Vehicle Systems

Foundational Systems

Crew Mobility Systems

Select Image

Reference Information

NASA Human Space Exploration Development

Habitation Systems

Robotic Precursor Activities
The Space Launch System (SLS) will carry the Orion spacecraft (left) as well as cargo and other systems, equipment and scientific payloads (below) to deep space.

- The SLS lift capabilities will evolve from 154,000 lbs up to 287,000 lbs based on future mission requirements.
- It is designed to meet a variety of crew and cargo needs and to support future asteroid, Mars, and science missions.
- The first SLS mission, targeted for 2020, will launch an uncrewed Orion spacecraft into deep space from Kennedy Space Center, FL.
- The SLS is managed by the Exploration Systems Development Division of the Human Exploration and Operations Mission Directorate.

The SLS will use proven hardware and manufacturing technology from the Space Shuttle and other exploration programs.

- The SLS core stage, developed by the Boeing Company, will be 212 ft tall with a diameter of 27.6 ft.
- It will use a liquid hydrogen and liquid oxygen propulsion system including four RS-25 engines from the Space Shuttle Program for the core stage and four RL10C-3 engines from the Delta IV for the upper stage.
- The SLS will also use solid rocket boosters, derived from the Space Shuttle Program, for the initial development flights.
- Industry will compete to design advanced boosters based on performance requirements and affordability considerations.

Images Credit: NASA
The National Space Policy of the United States, June 28, 2010 specifies that NASA shall:

- By 2025, begin crewed missions beyond the Moon, including sending humans to an asteroid.
- By the mid-2030s, send humans to orbit Mars and return them safely to Earth.

The “Copernicus” Mars Transfer Vehicle (MTV) concept, shown just prior to leaving Earth orbit, could be utilized for six crew Earth asteroid and Mars orbital missions under study by NASA.

- The 273 ft long MTV is propelled by a Nuclear Thermal Rocket (NTR) and consists of three basic components: (1) the supporting crewed payload; (2) an integrated “saddle truss” and liquid hydrogen propellant drop tank assembly that connects the payload and propulsion elements; and (3) NTR propulsion stage.
- A four crew Mars vehicle concept powered by a NTR is also being considered.

On May 22, 2019, Congress added funding to NASA appropriations that included $125 million for nuclear thermal propulsion development.

- A report accompanying the House bill called on NASA to develop “a multi-year plan that enables a nuclear thermal propulsion demonstration, including the timeline associated with the space demonstration, and a description of future missions and propulsion and power systems enabled by this capability.”
Three Heavy Launch Vehicles are used to deliver the six crew Mars Transfer Vehicle’s (MTV) key components to Earth orbit where it is assembled.

- Orion is launched by a crew launch vehicle and delivers the Mars crew to the MTV.
- After leaving Earth orbit, the drained liquid hydrogen drop tank, attached to the saddle truss, is jettisoned and the crewed MTV coasts to Mars.
- The crewed MTV design uses a trajectory with approximately a 6-month one-way transit to and from Mars.
- For long Mars missions, the crewed payload separates from the saddle truss and NTR propulsion stage.
  - The saddle truss and NTR propulsion stage is called the “Earth Return Vehicle” (ERV).
- The ERV returns to Earth.
- A Mars Ascent Vehicle returns the crew from the Martian surface.
- Prior to returning to Earth, the crewed payload docks to another ERV that had been pre-deployed to Mars orbit in advance of the crew.
- The MTV then returns to Earth and the crew is returned to the surface by Orion.
The working fluid (blue) in a nuclear thermal rocket (NTR), liquid hydrogen, is heated to a high temperature in the nuclear reactor, and then expands through a rocket nozzle to create thrust.

- Since the heat source is not based on the propellant, a low molecular weight working fluid, such as hydrogen, can be used to improve performance.
- The nozzle exhaust (red) provides the power for the turbine pump.
- The nuclear reactor's energy in this kind of thermal rocket replaces the chemical energy of the propellant's reactive chemicals in a chemical rocket.

- Due to the higher energy density of the nuclear fuel compared to chemical fuels, about $10^7$ times, the resulting propellant efficiency (effective exhaust velocity) of the engine is at least twice that of chemical engines.
- The overall gross lift-off mass of a nuclear rocket is about half that of a chemical rocket; when used as an upper stage, it roughly doubles or triples the payload carried to orbit.
In 2012, the Nuclear Cryogenic Propulsion Stage team at Marshall Space Flight Center (MSFC), Huntsville, AL started a three-year project to demonstrate the viability of nuclear propulsion system technologies.

- The team used MSFC’s Nuclear Thermal Rocket Element Environmental Simulator (NTREES) to perform realistic, non-nuclear testing of various materials for nuclear thermal rocket fuel elements.

- An engineer (left) in the Propulsion Research and Technology Branch of the Engineering Directorate at MSFC observes NTREES testing in progress.

The NTREES facility is designed to test fuel elements and materials in hot flowing hydrogen, reaching pressures up to 1,000 lbs per square inch and temperatures of nearly 5,000 degrees Fahrenheit.

- These conditions simulate space-based nuclear propulsion systems providing baseline data critical to the research team.

- A glimpse of NTREES testing in progress as a non-nuclear fuel element is heated to more than 3,200 degrees Fahrenheit while hydrogen is funneled through it (right).

- NASA and its partner federal agencies have also completed fabrication and testing of a new graphite composite fuel element for a 4,580 degrees Fahrenheit hot hydrogen flow system as of November 2015.

Credit: NASA
Nuclear Thermal Rocket Technologies Development

In August 2017, Marshall Space Flight Center (MSFC) in Huntsville, AL contracted with BWX Technologies, Inc. (BWXT) Nuclear Energy, Inc. of Lynchburg, VA, to further advance and refine nuclear thermal propulsion (NTP) technologies.

- BWXT will support NASA in the design and testing of a promising, low-enriched uranium based nuclear thermal engine concept.
- They have experience in developing and delivering nuclear fuels for the U.S. Navy.
- BWXT will design a nuclear reactor that uses low-enriched uranium nuclear fuel in the form of Cermet, or ceramic metallic, rods.
- Low-enriched uranium has a lower than 20% concentration of $^{235}\text{U}$.

- The glowing material shown being tested in MSFC’s Nuclear Thermal Rocket Element Environmental Simulator is a Cermat rod of low-enriched uranium.
- NASA's NTP engine system heats liquid hydrogen (LH2) to a high temperature in a nuclear reactor and the gases expand through a rocket nozzle to create thrust.
- A major advantage of NTP engines is they run much longer than chemical rocket engines and still produce significantly more thrust than an electric propulsion system, such as satellite ion thrusters.
- NASA and BWXT will also work to develop an exhaust capture system that would be used for future ground testing of the NTP engine.
- NASA has also partnered with Aerojet Rocketdyne to design a nozzle that could be mated to a reactor to produce thrust.
- NASA will study cryogenic storage options for carrying the LH2 engine propellant.
The initial Gateway configuration is powered by solar electric propulsion and will serve as an operations base for astronauts arriving from Earth in Orion and landing on the lunar surface in the Human Landing System, targeted for 2024.
- It will have substantial maneuvering capabilities to change orbits, enabling the crew departing the station to reach the South Pole surface landing site.
- The development is led by the International Space Station partners: Canada (CSA), Europe (ESA), Japan (JAXA), NASA and Russia (Roscosmos).

- The initial Gateway configuration will include the: Power and Propulsion Element (PPE), Utilization Module (UM) and Human Landing System (HLS), all launched by commercial rockets.
-- The PPE with high-power xenon ion thrusters and two roll-out solar panels is the outpost’s core power and propulsion module. NASA has selected Maxar Technologies to design, build and launch the PPE.
--- The solar arrays, developed by Deployable Space Systems in Santa Barbara, CA, generate at least 60 kilowatts of electricity at the beginning of the spacecraft’s 15-year design life.
--- The PPE is expected to weigh around 11,000 lbs at liftoff, half of that weight will be xenon propellant for the spacecraft’s ion engines.
-- The Utilization Module (UM) is a small pressurized habitat with multiple docking ports to connect the UM to the PPE, HLS and visiting Orion Crew Vehicles.
--- The HLS is the reusable landing and return vehicle for lunar exploration missions.
The initial Gateway configuration is powered by solar electric propulsion using xenon propellant.
- As of May 24, 2019, a supplier for the Power and Propulsion Element’s solar electric propulsion system has not been announced.
- There are a variety of ion thrusters used for solar electric propulsion including Hall thrusters.
  -- Hall thrusters (left) use a propellant, typically xenon, and accelerate ions by means of an electric potential.
- The first flight of an American Hall thruster on an operational mission was launched August 2010 on the military Advanced Extremely High Frequency geosynchronous communications satellite.

A schematic of a Hall thruster is shown to the right. Hall thrusters accelerate ions using an electric potential maintained between a cylindrical anode and a negatively charged plasma that forms the cathode.
- The bulk of the propellant, xenon gas, is introduced near the anode, where it becomes ionized.
- Xenon is used because of its low ionization potential per atomic weight and its ability to be stored as a liquid.
- The ions are attracted towards the cathode, they accelerate towards and through it, picking up electrons as they leave to neutralize the beam and leave the thruster at high velocity thereby generating thrust.
Large, deployable solar arrays are the most significant challenge for solar electric propulsion vehicles.

- The largest solar electrical power system ever flown in space provides electricity for the International Space Station (ISS) generating about 256 kW.

NASA’s Space Technology Program selected Northrop Grumman Space Components Deployables in Goleta, CA and Deployable Space Systems (DSS) of Santa Barbara, CA to develop advanced solar array systems.

- The companies had 18 months to develop their technologies under Phase I; one or both were expected to be selected for a Phase II award to demonstrate their technologies in space.

The technology proposes to achieve higher power levels and greatly improve mass and packaging efficiency of current solar arrays.

- Northrop’s design (above) is an accordion fanfold flexible blanket solar array; two arrays supplied power to the Phoenix lander after it landed on Mars in 2008.

- The Phase I demonstration of the “MegaFlex” arrays was completed in 2014 at Glenn Research Center, OH.

- DSS (right) features a flex-blanket solar array configuration; a 7-day flight experiment of the solar array was completed from the ISS in June 2017.

- DSS built two roll-out solar array winglets about 14.8 ft wide and 48 ft long and completed Phase 1 testing in 2014 at Glenn Research Center, OH.
In 2015, NASA awarded Next Step partnership contracts to three American propulsion companies to support the development of advanced deep-space electric propulsion systems needed for missions to destinations beyond Low Earth Orbit.

- State-of-the-art electric propulsion technology currently employed by NASA generates less than 5 kilowatts, and systems being developed for the Asteroid Redirect Mission are in the 40 kW range.
- Each company was selected to develop and demonstrate advanced electric propulsion systems using fixed-priced, milestone achievement-based contracts over three years.
- The three selected companies will develop propulsion technology systems in the 50 to 300 kW range to meet the needs of a variety of deep space mission concepts.
- In the third year, each company’s electric propulsion system will demonstrate a minimum of 100 hours of continuous operations at power levels of at least 100 kW.

The selected companies are:

- **Ad Astra Rocket Company** of Webster, TX - Demonstrate thermal steady state testing of a Variable Specific Impulse Magnetoplasma Rocket (VASIMR) with scaleability for human spaceflight.
  - VASIMR propulsion technology uses radio waves to ionize and heat propellant (argon, xenon, or hydrogen) and magnetic fields creating a plasma that is then accelerated to generate thrust for a spacecraft.
- **Aerojet Rocketdyne Incorporated** of Redmond, WA - Operational demonstration of the electric propulsion system with 250 kW nested Hall Thruster.
- **MSNW LLC** of Redmond, WA - Demonstrate flexible high-power electric propulsion for exploration class missions using the Electrodeless Lorentz Force thruster.
  - Thruster operates on water, argon, xenon, and other propellants.
Mars Entry, Descent and Landing Challenge

The Mars Science Laboratory rover, Curiosity, is the largest vehicle to safely land on the Martian surface on August 6, 2012.

- The one ton, 2,000 lbs, Curiosity required four distinct Entry, Descent and Landing (EDL) phases to land on the surface, as shown below:
  1) Atmospheric entry used a heat shield decreasing its hypersonic kinetic energy;
  2) Parachutes for aerodynamic deceleration slowed speeds for deceleration of the sky-crane platform;
  3) Propulsive deceleration of the sky-crane platform slowed speeds further and;
  4) The final touchdown of the rover's wheels via cables lowered from the sky-crane.

Human missions to Mars require landing multiple payload masses between 44,100 - 88,200 lbs (22 - 44 times Curiosity’s payload mass).

- To land 88,200 lbs of payload, masses of 176,400 - 242,500 lbs are required in Mars orbit prior to EDL.
- Precision landing is critical, as multiple mission elements will be required for mission success.
- The thin Martian atmosphere creates additional challenges, requiring a large drag area during entry.
- Aerocapture has mass benefit over chemical propulsive capture.
  - This requires thermal protection capable of enduring two large heat pulses during aerocapture and entry which may have a long-time interval in between (possibly months in the event of Martian dust storms).
  - Human EDL has additional challenges which may be unique or have lower priority for Mars robotic landings.

-- These constraints include: transition from entry to descent and landing, load magnitude and direction, reliability, timing of large attitude maneuvers (such as bank reversals or pitch-up during descent), and hazard detection and avoidance related maneuvering.
# Mars EDL Architecture Concepts

<table>
<thead>
<tr>
<th>Architecture Concepts</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>#7</th>
<th>#8</th>
<th>#9</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerocapture</strong></td>
<td>R ML/D AS</td>
<td>L HIAD</td>
<td>NTR</td>
<td>R ML/D AS</td>
<td>R ML/D AS</td>
<td>L HIAD</td>
<td>R ML/D AS</td>
<td>L HIAD</td>
<td>L HIAD</td>
</tr>
<tr>
<td><strong>Hypersonic</strong></td>
<td>R ML/D AS</td>
<td>L HIAD</td>
<td>SRP</td>
<td>L HIAD</td>
<td>L HIAD</td>
<td>L HIAD</td>
<td>R ML/D AS</td>
<td>L HIAD</td>
<td>L HIAD</td>
</tr>
<tr>
<td><strong>Supersonic</strong></td>
<td>SRP</td>
<td>SRP</td>
<td>SRP</td>
<td>SRP</td>
<td>S LHAID</td>
<td>S LHIAD</td>
<td>D SIAD</td>
<td>L SIAD-S</td>
<td>SRP</td>
</tr>
<tr>
<td><strong>Subsonic</strong></td>
<td>SRP</td>
<td>SRP</td>
<td>SRP</td>
<td>SRP</td>
<td>SRP</td>
<td>SRP</td>
<td>SRP</td>
<td>SRP</td>
<td>SRP</td>
</tr>
</tbody>
</table>

**Legend:**
- **R ML/D AS** - Rigid Mid-Lift/Drag Aeroshell
- **SRP** - Supersonic Retropropulsion
- **L HIAD** - Lifting Hypersonic Inflatable Aerodynamic Decelerator
- **NTR** - Nuclear Thermal Rocket Vehicle
- **S LHAID** - Same Lifting Hypersonic Inflatable Aerodynamic Decelerator
- **D SIAD** - Drag Deployable Supersonic Inflatable Aerodynamic Decelerator
- **L SIAD-S** - Lift Supersonic Inflatable Aerodynamic Decelerator with Skirt
Supersonic Retropropulsion (SRP) is a promising EDL technology for future Mars missions using retrorockets at supersonic conditions to augment vehicle deceleration.

- A slightly modified version of the SpaceX crewed Dragon capsule (right) could be used for Martian payload transport and a precursor to the long-term plans of sending a manned mission to Mars.
- The Dragon spacecraft has ferried supplies to the International Space Station (ISS) and it is being developed to transport astronauts to and from the ISS.
- The capsule has the capability to make a direct entry into the Martian atmosphere descending to the surface without a parachute system using retropropulsion for a precision landing.
- SpaceX SuperDraco rocket engines provide the retropropulsion.
- The engine is currently being tested by SpaceX for its launch-abort system on the ISS crew spacecraft.

Aerocapture uses the Martian atmosphere as a brake to slow down a vehicle transferring the energy associated with its high speed into thermal energy.

- The aerocapture maneuver can be accomplished by enclosing the vehicle in a rigid aeroshell structure (left).
- The shell acts as an aerodynamic surface, providing lift and drag, as well as protection from the intense heating experienced during high-speed atmospheric flight.
- Once the spacecraft is captured in orbit, the aeroshell is jettisoned.
On July 23, 2012, a three-stage Black Brant XI sounding rocket successfully launched the IRVE-3 HIAD system from NASA’s Wallops Flight Facility on Wallops Island, VA.

- After launch, the rocket climbed 280 miles into the skies over the Atlantic Ocean.
- During the flight test, the sounding rocket separated from the 680 lbs IRVE-3 and then its aeroshell was pumped full of nitrogen stretching a thermal blanket that covered the vehicle creating a heat shield.
- The heat shield protected a payload including the inflation system, steering mechanisms, and telemetry and camera equipment.
- The inflated heat shield and payload plummeted at about 7,670 miles per hour back through the atmosphere and landed in the ocean 350 miles down range.
- Cameras and instruments transmitted pictures and data to researchers in the Wallops Flight Facility control room.
- Select [https://www.youtube.com/watch?v=mFNH2cnTEPc](https://www.youtube.com/watch?v=mFNH2cnTEPc) to view an animation of the Inflatable Reentry Vehicle Experiment-3.

Images Credit: NASA
Mars EDL Horizontal Cargo Lander Concept

For EDL, the Horizontal Cargo Lander (HCL) concept uses a combination of hypersonic aero-assist and supersonic retro-propulsive braking maneuvers:

- The HCL’s Rigid Aeroshell provides lift and deceleration through the hypersonic regime;
- At low supersonic speeds, propulsive braking begins;
- The upper half of the aeroshell is jettisoned and parachutes are deployed briefly to help pull the lander away from the bottom of the aeroshell;
- This allows the aeroshell to free fall to the surface while the lander continues its propulsive descent towards the landing location.

Key components of the HCL include: the lander descent stage, Mars Ascent Vehicle (MAV), Small Pressurized Rover (SPR), Dynamic Isotope Power System (DIPS), Fission Surface Power System (FSPS), and In-situ Resource Utilization (ISRU) Plant, plus additional surface payload stored in cargo containers located in the front and back ends of the lander.

- The MAV’s four ascent engines are assumed to be supplied with descent propellant from adjacent tank sets and also used for EDL.
- The ISRU Plant includes production of MAV oxidizer and fuel on the Martian surface.
- The HCL and Rigid Aeroshell mass are estimated to be about 138,900 lbs and 88,200 lbs, respectively.
- The HCL is 69 times Curiosity’s payload mass.
EDL Testbed for Prototype Planetary Lander

NASA’s Morpheus Project has developed and tested a prototype planetary lander capable of vertical takeoff and landing at the Johnson Space Center, TX and Kennedy Space Center, FL.

- The Morpheus team is shown preparing the prototype lander (left) for a test flight at its Johnson Space Center, TX project based testbed.
- Designed to serve as a vertical testbed (left) for advanced spacecraft technologies, the vehicle provides a platform for bringing technologies from the laboratory into an integrated flight system at relatively low cost.
  - This allows individual technologies to mature into capabilities that can be incorporated into human exploration missions.
- Morpheus completed the first tether test of a new vehicle in 2013.
  - The test demonstrated stable hover and in-flight switching from the primary guidance to backup.

On April 30, 2014, the Morpheus lander (right) ignited its methane and oxygen powered engine and lifted off to begin a free flight test at the Kennedy Space Center, FL; its final test flight was in December 2014.

- Morpheus is a 10 ft diameter, 2,400 lb four-legged metal frame holding four spheres of propellant that feed into a single 5,300 lb thrust engine with a sensor system.
  - The sensor system is a 400 lb set of computers and three instruments called Autonomous Landing and Hazard Avoidance Technology (ALHAT).
- On the April 30, 2014 free Flight 12 test, Morpheus ascended to about 800 ft in altitude, hovered and landed safely in a 65-yard square of boulder-sized hazards.
  -- Select https://www.youtube.com/watch?v=vgsXrx2_eTw to view test Flight 12.

The sensor package and a host of technologies introduced by the lander may find themselves instrumental in the success of future exploration missions, perhaps propelling a descent stage landing people on Mars.
NASA planners are studying concepts for Mars Ascent Vehicles (left) for human spaceflight missions.

- The Mars Ascent Vehicle (MAV) will lift the crew from the surface of Mars and rendezvous with an orbiting habitat or a vehicle that will return them to Earth.
- In this artist’s concept, the fuel tanks are filled with liquid methane and liquid oxygen, and engines and thrusters provide the main thrust and attitude control.
- Methane is a promising fuel for the journey to Mars - it is more stable than liquid hydrogen, can be stored at more manageable temperatures, and could be produced from local resources on Mars, using “in-situ resource utilization.”

Data gathered from thruster testing (right) at the Marshall Space Flight Center (MSFC), AL will be used to develop optimized components that could support engine designs for exploration landers, MAVs and many other in-space applications.

- The distinct blue flame seen during the thruster tests is produced by the methane.
- The thruster being tested in October 2015 is part of a pressure-fed design that produces 4,000 lbs of thrust.
- To achieve 25,000 lbs of thrust required for larger Mars descent/ascent vehicles, and to enable engines to be throttled as needed, MSFC engineers are also developing a pump-fed engine design capable of up to 95,000 revolutions per minute to deliver methane to the thruster.

Credit Images: NASA
Crew Mobility Systems - Multi-Mission Space Exploration Vehicle

NASA plans to conduct human space exploration missions to a variety of destinations.
▪ To maximize the number of destinations NASA explores, space systems must be flexible, and minimize the number of systems developed.

The Multi-Mission Space Exploration Vehicle (MMSEV) would use the same cabin for in-space missions (satellite servicing, telescope assembly and exploration of near-Earth asteroids) as well as surface exploration on planetary bodies (the moon and Mars).
▪ The in-space missions' MMSEV is shown on the left.

On planetary surfaces, astronauts will need surface mobility to explore multiple sites across the lunar and Martian surfaces.
▪ The MMSEV surface concept has the small, pressurized cabin mounted on a wheeled chassis that would enable a mobile form of exploration.
- The pressurized cabin has a suitport that allows the crew to get into their spacesuits and out of the vehicle faster enabling multiple, short spacewalks as an alternative to one long spacewalk.
▪ Select https://www.youtube.com/watch?v=dHG873EDwCY to see the MMSEV.

Credit: NASA
The in-space version of the Multi-Mission Space Exploration Vehicle would have the pressurized cabin on a flying platform and allow astronauts to live inside for up to 14 days.

- It would provide robotic manipulator arms to grasp objects for observation.
- The vehicle will allow the crew easy access to space using suitports maximizing their productivity performing spacewalks outside of the cabin.
- The astronauts enter the two external mounted spacesuits using the suitports from within the cabin.
The surface exploration version of the MMSEV that is shown is part of NASA’s Desert Research and Technology Studies (RATS) field tests in Flagstaff, AZ.

- The electric-powered rover is 14.7 ft in length and 10 ft high with a wheelbase of 13 ft and can travel about 6.2 miles per hour and features 360-degree pivoting wheels that enable “crab style” sideways movement helping the vehicle maneuver over difficult terrain.
- The cockpit tilts providing the drivers with the best possible view of the terrain ahead.
- Astronauts can drive the mobility chassis, called the Chariot, while wearing spacesuits.
  - The Chariot can be used to carry cargo.
- The modular design allows various tools (winches, cable reels, backhoes, cranes and bulldozer blades) to be attached for special missions.
In a suitport system, a rear-entry spacesuit is attached and sealed against the outside of a spacecraft, space habitat, or Multi-Mission Space Exploration Vehicle (MMSEV).

- To go on an extra-vehicular activity (EVA), an astronaut enters the spacesuit from inside the vehicle; closes the suit backpack and vehicle's hatch (which seals to the backpack for dust containment).
- The astronaut then unseals and separates the suit from the vehicle and is ready to perform an EVA.
- To re-enter the vehicle, the astronaut backs up to the suitport and seals the suit to the vehicle before opening the hatch and backpack and transferring back into the vehicle.
- If the vehicle and suit do not operate at the same pressure, it will be necessary to equalize the two pressures before the hatch can be opened.

Select [https://www.youtube.com/watch?v=nPSbOsOJ9Ro](https://www.youtube.com/watch?v=nPSbOsOJ9Ro) to see the surface MMSEV capability.
A mock-up of the in-space MMSEV is shown mounted on an air sled moving across the air-bearing floor at Johnson Space Center, TX.

- MMSEV habitability and mobility were evaluated during the tests.
- The testing started in late 2011 and focused on determining the functionality and habitability of the MMSEV during the tests.
- Three days and two nights simulations included the two-person crew living, working, eating, sleeping, and exercising in the MMSEV cabin.
- Throughout the day, the crew traded responsibilities as extravehicular activity and intra-vehicular crewmembers.
- During the extravehicular activity, the crews performed a variety of simulations that future crews could conduct on a mission to a near-Earth asteroid, using the suitports on the aft end of the MMSEV to exit the vehicle.
Suitport Pressure Tests with Z-1 Prototype Spacesuit

A suitport concept is shown being tested with the Z-1 prototype spacesuit with backpack; the first manned tests of the suitport occurred in July 2012.

- Testing has taken place inside the human-rated thermal vacuum chamber B at Johnson Space Center, TX.
- NASA has conducted differential pressure tests of two suitport concepts using the Z-1 prototype spacesuit.
- During the initial manned tests, the spacesuit was kept at a pressure of 14.7 lbs/square inch (1 atmosphere) with the chamber pressure equivalent to an altitude of 21,000 ft.
- Additional manned tests were also conducted in September and August 2012, where the spacesuit pressure was 8 lbs/square inch (0.5 atmosphere) and the vacuum chamber at roughly 0 lbs/square inch (0 atmosphere).
- Suitports may eventually be tested on the International Space Station.
Z-1 Prototype Spacesuit

NASA is designing the Z series prototype spacesuits to be used for both micro-gravity and planetary extra-vehicular activities.

- The Z-1 suit is the first in a planned series of NASA prototype spacesuits.
- The Z-1 prototype spacesuit offers enhanced mobility for space walks on the Moon and Mars.
- Along with a NASA designed portable life support system (PLSS), the new higher-pressure Z-1 suit allows for bypassing pre-breathe and allows for quick donning of the suit and exit of the spacecraft.
- The Z-1 is the first suit to be successfully integrated into a suitport dock mechanism eliminating the need for an air lock and reducing the consumable demands on long term missions.
- Through a back-mounted suitport plate, the suit can be docked to an external hatch on a rover or space vehicle.
- The suitport allows astronauts to slide directly into a spacesuit from within a vehicle.

- An inner hatch cover and the PLSS are removed for access to the spacesuit.
- The Z-1 prototype was designed and built by ILC Dover for NASA.
In November 2012, the mobility of the Z-1 spacesuit was assessed in partial gravity aircraft flight tests (left).
- Parabolic flight on the C-9 aircraft allows full translational and rotational degree-of-freedom and applies offload to all parts of the body.
- It is the most realistic partial gravity simulation, but volumetrically limited, and the simulation lasts less than 30 seconds.
- The aircraft gives its occupants the sensation of weightlessness by following an (approximately parabolic) elliptic flight path relative to the center of the Earth. While following this path, the aircraft and its payload are in free fall at certain points of its flight path.

Credit Images: NASA

The design of the prototype Portable Life Support System (PLSS) for the advanced spacesuit continues.
- The PLSS is a backpack on the spacesuit that, in conjunction with the Pressure Garment, provides all of the life support functions including supplying oxygen, removing carbon dioxide and trace contaminants, providing ventilation flow and cooling the crew member and onboard electronics.
- The PLSS 2.0 was developed in 2012 with extensive functional evaluations and system performance testing through mid 2014. This is the first new PLSS to be developed since the space shuttle spacesuit was introduced in 1981.
- In late 2014, PLSS 2.0 was integrated with the Mark III spacesuit in an ambient laboratory environment to facilitate manned testing (right). Testing was successful with no issues that necessitated major modifications.
- Future iterations of the Z-1 and PLSS backpack will merge in the human-rated thermal vacuum chamber at Johnson Space Center, TX and, eventually, support exploration missions.
The Z-2 (left and below) is the newest prototype in NASA’s next-generation spacesuit, the Z-series.

- Each iteration of the Z-series will advance new technologies that will be used in a suit worn on Mars.
- Since the Z-series is still a prototype, or non-flight, the design will not be making a trip into space.
- The Z-2 suit is expected to weigh 143 lbs.
- It will be designed to interface with both classical airlocks and suitports.
- The advanced prototype Z-2 suit was delivered to NASA in October 2015 for testing at Johnson Space Center, TX in a human-rated vacuum chamber in 2016.

There are many key advances in the Z-2 suit when compared to the previous Z-1:

- The most significant is that the Z-1 had a soft upper torso and the Z-2 has a hard, composite upper torso.
- This composite hard upper torso provides the much-needed long-term durability that a planetary Extravehicular Activity suit requires.
- The shoulder and hip joints differ significantly based on evaluations performed during the last two years with the Z-1 to look at different ways of optimizing mobility of the complex joints.
- The boots are closer in design to those that would be worn on a suit used in space, and the Z-2 materials are compatible with a full-vacuum environment.
- The suit will include electroluminescent wiring; never used before.
Engineers and technicians at Johnson Space Center (JSC) in Houston, TX are shown testing the spacesuit astronauts will wear in the Orion spacecraft on trips to deep space called the Orion Crew Survival System (OCSS).

- On June 22, 2017, members of the JSC team participated in a Vacuum Pressure Integrated Suit Test to verify enhancements to the suit to meet test and design standards for the Orion spacecraft.
- During the test, the suit was connected to life support systems and then air was removed from the 11-foot thermal vacuum chamber to evaluate the performance of the suits with conditions similar to the spacecraft in deep space.

The OCSS suit is a derivative of the launch, entry, and abort spacesuit used during the Space Shuttle Program called the Advanced Crew Escape System (ACES) spacesuit.

- ACES was the launch and re-entry suit that emerged after the 1986 space shuttle Challenger accident occurred during launch.
- After the 2003 space shuttle Columbia loss during reentry was investigated, the ACES helmet was judged heavy enough to cause shoulder injuries and an outflow of oxygen from the suit into the shuttle cabin was deemed a potential fire hazard.
- The OCSS suit evolved from the Columbia accident “lessons learned” and Orion’s Environmental Control Life Support System capabilities.
- The suit will provide the Orion astronauts with six days of life support should the capsule depressurize during its lunar journey, time enough to return to Earth or perhaps find refuge at the lunar Gateway.
The Exploration Extravehicular Mobility Unit (xEMU) is being considered for deep space.

- As of October 2017, the technologies developed over the last 10 years were being pulled into a flight hardware development effort.
- The effort focused on maturing component technologies, integrating them into prototype systems, and demonstrating them in testing.
- This effort culminated in building and testing the Portable Life Support System (PLSS) 2.0 and Z-2 suit.

- In July 2019, the xEMU began a preliminary design review.
- In the early to mid-2020s, the xEMU with the upgraded PLSS and Hard Upper Torso (HUT) will participate in spacewalk demonstrations on the International Space Station (ISS).
- Key PLSS advances were made in these systems: battery power, breathing-air supply, carbon-dioxide removal, and cooling.
- The HUT forms the rigid enclosure about the upper body.
- The xEMU PLSS and HUT will support shaping the architecture for a new Moon suit.

- An all-purpose suit for lunar exploration would help to develop a suit for the Martian terrain.
- To ease donning and removing the spacesuit, the xEMU will feature a rear entry.
- An adjustable HUT shoulder will help to accommodate a wider range of male and female body types.

- Many experts believe the xEMU spacesuit should be retired.

- The Extra Mobility Unit came together more than four decades ago and has been updated and maintained well beyond the original 15-year design life.
- It originally was developed for arm and hand intensive extra vehicular activities in the space shuttle’s payload bay and later adapted for the ISS.
Regardless of what surface astronauts are exploring, at the end of a long day, they need a base of operations to which they can return.
- NASA architects, engineers and scientists are already creating exactly that - sustainable, space-based living quarters, workspaces and laboratories for next-generation human exploration missions.

To assess new technologies, NASA has created the Habitat Demonstration Unit (HDU) Project to develop surface habitat configurations for testing and evaluation.
- The HDU is being used in conjunction with the Research and Technologies Studies tests in Arizona.
  - The Dust Mitigation Module and Hygiene Module (toilet, hand wash and whole, body wash) are connected at two HDU ports.
  - The HDU is a one story, 4-port habitat; rovers can dock at the other ports.
  - The HDU shell can accommodate an inflatable loft for additional laboratory or habitation volume.
  - The HDU shell has a 16.4 ft inside diameter and a total height of 10.8 ft.
  - The interior of the HDU shell (right) includes: a tele-robotic workstation (B - Tele-operations), a spacesuit/general maintenance workstation (D - S/GMWS), a life science/medical operations workstation (F - LS/MOWS), a geology laboratory (H - GeoLab) and a lift to/from the loft in the center of the shell.
GeoLab provides a safe, contained working space for crew members to perform preliminary examination and characterization of geologic samples. The glovebox, used on the 2011 RATS mission, is composed of three antechambers (airlocks) that pass through the shell of the DHU. These antechambers allow geologic samples to enter and exit the main glovebox chamber directly from/to the outside, thereby minimizing potential contamination from inside the habitat. Cameras provide real-time displays of operations inside the workstation and around the antechamber outside doors.

Two surface Multi-Mission Space Exploration Vehicles (MMSEV) are shown docked to the Habitat Demonstration Unit (HDU) as part of the 2011 Research and Technologies Studies tests (RATS).

- The two rovers repeatedly performed docking and undocking maneuvers with the two HDU hatch interfaces.
In March 2015, NASA announced new partnerships with commercial industry to advance habitation concept studies (to be completed in September 2016) and technology development projects. Selections are intended to augment the Orion capsule (left) with the development of capabilities to initially sustain a crew of four for up to 60 days in cis-lunar space, between Earth and the Moon, with the ability to scale up to transit habitation capabilities for future Mars missions (below).

NASA awarded seven companies habitation projects.

- The habitation projects will have initial performance periods of up to 12 months, at a value of $400,000 to $1 million for the study and development efforts, and the potential for follow-on phases to be defined during the initial phase.

Four companies will address habitation concept development:
- Bigelow Aerospace LLC of North Las Vegas, NV
- The Boeing Company of Pasadena, TX
- Lockheed Martin Space Systems Company of Denver, CO
- Orbital ATK of Dulles, VA

Three companies selected to advance development of Environmental Control and Life Support Systems:
- Dynetics Incorporated of Huntsville, AL
- UTC Aerospace Systems of Windsor Locks, CT (formerly Hamilton Sundstrand Space Systems International)
- Orbital Technologies Corporation of Madison, WI

In December 2015, Congress instructed NASA to step up the development of a deep space habitation module to no later than 2018.
The NextSTEP Habitation effort began in 2015 with four companies completing year-long concept studies.

- Those studies set the foundation for prototype development from 2016-2018; this time, five companies submitted concepts as well as a concept study outline from a sixth company, NanoRacks.
- Prototypes testing will help NASA evaluate the design standards, common interfaces, and requirements for a future U.S. Gateway habitat module, while reducing risks for eventual flight systems. The six prototype approaches are:
  1) **Lockheed Martin** (LM) - The Gateway concept image (left) features LM’s habitat design; testing is at Kennedy Space Center, FL.

- The LM prototype is based on a Multi-Purpose Logistics Module for the International Space Station. The design leverages the capabilities of LM’s robotic planetary spacecraft and the Orion capsule that will transport astronauts to and from the Gateway. The prototype includes a reconfigurable space that could support a variety of missions, and it combines hardware prototyping and software simulation during the test.

  2) **Northrop Grumman** (NG) - The Gateway concept image (right) features NG’s habitat design; testing is at Johnson Space Center, TX.

- NG’s prototype leverages the company’s Cygnus spacecraft that delivers supplies to the International Space Station. The Cygnus flew its maiden flight in 2013, and it is already human-rated. NG’s habitat mockup focuses on providing a comfortable, efficient living environment as well as different internal configuration possibilities.
3) **Boeing** - The Gateway concept image (left) features Boeing’s habitat design; testing is at Marshall Space Flight Center, AL.
- Proven space station heritage hardware is the key ingredient in Boeing’s Exploration Habitat Demonstrator. Named the prime space station contractor in 1993, the company developed multiple International Space Station elements. Their demonstrator will leverage heritage assets with a focus on optimizing interior volume including isolated areas offering the capability to use different atmospheres for payloads without impacting cabin atmosphere.

4) **Sierra Nevada Corporation** (SNC) - The Gateway concept image (right) features SNC’s habitat design; testing is at Johnson Space Center, TX.
SNC’s Large Inflatable Fabric Environment (LIFE) habitat is designed to launch in a compact, “deflated” configuration, then inflate once it is in space. The benefit of inflatables (also called “expandables”) is their final configuration is capable of providing much larger living space than traditional rigid structures, which are limited in size by the payload volume of the rocket used to launch them. The LIFE Prototype inflates to 27 ft in diameter and simulates three floors of living areas.
5) **Bigelow Aerospace** (BA) - The Gateway concept image (left) features BA’s habitat design; testing is at Bigelow Aerospace, North Las Vegas, NV. Bigelow’s B330 prototype is an expandable module that expands in space, as its name suggests, to provide 11,654 cubic feet of livable area. Bigelow sent a smaller module, the Bigelow Expandable Activity Module (BEAM) to the International Space Station in 2015, where astronauts expanded the structure with compressed air tanks. The BEAM completed a two-year demonstration aboard the station, proving soft-goods resilience to the harsh space environment. Following its demonstration period, NASA extended BEAM’s time aboard the station to become a storage unit.

6) **NanoRacks** - The image (right) is from NanoRack’s concept study showing their habitat docked to the International Space Station. NanoRacks proposed yet another concept to maximize habitable volume for Gateway astronauts. The company completed a feasibility study outlining the concept to convert and outfit a propellant tank into a deep space habitat. The company’s idea is to refurbish and repurpose a spent rocket propellant tank, leveraging the natural vacuum of space to flush the tank of residual propellants.
March 2017 - NASA's NextSTEP, Phase 2 commercial partnership contract with Lockheed Martin (LM) has led to an approach that uses the area around the Moon as a “proving ground” for human missions to Mars.

- LM has built onto its NextSTEP prototype development a “Mars Base Camp” concept (left) that would send a Deep Space Transport (DST) to Mars from lunar orbit, supported by the Gateway space station.
- LM also added the capability of the vehicle to be assembled at Gateway and transport a six-member crew to Mars orbit.

- The Mars Base Camp concept is being proposed to NASA as a possible version of the DST, a crewed interplanetary spacecraft to support science exploration missions to Mars of up to 1,000 days.
- To reach Mars and return to the Gateway, the transport would use two liquid-propellant stages and a high-power solar electric propulsion system.
- In September 2017, the plan was updated including a concept for a reusable crewed shuttle called Mars Ascent Descent Vehicle (MADV).
- MADV is a single-stage system that uses Orion systems as the command deck; it could allow astronauts to explore the surface for two weeks at a time before returning to the Mars Base Camp.
- As of April 2018, the Mars Base Camp vehicle was still a concept to be studied, and NASA has not officially proposed the mission in an annual U.S. federal government budget cycle.

Select [https://www.youtube.com/watch?v=vLpZUMflJX0](https://www.youtube.com/watch?v=vLpZUMflJX0) for the Lockheed Martin Mars Base Camp concept.
Inflatable Habitat Module Starts ISS Demonstration

The Bigelow Expandable Activity Module (BEAM), provided by Bigelow Aerospace, demonstration supports the development of a deep space habitat for human missions beyond Earth orbit.

- The BEAM arrived at the ISS, carried by the SpaceX Dragon spacecraft, on April 10, 2016.
- Astronauts installed the module on the aft port of the Tranquility node using the station’s robotic arm.
- After the BEAM was berthed to the ISS Tranquility node, the crew activated a pressurization system to expand the structure to its full size (left) using air stored within the packed module.

-- Progression of the expansion of the BEAM to its full size on May 28, 2016 is shown below.

Credit Images: NASA
In 2012, NASA’s Extreme Environment Mission Operations (NEEMO) focused their activities on understanding what a mission to an asteroid will be like.

- This crew of NEEMO aquanauts has been investigating communication delays, restraint and translation techniques, and optimum crew size as they relate to a human mission to an asteroid.
- The international crew of four aquanauts has been working in the National Oceanic and Atmospheric Administration’s Aquarius Reef Base undersea research habitat off the coast of Key Largo, FL, 63 ft below the surface of the Atlantic Ocean.

A simulated asteroid exploration mission (left) with the Multi-Mission Space Exploration Vehicle (MMSEV) and virtual reality was conducted in 2012.

- The view is from the inside of the MMSEV as the simulated asteroid mission is running on video screens.
- Included was a virtual “fly” down to the asteroid and a spacewalk to collect rock samples.

Credit: NASA
Desert Research and Technology Studies (RATS) is a NASA-led team of engineers, researchers, and scientists working together to prepare for future human and robotic exploration missions.

- During the 2011 Desert RATS, researchers used two surface Multi-Mission Space Exploration Vehicles (MMSEV) to explore and test science data collection, communications protocols, mission operations, and advanced technology in the vicinity of Black Point Lava Flow in northern Arizona.
- Two geologists (left) are shown simulating a spacewalk near their surface MMSEV.

- Test scenarios included future missions to near Earth asteroids, the Moon and Mars.
- Mission simulations help determine system requirements for exploring distant locations while developing the technical skills required of the next generation of astronauts.
- A geologist (right) gathers a sample on a spacewalk, while attached to the Astronaut Positioning System (APS), during the 2011 Desert RATS near Black Point Lava Flow, AZ.
- The astronaut would be maneuvered into position by the APS attached to the front of the surface MMSEV chassis.
R2 is faster, more dexterous and more technologically advanced than its predecessors and able to use its hands to do work beyond previous humanoid robots.

Select [https://www.youtube.com/watch?v=glLX_sKRU2I](https://www.youtube.com/watch?v=glLX_sKRU2I) to see the R2 first movement test on the ISS recorded on October 13, 2011.

- In February 2012, Robonaut 2, nicknamed R2, shook hands with NASA astronaut Dan Burbank (left) in the space station’s Destiny laboratory.
  -- This was the first human/robotic handshake to be performed in space.
  -- R2 is the next generation dexterous robot, developed through a Space Act Agreement by NASA and General Motors.

- In September 2014, NASA astronaut Steve Swanson poses with R2 after completing an upgrade that gave the R2 legs (right).
  -- Future enhancements may allow the robot to move more freely throughout the station’s interior and eventually the exterior.

- R2 operates via ground commanding with little interaction by the crew members.
  -- The exception to this is during Robonaut Tele-Operation (RTS) sessions.
  --- During RTS sessions, crew members don a 3D visor, gloves and a vest and R2 will mimic their motion.

- Shortly after the legs were added, R2 started to experience problems and it was returned to Johnson Space Center, TX where engineers overhauled its electrical system and performed upgrades; it is expected to return to the ISS in late 2019.
The Mars Science Laboratory (MSL) Radiation Assessment Detector (RAD) acquired radiation data during the interplanetary cruise from Earth to Mars and on the surface of Mars in 2012.

- RAD (right) is continuing to collect data that will allow scientists to calculate the equivalent dose (a measure of the effect radiation has on humans) to which astronauts will be exposed on the surface of Mars.

- The 96 mile wide Gale Crater is an estimated 3.5 to 3.8 billion-year-old impact crater with a 3.4 mile high mountain at its center.
- Mount Sharp formed when Gale Crater was first filled in by water-deposited sediments, and then wind erosion scoured out the sediments leaving the mountain.
- Curiosity’s mission is to determine whether Mars ever was, or is, habitable to microbial life.
- The rover, which is about the size of a MINI Cooper automobile, is equipped with 17 cameras and a robotic arm containing a suite of specialized laboratory-like tools and instruments.
- Curiosity is powered by a radioisotope thermoelectric generator.
- As of July 30, 2019, the rover had traveled 13.1 miles from its landing site.
Mars Mission - MEDA

Mars Environmental Dynamics Analyzer (MEDA) is a suite of environmental sensors on the Mars 2020 rover (left) planned to launch on July 17, 2020 from Cape Canaveral Air Force Station, FL.

- MEDA is designed to record dust optical properties and six atmospheric parameters: wind speed/direction, pressure, relative humidity, air temperature, ground temperature, and radiation in discrete bands of ultraviolet, visible, and infrared ranges of the spectrum.
- MEDA will help prepare for human exploration by providing daily weather reports and information on the radiation and wind patterns on Mars.

- Dust dominates Martian weather the way water dominates Earth’s weather; MEDA helps teach us about the dust cycle on Mars and its impact on the weather.

- The Mars 2020 is a rover mission by NASA's Mars Exploration Program with a touch down in Jezero crater on Mars on February 18, 2021 having a mission duration of at least one Mars year (about 687 Earth days).
- The rover’s design is derived from the Curiosity rover, using many components already fabricated and tested, and includes different scientific instruments and a core drill.
- It will investigate an astrobiologically relevant ancient environment on Mars and investigate its surface geological processes and history, including the assessment of its past habitability, the possibility of past life on Mars, and the potential for preservation of biosignatures within accessible geological materials.
- The rover will cache sample containers along its route for a potential future Mars sample-return mission.
Reference Information - Sheet 1 of 3

Images:

Text:
https://www.nasa.gov/

Flight Hardware, Frank Morring, Jr; Aviation Week and Space Technology; September 15/25, 2016; Volume 178, Number 19, page 37 - the Space Launch System first flight progress

http://ntrs.nasa.gov/

Nuclear Option, Guy Norris; Aviation Week and Space Technology; September 28-October 11, 2015; Volume 177, Number 19, page 48-49 - nuclear thermal rocket for deep space missions is discussed

https://spacenews.com/
http://en.wikipedia.org/
http://trajectory.grc.nasa.gov/
https://www.nasa.gov/
https://www.popularmechanics.com/
https://www.dss-space.com/
https://www.militaryaerospace.com/
https://www.northropgrumman.com/
http://www.spaceref.com/
http://www.space.com/
http://www.adastrarocket.com/aarc/
http://mars.jpl.nasa.gov/
Text (Continued):

http://aviationweek.com/

*Mars Entry, Descent, and Landing (EDL): Considerations for Crewed Landing*, R. R. Sostaric and C. C. Campbell, NASA Johnson Space Center, TX, 2012 - presentation includes the challenges of human landings on Mars

*Aerocapture Technology Fact Sheet*, NASA Marshall Spaceflight Center, AL, May 2005 - description of aerocapture and rigid aeroshells

https://gameon.nasa.gov/


http://morpheuslander.jsc.nasa.gov/
http://www.rocketstem.org/
http://www.jsc.nasa.gov/
http://jscfeatures.jsc.nasa.gov/
http://www.sciencealert.com/

*Searching for Spacesuits*, Mark Carreau; Aviation Week and Space Technology; July 15/28, 2019; Volume 181, Number 14, page 37 - developing spacesuits for existing and future space programs

https://oig.nasa.gov/
https://www.spacegrant.org/
http://research.jsc.nasa.gov/

*Selling the Gateway*, Frank Morring, Jr.; Aviation Week and Space Technology; April 17-30, 2017; Volume 179, Number 8, page 22 - the deep space gateway and transport plan is discussed

https://www.flickr.com/
https://blogs.nasa.gov/
Text (continued):
http://ares.jsc.nasa.gov/
http://spaceflight.nasa.gov/
https://spacenews.com/
https://www.jpl.nasa.gov/
https://mars.nasa.gov/
https://www.rocket.com/
http://en.m.wikipedia.org/
http://photojournal.jpl.nasa.gov/

Videos:
Inflatable Reentry Vehicle Experiment 3
https://www.youtube.com/watch?v=mFNH2cnTEPc
Morpheus Test Flight 12
https://www.youtube.com/watch?v=vgsXrx2_eTw
Multi-Mission Space Exploration Vehicle
https://www.youtube.com/watch?v=dHG873EDwCY
Surface Multi-Mission Space Exploration Vehicle
https://www.youtube.com/watch?v=nPSbOsOJ9Ro
Lockheed Martin Mars Base Camp Concept
https://www.youtube.com/watch?v=vLpZUMflJX0
First Movement Test of Robonaut 2 on the International Space Station
https://www.youtube.com/watch?v=gILX_sKTU2I
NASA Advanced Exploration Systems (AES) Division

AES are the rapid development and testing of prototype systems and validation of operational concepts to reduce risk and cost of future exploration missions; the domain areas are:

**Vehicle Systems**
- Systems to enable human and robotic exploration vehicles, including advanced in-space propulsion, extensible lander technology, modular power systems, and automated propellant loading on the ground and on planetary surfaces.

**Crew Mobility Systems**
- Systems to enable the crew to conduct “hands-on” surface exploration and in-space operations, including advanced space suits, portable life support systems, and EVA tools.

**Habitation Systems**
- Systems to enable the crew to live and work safely in deep space, including beyond earth orbit habitats, reliable life support systems, radiation protection, fire safety, and logistics reduction.

**Foundational Systems**
- Systems to enable more efficient mission and ground operations and those that allow for more earth independence, including autonomous mission operations, avionics and software, in-situ resource utilization, in-space manufacturing, synthetic biology, and communication technologies.

**Robotic Precursor Activities**
- Robotic missions and payloads to acquire strategic knowledge on potential destinations for human exploration to inform systems development, including prospecting for lunar ice, characterizing the Mars surface radiation environment, radar imaging of NEAs, instrument development, and research and analysis.
Advanced Electric Propulsion Systems Progress

The primary goal for Ad Astra, MSNW LLC and Aerojet Rocketdyne is to demonstrate 100 hours of continuous, steady-state operation of an advanced plasma-based propulsion system operating at 100 kW during its contracted 3-year time period.

- The demonstrations also required development and successful operation of a Power Processing Unit (PPU), feed system and other key components.
- Key performance goals included specific impulses ranging from 2,000 to 5,000 seconds, total system efficiency greater than 60%, projected operational life of over 10,000 hours, and a total subsystem specific mass less than 11 lbs/kW.
- In addition, the technologies had to be scalable to megawatt power levels.

The following three companies have made significant progress since they started:

- **Ad Astra** - After exercising its 3-year contract option in August 2017, Ad Astra’s VASIMR demonstrated 100 hours of cumulative operation in 6.5-minute intervals at power levels of 100 kW.
  -- The 100-hour, 100 kW steady-state tests for Ad Astra were expected to be completed by November 2018; as of October 2018, it is not known if the tests were conducted.

- **MSNW LLC** - The 3-year contract option for their Electrodeless Lorentz Force thruster was exercised in November 2017, and preparations were underway for the demonstration tests at MSNW in Redmond, WA.
  -- The 100-hour, 100 kW steady-state tests for MSNW LLC were expected to be completed by November 2018; as of October 2018, it is not known if the tests were conducted.

- **Aerojet Rocketdyne (AR)** - AR exercised the 3-year option in February 2018.
  -- In addition, thruster/facility risk reduction tests were completed over last year at Glenn Research Center in Cleveland, OH, where the thruster operated at 100 kW for 10 minutes and 80 kW for 3 hours.
  -- A 10 kW test of the thruster, PPU and feed system was completed at the University of Michigan in February 2018.
  -- AR was expected to complete the 100-hour, 100 kW steady-state tests in August 2018; as of October 2018, it is not known if the tests were conducted.
  -- The AR thrusters could be used on the Gateway Power and Propulsion Element (PPE).
    --- Built with commercial partners, the PPE will demonstrate 50 kW class solar electric propulsion to support exploration on and near the Moon, and beyond, including Mars.
The three Environmental Control and Life Support Systems (ECLSS) projects are:

- **Dynetics Inc.** of Huntsville, AL will develop a new rapid, highly efficient system removing carbon dioxide (CO₂) and potentially other undesirable gases from the spacecraft cabin air (left).
  - Dynetics fabricated separation units for a laboratory test bed.
  - The company plans to demonstrate a CO₂ scrubbing system on the International Space Station.
  - The FY17 Milestone is to complete a fifth-generation design for CO₂ separation.

- **UTC Aerospace Systems** of Windsor Locks, CT will study modular life support system concepts and incorporate an Advanced Exploration Systems-developed life support system into a modular pallet design.
  - The FY17 Milestone is to deliver the mockup pallet for verifying interfaces with prototype habitats.

- **Orbital Technologies Corporation** (ORBITEC) of Madison, WI plans to develop and demonstrate Hybrid Life Support Systems (HLSS) using plant growth modules in a habitat wall (right).
  - The study will include analyzing various HLSS configurations including systems that leverage the relationship between plants and microorganisms (right), and systems that use chemical processes.
  - ORBITEC completed a prototype “Greenwall” plant growth module. The FY17 Milestone is to identify flight equivalent materials.
Robonaut 2 with Lower Torso and Legs

A lower torso with legs was launched on the SpaceX-3 commercial cargo flight April 18, 2014 and arrived at the International Space Station (ISS) on April 20.

- After the legs were attached to the R2 torso, the robot could fully extend to a span of 9 ft, giving it flexibility for movement around the ISS.

- Each leg has seven joints and a device on what would be the foot, called an "end effector," which allows the robot to take advantage of handrails and sockets inside and outside the station.

- A vision system for the end effectors is also used to verify and automate each limb's approach and grasp.

- The new lower torso provides R2 with the mobility it needs to help with regular and repetitive tasks inside and outside the ISS.

- The new legs are designed for work inside and outside the station.

- However, upgrades to the ISS R2’s upper body will be necessary before it can begin work outside the station.

- The goal is to free up the crew for more critical work, including scientific research.

- The image shows the R2 with lower torso and legs being demonstrated on the ground by NASA.

Credit: NASA
MSL Radiation Measurements and Exposure Comparisons

The Radiation Assessment Detector (RAD) measures the radiation from two sources, galactic cosmic rays and solar energetic particles.

- The graph (left) plots measurements made during the rover's first 10 months on Mars. The vertical axis is in micrograys per day; a microgray is a unit of measurement for absorbed radiation dose.
- The horizontal axis is time, labeled on the bottom as months and on the top as the number of sols (Martian days) since landing.
- Only one solar particle event (Apr) had been observed by RAD on the surface of Mars, and it was rather weak.

RAD measurements on the rover during the flight to Mars and on the surface enabled an estimate of the radiation astronauts would be exposed to on an expedition to Mars.

- NASA reference missions have durations of 180 days for the trip to Mars, a 500-day stay on Mars, and another 180-day trip back to Earth.

- RAD measurements inside shielding provided by the spacecraft show that such a mission would result in a radiation exposure of about 1 sievert, with roughly equal contributions from the three stages of the expedition.
- A Sievert is a measurement unit of radiation exposure to biological tissue.

- The graph shows the estimated amounts for humans on a Mars mission and amounts for some of the other activities.