and control, as well as automated rendezvous and docking, and crew interfaces. Engineers also used the facility to perform early development, integration, and dry-run testing of Orion avionics hardware



▲ Teams conduct a vertical drop test of an Orion test article as part of water-impact testing at the Hydro Impact Basin at Langley's Landing and Impact Research Facility. *Image credit: NASA*

and software and associated internal and external crew module interfaces using flight-representative software and an appropriate suite of ground support tools, systems, and software.

Lockheed Martin's Orion Integrated Test Lab, or ITL, located near Denver, runs full mission scenarios from prelaunch to landing, or specific phases of the flight. The lab uses a full-size Orion mockup with a fully integrated set of Orion's crew module and service module avionics, power, wiring, guidance, navigation, and control hardware. The lab's systems connect to the MCC, which allow for real-time monitoring and commanding of the spacecraft in Houston in order to simulate the Artemis I mission.

Tests performed in the ITL are essential for identifying software problems and validating proper functionality and performance of the spacecraft avionics system.

An ITL configuration is the highest-fidelity test platform that Orion avionics hardware and software would experience prior to actual testing regimens on the assembled spacecraft, providing as close to a "test like you fly" environment as can be assembled within a lab setting.

Flight Control Team Training and Testing

The flight control team began training for the Artemis I mission in 2019 and will continue in the weeks prior to launch. They constantly refine and practice procedures they will use on the ground to monitor, command, and control Orion. Flight controllers in the MCC prepare by simulating various parts of Orion's journey, from launch through outbound powered flyby to the Moon, including the trans-lunar injection burn that sends the spacecraft out of Earth orbit and toward the Moon. The MCC also simulates Orion's orbit around the Moon and return powered flyby from the Moon through entry, descent, landing, and recovery, including the final trajectory corrections and burns Orion will need to enter the atmosphere and splash down in the Pacific Ocean.

Simulations and testing have included joint operations between industry partners and NASA's flight operations team, with NASA doing real-time monitoring and commanding of the simulated version of Orion at the ITL in Denver from the MCC in Houston. Testing has also been done with a low-fidelity Orion mockup and with the actual Orion spacecraft at the Exploration Development Lab in Houston.

Engineers also tested the Orion communications system to ensure that the spacecraft and the MCC could flawlessly communicate and send data through NASA's satellite networks in space and on the ground. The MCC verified that these communication systems work with Orion during tests of different Artemis I scenarios from launch to landing.

Management Roles and Facilities

Armstrong Flight Research Center

Armstrong Flight Research Center has supported Orion's flight testing in preparation for Artemis I. Armstrong was the developmental flight instrumentation (DFI) lead for Ascent Abort-2 and supported flight test development and system integration, ground operations definition, planning, and personnel; it also provided component testing. The team also led test vehicle integration and DFI for the Pad Abort-1 (PA-1) flight test and was the integrated product team lead for construction of the flight's launch site. Armstrong also led the Ikhana remotely piloted aircraft that was used to capture live video during the Orion entry and landing for Exploration Flight Test-1. The center also supported Orion's Capsule Parachute Assembly System (CPAS) during parachute qualification testing.

Goddard Space Flight Center

Goddard Space Flight Center supports Orion communication and navigation operations through NASA's Near Space Network (NSN), including a constellation of Tracking and Data Relay Satellites (TDRS) and associated ground stations. The center also provides tracking and navigation support with its Flight Dynamics Facility.

Goddard supports the NASA Communications Network (NASCOM), which carries command and telemetry data and provides mission-critical voice loops between ground stations, mission control centers, and other ground segments. The Goddard team also supports NASA's Search and Rescue office, which provides the responsive location services for Orion crew recovery.

Jet Propulsion Laboratory

The Jet Propulsion Laboratory supports Orion systems engineering and integration. The team also provides independent validation of Orion's thermal protection system and parachutes and provides advanced spacecraft environmental monitoring.

Johnson Space Center

NASA's Orion program is managed at Johnson, where engineers oversee the design, development, and testing of the spacecraft, as well as spacecraft manufacturing taking place across the country and in Europe. Johnson is also home to the nation's astronaut corps and the iconic Christopher C. Kraft Mission Control Center.

Mission Control Center (MCC)

Since 1965, NASA's MCC has been the helm of America's human spaceflight and is the primary facility where flight controllers command and control human spacecraft missions. MCC is the facility from which flight operations personnel will remotely monitor and operate the Orion spacecraft and receive data from Orion and the SLS rocket during Artemis missions.

The MCC is composed of several flight control rooms (FCRs), including FCR-1; FCR-2; and the Red, White, and Blue FCRs. Johnson upgraded the White FCR from its shuttle legacy configuration into a modern mission control configuration to serve as the mission control for flights of NASA's Orion spacecraft.

White Sands Test Facility

NASA's White Sands Test Facility in New Mexico is a component of Johnson that tests and evaluates potentially hazardous materials, spaceflight components, and rocket propulsion systems for NASA centers, other government agencies, and commercial industry. This work includes testing Orion's service module, the powerhouse of the spacecraft that provides in-space propulsion, power, and other astronaut life-support systems, including consumables like water, oxygen, and nitrogen.

Kennedy Space Center

Neil Armstrong Operations and Checkout (O&C) Building

When the Artemis I Orion spacecraft arrived at Kennedy following initial manufacturing at Michoud Assembly Facility in New Orleans, it was placed in the O&C building. The O&C contains a large room called a high bay that operates as a high-tech factory, and it was there that the spacecraft was assembled and readied for Artemis I. The high bay includes unique tooling stations, test fixtures, chambers, and clean rooms for the buildup and testing of the spacecraft.

The facility is capable of processing multiple spacecraft in varying production phases. Orion spacecraft for EFT-1 and Artemis I have been completed in the O&C with the assembly of spacecraft for future Artemis missions well underway.

Marshall Space Flight Center

More than 1,500 parts for the spacecraft have been fabricated in Marshall's machine shop, including clips, sleeves, and rod ends used for unique connections on the Orion spacecraft. Marshall assists Orion's European Service Module (ESM) Integration Office by providing Orion isolation valve refurbishment and Orion gas valve seat material testing, as well as support for Orion's service module propulsion systems with subsystem-level hot fire test operations, along with data review.

Other contributions include support related to space and terrestrial environments, including radiation, plasma, sea states, atmosphere, and winds; and plume and aerothermodynamic analysis and consultation.

The LAS integration and transition to production operations is managed by Marshall with Lockheed Martin as the lead contractor. Marshall also provides fabrication, production, and assembly support to NASA teams across the Orion Program. This effort includes the integration of Orion and the SLS rocket.

Michoud Assembly Facility

Michoud is a component of Marshall where manufacturing and assembly of some of the largest parts of the Orion spacecraft, including Orion's pressure vessel, take place. The work done at Michoud includes the production and welding of the Orion crew module pressure vessel structure, the production of the crew module adapter structure, the production of heat shield block material and composite panels, the production of service module fairings, and the assembly and integration of LAS structural components.

Langley Research Center

Landing and Impact Research Facility

Engineers performed water impact testing on Orion at the Hydro Impact Basin at Langley's Landing and Impact Research Facility. The water basin is 115 feet long, 90 feet wide, and 20 feet deep. The basin is located at the west end of the gantry, which is a 240-foot-high, 400-foot-long, 265-foot-wide A-frame steel structure. The gantry provides the ability to control the orientation of the test article while imparting a vertical and horizontal impact velocity, which is required for human-rating spacecraft.

Glenn Research Center

Glenn serves as the lead for ESA/Airbus integration and management. It also leads in spacecraft mechanisms, pyrotechnics, and structures. Furthermore, the center is a co-lead for the crew and service module and spacecraft adapter. It also provides support for spacecraft integration; test and verification; avionics, power and wiring subsystems; and software and Guidance Navigation & Control.

Neil A. Armstrong Test Facility

Neil A. Armstrong Test Facility, formerly known as Plum Brook Station, is a remote test facility near Sandusky, Ohio, and home to four world-class test facilities, which perform complex and innovative ground tests for the international space community. Engineers conducted major tests for the Orion spacecraft at the facility's Space Environments Complex, which houses the world's largest and most capable space environment simulation facilities. These include the Space Simulation Chamber, which simulates the thermal and vacuum conditions of space and provides an environment in which to test electromagnetic interference; the Reverberant Test Facility, a 100,000-cubic-foot reverberant acoustic chamber; and the Mechanical Vibration Facility, a vibration table capable of testing an entire spacecraft in all three axes.

Ames Research Center

Ames has contributed to a variety of testing and development activities for the Orion spacecraft. Engineers at Ames helped develop and test materials for Orion's heat shield and cone-shaped back shell using Ames' Arc Jet Complex under various heating and pressure environments selected to simulate flight conditions. Using Ames' Unitary Plan Wind Tunnel, teams also tested models of Orion at supersonic air speeds. Additionally, researchers at Ames used supercomputing capabilities to predict and better understand how different abort scenarios—from the launchpad to the edge of space—will affect vibration levels on the spacecraft.

Industry and International Partners

Lockheed Martin

Lockheed Martin is the lead contractor for the design, development testing, and production of the Orion spacecraft for NASA's Artemis missions. As lead contractor for Orion, Lockheed Martin manufactures the spacecraft's crew module, LAS, and crew module adapter. The company also integrates Orion's service module into a completed spacecraft. Lockheed Martin's Orion Program Office is based in Houston, where teams conduct Orion engineering and design. The team performs the majority of the Orion engineering work in Denver, manufactures the crew module pressure vessel and thermal protection materials at Michoud, and completes final assembly of the spacecraft in the O&C at Kennedy and at Lockheed Martin's Spacecraft, Test, Assembly and Resource Center nearby.

Northrop Grumman

Northrop Grumman produces the launch abort motor and the attitude control motor for the Orion spacecraft's LAS under an agreement with Lockheed Martin. The abort motor is manufactured at the company's facilities in Magna, Promontory, and Clearfield, Utah, and the attitude control motor is produced at the company's facility in Elkton, Maryland.

Aerojet Rocketdyne

Aerojet Rocketdyne provides eight auxiliary engines and 12 reaction control thrusters for the Orion crew module as well as the jettison motor for the LAS, under contract to Lockheed Martin. The company also manufactures the high-pressure helium tanks that inflate Orion's flotation system for water-based landings. Orion's auxiliary engines and reaction control thrusters are produced at Aerojet Rocketdyne's facility in Redmond, Washington. The jettison motor is a combined effort of the company's facilities in Orange, Virginia, and Huntsville, Alabama.

Aerojet Rocketdyne will also develop the Orion main engine that will be integrated into Orion's service module on Artemis missions VII through XIV, replacing the Orbital Maneuvering System Engine repurposed from the Space Shuttle Program, also manufactured by Aerojet Rocketdyne.

European Space Agency and Airbus

Orion's European Service Module is provided by ESA and built by main contractor Airbus. Workers across 10 European countries and the United States supply components for the service module, including Germany, Italy, Switzerland, France, Belgium, Sweden, Denmark, Norway, Spain, and the Netherlands. The final product is assembled at Airbus facilities in Bremen, Germany, before being shipped to NASA.

Quick Facts

Orion Summary

Gross liftoff weight	72,000 lb (32,650 kg)
Trans-lunar injection mass	53,000 lb (24,050 kg)
Post-trans lunar injection mass	51,500 lb (23,850 kg)
Usable propellant	16,000 lb (7, 250 kg)

Launch Abort System

Height	50 ft from LAS tip to LAS/SM interface, with ogive panels
Diameter	3 ft (1 m) at tower 17 ft (5.2 m) at base
Liftoff weight	16,700 lb (7,600 kg)
Propellant weight	5,700 lb (2,600 kg)
Abort motor weight	7,600 lb (3,450 kg) includes 4,700 lb (2,100 kg) of propellant 400,000 lb (181, 400 kg) of peak thrust
Attitude motor weight	1,700 lb (750 kg) includes 650 lb (300 kg) of propellant 7,000 lb (3,200 kg) of thrust
Jettison motor weight	900 lb (400 kg) includes 350 lb (150 kg) of propellant 40,000 lb (18,100 kg) of thrust

Crew Module (Crew and Cargo Transport)

Height	11 ft (3.3 m)
Diameter	16.5 ft (5 m)
Pressurized volume (total)	690.6 ft^3 (19.5 m^3)
Habitable volume (net)	316 ft^3 (9 m^3)
Reaction control system vacuum engine thrust	160 lbf (75 kgf)/engine
Return payload	220 lb (100 kg)
Landing weight	18,200 lb (8,250 kg)
Gross liftoff weight	20,600 lb (9,350 kg)

Service Module (Propulsion, Electrical Power, Fluid Storage)

Length	15.7 ft (4.75 m)
Diameter	16.5 ft (5 m)
Gross liftoff weight	30,900 lb (14,000 kg)
Engines/thrusters	24 reaction control system thrusters 50 lb (23 kg) of thrust each 8 auxiliary engines 110 lb (50 kg) of thrust each 1 Orbital Maneuvering System 6,000 lb (2,700 kg) of thrust
Solar arrays	4 arrays 15,000 solar cells 62 ft (19 m) when deployed 11 kW of regenerable electrical power

Spacecraft Adapter

Weight of spacecraft adapter jettisoned fairings	2,800 lb (1,300 kg)
Weight of spacecraft adapter	1,000 lb (450 kg)

Parachutes

Three Forward Bay Cover Parachutes

Diameter	7 ft (2.15 m)
Length	100 ft (30 m)
Weight	8 lb (3.5 kg) each
Material	All Kevlar materials
Deployment altitude	26,500 ft (8,000 kg)
Deployment speed	475 ft (145 m) per second (324 mph) (520 kph)
Density	Approx. 49 lb (785 kg) per ft^3 (roughly the same as oak)
Final packed size	7.2-in by 6.9-in (18-cm by 17-cm) (0.16-ft^3) (.005 m^3) cylinder

Two Drogue Parachutes

Diameter	23 ft (7 m)
Length	100 ft (30 m)
Weight	60 lb (27 kg) each
Material	Kevlar and nylon materials
Deployment altitude	25,000 ft (7,600 m)
Deployment speed	450 ft (140 m) per second (307 mph) (500 kph)
Density	Approx. 40 lb (640 kg) per ft^3 (roughly the same as oak)
Final packed size	16.5-in by 16.2-in (42-cm by 41-cm) (2-ft^3) (.06 m^3) cylinder

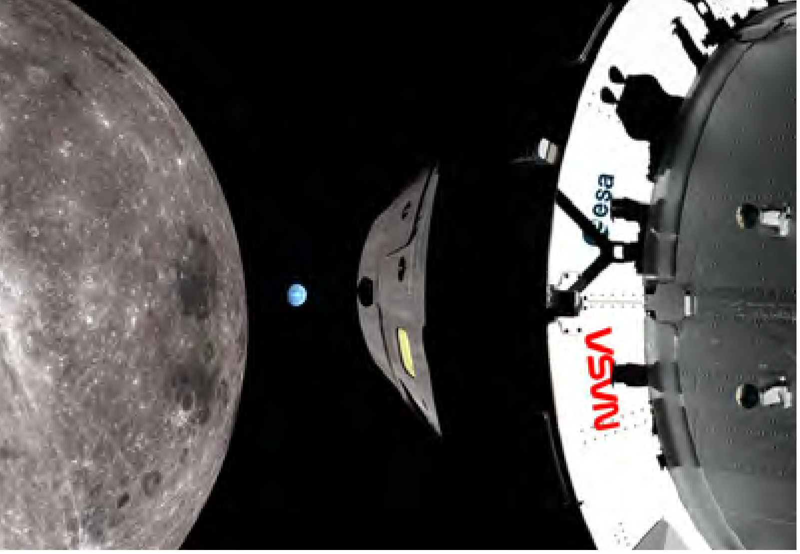
Three Pilot Parachutes

Diameter	10 ft (3 m)
Length	70 ft (21 m)
Weight	9 lb (4 kg) each
Material	Kevlar and nylon materials
Deployment altitude	9,500 ft (2, 895 m) altitude
Deployment speed	190 ft (58 m) per second (130 mph) (81 kph)
Density	Approx. 35 lb (560 kg) per ft^3 (roughly the same as pine)
Final packed size	6.8-in by 13.3-in (17-cm by 34-cm) (0.3-ft^3) (.008 m^3) cylinder

Three Main Parachutes

Diameter	116 ft (35 m)
Length	220 ft (67 m)
Weight	270 lb (120 kg) each
Material	Kevlar and nylon materials
Deployment altitude	9,000 ft (2,750 m)
Deployment speed	190 ft (60 m) per second (130 mph) (210 kph)
Density	Approx. 44 lb (700 kg) per ft^3 (roughly the same as oak)
Final packed size	Approx. 7 ft^3 (.2 m^3); irregular shape to fit into the Orion forward bay

SLS and Orion Livery and External Markings



▲ The NASA logotype, or "worm" logo, and ESA logo are seen in this illustration of the Orion spacecraft in space near the Moon on the Artemis I mission. *Image credit: NASA*

In addition to the SLS core stage's distinctive orange color, several other markings are visible on the outside of the rocket and Orion spacecraft.

The most visible are the national and agency livery, or distinctive exterior markings, such as "USA," the U.S. flag, the NASA insignia known as the "meatball" or the logotype known as the "worm," and the ESA mark.

SLS, Orion, and the mobile launcher also have black-and-white markings that play an important role in Artemis I. Called photogrammetric markings, the black-and-white checkerboards, squares, and circles on the outside of the rocket serve as imagery references for engineering photo and video documentation of SLS attitude and position relative to ground structure during liftoff and ascent. Markings range in size from 0.2 inches to 3 by 3 feet. Multi-checkered pattern markings on the solid rocket boosters measure 24 by 130 inches.

Some of the markings are visible only to internal cameras and will capture separation and jettison events. The launch vehicle stage adapter has eight internal markings; the interim cryogenic propulsion stage (ICPS) has 12; the forward bay of Orion's service module has 30; the spacecraft adapter has 12; and spacecraft adapter jettison panel 1 has 12 markings.

Engineers are interested in every movement of the rocket, in every phase of flight, from the launch pad to its return to Earth. Most of the markings will be used during separation events, such as SLS from the mobile launcher, boosters from the core stage, core stage and launch vehicle stage adapter from the ICPS, and ICPS and Orion stage adapter from Orion and its service module.

The markings help to characterize these movements, and the data will feed back into computer models to help engineers understand actual vs. predicted movements. Every key launch event and its marking were analyzed for placement. Key considerations were where to place on-board cameras to survive the harsh launch environment, as well as ground camera locations.

Livery and Photogrammetric Markings

The Orion spacecraft is adorned with several distinctive external markings for the Artemis I mission. The NASA insignia, known as the "meatball," appears along with the ESA logo on the spacecraft adapter jettison fairing panels that will be visible from the launch pad and protect the service module during launch. The NASA logotype, referred to as the "worm," is painted on the outboard wall of the spacecraft's crew module adapter and will be visible both on the pad and in space. The worm and ESA logo will also appear on the underside of the crew module adapter but will be visible only while Orion is in space. The NASA meatball and an American flag are also painted on the exterior of the crew module and will be visible while Orion is in space and may be visible when Orion returns to Earth after its blazing reentry through the atmosphere.

Orion hardware will also include photogrammetric markings that serve as imagery references for engineering photo and video documentation during liftoff and ascent in addition to those on the SLS rocket.

Cameras

SLS and Orion have several cameras on the rocket, as well as inside and outside the spacecraft, that will gather engineering pictures and video to inspect systems and capture imagery during the mission.

SLS has a total of eight cameras, with four on the engine section that look upward, two on the intertank looking toward the bottom of the rocket, and two inside the launch vehicle stage adapter to capture the ICPS separation event. Orion has seven external cameras and five cameras inside the spacecraft. Each of the solar array wings has a wireless camera near the tip that can be pointed to inspect the exterior of the spacecraft, as well as three cameras mounted on the crew module adapter—two point toward the service module at different angles, and one points upward toward the crew module inside the crew module adapter to capture separation prior to reentry. Three cameras are mounted inside Orion to capture views from inside and outside the crew module, with one looking out the top docking hatch window, one looking out the front pilot window, and one mounted between the pilot seats looking at where the instrument panel will be located on future missions. Two additional exterior cameras face the forward bay cover.

In addition to the cameras on SLS and Orion, there are more than 150 ground cameras used for inspecting or monitoring the rocket during launch.

▲ The NASA "worm" livery and black-and-white photogrammetric markings are visible on completed solid rocket motor segments. *Image credit: NASA*

▼ Technicians with lead solid rocket boosters contractor Northrop Grumman paint photogrammetric markings on one segment of an SLS solid rocket motor.

Exploration Ground Systems

Introduction

The Exploration Ground Systems (EGS) program is helping to build a diverse future in spaceflight at Kennedy, which has served as the nation's gateway to exploring the universe for more than 50 years. Taking the knowledge and assets of NASA's successful spacefaring past, EGS' mission is to transform the center from a historically government-only launch complex to a spaceport that can handle several different kinds of spacecraft and rockets—both government and commercial.

HELPFUL RESOURCES

For more information about Exploration Ground Systems (EGS), visit https://www.nasa.gov/groundsystems

SOCIAL MEDIA

Twitter: https://www.twitter.com/NASAGroundSys

Facebook: https://www.facebook.com/NASAGroundSystems

Unlike previous work focusing on a single rocket or spacecraft, such as the Saturn V or space shuttle, EGS is preparing the infrastructure to support several different spacecraft and rockets, including the SLS rocket and the Orion spacecraft for Artemis I. A key aspect of the program's approach to long-term sustainability and affordability is to make processing and launch infrastructure available to commercial and other government customers, thereby distributing the cost among multiple users and reducing the cost of access to space.

A view of the Vehicle Assembly Building at NASA's Kennedy Space Center during sunrise on Jan. 19, 2022, with the SLS rocket and Orion spacecraft for the agency's Artemis I mission stacked inside. *Image credit: NASA*

Overview

EGS was established to develop and operate the systems and facilities necessary to process, assemble, transport, and launch rockets and spacecraft. Jacobs is the lead ground and launch operations contractor for EGS at Kennedy, conducting all Artemis I flight hardware acceptance, processing, stacking, integration, testing, and launch support.

For Artemis missions, EGS is focusing on the equipment, management, and operations required to safely connect the Orion spacecraft with the SLS rocket; move the rocket to the launch pad; successfully launch it into space; and recover the spacecraft once it has splashed down. To meet this challenge, EGS upgraded Launch Pad 39B, the crawler-transporters, the 52-story Vehicle Assembly Building (VAB), the Launch Control Center's Young-Crippen Firing Room 1, and other facilities.

Future Missions and Configurations

Following the uncrewed Artemis I mission, EGS will continue upgrades to support crewed missions with the Block 1 configuration of the SLS rocket for Artemis II and III. Launch Pad 39B is ready for Artemis I, and a new liquid hydrogen tank and emergency egress system at the pad will support Artemis II, the first crewed launch. The new liquid hydrogen tank will hold about 1.25 million gallons of usable liquid hydrogen propellant to support the SLS rocket and is the largest tank ever built for NASA. The emergency egress system will provide an escape path for the astronauts and ground crew in the unlikely event of an extremely hazardous situation at the level of the crew access arm on the mobile launcher.

Following Artemis III, NASA will build a second mobile launcher, also known as ML2, to support the SLS Block 1B and Block 2 configurations. The next SLS configurations will use the exploration upper stage, which will replace the ICPS as the rocket's upper stage, allowing NASA to

…the Exploration Ground Systems (EGS) program is helping to build a successful and diverse future in spaceflight.

An aerial view of Launch Complex 39B with Exploration Ground Systems' mobile launcher for the Artemis I mission on the pad. *Image credit: NASA* send astronauts and heavy cargo to the Moon on a single launch. The ML2 will accommodate the new upper stage and structural adapters that increase the height of SLS on the more powerful configurations. Although the next SLS configurations will be about 40 feet taller than Block 1, the tower of the second mobile launcher is planned to be only about seven feet taller than the first mobile launcher to fit in the VAB and on Launch Pad 39B. However, wind will have a greater effect on the taller configurations of the rocket and impart higher loads on the mobile launcher. In addition, select swing arms and interfaces must be located at different elevations for ML2 to accommodate the height increase, and the new upper stage also requires different interfaces from those with ML1, as well as two new swing arms.

Elements

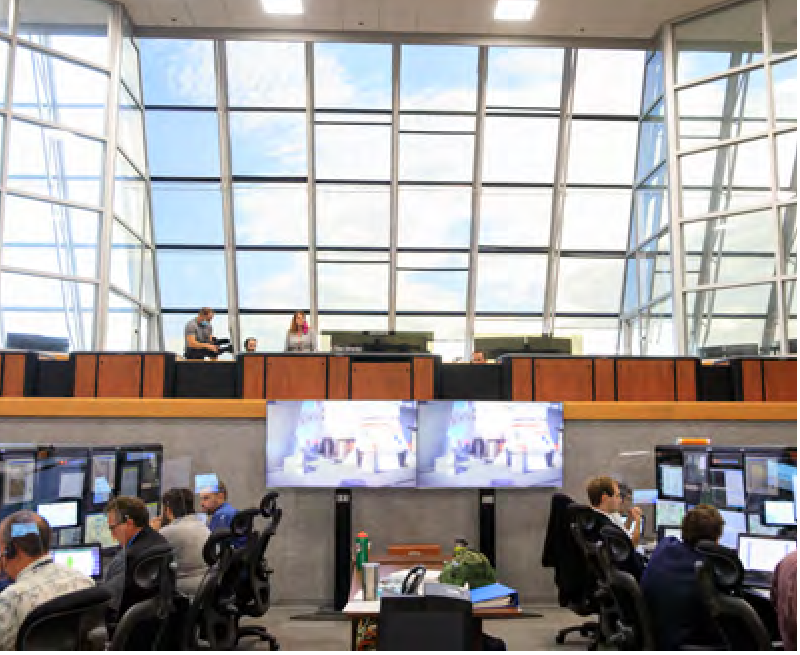
Launch Complex 39

Launch Complex 39 consists of the VAB for final assembly and testing of the rocket and spacecraft; a crawlerway used by the crawler-transporter that will carry the rocket on top of the mobile launcher between the VAB and the pad; the Launch Control Center, which contains the firing rooms for commanding the launch; various operational support buildings; and launch sub-complexes for separate launch pads, which include 39A and 39B—with Launch Pad 39B supporting SLS launches to send Orion on Artemis missions to the Moon.

Vehicle Assembly Building

One of the largest buildings in the world by volume, the VAB covers eight acres and is 525 feet tall and 518 feet wide. The VAB was constructed for the assembly of the Apollo Saturn V Moon rocket, the largest rocket made by humans at the time. It is made up of 65,000 cubic yards of concrete, and its frame is constructed from 98,590 tons of steel. It stands atop a support base of 4,225 steel pilings driven 164 feet into bedrock. The last structural beam was positioned in the VAB in 1965. The interior construction, including the construction of the extensible work platforms, was completed in 1966. The building is

▲ In this view looking up in High Bay 3 of the VAB at NASA's Kennedy Space Center on Mar. 16, 2022, all of the work platforms that surround the Artemis I SLS and Orion spacecraft are fully retracted. *Image credit: NASA*



▲ Teams at NASA's Kennedy Space Center participated in the first joint integrated launch countdown simulation for Artemis I inside Firing Room 1 of the Launch Control Center on July 8, 2021. Seen at the top of the room is Charlie Blackwell-Thompson (right), the launch director for Artemis I. The training exercise involved engineers from Kennedy, Marshall, and Johnson coming together to rehearse all aspects of the launch countdown. *Image credit: NASA*

located 3.5 miles from Launch Pad 39A and 4.2 miles from Launch Pad 39B.

The iconic facility serves as the central hub of NASA's premier multi-user spaceport, capable of hosting several different kinds of rockets and spacecraft at the same time. Whether the rockets and spacecraft are going into Earth orbit or being sent into deep space, the VAB will have the infrastructure to prepare them for their missions.

The tallest portion of the VAB is called the high bay. There are four high bays, two on the east side and two on the west side of the building. Each has a 456-foot-high door, enabling rockets to be stacked vertically and then rolled out to the launch pad. The high bay doors are the largest in the world and take about 45 minutes to open or close completely.

There are five overhead cranes inside the VAB, including two that can hold 325 tons. Operated from cabs near the VAB's ceiling, the cranes are precise enough to lower an object onto an egg without cracking it.

NASA removed the shuttle-era work platforms and installed ten levels of new work platforms, 20 platform halves altogether, in high bay 3 to surround the SLS rocket and the Orion spacecraft for access during processing for Artemis missions. Several miles of Apollo- and shuttle-era abandoned copper and lead-shielded cabling also were removed to make room for the installation of state-of-the-art command, communication, and control systems needed to perform testing and verification prior to rollout to the launch pad.

Platforms A–K

Each of the giant steel platforms measures about 38 feet long and 62 feet wide, weighing between 300,000 and 325,000 pounds. The platforms are attached to rail beams that provide structural support and contain the drive mechanisms to retract and extend them. Each platform rides on four Hillman roller systems that are located two on each side—much like a kitchen drawer glides in and out.

- **Platform A** (346 feet above the VAB floor) provides access to the Orion spacecraft's LAS for Orion Lifting Sling removal and installation of the closeout panels. LAS Antenna Testing (Antenna Hat installation for testing) is also performed at this level.
- **Platform B** (311 feet above the VAB floor) provides access to the Orion Service Module Umbilical and has emergency egress stairs from the Crew Access Arm White Room.
- **Platform C** (280 feet above the VAB floor) provides access to the Orion stage adapter and the ICPS. Engineers use this level for operations to join the ICPS with the launch vehicle stage adapter and also with the ICPS umbilical. Platform C also makes it possible to open the LVSA upper access doors for entry to the top of ICPS.
- **Platform D** (264 feet above the VAB floor) makes it possible to open the LVSA lower access doors for entry to the ICPS to perform flight battery and computer installation on the ICPS equipment shelf.
- **Platform E** (246 feet above the VAB floor) provides access to the core stage forward skirt umbilical. Engineers use an elevated access platform on this level for operations to join the LVSA and core stage. Entry into the core stage forward skirt is necessary to access components of the rocket's avionics for verification operations.

- **Platform F** (192 feet above the VAB floor) provides access to the core stage intertank and the core stage intertank umbilical. Engineers use the multi-level ground support equipment access platform, referred to as F-1, on this level for access to the booster forward assemblies and the core stage to booster forward attach points. The upper level of F-1 is used for lifting sling removal during booster stacking to join the forward assembly.
- **Platform G** (166 feet above the VAB floor) provides access for booster segment stacking operations of the forward segment to the forward center segment and booster systems tunnel cable routing and closeouts.
- **Platform H** (139 feet above the VAB floor) provides access to the booster segment for operations to join the forward center segment to the center segment, as well as booster systems tunnel cable routing and closeouts.
- **Platform J** (112 feet above the VAB floor) provides access for operations to join the center booster segment to the aft center segment, as well as booster systems tunnel cable routing and closeouts.
- **Platform K** (86 feet above the VAB floor) provides access for booster segment stacking operations of the aft center segment to the booster aft assembly and booster systems tunnel cable routing and closeouts. Level K-1 is installed under the platform for access to the core stage and lower booster attach points.

Launch Pad 39B

NASA has upgraded Launch Pad 39B from its previous uses under Apollo and the Space Shuttle Program to support the SLS rocket and other potential users. The guiding principle behind the upgrades and modifications has been to make the area a "clean pad," which will allow a variety of rockets to launch from the pad. The basics that all rockets need, such as electrical power, a water system, a flame trench, and a safe launch area, are in place. The other needs of individual rockets, including access for

Standing atop the mobile launcher, NASA's Space Launch System (rocket and Orion spacecraft) can be seen at Launch Pad 39B at Kennedy Space Center on Mar. 18, 2022. *Image credit: NASA*

▲ NASA's mobile launcher, atop Crawler-Transporter 2, moves into High Bay 3 at the Vehicle Assembly Building (VAB) on Sept. 8, 2018, at Kennedy Space Center. *Image credit: NASA*

workers, can be met with the towers or other structures that deliver the rocket to the pad.

During refurbishment projects, teams replaced 1.3 million feet of copper cables with 300,000 feet of fiber cable, installed new bypass lines and valves, removed the heritage liquid oxygen vaporizer, installed a liquid hydrogen separator vaporizer, replaced the heritage environmental control system equipment, and replaced the fire suppression piping around the entire pad complex. The vaporizers convert the liquid oxygen or hydrogen into gas, which then is fed back into the tank to pressurize it to begin the flow to the rocket.

Launch Pad Systems and Elements

Sound Suppression System

The purpose of the sound suppression system is to dampen sound, vibrations, and extreme heat during liftoff to keep the rocket and the launch pad safe. The water tower for the Ignition Overpressure and Sound Suppression System holds roughly 400,000 gallons of water, or enough to fill 27 average swimming pools. At ignition and liftoff, this water is dumped on the mobile launcher and inside the flame trench in less than 30 seconds. The peak flow rate is 1.1 million gallons per minute, high enough to empty roughly two Olympic-size swimming pools in one minute. The water tower was sandblasted and repainted so it can continue to withstand the corrosive salt air from the nearby Atlantic Ocean.

Flame Trench

The flame trench contains a flame deflector to safely divert the exhaust plume from the SLS rocket during launch. The refurbished flame trench is 450 feet long—the size of one and a half football fields—and the new flame deflector will experience a peak temperature of 2,200 degrees Fahrenheit (1,204 degrees Celsius) during launch. Teams removed Apollo-era bricks from the flame trench and installed more than 96,000 heat-resistant bricks, in three different sizes, using bonding mortar and, where required, steel plate anchors. In areas where significant temperature and pressure will occur, technicians fastened steel plate anchors to the walls at intervals to reinforce the brick system.

The deflector is made up of 150 steel plates, each weighing up to 4,000 pounds, and it measures 57 feet wide, 43 feet high, and 70 feet long. The deflector's north side is slanted at about a 58-degree angle and will redirect the rocket's exhaust, pressure, and intense heat to the north at liftoff.

The flame trench and deflector are above ground level, and the two main structures on either side of the flame trench serve as the platform to support the mobile launcher and rocket. These structures are the catacombs on the east side and the Pad Terminal and Communication Room (PTCR)/Environmental Control System (ECS) room on the west side of the flame trench, which is the area below the pad containing water lines and piping. As part of the refurbishment, teams also reinforced the roof of the catacomb to be able to support 25.5 million pounds.

Lightning Towers

Teams installed three 600-foot-tall masts with overhead wires used to transmit electrical energy around the perimeter of the pad to provide lightning protection for rockets as they are processed and launched from the pad.

Propellant Systems

Along the pad perimeter are storage spheres for liquid oxygen to the northwest of the pad and liquid hydrogen to the northeast of the pad. The liquid oxygen system holds in excess of 850 thousand gallons of liquid oxygen, which is transferred to the SLS rocket during launch countdown via lines from the sphere to the pad. The liquid hydrogen system holds in excess of 850 thousand gallons of liquid hydrogen, which is transferred to the SLS rocket during launch countdown via vacuum jacketed lines from the sphere to the pad. A second liquid hydrogen sphere is under construction to store in excess of 1.25 million gallons of liquid hydrogen for transfer to the rocket beginning with the second launch of SLS.

Mobile Launcher

Weighing over 11 million pounds and standing 400 feet tall, the mobile launcher is the ground structure that will be used to assemble, process, and launch the SLS rocket and Orion spacecraft from Launch Pad 39B for the first three Artemis missions.

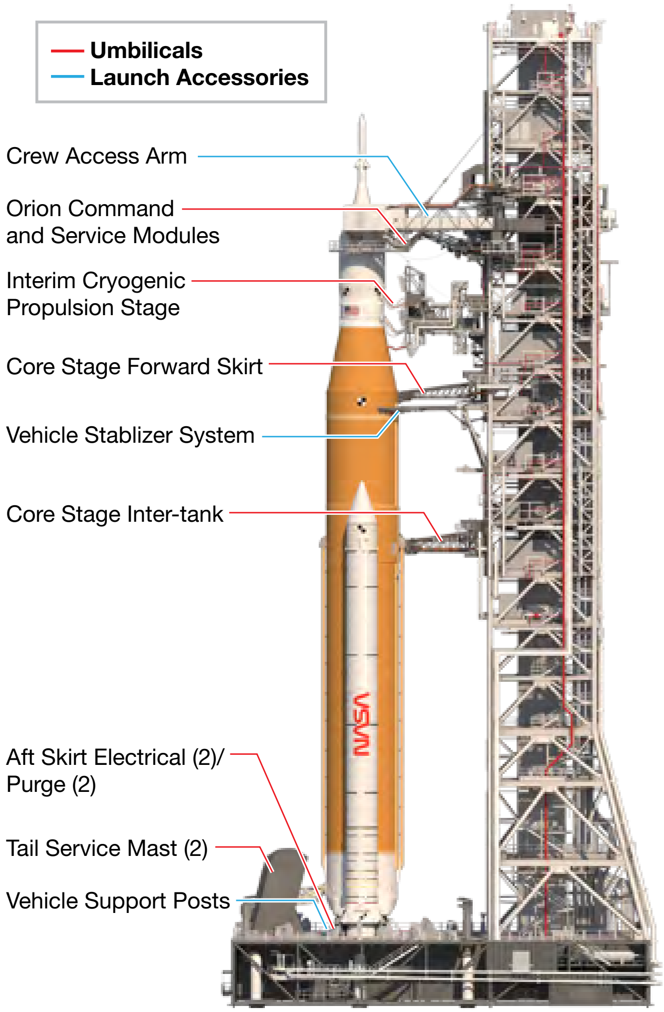
The launcher is designed to support the assembly, testing, checkout, and servicing of the rocket, as well as to transfer it to the pad and serve as the structural platform from which it will launch. During preparations for launch, the crawler-transporter will pick up and move the mobile launcher into high bay 3 in the VAB. The launcher will be secured atop support posts, called mount mechanisms, and the crawler will move out of the way.

The mobile launcher for the Block 1 configuration of the SLS rocket consists of a two-story base, which is 25 feet high, 165 feet long, and 135 feet wide. The base serves as the platform for the rocket and a tower that will be equipped with several connection lines, called umbilicals, and launch accessories that will provide SLS and Orion with power, communications, coolant, propellant, and stabilization prior to launch. The tower stands about 345 feet tall and contains a walkway for personnel and equipment entering the crew module during launch preparations, as well as astronauts on crewed missions. There are tower floor levels every 20 feet for personnel to access the rocket and ground support equipment.

The launcher will roll out to the pad for launch atop the crawler-transporter, carrying SLS and Orion. After the crawler-transporter makes the eight-hour trek to the pad just over four miles away, engineers will lower the launcher onto the pad and remove the crawler-transporter. During launch, each umbilical and launch accessory will release from its connection point, allowing the rocket and spacecraft to lift off safely from the launch pad.

Umbilicals

Aft Skirt Electrical Umbilicals: Two aft skirt electrical umbilicals connect to the SLS rocket at the bottom outer edge of each booster and provide electrical power and data connections to the SLS rocket until it lifts off from the launch pad. The umbilicals act like a telephone line and carry a signal to another subsystem on the mobile launcher called the launch release system. This system distributes the launch signal to the rest of the launch



▲ Diagram of the umbilicals and launch accessories for the SLS.

accessories and the SLS boosters, and it initiates the launch release command.

Aft Skirt Purge Umbilicals: Two aft skirt purge umbilicals connect to the SLS rocket at the bottom outer edge of each booster to remove potentially hazardous gases and maintain the required temperature range of components through a heated gaseous nitrogen purge to the cavity of each booster's aft skirt. Teams connect these umbilicals during stacking operations in the VAB, and they remain connected until released during liftoff.

Tail Service Mast Umbilicals: Two tail service mast umbilicals connect the zero-level deck on the mobile launcher to the SLS rocket core stage aft section. These umbilicals are about 33 feet tall and provide liquid oxygen and liquid hydrogen fluid lines and electrical cable connections to the SLS core stage engine section to support propellant handling during pre-launch operations. The umbilicals tilt back before launch to ensure that all hardware safely and reliably disconnects and retracts from the rocket during liftoff.

Core Stage Intertank Umbilical: The core stage intertank umbilical is a swing arm umbilical that connects to the SLS core stage intertank. The intertank umbilical's main function is to vent gaseous hydrogen, which is boiloff from the extremely cold liquid hydrogen fuel, from the core stage. The arm also provides conditioned air, pressurized gases, and power and data connection to the core stage. This umbilical, located at the 140-foot level on the mobile launcher tower, swings away at launch.

Core Stage Forward Skirt Umbilical: The core stage forward skirt umbilical is located at the 180-foot level on the mobile launcher tower, above the liquid oxygen tank. This umbilical will swing into position to connect to the core stage forward skirt of the SLS rocket and then swing away before launch. Its main purpose is to provide conditioned air and nitrogen gas to the SLS Core Stage Forward Skirt cavity.

Interim Cryogenic Propulsion Stage Umbilical: The interim cryogenic propulsion stage umbilical is located at about the 240-foot level on the mobile launcher tower. This umbilical supplies fuel, oxidizer, purge air, gaseous nitrogen and helium, and electrical connections to the interim cryogenic propulsion stage of the SLS rocket. The umbilical also provides hazardous gas leak detection and swings away before launch.

Orion Service Module Umbilical: The Orion service module umbilical connects the mobile launcher tower to the Orion service module. The umbilical is located at the 280-foot level of the tower and, prior to launch, will transfer liquid coolant and air for the electronics and purge air and nitrogen gas for the environmental control system to support the spacecraft and the LAS. The umbilical tilts back before launch.

Launch Accessories Crew Access Arm: The crew access arm is located at the 274-foot level on the mobile launcher tower. The arm rotates from its retracted position and interface with the SLS rocket at the Orion crew hatch location to provide entry to and exit from the Orion crew module during operations in the VAB and at the launch pad. The access arm provides a clean and controlled work area for people and equipment entering the crew module, an egress path during an emergency, and access to servicing panels for the Orion crew module and service module. On crewed missions, the access arm also provides entry and exit for astronauts. The arm retracts from the Orion spacecraft before launch.

Vehicle Stabilizer System: The vehicle stabilizer system is located at the 200-foot level of the mobile launcher tower and provides a structural interface to the SLS core stage. The system helps reduce core stage motion during rollout to the launch pad, processing operations, high-wind events at the pad, and the launch countdown. The stabilizer drops down and away from the rocket at launch.

Vehicle Support Posts: Eight posts support the load of the solid rocket boosters, with four posts for each booster. The support posts, made of cast steel, are five feet tall and each weigh about 10,000 pounds. They are located on the deck of the mobile launcher and are instrumented with strain gauges to measure loads during stacking, integration, rollout, and launch operations. The posts will structurally support the SLS rocket through T-0 and liftoff.

Crawler-Transporter

NASA has upgraded one of a pair of behemoth machines, called crawler-transporters, to handle the combined SLS rocket and mobile launcher combination. NASA modified Crawler-Transporter 2, also known as CT-2, for Artemis from its previous use to move the space shuttle and Saturn V rocket with redesigned and upgraded roller bearings, a new assembly that can carry a greater load, and an improved lubrication system. The crawler's uprated load-carrying capacity is 18 million pounds, 50% higher than the original design. The crawler does not interface with the rocket, enabling it to also carry other future rockets with no additional modifications needed.

Larger than the size of a baseball infield and powered by locomotive and large electrical power generator engines, the crawler weighs approximately 6.6 million pounds, and the overall size of the crawler is 131 feet long, 114 feet wide, and 20 to 26 feet tall, based on the position of the jacking equalization and leveling cylinders. The crawler was designed to travel 2 mph unloaded, and speed while carrying a rocket and spacecraft is limited by analysis that determines what rate provides the smoothest ride. As of the end of 2021, CT-2 has traveled 2,365 miles.

Able to raise and lower its sides and corners independently, the crawler is designed to roll underneath the mobile launcher while inside the VAB, pick it up, and steadily carry it 4.2 miles to Launch Pad 39B. The crawler has four reinforced pickup points on its surface that secure into place underneath the mobile launcher to carry it to the pad. Pinch blocks are located at three of the four pickup points to secure the load being carried. The crawler uses its hydraulic suspension to keep the platform level all the way to the top pad, which is built atop a sloping pyramid, where it sets the platform in place.

Once the crawler makes the eight-hour trek to the pad with engineers and technicians aboard, the mobile launcher and SLS will be lowered onto pad mount mechanisms. After platforms are lowered and power transfers are complete, the crawler rolls back down the pad slope and parks just outside the pad perimeter gate. The crawler will wait there until a few days prior to launch in case a rollback is required. Then it will roll to a parking site to be protected during launch.

Crawlerway

The crawlerway is the 4.2-mile path from the VAB to Launch Pad 39B that was constructed in 1964. From outside edge to outside edge, the crawlerway is 130 feet wide and is composed of two 40-foot lanes, with a 50-foot grass median strip in between them. The top layer is composed of a river walk 4 inches (10 centimeters) thick on the straight sections and 8 inches (20 centimeters) thick on curves. Underneath is at least four feet of crushed lime rock, which sits atop as much as 20 feet of hydraulically compressed fill. From the VAB to Pad B there is approximately 45,000 tons of rock.

For the Artemis I mission, the path from the VAB to Launch Complex 39B must be able to support at least

25.5 million pounds for the crawler as well as the massive weight of the SLS rocket, the Orion spacecraft, and the mobile launcher. Teams have performed crawlerway conditioning to ensure that the crawlerway is strong enough to withstand the weight and provide stability for the Artemis I mission, as well as even heavier loads in anticipation of heavier payloads on future missions.

Conditioning the crawlerway is essential to preventing a phenomenon called liquefaction, in which the crawler-transporter, the mobile launcher, and the load on it causes the crawlerway to vibrate and shake the soil to the point that the soil itself will behave like a liquid instead of a solid, causing the crawler to tip to one side or the other.

To condition the crawlerway, technicians lifted dozens of concrete blocks, each weighing over 40,000 pounds, onto a mobile launcher platform previously used for the space shuttle and CT-2. Engineers then drove the loaded transporter up and down the path between the VAB and launch pad, with each pass increasingly compacting the soil.

Software

Spacecraft Command and Control System

The computer software and hardware that operate, monitor, and coordinate the ground equipment for the launch of the SLS rocket and Orion spacecraft are called the spacecraft command and control system (SCCS). The SLS rocket and Orion spacecraft generate about 100 megabytes

▼ Teams at Kennedy work to strengthen the crawlerway for launch by driving Crawler-Transporter 2 (CT-2), carrying a mobile launcher platform that was used during the Space Shuttle Program, back and forth on the crawlerway on Jan. 22, 2021, with several cement blocks, each weighing about 40,000 pounds. *Image credit: NASA*

▲ NASA's' mobile launcher makes a solo trek along the crawlerway atop Crawler-Transporter 2 to Kennedy's Launch Complex 39B on June 27, 2019. *Image credit: NASA*

of data per second at liftoff, demanding a robust computer system that can process the volume and speed of this information needed to deliver to that data to the launch team and corresponding mission systems in real time. The system is the electronic hub where information traveling to and from the SLS core stage, the rocket's ICPS, Orion, ground systems, and the operators inside the firing room intersect. During loading and launch, the software will process up to 575,000 changes per second.

The SCCS represents a suite of advanced software tailored to the unique needs of SLS and the Orion spacecraft. It is designed to take advantage of modern computers, servers, and information technology to provide a faster, safer, and more reliable network than systems previously developed to support the space shuttle. Engineers also designed it to be upgraded and adapted to support the rocket and spacecraft as they are flown in different configurations and advanced variants.

Recovery Operations

In addition to the hardware elements that are part of the ground systems supporting launch, the landing and recovery team, led by EGS from Kennedy, will be responsible for safely recovering the Orion capsule, as well as crew on future missions, after splashdown and returning them to land. The interagency landing and recovery team consists of personnel and assets from the U.S. Department of Defense, including Navy amphibious specialists and Air Force weather specialists, and engineers and technicians from Kennedy, Johnson, and Lockheed Martin.

Before splashdown of the spacecraft, the recovery team will head out to sea in a Navy amphibious ship that has a well deck at the waterline to allow boats to dock inside the back of the ship. At the command of the NASA recovery director, Navy divers and other team members in several inflatable boats will approach Orion. When Orion is ready to be pulled into the well deck, the divers will attach a cable, called the winch line, and up to four additional tending lines to attach points on the spacecraft to pull the spacecraft into the ship. The winch will pull Orion into a specially designed cradle inside the ship's well deck, and the other lines will control the lateral motion of the spacecraft. Once Orion is positioned above the cradle assembly, the team will drain the well deck and secure Orion on the cradle.

During a crewed mission, astronauts can be recovered in either open water or the well deck of the ship, depending on sea conditions and other factors on the day of landing. For an open-water crew egress, the Navy divers will install a stabilization collar around the spacecraft as well as an inflatable platform, known as the front porch, to assist with stabilizing Orion and helping recover the astronauts. During crew recovery in the well deck, technicians will pre-position a crew egress stand to access and recover the crew after the spacecraft is fully recovered into the well deck.

Open-water personnel will work to recover Orion's forward bay cover and three main parachutes to the port side of the Navy ship, where a crane will lift them onto the ship's main deck. If teams recover the jettisoned cover and parachutes, engineers can inspect the hardware and gather additional performance data. Teams will transport the spacecraft and other hardware on the ship from the landing site to a pier at U.S. Naval Base San Diego. After technicians secure Orion and the other associated hardware in the recovery transportation fixture, a platform nicknamed the Armadillo, they will transport the hardware by truck to Kennedy.

▲ Inside High Bay 3 of the Vehicle Assembly Building at Kennedy Space Center, the work platforms are shown retracted from around the Artemis I Space Launch System on Sept. 20, 2021. All 10 levels of platforms were extended and retracted as part of an umbilical test. *Image credit: NASA*

Testing

Integrated Test and Checkout Tests to Prepare for Flight

The integrated test and check out series performed after SLS was assembled in the VAB and at the launch pad thoroughly tested all the systems, end to end, prior to launch.

- **Modal Tests:** These tests characterize vibration "modes" for the integrated structure using hydraulic shakers and calibrated hammers.
- **Interface Verification Test:** Also performed with the Orion stage adapter test article and the Orion simulator, as well as with the Artemis I Orion, this test verifies functionality and interoperability of SLS-to-Orion interfaces.
- **Communications End-to-End Test:** This test validates communications between the integrated rocket and spacecraft and the ground using a radio frequency antenna in the VAB, another near the pad that covers the first few seconds of launch, and a more powerful antenna that uses the Tracking and Data Relay Satellite System and the Deep Space Network.
- **Umbilical Release and Retract Test:** This process tests the timing of booster arming and firing and the command for umbilical release.
- **Vehicle Assembly Building Project-Specific Engineering Test:** This test performs element-level testing of SLS in the VAB.
- **Countdown Sequence Test:** With a simulated launch countdown inside the VAB, this test demonstrates the ground launch software and ground launch sequencer, which checks for health and status of the rocket and spacecraft sitting on the pad.
- **Flight Safety System Test:** This test serves as a rehearsal for pre- and post-wet dress and ordnance and flight termination system communications.
- **Dynamic Rollout Test:** This test rolls the integrated rocket and spacecraft from the VAB to Launch

Complex 39B and back again to compare actual loads to analytical models.

- **Pad Project-Specific Engineering Tests:** These procedures at the launch pad test radio frequency, as well as guidance, navigation, and control; they also perform final ordnance tests.
- **Wet Dress Rehearsal:** This process tests propellant loading procedures, structural response, thermal conditioning and loading procedures, the vehicle control system, avionics and software checkout, electromagnetic interference, guidance and navigation, the main propulsion system, engine and booster nozzle steering, and more.

Crawler-Transporter

Engineers tested the new modifications on CT-2 incrementally to prepare for the first integrated flight test of SLS and Orion. The 20-year-life modifications roll-tested the new 1,500-kilowatt generators, parking and service brakes, control system modifications, diesel engine refurbishments, vent hoods, exhaust, and other upgrades.

Sound Suppression Testing

Water flow sound suppression tests at Launch Pad 38B are one of the final checkouts ahead of the launch of Artemis I. At launch, the SLS rocket will produce nearly nine million pounds of thrust—and a lot of sound. The purpose is to reduce and dampen damaging acoustic and thermal energy and high-pressure sound waves that could otherwise damage the mobile launcher, the launch pad infrastructure and flame trench, and even the rocket. During liftoff, the sound level reaches 176 decibels, and the water flow cuts vibrations and sound down by a few decibels, sufficient to minimize pad damage.

▲ A wet flow test at Launch Pad 39B on Sept. 13, 2019, tests the sound suppression system that will be used for the launch of NASA's Space Launch System for the Artemis I mission. During the test, about 450,000 gallons of water poured onto the Pad B flame deflector, the mobile launcher flame hole, and the launcher's blast deck. *Image credit: NASA*

▲ Navy divers practice recovering a mock Orion capsule during an Underway Recovery Test on Nov. 3, 2021. *Image credit: NASA*

Underway Recovery Testing

Teams have practiced procedures and operations in Johnson's Neutral Buoyancy Laboratory pool and in the open water off the coast of California during a series of underway recovery tests, using a test version of the Orion spacecraft and other equipment that will be used during recovery operations. The term "underway" refers to recovery tests done when a ship is at sea.

These tests help to evaluate and improve recovery procedures and hardware ahead of Orion's flight on Artemis I and prior to the first crewed mission, Artemis II. Testing also included recovering the spacecraft from Orion's first flight test, EFT-1, when Orion splashed down in the Pacific Ocean about 600 miles off the coast of San Diego, California, at the end of the test.

Launch Simulations

In preparation for Artemis I, teams in the Launch Control Center (LCC) have been performing launch simulations that involve rehearsing all aspects of the launch countdown. Under the leadership of the Artemis I Launch Director, Kennedy's team of engineers are seated at consoles inside Firing Room 1 and Firing Room 2 of the LCC for the simulations, using software to replicate the commands and operations they will be giving and monitoring on launch day. Launch countdown simulations also include the participation of engineers and test directors from Johnson and Marshall.

Simulations include training exercises that introduce fictional but realistic problems for engineers to identify and work through. They take teams from cryogenic loading—filling tanks in the SLS core stage with supercold liquid hydrogen and liquid oxygen—all the way through countdown and liftoff. These tests ensure that the Artemis I launch team is prepared for launch day.

Management Roles and Facilities

Kennedy Space Center

Kennedy is home to the Exploration Ground Systems Program and has transformed many facilities from their heritage shuttle or Saturn V and Apollo roles to support Artemis missions, focusing on the equipment, management, and operations required to safely process, assemble, transport, and launch the Orion spacecraft and SLS rocket.

Multi-Payload Processing Facility

A unique facility at Kennedy, the Multi-Payload Processing Facility (MPPF) is used to fuel the Orion spacecraft with hazardous propellants and other fluids the spacecraft will need for the journey around the Moon.

The spacecraft is moved out of the O&C aboard a transport pallet and air-bearing system that sits on top of a transporter. In the MPPF, it is moved into a service stand that provides 360-degree access, allowing engineers and technicians from EGS, Jacobs, and other support organizations to fuel and service the spacecraft. Crane operators remove the transportation cover and use fuel lines and several fluid ground support equipment panels to load the various gases and fluids into the crew and service modules.

When Orion returns to Earth after its mission, technicians will transport it to the MPPF, where they will use specialized equipment to remove unused hazardous propellants from its tanks during spacecraft post-flight processing.

Launch Abort System Facility

After fueling in the MPPF, teams move the Orion spacecraft to the Launch Abort System Facility. The 50-foot -tall LAS, including ogive panels, is prepared horizontally inside the facility and then positioned on top of Orion for launch and ascent into orbit. The facility is taller than many processing facilities at Kennedy to allow clearance for vertical assembly of the Orion spacecraft with the LAS. The facility has cranes and other equipment needed to integrate the system during launch processing.

Booster Fabrication Facility

The Booster Fabrication Facility (BFF) is a 45-acre site at Kennedy, located near the VAB and the mobile launcher site. Northrop Grumman, lead contractor for boosters, and NASA engineers use the facility to refurbish, manufacture, and assemble the aft skirt assembly and forward assembly for the twin solid rocket boosters on SLS.

The BFF consists of seven buildings and includes facilities for the SLS Program's solid rocket booster processing and administrative offices. The buildings that most significantly contribute to booster hardware processing include the Manufacturing Building, Multi-Purpose Logistics Facility, and Aft Skirt Test Facility.

Rotation, Processing and Surge Facility

The Rotation, Processing and Surge Facility (RPSF) receives the booster segments for the SLS rocket and prepares them for integration with other hardware in the VAB prior to launch.

The facility is over 90 feet high, more than 190 feet long, and about 90 feet wide. The large open area, called the high bay, contains several work stands and platforms to provide access to hardware during processing. Two 200-ton cranes, one located at the east end of the building and the other at the west end, are positioned to lift the booster segments from a horizontal position to a vertical position. A crane control room provides access for two crane operators.

Railroad tracks lead to and continue through the facility to allow for transport and delivery of the large segments. During processing activities for the SLS rocket, the five booster segments will arrive at the RPSF by rail. Technicians will inspect the segments and rotate them to a vertical position for stacking operations.

The RPSF also will receive the booster aft skirt from the BFF. During processing, the aft segment is attached to the aft skirt and aft exit cone that covers the nozzle to compose the lower part, called the aft assembly. Teams will transport the aft assembly, three center segments, and the forward segment to one of two smaller surge facilities that are part of the RPSF complex for storage until needed for stacking.

Launch Equipment Test Facility

The Launch Equipment Test Facility (LETF) is a versatile test and development area used to test a wide variety of large-scale hardware and ground support equipment components.

Upgraded from its shuttle heritage to support Artemis missions, the LETF provided a proving ground to safely assess machinery to support the launch of the SLS rocket. Equipment at the facility can recreate liftoff and operational conditions to test component performance and can supply cryogenics, hydraulics, electrical systems, environmental control systems, and other commodities. Engineers build prototypes and test designs at the LETF on machinery that duplicates sections of a launch pad and simulates pressures and forces of launch to test in flight-like conditions.

LETF Components

- **Vehicle Motion Simulator:** The vehicle motion simulator emulates all the movements a rocket makes as it is rolled to the launch pad and, more importantly, through the first 30 milliseconds of flight. This process allows exact simulations of the force and conditions under which umbilicals and other launch equipment must work to become qualified for use.
- **North and East Towers:** There are two towers at the LETF built to mirror the launch towers used for rockets. The simulation towers, while shorter than the structures seen at launch pads, are outfitted with the same features so engineers can evaluate launch pad designs ahead of rolling out a rocket. The north tower is a 60-foot-tall structure, and the east tower stands 40 feet tall. Umbilical and access arms can be attached to the towers and used with the vehicle motion simulator to perform qualification testing.
- **Test Fixture:** Engineers use the 600-ton test fixture for multipurpose proof loading and conducting experiments to ensure hardware and ground support components can meet engineering requirements.
- **Water Flow Test Loop:** Teams verify fluid lines and components such as valves, pumps, and meters in a test apparatus that can run parts and lines through high-flow tests to confirm them for operation and other uses.
- **Cryogenic Systems:** The LETF is equipped with a cryogenic system for safely handling and using super-cold chemicals and propellants commonly used in rocketry. Liquid nitrogen and liquid hydrogen can be pumped to areas of the LETF to accurately simulate launch operations with the vehicle motion simulator, towers, and other areas of the facility.
- **Control Room, Workshops, and High Bay:** The LETF is equipped with a full control room and the infrastructure to provide video and high-speed data to controllers, along with feeds for detecting hazardous gas leaks and other systems necessary to safely operate launch support equipment.

Additionally, the LETF includes shops to make and assemble cables and pneumatic, hydraulic, and gas pressure systems for use throughout Kennedy facilities. There are machine and welding shops and an electrical shop.

The LETF high bay is an indoor structure large enough to host the assembly of the large ground support structures. It is equipped with environmental control systems and an overhead crane.

Launch Control Center

The Rocco A. Petrone Launch Control Center (LCC) contains several control rooms, known as firing rooms, from which countdown and launch operations are supervised and commanded. Once the rocket has cleared the launch tower, control switches from the LCC over to Johnson's MCC. Many activities involved with preparing rockets, spacecraft, and payloads for space can be controlled by engineers sitting at computer terminals in the firing rooms. Likewise, all activities at the launch pads can be run from a firing room. The LCC is also equipped with a suite of complex software linking the launch team operators inside the main firing room to the SLS rocket and Orion spacecraft in processing areas such as the VAB and the mobile launcher, as well as at Launch Complex 39B, and to controllers at the Space Force Eastern Range and personnel at other NASA control centers.

- **Young-Crippen Firing Room:** Today's modernized firing rooms serve as the brain behind launch operations. EGS modified the Young-Crippen Firing Room, also known as Firing Room 1, for Artemis with the advanced computer and software systems that will allow greater situational awareness for launch controllers. Firing Room 1 will serve as the main firing room for Artemis I.
- **Firing Rooms 2 and 3:** Firing Rooms 2 and 3 will also support Artemis. EGS upgraded Firing Room 2 to support software verification and validation testing, provide simulation support, and serve as the location for support launch team personnel for Artemis missions on launch day. Teams have repurposed Firing Room 3 for use as a software design and development environment focused on software required to operate and control ground and flight hardware.

Industry Partners

Jacobs

Jacobs provides comprehensive services to NASA's Artemis missions as a contractor to EGS, the Orion program, and the Space Launch System. Jacobs is the lead ground and launch operations contractor for EGS at Kennedy, conducting all Artemis I flight hardware acceptance, processing, stacking, integration, testing, and launch support. The team helped develop the Artemis I launch control software and supports NASA in the LCC firing rooms for all countdown activities. At Marshall, Jacobs provided core stage systems engineering and integration support, and at Johnson, the team supported Orion parachute system development and fabrication.

Quick Facts

Mobile Launcher 1 (ML1)

Total height above ground	~400 ft (~122 m)
Two-story base	25 ft (7.7 m) high × 165 ft (50.3 m) long × 135 ft (41.1 m) wide
Height off ground	22 ft (6.7 m), "0" deck is 47 ft (14.3 m) off the ground
Height of six steel mount mechanisms	22 ft (6.7 m) (in VAB or on launch pad)
Height above the ground of mobile launcher deck when positioned on six steel mounts	47 ft (14.3 m) (in VAB or on launch pad)
The booster aft skirt sits on Vehicle Support Posts (VSPs)	Eight to support the rocket (four per booster) on the mobile launcher platform during transfer to the pad and at liftoff
Tower	40 ft (12.2 m) square, about 345 ft (105.2 m) tall
Tower floor levels	Every 20 ft (6.1 m) for personnel access to the rocket and ground support equipment
Approximate ML1 weight	~11.3 million lb (~5,125.6 t)

Crawler-Transporter

Height	Ranges from approximately 20 ft (6.1 m) to 26 ft (1.8 m), based on the position of the jacking, equalization, and leveling cylinders
Size	Overall: 131 ft (40 m) long × 114 ft (35 m) wide. The mobile launcher contacts the crawler at four points, arranged in a 90-ft (27.4-m) square (same as the base line on a professional baseball field)
Weight	Approximately 6.65 million lb (or the weight of about 15 Statues of Liberty or 1,000 pickup trucks)
Speed	Loaded: 1 mph Unloaded: 2 mph
Load capacity	Able to transport 18 million lb (3,016.4 t) (or the weight of more than 20 fully loaded 777 airplanes)
Tower	40 ft (12.2 m) square, about 345 ft (105 m) tall
Hydraulic system	Reservoir capacity: 2,500 gal (11,365 L) Steering: 4 pumps, 34.4 gallons (156.4 L) per minute (gpm)(lpm) @ 1,200 revolutions per minute (rpm) per pump Steering pressure: 5,000 psi (34,474 kPa) maximum JEL: 8 pumps, 60 gpm (227 lpm) max, 15–20 gpm (56.8–75.7 lpm) nominal @ 1,200 rpm per pump JEL pressure: 3,000 psi (20,670 kPa) maximum

Electrical Systems

DC power system	16 locomotive traction motors: 375 hp (280 kW) Diesel engines: Alco, 16 cylinders (2 @ 2,750 hp [2,051.5 kW] each, for DC) Generators (DC): 4 @ 1,000 kW each
AC power system	Runs all onboard systems Diesel engines: Power, 16 cylinders, 2 @ 2,220 hp each, for AC power Generators (AC): 2 @ 1,500 kW each
Capacity	Diesel fuel capacity: 5,000 gallons (18,927.1 L) Fuel consumption: 1 gal per 32 ft (10 m) (approximately 165 gal (750 L) per mi); Drive system gear ratio: 168:1

Vehicle Assembly Building

- One of the largest buildings in the world by area, the VAB covers eight acres and is 525 feet (160 meters) tall and 518 feet (158 meters) wide.
- At 130,130,415 cubic feet (3,684,883 cubic meters), it is one of the largest buildings in the world by volume.
- It is made up of 65,000 cubic yards (49,696 cubic meters) of concrete, and its frame is constructed from 98,590 tons of steel. It stands atop a support base of 4,225 steel pilings driven 164 feet (50 meters) into bedrock.
- The VAB high bay doors are the largest in the world at 456 feet (139 meters) high and take about 45 minutes to completely open or close.
- The building is home to a NASA logo that covers 12,300 square feet (1,142.7 square meters) and the largest American flag, at 209 feet (64 meters) tall by 110 feet (33.5 meters) wide, painted on the side of the VAB.
- The flag originally was painted onto the VAB in 1976 for the Bicentennial Exposition on Space and Technology.
- In 2020, repainting the American flag and the NASA logo required more than 500 gallons (1,893 liters) of paint.
- There is no platform I in the VAB so that it is not confused with the numeral 1.
- The building is listed in the National Register of Historic Places and is designated as a National Historic Civil Engineering Landmark.

Launch Pad 39B

- During refurbishment projects, 1.3 million feet (396,240 meters) of copper cables were removed and replaced with 300,000 feet (91,440 meters) of fiber cable.
- The water tower for the Ignition Overpressure and Sound Suppression System holds roughly 400,000 gallons (1,818,436 liters) of water, or enough to fill 27 average pools. This water is dumped on the mobile launcher and inside the flame trench in less than 30 seconds. The peak flow rate is 1.1 million gallons per minute (4,163,953 liters per minute), high enough to empty roughly two Olympic-size swimming pools in one minute.
- The three lightning towers are about 600 feet (183 meters) tall—taller than the VAB, which is 525 feet (160 meters) tall.
- The catacomb roof was reinforced to be able to support 25.5 million pounds (11,340 tons)—the equivalent of 2,125 average-size African elephants.
- The refurbished flame trench and new flame deflector will withstand temperatures of between 3,000 degrees and 5,600 degrees Fahrenheit (1,649 and 3,093 degrees Celsius) during launch.
- More than 96,000 bricks were installed on the walls of the flame trench during the refurbishment project.
- The flame trench is 450 feet (137 meters) long; that is equal to the length of about 1.5 football fields.
- The flame deflector is made up of about 150 steel plates, each weighing up to 4,000 pounds (1,814 kilograms).
- Liquid oxygen and liquid hydrogen tanks store supercooled liquid gases (that are used for propellant) at minus 297 degrees and minus 423 degrees Fahrenheit (147 and minus 423 degrees Celsius), respectively.
- Apollo 10 was the first mission to begin at Launch Pad 39B when it lifted off on May 18, 1969, to rehearse the first Moon landing.
- Three crews of astronauts launched to the Skylab space station in 1973 from Pad 39B.
- Three Apollo astronauts who flew on the historic Apollo-Soyuz Test Project mission to link up in space also launched from Pad 39B.

Space Communication and Navigation Systems

Artemis missions will rely on NASA's comprehensive communications network services for journeys to lunar orbit. NASA's worldwide network infrastructure will provide seamless communications, with different service levels as Orion leaves Earth, orbits the Moon, and returns safely home.

NASA's Near Space Network and NASA's Deep Space Network will support communication and navigation services. Communication services allow flight controllers to send commands to the spacecraft and receive data from Orion, the Space Launch System, and the rocket's upper stage. Navigation, or tracking, services enable the flight controllers to calculate where the spacecraft are along their trajectory through space.

NASA's Near Space Network

NASA's Near Space Network provides a suite of communications and navigation services through commercial and government-owned, contractor-operated network infrastructure. The network will provide communications and navigation services during launch and navigation services at various points on the journey to the Moon.

Near Space Network Direct-To-Earth Services

The Near Space Network's Launch Communications Segment (LCS) includes three ground stations along Florida's coast to meet the specific needs of the SLS rocket and will provide links to both Orion and SLS during prelaunch and launch for Artemis I. Specifically, the first two stations along the rocket's flight path will provide uplink and downlink communications between the rocket and mission controllers. In the final phases of ascent, the third station will downlink high-rate telemetry and video from SLS while Orion connects to communications relay satellites. The Near Space Network's navigation services extend to Orion's journey from low-Earth orbit to the Moon and back through ground stations in Santiago, Chile, and Hartebeesthoek, South Africa.

Near Space Network Relay Services

The Near Space Network also provides services to Artemis I through NASA's Tracking and Data Relay Satellite (TDRS) constellation, which can provide near-continuous communications services. Located about 22,000 miles above Earth, TDRS relay data from spacecraft at lower altitudes to ground antennas during launch and low-Earth orbit phases of the Artemis I mission. TDRS will continue service until Orion and ICPS leave its coverage volume, when NASA's Deep Space Network takes over, and then again on Orion's return to Earth, from the final return trajectory correction burn through splashdown.

NASA's Deep Space Network

The Deep Space Network (DSN) will handle communications beyond low-Earth orbit. Additionally, the network will facilitate communications during the deployment of CubeSats that will fly as secondary payloads on Artemis I with their own science and technology missions. The DSN consists of three facilities spaced equidistantly from each other—approximately 120 degrees apart in longitude—around the world. These sites are at Goldstone, near Barstow, California; near Madrid, Spain; and near Canberra, Australia. The strategic placement of these sites permits constant communication with spacecraft as Earth rotates—before a distant spacecraft sinks below the horizon at one DSN site, another site can pick up the signal and carry on communicating.

The Near Space Network and Deep Space Network will work together to support navigation for Orion so that engineers can employ a technique called three-way Doppler tracking. Using this method—with two ground stations on Earth in contact with Orion simultaneously, one from each network—NASA can triangulate Orion's location relative to the ground stations.

Acronym List

BFF	Booster Fabrication Facility
CMUS	crew module uprighting system
CT-2	Crawler-Transporter 2
DFI	developmental flight instrumentation
DSN	Deep Space Network
EFT-1	Exploration Flight Test-1
EGS	Exploration Ground Systems
ESA	European Space Agency
ESDMD	Exploration Systems Development Mission Directorate
ESM	European Service Module
FAST	Final Assembly and System Testing
FCM	flight computer module
GNC&P	Guidance, Navigation, Control, and Propulsion
gpm	gallons per minute
ICPS	interim cryogenic propulsion stage
ITL	Integrated Test lab
JEL	Jacking, Equalizing, Leveling
kph	kilometers per hour
LAS	launch abort system
LCC	Launch Control Center
LETF	Launch Equipment Test Facility
LVSA	launch vehicle stage adapter
MCC	Mission Control Center
ML1	Mobile Launcher 1
ML2	Mobile Launcher 2
MPPF	Multi-Payload Processing Facility
O&C	Neil Armstrong Operations and Checkout Building
OMS	Orbital Maneuvering System
PBAN	polybutadiene acrylonitrile
PDU	power and data unit
PQM	propulsion qualification module
PSI	pounds per square inch
PTCR	Pad Terminal and Communication Room
rpm	revolutions per minute
RPSF	Rotation, Processing and Surge Facility
SCCS	Spacecraft Command and Control System
SLS	Space Launch System
TDRS	Tracking and Data Relay Satellite
TLI	trans-lunar injection
TUFI	toughened uni-piece fibrous insulation
ULA	United Launch Alliance
VAB	Vehicle Assembly Building
VSP	Vehicle Support Post

▲ A Goldstone 111.5-foot (34-meter) Beam Waveguide antenna tracks a spacecraft as it comes into view. The Goldstone Deep Space Communications Complex is located in the Mojave Desert in California. *Image credit: NASA*

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