The NASA Authorization Act of 2010 requires the following minimum capabilities:

- The Orion Multi-Purpose Crew Vehicle (MPCV) must be able to serve as the primary crew vehicle for missions beyond low Earth orbit (LEO).
- The vehicle must be able to conduct regular in-space operations such as rendezvous, docking and extravehicular activity, in conjunction with payloads delivered by the Space Launch System or other vehicles in preparation for missions beyond LEO.
- The vehicle must provide an alternative means of crew and cargo transportation to and from the International Space Station, in the event other vehicles, whether commercial or partner-supplied, are unable to perform that function.
- The vehicle must have the capability for efficient and timely evolution.
Launch Abort System (LAS)
- The LAS propels the crew module to safety in the event of an emergency during launch or the climb to orbit.
- Protects the crew module from dangerous atmospheric loads and heating then jettisons after it is through the initial mission phase of ascent to orbit.

Crew Module (CM)
- The CM is the transportation capsule that provides a safe habitat for the crew, storage for consumables and research instruments, and serves as the docking port for crew transfer.
- It is the only part of Orion that returns to Earth.

Service Module (SM)
- SM supports the CM from launch through separation prior to reentry.
  - Provides propulsion capability for orbital transfer, attitude control, and high altitude ascent aborts.
  - The SM provides all the CM consumables needed to maintain a habitable environment.
  - Transports unpressurized cargo and scientific payloads.

Stage Adapter
- The shroud encapsulates the SM providing protection and the structural transition to the launch vehicle (LV); the shroud is jettisoned after LV separation.

Spacecraft Adapter
- Supports the Crew Vehicle (CV) during launch and ascent; the CV separates from the LV using pyrotechnics.
Crew Vehicle Mission Phases

Launch

Launch Abort System Jettison

Preparation for Leaving Earth Orbit

Mission Operations

Re-entry

Landing/Recovery

Credit: NASA and Lockheed Martin
August 31, 2011 - Lockheed Martin successfully completed the first of a series of acoustic tests on the Orion Crew Vehicle (CV) consisting of the crew module and the launch abort system.

- Built to spaceflight specifications, the Orion CV ground test vehicle is the first full-scale spacecraft built to support the development of the human space flight vehicle.

- The series of tests, conducted at Lockheed Martin’s Reverberant Acoustic Laboratory chamber near Denver, CO, exposed the spacecraft to acoustic forces as high as 150 decibels (equivalent to being 50 yards from a jet).

- The sound pressure tests last only a few minutes and were completed incrementally to allow engineers to isolate and understand the behavior of each of the major components.

- After the acoustic tests, the spacecraft remained in the chamber for the modal survey testing in which vibrating stingers were applied to the spacecraft structure to measure responses to simulated launch environments.

-- The acoustic and modal tests verified that the spacecraft can withstand the extreme noise and vibration that the vehicle would experience during a launch or an emergency abort.

Credit: Lockheed Martin
• September 2011 - The Orion Crew Vehicle (CV) ground test vehicle is shown in the Reverberant Acoustic Laboratory chamber near Denver, CO.
- The Orion CV ground test vehicle is shown after the launch abort vehicle configuration test at Lockheed Martin's facilities near Denver, CO.
-- The spacecraft was exposed to sound pressure levels that emulate those experienced at launch and if an abort is needed to carry the crew to safety away from a potential problem on the launch pad or during ascent.
-- The vehicle was covered with fillets and panels that resemble the vehicle's launch configuration.
--- The Launch Abort System encloses the crew module.
--- The Stage Adapter is located below the Launch Abort System.
---- The adapter was not tested.

Credit: Lockheed Martin
December 20, 2011 - An airplane dropped an Orion test article from an altitude of 25,000 ft above the U.S. Army's Yuma Proving Grounds. Orion's drogue chutes were deployed between 15,000 and 20,000 feet, followed by the pilot parachutes, which then deployed two main landing parachutes.

-- This particular drop test examined how Orion would land under two possible failure scenarios.

--- Orion's parachutes are designed to open in stages, called reefing, to manage the stresses on the parachutes after they are deployed.

---- The reefing stages allow the parachutes to sequentially open, first at 54% of the parachutes' full diameter, and then at 73%.

--- This test examined how the parachutes would perform if the second part of the sequence was skipped.

-- The second scenario was a failure to deploy one of Orion's three main parachutes, requiring the spacecraft to land with only two.

--- Orion landed on the desert floor at a speed of almost 33 ft per sec, which is the maximum designed touchdown speed of the spacecraft.
In 1996, NASA Johnson Space Center, TX began development of the Advanced Docking Berthing System. The NASA Docking System (NDS) was developed for future U.S. human spaceflight vehicles, such as Orion and the Commercial Crew Program vehicles. The NDS is NASA’s implementation of the International Docking System Standard (IDSS), an attempt by the International Space Station Multilateral Coordination Board to create an international spacecraft docking standard. The NDS, Block 1, was designed and built by The Boeing Company in Houston, TX to meet the IDSS standards. Design qualification testing took place through January 2017.
The crew module (CM) will hold 6 crew members for low Earth orbit (LEO) missions and 4 to 6 for beyond LEO missions.

- A maximum of 3 astronauts flew in the smaller Apollo and 7 in the larger space shuttle.
- The CM has a 32.5° conical shape similar to the Apollo Command Module.
- It is 16.5 ft in diameter and 10.83 ft in length with a weight of 21,400 lbs (LEO) and 19,650 lbs (beyond LEO); Apollo was 12.83 ft in diameter and 10.58 ft long.
- The CM will be recovered after a water landing similar to Apollo.
- Unlike Apollo, the CM will be reused for up to 10 flights.
August 30, 2010 - The first Orion Crew Module, built to space flight specifications, successfully passed a structural proof pressure test at the Michoud Assembly Facility in New Orleans, LA allowing the hardware to advance to subsystem assembly and integration.

- The successful tests demonstrated a leak-free structure fabricated using self-reacting friction stir welding techniques, a technology that produces stronger and higher quality joints when compared with conventional welding approaches.
- The pressurization test demonstrated weld strength capability, and advanced aluminum-lithium alloy structural performance at maximum flight operating pressures.
August 2016 - The Orion Crew Module (CM) heat shield structure for the Exploration Mission-1 (EM-1) spacecraft was completed and shipped by Lockheed Martin (LM) in Waterton, CO to Kennedy Space Center, FL.
- The heat shield, located at the base of the spacecraft, is designed to endure the extreme heat and deflect it from the CM.
- The 16.5 ft diameter CM heat shield is the largest composite heat shield ever built.

During the manufacture of the heat shield for the Orion Exploration Flight Test-1 (EFT-1) engineers determined that the strength of the heat shield structure was below expectations.
- Analysis showed, and the December 2014 flight proved, that the heat shield would work for EFT-1.
-- However, the EM-1 spacecraft will experience colder temperatures in space and hotter temperatures upon reentry, requiring a stronger heat shield.
- Through lessons and data obtained from building and flying the EFT-1 heat shield, the NASA and LM team was able to make a design update meeting the EM-1 strength requirements.
May 13, 2011 - The Crew Module Ground Test Article (GTA) successfully completed the Pressure Influence Coefficient testing at the Lockheed Martin facility in Waterton, CO. The test is performed to identify potential weaknesses in the integrated GTA structure under 10 lbs/square inch of pressure. Initial results show that the structure performed as expected and all test objectives were met.

The GTA was built from the unit that successfully completed the structural proof pressure test at the Michoud Assembly Facility in New Orleans, LA on August 30, 2010. The heat shield and thermal protection backshell were added to the GTA by Lockheed Martin in Denver in preparation for performance testing to ensure the vehicle can meet the challenges of ascent, on-orbit operations, and safe landing.
The August 25, 2016 “splash” test of the Orion Crew Module (CM) Ground Test Article is shown in the Hydro Impact Basin at NASA’s Langley Research Center in Hampton, VA. The simulated water landing of a space capsule using a 14,400 lb mock-up covered with sensors is capable of detecting forces that the structure and its astronaut crew would experience.

- The landing and impact research facility, also known as the “gantry,” initiated the test by firing pyrotechnic devices releasing the CM mock-up from its tethers.

-- The test vehicle took flight swinging across the sky; seconds later, it splashed into the Hydro Impact Basin, an oversized pool.

- The test was the ninth in a series of 10 tests taking place at the Langley Research Center.
January 2018 - The integrated NASA and U.S. Navy team are aboard the USS Anchorage testing out new ground support equipment and practicing procedures for the recovery of the Orion Command Module and its crew from deep space missions.

- After traveling through space at 25,000 miles per hour, the Orion spacecraft will slow to 300 mph after it passes through the Earth’s atmosphere and slows down to 20 mph before it safely splashes down in the Pacific Ocean.

- The Kennedy Space Center’s NASA Recovery Team moves to the capsule’s location quickly and brings it and the astronauts safely aboard the U.S. Navy recovery ship.
Despite its conceptual resemblance (left) to the 1960s-era Apollo, the crew module (CM) will use several improved technologies:
- A nitrogen/oxygen mixed atmosphere at either sea level (14.69 lbs/square inch) or reduced (8.01 to 10.20 lbs/square inch) pressure.
- Improved waste-management facilities, with a miniature camping-style toilet and the unisex “relief tube.”
-- The “relief tubes” were used on the space shuttle (whose system was based on Skylab) and the International Space Station (based on the Russian Soyuz, Salyut, and Mir systems).
- The “Glass cockpit” digital control smart systems, including voice controls, are derived from the Boeing 787.
- An “autodock” feature, similar to the Russian Progress spacecraft and the European Automated Transfer Vehicle, has provisions for the flight crew to take over in an emergency.
- More advanced computers than those used on previous human spacecraft.
- Spacesuit engineers demonstrate how four crew members would be arranged for launch inside the CM using a mockup at Johnson Space Center, TX.
The service module (SM) to the left provides support to the CM from launch through CM separation to enable LEO and beyond LEO missions with minimal impact to the CM.
- The SM supports a 21.1 day crewed mission.
- It provides accommodation for International Space Station (ISS) un-pressurized cargo and beyond LEO mission equipment.
- The SM has a 16.5 ft diameter stepped cylindrical shape that is 15.67 ft in length.
- The SM will be encapsulated by a fiberglass spacecraft adapter that will be jettisoned after launch vehicle separation.
- The SM separates from the CM prior to the CM returning to Earth.

The SM is based upon the European Space Agency’s unmanned Automated Transfer Vehicles (ATV) that delivered supplies to the ISS.
- The ATV-derived SM provides the propulsion, power, and thermal control, as well as supplying water and other consumables to the crew in the CM.
-- NASA supplies the shuttle-derived Orion Main Engine.
- The Automated Transfer Vehicle-3 is shown to the right approaching the ISS on March 28, 2012.
- The unmanned cargo spacecraft docked to the space station and delivered supplies.
- The initial static tests of the structure were performed at Thales Alenia Space.
- On December 21, 2016, a series of dynamic tests essential for building the SM flight article were completed at Plum Brook Station; the tests included:
  - The test article was shaken to reproduce the vibrations of launch and tested in the acoustic chamber to verify it can withstand the extreme sounds of a rocket ascent.
  - A qualification model solar array was deployed as it would shortly after launch.
  -- To view the test, select https://www.youtube.com/watch?v=i_UieK_13_w
  - A pyro-shock test of the Spacecraft Adaptor simulated the shock the SM experiences during separation from the Space Launch System.
- The SM passed its testing on December 12, 2016 and will now be used by NASA in the Orion Crew Module Structural Test Article for further testing at the vehicle level.

In November 2015, Airbus Defense and Space delivered the first service module (SM) structural test article (left) to NASA’s Plum Brook Station test center in Sandusky, OH.
- The test article was built by Thales Alenia Space in Turin, Italy.
- It is the first of a series of service modules developed by Airbus on behalf of the European Space Agency (ESA).
- The test article is an exact copy of the SM flight model, only without the functionality.
-- The SM provides propulsion, energy supply and central elements of the crew module life support system.

Credit: NASA
- The OME is a pressure-fed, regeneratively cooled, storable bi-propellant engine that is a technically advanced, increased performance version of Aerojet’s flight-proven 6000 lbs thrust space shuttle Orbital Maneuvering System (OMS) engine.  
- The test series verified the engine’s combustion stability and injector performance data to anchor mathematical models.  
- June 2016 - An OME is seen during vibration testing at Johnson Space Center in Houston, TX.  
- The OME on the unpiloted first Orion space mission is a repurposed OMS engine that has flown 19 times in space before on the Space Shuttle Challenger, Discovery and Atlantis.

- September 30, 2010 - Aerojet Rocketdyne successfully completed the development injector testing for the 7500 lbs thrust Orion main engine (OME) at Sacramento, CA.  
- The OME will provide thrust requiring large velocity changes such as Earth orbital insertion, translunar/trans Earth injection, Earth de-orbit, and emergency thrust for high-altitude abort scenarios.
The launch abort system (LAS) is comprised of:
- The abort motor is the primary motor that is used to propel the crew module away from the launch vehicle.
- The attitude control motor steers the vehicle to actively maintain stability and reorient it as needed.
- The jettison motor will pull the whole launch abort system away from the crew module and make way for parachute deployment and landing.
- In addition to the motor stack, the LAS includes miscellaneous electrical components, separation mechanisms, ordnance, harnesses and the following structures:
  -- A nose cone aero structure.
  -- Forward and aft interstage transition structures.
  -- The aero closeout covers the crew module.
After a safe launch and ascent, the launch abort system (LAS) is jettisoned by initiating the support strut pin pullers and then the jettison motor.

In the event of an emergency on the launch pad or during ascent:
- The LAS will separate the CM from the SM and launch vehicle using the abort motor;
- The abort motor burns out;
- The LAS and CM undergo;
  -- A controlled coast;
  -- Begins and completes reorientation;
  -- The attitude control motor dampens out the reorientation maneuver and the CM heat shield is pointed toward Earth at an angle;
- The LAS is jettisoned by initiating the support strut pin pullers and then the jettison motor.
Launch Abort System Flight Test

- April 8, 2010 - The launch abort system (LAS) is shown (left) being prepared for the first Pad Abort Flight Test on the launch pad at the U.S. Army’s White Sands Missile Range, NM.
- The integrated flight test evaluated the ability of the LAS to pull a boilerplate crew module to safety in the event of an emergency on the launch pad.
- The first Pad Abort Test LAS without the boilerplate crew module was 43.8 ft long and weighed about 15,571 lbs.

Credit: White Sands Missile Range

- May 6, 2010 - The first Pad Abort Flight Test was a success.
- The flight lasted 97 seconds from launch until the boilerplate crew module touchdown about 1 mile north of the launch pad.
- The boilerplate crew module’s post landing at White Sands Missile Range is shown to the right.

- Ascent Abort Test-2 is targeted for April 2019 to verify the LAS can steer the crew module and astronauts to safety in the event of an issue with the Space Launch System after liftoff.

Credit: White Sands Missile Range
The stage adapter test article (left) that connects the Orion spacecraft to a United Launch Alliance Delta IV rocket for its first mission, Exploration Flight Test-1, successfully completed the structural loads testing on January 30, 2014 at Marshall Space Flight Center, AL.
- During the structural loads test, the adapter was attached with lines running in different directions on the hardware.
-- Hydraulic pressure was added to the lines in increments pushing on the adapter to evaluate its structural integrity.

Three stage adapter panels or fairings, encapsulating a stand-in for the service module (SM), successfully detached and fell into a catch system during a test (right) on November 6, 2013 at Lockheed Martin’s facility in Sunnyvale, CA.
- The three panels are designed to support the upper crew vehicle during launch and ascent, and are jettisoned at an altitude of about 560,000 ft.
Exploration Flight Test-1 Launch

- A United Launch Alliance Delta IV Heavy rocket lifts off from Space Launch Complex 37 at Cape Canaveral Air Force Station, FL on December 5, 2014 carrying the Orion spacecraft on the unpiloted Exploration Flight Test-1 (EFT-1) to Earth orbit.

- The Delta IV Heavy first stage consists of three common booster cores powered by Rocketdyne RS-68 engines that burn liquid hydrogen and liquid oxygen.

- The second stage is also cryogenic powered by a Pratt & Whitney RL-10B2 engine.

- During the two-orbit, four-and-a-half hour EFT-1 mission, engineers tested the Orion systems critical to crew safety including the launch abort system, the heat shield and the parachute system.

- EFT-1 was equivalent to the 1967 Apollo 4 mission, which validated the Apollo flight control system and the heat shield at re-entry conditions planned for the return from lunar missions.
Orion reentered the atmosphere from an apogee of 3,604 miles, approximating a lunar return, at a velocity of 20,000 miles per hour and 3,500 °F (500 °F below predicted).
- The EFT-1 was a success with the spacecraft maneuvering in space, passing through the Van Allen radiation belts without apparent avionics anomalies, surviving reentry and deploying a series of 11 drogue and main parachutes before splashing down in the Pacific Ocean off California and using a new approach to recovery at sea by the U.S. Navy.
- Even before the USS Anchorage brought the capsule into port at San Diego on December 8, experts in the amphibious warship's well deck examined the heat shield to see how it held up on reentry.
-- The Orion program has decided to build the heat shield in approximately 180 blocks rather than as a monolithic structure as a result of testing the design in space on EFT-1.
- The EFT-1 Orion spacecraft configuration (shown above in Earth orbit) includes:
  - Launch Abort System (not shown)
  - Crew Module - Un-crewed capsule
  - Service Module - Modified Delta IV upper stage
Space Launch System

The NASA Authorization Act of 2010 requires the following minimum capabilities:

- The Space Launch System (SLS) vehicle must be able to initially lift 154,000 - 220,000 lbs (70 - 100 metric-tons) to low Earth orbit, and must be evolvable to 286,000 lbs (130 metric-tons) or more.
- Three versions of the SLS vehicle architecture are planned: Block 1, Block 1B, and Block 2.
- The vehicle must be able to lift an Orion Multi-Purpose Crew Vehicle.
- The SLS initial lift version is shown launching the Orion Multi-Purpose Crew Vehicle.
- The vehicle must be capable of serving as a backup system for supplying and supporting cargo and crew delivery requirements for the International Space Station in the event such requirements are not met by available commercial or partner-supplied vehicles.
- The SLS rocket incorporates technological investments from the Space Shuttle and Constellation Programs in order to take advantage of proven hardware and cutting-edge tooling and manufacturing technology.

Credit: NASA
NASA has selected a 27.6 ft diameter shuttle-derived vehicle with two stages and two strap-on boosters as its initial lift capability (70 metric ton) SLS.
- The architecture was selected, largely, because it utilizes an evolvable developmental approach.
-- This provides a modular launch vehicle that can be configured for specific mission needs using a variation of common elements.
- The SLS crew configuration will use a liquid hydrogen and liquid oxygen propulsion system which will include four RS-25 engines from the Space Shuttle Program for the core stage.
-- The vehicle will also use two 12.17 ft diameter five-segment solid rocket boosters for the first stage.
-- The upper stage will initially be the human-rated Interim Cryogenic Propulsion Stage followed by the more capable Exploration Upper Stage.
-- The rocket will have the ability to lift 154,000 lbs of payload with a first stage thrust of 8.8 million lbs.
- The Saturn 5 rockets that powered the Apollo moon program stood 363 ft tall, generated 7.5 million lbs of first stage thrust and were capable of boosting 263,000 lbs of payload to low Earth orbit.
- The first SLS flight, Exploration Mission-1, will launch an un-crewed Orion spacecraft in June 2018.

Credit: NASA
The evolved lift capability (130 metric ton) SLS is an upgraded version of the shuttle-derived initial lift vehicle equipped with four RS-25 shuttle main engines.

- The cargo configuration will have a liftoff thrust of 9.2 million lbs and be able to launch more than 286,000 lbs of cargo into low Earth orbit.
- Keeping the 27.6 ft core stage diameter the same as the shuttle's external tank permits use of existing ground launch equipment.
- The Mobile Launcher Platform hardware constructed for the Ares I rocket is being modified to support launching the SLS.
- The Exploration Upper Stage will be powered by four RL-10 engines developed by Aerojet Rocketdyne.
- The cargo configuration will require advanced boosters to evolve to the 130 metric-ton capability that Congress ordered in the 2010 NASA reauthorization legislation.
- An advanced booster competition was initiated by NASA that included solid-fuel and liquid-fuel booster options.
- All funded efforts demonstrated and examined concepts and hardware demonstrations.
- This would precede the follow-on design, development, testing and evaluation competition for the advanced booster.
- The Orbital ATK proposal for a solid-fuel advanced booster was strongly favored by NASA in February 2015.
The Space Launch System (SLS) Core Stage (CS) consists of 5 parts (left).- The CS is about 212 ft tall with a diameter of 27.6 ft, and it has an empty weight of about 188,000 lbs.- Cryogenic liquid hydrogen (LH$_2$) and liquid oxygen (LOX) feed four RS-25 engines.- The CS is being built at NASA’s Michoud Assembly Facility (MAF) in New Orleans, LA.

In September 2016, the CS LH$_2$ tank (right) completed welding at MAF on the Vertical Assembly Center, a spacecraft welding tool.- The aluminum tank will be assembled into the first SLS rocket to launch the Orion spacecraft, without a crew, in 2018.-- Standing more than 130 ft tall, the LH$_2$ tank is the largest cryogenic fuel tank for a rocket in the world.-- Together, the LH$_2$ and LOX tanks hold 733,000 gallons of propellant to produce a total of 2 million lbs of thrust, and they are covered with orange foam insulation.
Core Stage RS-25 Engine Testing

- Four RS-25 engines will provide the propulsion for the SLS core stage.
- A RS-25 engine is shown in January 2015 undergoing the first hot-fire test since the end of the 2009 space shuttle main engine testing.
-- The RS-25 engine was fired for a 500 second test at Stennis Space Center, MS.
- The SLS test program is adapting an inventory of RS-25 flight engines as well as new electronic engine controllers.
-- The engines for SLS will encounter colder liquid oxygen temperatures than the shuttle; greater inlet pressure due to the taller core stage liquid oxygen tank and higher vehicle acceleration, and more nozzle heating due to the four-engine configuration and their position in-plane with the SLS solid rocket booster’s exhaust nozzles.
- RS-25 engine hot-fire testing has continued with the first in 2018 occurring on January 16 and a second test on February 1.
-- This test marked the completion of green run testing for all four of the new RS-25 engine flight controllers needed for the second flight of the SLS core stage.
- The RS-25 engine is built by Aerojet Rocketdyne of Sacramento, CA.
Solid Rocket Booster Test

- QM-1 tested the SRB at a cold motor conditioning target of 40 degrees Fahrenheit, the colder end of its accepted propellant temperature range.
-- When ignited, temperatures inside the booster reached nearly 6,000 degrees Fahrenheit.
-- The two-minute, full-duration ground qualification test provided NASA with critical data on 82 qualification objectives that will support certification of the SRB for flight.
--- Engineers now will evaluate the data, captured by more than 530 instrumentation channels on the booster.
- During the EM-1 flight, the two SRBs, each having a length of 177 ft, will provide more than 75% of the thrust needed to escape the gravitational pull of the Earth.
-- The last booster segment for EM-1 was loaded with solid fuel in June 2017 and work on all of the EM-1 segments should have been completed by November 2017.

On June 28, 2016, a 154 ft long five-segment solid rocket booster (SRB) completed a successful ground test before the next test, the first Space Launch System (SLS) flight, Exploration Mission-1 (EM-1).
- The second and final qualification motor (QM-2) test for the Space Launch System’s booster was conducted at Orbital ATK Propulsion Systems test facilities in Promontory, UT.
- QM-1 successfully tested the SRB’s performance at high temperature conditions on March 11, 2015.
On January 19, 2017, NASA successfully completed the EUS preliminary design review beginning development of components. NASA partnered with the U.S. Air Force to study the next generation upper stage propulsion, formalizing the agencies joint interests in a new upper stage engine to replace the Aerojet Rocketdyne RL-10.

- NASA needed a RL-10 class engine for the SLS second stage to push massive payloads beyond Earth orbit.

-- The Common Extensible Cryogenic Engine (CECE) was a testbed to develop RL-10 engines that throttle well.

--- CECE completed the fourth and final series of hot-fire tests (right) on a 15,000 lb thrust class cryogenic technology demonstrator engine that quickly throttles up and down.

- EUS will be powered by four RL10-C3 engines using liquid hydrogen and liquid oxygen to produce a total thrust of 99,000 lbs.

- A new universal stage adapter will connect the EUS to the Orion spacecraft and it will be able to carry large co-manifested payloads, such as a habitat.
SLS Advanced Booster

- SLS is evolving from the 70 metric ton crew launcher, known as block I, into the 105 metric ton vehicle, Block IB, before eventually advancing into the 130 metric cargo launcher, Block II.
- A competition will decide between proposals creating an advanced booster option for SLS.
- This has led to the Advanced Booster Engineering Demonstration and/or Risk Reduction procurement process.
- ATK Orbital’s proposal for a solid-fuel advanced booster, shown on the left, is 40% less expensive and 24% more reliable than their current SLS Block I solid-fuel booster.
- In 2013, ATK Orbital successfully completed testing of an advanced booster filament wound composite case with a 7.67 ft diameter by 27 ft long structure, shown below.
- Four of the composite cases would be used on the advanced booster instead of the five steel cases used on Block I.

--- Several companies proposed liquid-fuel advanced boosters including Aerojet Rockeydyne and partner Dynetics using a F-1 based engine from the Saturn era that could enable SLS to lift 150 metric tons into orbit.
--- As of February 2015, ATK Orbital’s solid-fuel advanced booster appears to be NASA’s clear favorite due to issues with all versions of the liquid-fuel booster such as stack high acceleration forces and a completely new mobile launcher design.
The NASA Authorization Act of 2010 supports an overall growth in science, aeronautics, and space technology and defines a long-term goal for human spaceflight to expand a permanent human presence beyond low Earth orbit.
The Deep Space Transport (DST) is a NASA crewed interplanetary spacecraft concept to support science exploration missions to Mars of up to 1,000 days. The DST (right) is based on Lockheed Martin’s NextSTEP habitat contract design as well as adding the capability of the vehicle being assembled at the LOP-G and transporting a six-member crew to Mars orbit. As of April 2018, the DST is still a concept to be studied, and NASA has not officially proposed the project in an annual U.S. federal government budget cycle.

As part of the fiscal year 2019 budget proposal, NASA is planning to build the Lunar Orbital Platform-Gateway (LOP-G) in the 2020s. The LOP-G is a lunar orbit space station used as a staging point for lunar exploration and where astronauts test the systems needed for destinations including Mars. The LOP-G (left) is based on Boeing’s NextSTEP habitat contract design using modules developed from International Space Station (ISS) heritage; Boeing is the prime contractor for the ISS. The development of the LOP-G is led by the ISS partners: ESA, NASA, Roscosmos, JAXA and CSA for construction in the 2020s.
# Lunar Orbital Platform-Gateway Concept Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
<th>Notes</th>
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<tbody>
<tr>
<td>2023</td>
<td>Crew launch by SLS; Power and Propulsion Element launch by commercial rocket.</td>
<td>Select <a href="https://www.youtube.com/watch?v=XcPtQYalkcs">https://www.youtube.com/watch?v=XcPtQYalkcs</a> to view EM-1 animation.</td>
</tr>
</tbody>
</table>
|      | Gateway configuration (blue) | Known Parameters:  
  - Gateway to architecture supports Phase 2 and beyond activities  
  - International and U.S. commercial development of elements and systems  
  - Gateway will translate uncrewed between cislunar orbits  
  - Ability to support science objectives in cislunar space  
Open Opportunities:  
  - Order of logistics flights and logistics providers  
  - Use of logistics modules for available volume  
  - Ability to support lunar surface missions |

Credit: NASA

(1) Crew launch by SLS; Power and Propulsion Element launch by commercial rocket.  
- Select [https://www.youtube.com/watch?v=XcPtQYalkcs](https://www.youtube.com/watch?v=XcPtQYalkcs) to view EM-1 animation.  
- Modified LOP-G timeline is from NASA Advisory Council briefing on March 28, 2017.  
- Select [https://youtu.be/OyoFeRS4-I0](https://youtu.be/OyoFeRS4-I0) for Boeing Gateway video.
The DST timeline is from a NASA Advisory Council briefing on March 28, 2017.

Abbreviations:
- **P/L**: Payload
- **t**: metric tonne
- **NRHO**: Near Rectilinear Halo Orbit
- **CMP**: Configuration Management Plan
- **EM**: Exploration Mission
- **SLS**: Space Launch System
- **TLI**: Trans Lunar Injection
- **LOP-G**: Lunar Orbital Platform-Gateway
- **Block 1B**: SLS configuration
- **DST**: Deep Space Transport
- **Block 2**: SLS configuration

Potential Missions

Low Earth Orbit (Back-Up)

Asteroid Redirect Mission

Credit: Lockheed Martin

Credit: NASA

High Earth Orbit

Credit: NASA

Near Earth Asteroid

Credit: Lockheed Martin
ISS Low Earth Orbit Mission (Back-Up)

- International Space Station (ISS) missions can provide back-up crew and cargo transportation capability to and from the ISS.
- Missions to the ISS can test critical subsystems before the more difficult missions take place.
  - Water and air recovery processes, along with other environmental control and life support system (ECLSS) components, must be perfected for maximum efficiency and reliability.
  - If the systems can be made to function under excessive and improper use, nominal usage on long-duration missions should be very reliable.
  - Contingency situation simulations employing Orion would benefit mission control and planners, alerting them to any deficiencies in emergency responses that could be improved upon for future missions.

Credit: Lockheed Martin
High Earth Orbit Mission

- The Orion spacecraft is shown servicing the Advanced Technology Large Aperture Space Telescope (ATLAST) 9.2 meter observatory using robots and humans in HEO.
- The future ATLAST telescope is envisioned to be serviced in HEO using Orion, a telescope servicer and a servicing barge.

- Orion with dedicated satellite servicing equipment could be used to repair and maintain existing and future satellites in High Earth Orbit (HEO) and Geostationary Earth Orbit (GEO).
  - HEO is a geocentric orbit with an altitude higher than 22,236 miles above Earth.
    -- A popular orbit for magnetospheric measurement and astronomical satellites.
  - GEO is a circular orbit positioned about 22,258 miles above Earth’s equator.
    -- A satellite appears stationary relative to the rotating Earth (includes communications and weather satellites).

- Most satellites are expensive pieces of hardware that still have much utility after a critical resource has been expended or a technology has become obsolete.
- Sending a servicing vehicle to repair or replace a broken critical component or transport the satellite into another orbit will derive additional utility from what would have been a loss.
- Satellite servicing operations could include: refueling, repair, maintenance or upgrading satellites after they are launched.
The Asteroid Redirect Mission (ARM) was a space mission proposed by NASA in 2013.
- The Asteroid Retrieval Robotic Mission (ARRM) spacecraft would have rendezvoused with a large Near Earth Asteroid and used robotic arms with anchoring grippers to retrieve a 13 ft boulder from the asteroid.
- The ARRM spacecraft would have characterized the asteroid and demonstrated at least one planetary defense technique.

- The spacecraft would have transported the boulder to a stable lunar orbit, where it could have been further analyzed by both robotic probes and by a future Orion mission designated the Asteroid Redirect Crewed Mission (ARCM).
  - If it had been funded, ARCM would have launched with the additional objectives to test a number of new capabilities needed for future human expeditions to deep space, including advanced ion thrusters.
  - The proposed 2018 NASA budget called for the cancellation of ARM and NASA announced the “close out” on June 13, 2017.
- Key technologies being developed for ARM will continue, especially the ion thruster propulsion system.
Near Earth Asteroid Mission

- Near Earth Asteroids (NEA) come close enough to Earth that the proximity of some NEAs makes them ideal destinations for human exploration missions.
- An asteroid mission would have many benefits including:
  -- Astronauts could explore asteroids bringing back samples to learn about the formation and evolution of the solar system.
  -- Improve the understanding of the threat to Earth from asteroid impacts developing the practical knowledge needed to protect Earth and test this capability.
  -- The feasibility of harnessing asteroid resources could be assessed.
- Progressively, more challenging asteroid missions could provide an opportunity to incrementally develop the expertise needed for long missions in deep space without the leap in cost, complexity, duration, distance, and radiation exposure required for missions to Mars.

Concept Credit: Lockheed Martin
Develop Capabilities

The NASA Authorization Act of 2010 supports investing in space technologies and robotics capabilities that are tied to the overall space exploration framework and supports U.S. innovation and competitiveness.

- The NASA capability-driven framework approach:
  - Establish missions defined by multiple possible destinations.
    -- Define design reference missions (DRMs) to determine required functions and capabilities.
  - Utilize common elements across all of the DRMs.
    -- Size element functionality and performance to support the missions.
    -- The common element and DRM analyses are still in work, but appear feasible.
  - Assess key contingencies and abort scenarios to determine and allocate any additional key element(s) capabilities.
    -- Iterate element sizing and functionality to ensure key contingency and abort scenarios are addressed.
  - Establish the key driving requirements for the common elements.
    -- Determine the technology needs for each element.
  - Identify the key decision points for the element/capability phasing.
    -- Define the decision trees/paths for the transportation architecture and destination architecture.
  - Assess the various manifest scenarios for costing and other constraint analysis.
    -- Select various strategies for the acquisition approach and affordability.
  - Actively seek international and commercial involvement where possible.
Design Reference Mission (DRM) to Common Element Mapping Example

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* MPCV entry velocity could be driven by these missions for certain targets, if selected.

Flexible mission analysis validates that several fundamental building blocks, including the Space Launch System and Multi-Purpose Crew Vehicle, are needed to support multiple destinations.

Driving: There is something in this DRM that is “driving” the performance requirement of the element.
Example: Entry speeds for MPCV driven by NEA DRM.

Required: This element must be present to accomplish this DRM.
Example: SEV required for full Capability NEA, but not for other DRMs.

D/R/B Element allocations based on 2010 Authorization Act and other conditions. Different constraint basis would result in different element allocations/options.
Notional Architecture Elements

Space Launch System
Multi-Purpose Crew Vehicle
Cryogenic Propulsion Stage
Solar Electric Propulsion
Lunar Lander
Mars Elements

Graphics are Conceptual Only - Design and Analysis On-going

EVA Suit
Multi-Mission Space Exploration Vehicle
Deep Space Habitat
Robotics & Extravehicular Activity Module
Kick Stage
Near Earth Asteroid Science Package

Credit: NASA
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Credit: NASA
### Technology Applicability to Destination Overview

#### Sheet 2 of 3

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<th>Technology Category</th>
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<tr>
<td>1-3 Space Radiation</td>
<td>4-8 Avionics</td>
<td>9 Thermal Management</td>
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<tr>
<td>10-12 Mechanisms and Structures</td>
<td>13-15 Robotics</td>
<td>16-19 Space Suit</td>
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<tr>
<td>20 Environment Mitigation</td>
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#### Required Technology
- **LEO (31A)**
- **Advanced LEO (31B)**
- **Cislunar (32A,B & 33A,B)**
- **Lunar Surface - Sortie (33C)**
- **Lunar Surface - GPOLD (33X)**
- **Min NEA (34A)**
- **Full NEA (34B)**
- **Mars Orbit**
- **Mars Moons (35A)**
- **Mars Surface (35B)**

- **Mgmt Management**
- **HLLV Heavy Lift Launch Vehicle**
- **EVA Extravehicular Activity**
### Technology Applicability to Destination Overview

#### Sheet 3 of 3

<table>
<thead>
<tr>
<th>Technology Category</th>
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<th>Destination (DRM Number)</th>
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<tr>
<td>4-6 Nuclear Propulsion</td>
<td>- Fission Power for Nuclear Electric Propulsion (NEP) - Nuclear Thermal Propulsion (NTP) Engine - Fission Power for Surface Missions</td>
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<tr>
<td>7-8 Inflatable Habitat</td>
<td>- Inflatable Habitat Flight Demo (flight demo launch) - Inflatable Habitat Tech Development (including demo)</td>
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<tr>
<td>9 In-Situ Resource Utilization (ISRU)</td>
<td>- In-Situ Resource Utilization (ISRU)</td>
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<tr>
<td>10-14 Maneuvering Operations</td>
<td>- TPS -- low speed (&lt;11.5 km/sec; Avcoat) - Thermal Protection System (TPS) -- high speed - NEA Auto Rendezvous, Prox Ops, and Terrain Relative Navigation</td>
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<tr>
<td>15 Supportability and Logistics</td>
<td>- Precision Landing - Entry, Decent, and Landing (EDL)</td>
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<td>19 Non-Toxic RCS</td>
<td>- In-Space Chemical (Non-Toxic Reaction Control System)</td>
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#### Required Technology
- Demo Demonstration
- In-Situ Situated in the original, natural, or existing place or position
- Prox Ops Proximity Operations
- RCS Reaction Control System

#### Technology Category
- 1-3 Solar Electric Propulsion
- 4-6 Nuclear Propulsion
- 7-8 Inflatable Habitat
- 9 In-Situ Resource Utilization
- 10-14 Maneuvering Operations
- 15 Supportability and Logistics
- 16-18 LO2/Methane RCS and Propulsion Stage
- 19 Non-Toxic RCS
- 20 HLLV Oxygen-Rich Staged Combustion Engine

#### Key Values
- 11.5 km/sec = 11.5 kilometers/second or 25.7 miles/hour

Credit: NASA
Partnerships Overview

The NASA Authorization Act of 2010 supports the long-term goal to expand permanent human presence beyond low Earth orbit and to do so, where practical, in a manner involving partnerships.

- **Partnership**: A partnership is an agreement between NASA and one or more entities that provides tangible benefit and shares cost, equity, and/or risk between all of the parties.
  - For international partners, this should be done on a no-exchange of funds basis.

- National Space Policy mandates that NASA:
  - "Expand international cooperation;"
  - "Energize competitive domestic industries;"
  - "Strengthen inter-agency partnerships."

- Potential benefits to NASA and/or the nation include:
  - Economic incentive (expansion, prosperity, innovation);
  - Enhancement through foreign technology and ideas enabling new domestic industries;
  - Enable new domestic industries;
  - Promote foreign policy interests;
  - Affordability to enable achieving missions that would otherwise be unaffordable;
  - Sustainability to achieve goals including cost and operational capability;
  - Schedule acceleration;
  - Ensure domestic space industrial base viability;
  - Avoid domestic capital investments which are significant and sustained;
  - Have multiple users spreading the cost base.
Expand NASA Partnerships to Enable Exploration

- **International**
  - The International Space Exploration Coordination Group (ISECG) exchanges information regarding interests, objectives, and plans in space exploration with the goal of strengthening both individual exploration programs as well as the collective effort.
  - 14 international space agencies from: Australia, Canada, China, Europe, France, Germany, India, Italy, Japan, Republic of Korea, Russia, Ukraine, United Kingdom, and United States.
  - Strong international partnership interest/collaboration in analog field tests (tests on Earth prepare for exploration missions).
    ---- The updated document reflects ongoing dialog and continued preparation for exploration beyond low Earth orbit.
    --- Europe (ESA) provides the Orion Service Module (right).

- **Commercial** - traditional and non-traditional (“NewSpace”) 
  - Robust interest in surface systems including: cargo/logistics, power, communications/navigation, surface mobility, robotics, deep space habitation, and advanced solar electric propulsion.
  - Includes: Google, Caterpillar and General Motors.

- **Intergovernmental, academia and technology**
  - Leverages other government programs and technologies.
  - Includes: DOD, DOE, DARPA, NOAA and NSF.

- **Science**
  - Synergy (human and robotic) that includes OSEWG and external groups such as NLSI, LSI, LEAG, and ILEWG.
In partnership with General Motors, NASA developed the Robonaut 2 (R2) dexterous humanoid robot for testing on the International Space Station (ISS).
- R2 (left) is shown after installation of the legs on the ISS in 2014.
- Further upgrades could be added to allow R2 to work outside the ISS in the vacuum of space.

In 2015, NASA announced new partnerships with six commercial companies to advance deep space habitation concept studies and technology development projects.
- Concepts included Gateway (right) as well as transit habitation capability for future Mars missions.
- The studies were also used to develop insights into the Gateway solar electric propulsion system.

In 2015, NASA also announced new partnerships with three American propulsion companies to support the development of advanced deep space electric propulsion systems needed for missions to destinations beyond low Earth orbit.
- The three selected companies will develop propulsion technology systems (left) in the 50 to 300 kilowatt range to meet the needs of a variety of deep space mission concepts.
- The performance period is no more than 3 years focused on ground testing.
Affordability

NASA is committed to meeting the goals and requirements of the NASA Authorization Act of 2010 to the best of its ability and in a way that is affordable and offers the best value to the nation.

- **Affordability**: The ability of NASA to safely execute missions within the available funding constraints (long term and short term).
  - Include program/project management, risk management culture, systems engineering, workforce/infrastructure, and acquisition approaches.

- Opportunities to address affordability in program/project formulation and planning include:
  - Levy lean development approaches and “design-to-cost” targets on implementing programs.
  - Identify and negotiate international partner contributions.
  - Identify and pursue domestic partnerships.

- Traditional development includes:
  - Balance large traditional contracting practices with fixed-price or cost challenges coupled with in-house development.
  - Use the existing workforce, infrastructure, and contracts where appropriate; address insight/oversight, fixed-costs, cost analysis and cost estimation.

- Adopt alternative development approaches including:
  - Leverage civil servant workforce to do leading-edge development work.
  - Attempt to minimize the use of NASA-unique infrastructure, seeking instead to share infrastructure costs where feasible.
  - Specifically, taking advantage of the existing resources to initiate the development and help reduce the upfront costs on the elements: Multi-Mission Space Exploration Vehicle, Solar Electric Propulsion Freighter, Cryogenic Propulsion Stage, and Deep Space Habitat.
Images:
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Human Space Exploration Guiding Principles

- Conduct a routine cadence of missions to solar system destinations including the Moon and Near Earth Asteroids with the Mars’ surface as a horizon destination for human exploration.
- Build capabilities that will enable future exploration missions and support the expansion of human activity throughout the inner solar system.
- Inspire through numerous “firsts.”
- Fit within the projected NASA Human Space Exploration budget (affordability and sustainability).
- Use and leverage the International Space Station.
- Balance the high-payoff technology infusion with mission architectures and timeline.
- Develop an evolutionary family of systems and leverage commonality as appropriate.
- Combine the use of human and robotic systems.
- Exploit the synergies between science and human space exploration objectives.
- Leverage non-NASA capabilities (e.g., launches, systems, facilities).
- Minimize the NASA-unique supply chain and new facility starts.
- Pursue “lean” development and operations’ “best practices.”

Objective: A capability-driven approach to human exploration rather than one based on a specific destination and schedule.
SLS Architecture Evolution

- Block 1, Block 1B and Block 2 will use the same core stage with four main engines, but Block 1B will feature a more powerful second stage called the Exploration Upper Stage (EUS), and Block 2 will combine the EUS with upgraded boosters.
- Block 1 has a baseline low Earth orbit (LEO) payload capacity of 70 metric tons and Block 1B has a baseline of 105 metric tons.
- The proposed Block 2 will have a lift capacity of 130 metric tons, which is similar to that of the Saturn V.
-- Some sources state this would make the SLS the most capable heavy lift vehicle built; although the Saturn V lifted approximately 140 metric tons to LEO during the Apollo 17 mission.
NASA Partnerships - Abbreviations and Definition

- **ESA** - European Space Agency
- **“NewSpace”** - The term is defined as an approach to space development that differs significantly from that taken by NASA and the mainstream aerospace industry.
- **ISS** - International Space Station
- **DOD** - Department of Defense
- **DOE** - Department of Energy
- **DARPA** - Defense Advanced Research Projects Agency
  - DARPA was established to maintain the technological superiority of the U.S. military.
- **NOAA** - National Oceanic and Atmospheric Administration
  - NOAA is a federal agency focused on the condition of the oceans and the atmosphere.
- **NSF** - National Science Foundation
  - NSF is a United States government agency that supports fundamental research and education in all the non-medical fields of science and engineering.
- **OSEWG** - Outpost Science and Exploration Working Group
  - The purpose of the OSEWG is to guide exploration and science investigations during lunar sortie and outpost missions with extensibility to future Mars missions, so that synergies may be exploited.
- **NLSI** - NASA Lunar Science Institute
- **LSI** - Life Sciences Institute
  - LSI is dedicated to discovering the fundamental biological mechanisms underlying health and disease in an environment designed to catalyze research ideas and interests.
- **LEAG** - Lunar Exploration Analysis Group
- **ILEWG** - International Lunar Exploration Working Group
  - ILEWG is a public forum sponsored by the world’s space agencies to support international cooperation towards a world strategy for the exploration and utilization of the Moon.