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The International Orion Spacecraft is off towards the stars.

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Abstract

Following a very successful year of manufacturing, assembly and testing in factories located around the globe, NASA and ESA are preparing to deliver the major Exploration Mission-1 (EM-1) Orion flight elements, including the Crew Module, ESA Service Module and Launch Abort System. This international effort to design and develop a deep space exploration capable human spacecraft is rapidly transitioning from the design, development and test phase to the early test flight and production phase. Two major flight tests, an Ascent Abort test and EM-1, Orion's first flight onboard NASA's new heavy lift Space Launch System, are planned for the near future. Further, Orion will play a crucial role in the ambitious new Deep Space Gateway human exploration Program.

This paper gives a short overview of the system and subsystem configuration of the Orion spacecraft, including NASA and ESA contributions, a status of EM-1, AA-2 and EM-2 spacecraft production, and a look at Orion's role in the construction and operation of the Deep Space Gateway. The paper will also address the innovative international cooperation methods being employed to conduct Orion and Service Module integration.

Acronyms/Abbreviations

AA-2 = *Ascent Abort 2*
ACM = *Abort Control Motor*
AM = *Abort Motor*
ARB = *Apogee Raise Burn*
ATB = *Abort Test Booster*
ATV = *Autonomous Transfer Vehicle*
BEO = *Beyond Earth Orbit*
CCAFS = *Cape Canaveral Air Force Station*
CM = *Crew Module*
CMA = *Crew Module Adapter*
CMUS = *Crew Module Uprighting System*
EFT-1 = *Exploration Flight Test 1*
EGS = *Exploration Ground Systems*
EM-1 = *Exploration Mission 1*
EM-2 = *Exploration Mission 2*
EMC = *Electromagnetic Compatibility*
EMI = *Electromagnetic Interference*
ESA = *European Space Agency*
ESM = *European Service Module*
FTA = *Flight Test Article*
FTV = *Flight Test Vehicle*
ISS = *International Space Station*
JM = *Jettison Motor*
KSC = *Kennedy Space Center*
LAS = *Launch Abort System*
LAV = *Launch Abort Vehicle*
Lbf = *pounds force*
MMOD = *Micro-meteoroid Orbital Debris*
NASA = *National Aeronautics and Space Administration*
Nmi = *nautical miles*
OMSE = *Orbital Maneuvering System Engine*
PA-1 = *Pad Abort 1*
RCS = *Reaction Control System*
SA = *Spacecraft Adapter*
SAJ = *Spacecraft Adapter Jettisoned Fairings*
SLC = *Space Launch Complex*
SLS = *Space Launch System*
SM = *Service Module*
TLI = *Trans Lunar Injection*
US = *United States*

1. Introduction

After over 37 years of amazing accomplishments in low earth orbit, NASA and ESA are looking outward and developing an even more ambitious human space program, the exploration of beyond earth orbit destinations. Central to this goal of human space exploration is the Orion spacecraft. Orion will carry people from the surface of the earth to destinations further than anyone has travelled before and return them safely to earth. The Orion Program was formed by NASA in 2006 and joined NASA's Space Launch System (SLS) and Exploration Ground Systems (EGS) Programs to form an Exploration Systems Enterprise. In 2012, NASA and ESA signed an agreement to make Orion an international collaboration. As their contribution, ESA will provide the ESA Service module (ESM), the Orion element that provides propulsion, power generation, thermal control and consumables storage for the spacecraft. Preparations for the first beyond earth orbit voyage known as Exploration Mission 1 (EM-1) and subsequent missions are well underway at NASA and ESA facilities around the world.

2. Spacecraft overview

The Orion spacecraft consists of the following modules:

- Launch Abort System (LAS)
- Crew Module (CM)
- Crew Module Adapter (CMA)
- European Service Module (ESM)
- Spacecraft Adapter (SA) and Spacecraft Adapter Jettisoned Fairings (SAJ)

NASA provides all of the modules with the exception of the ESM, which is provided by ESA. The Orion spacecraft will serve as the primary crew vehicle for human exploration missions Beyond Earth Orbit (BEO). The vehicle will be capable of conducting regular in-space operations in conjunction with payloads delivered by the SLS launch vehicle.

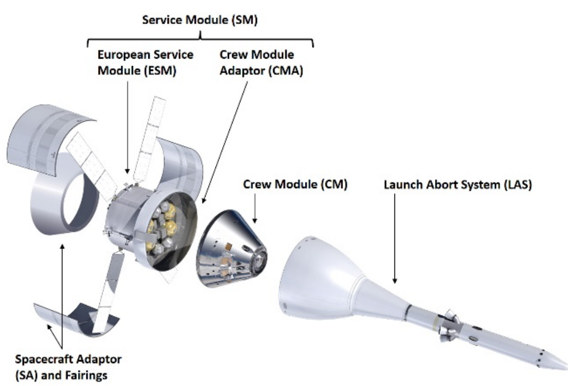

Figure 1: Orion Spacecraft Overview

2a. Crew Module (CM)

The CM provides a habitable pressurized volume to support crewmembers and cargo during all phases of a given mission. It provides a safe habitat for the crew from launch through landing and recovery. It provides a habitable atmosphere and other crew life support functions. Onboard avionics provide the crew situational awareness, control, and communications capabilities. The CM also protects the crew and vehicle from harsh external radiation and micro-meteoroid orbital debris (MMOD) space environments.

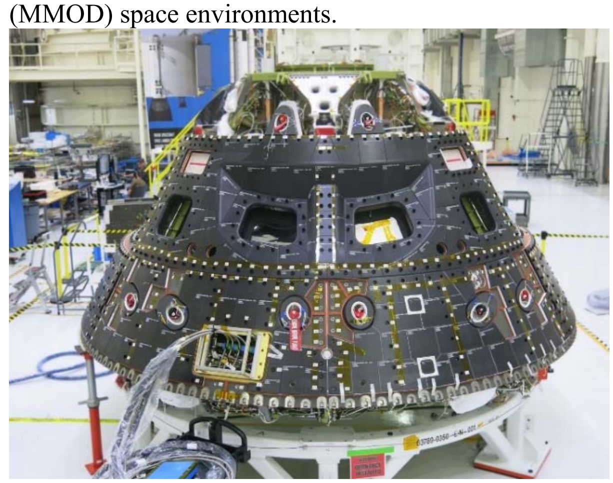

Figure 2: Crew Module

For reentry and landing, the CM serves as a standalone module. It maintains stable hypersonic, transonic and subsonic atmospheric flight, provides protection from the heat of reentry, stores and distributes power during reentry and landing, provides guidance, navigation and attitude control, provides systems monitoring and control and provides thermal control from SM separation through landing.

The CM has a liftoff mass of 22,900 lbm and a nominal landed mass of 20,500 lbm. For exploration missions, Orion can carry a crew of four for an undocked mission durations of 21 days. The CM primary structure is composed of 7 pieces of aluminum (docking tunnel, forward bulkhead, 3 cone segments, the aft barrel, and the aft bulkhead) that are precision machined and friction-stir welded together. A series of gussets and longerons attach to the primary structure to create a scaffolding that enables wiring, tubing, cold plates, avionics, communications and tracking equipment, ammonia tanks, propellant systems, and sensors to be mounted to the exterior of the structure. A series of backshells, covered in a thermal protection system (similar to shuttle tiles) are fitted over the scaffolding to provide a smooth outer mold line and provide thermal protection during reentry.

The exterior of the forward bay contains several key landing and recovery systems including the communications antennas, the parachutes and an uprighting system. The CM uses a series of 11 parachutes to reduce the speed of the vehicle until is safely lands in the water. Since in the water, the CM is stable right-side up and upside down, the crew module uprighting system (CMUS) is used to maintain the CM in an upright position after landing. CMUS is a group of 5 bags that deploy and remain inflated providing stability to the landed vehicle.

The interior of the pressurized primary structure is where the crew lives and works. It contains the crew life support systems, the seats, the displays and control panel, the waste management system and a functional hygiene bay, a water dispenser, crew stowage, exercise device, cameras, communications equipment, and radiation monitors. The crew module contains 6 windows which consist of pressure panes on the inside and thermal panes on the outside

Attached to the bottom of the spacecraft is the heatshield. It is composed of a titanium stringer skeleton with a carbon laminate skin and AVCOAT blocks mounted to the skin. This ablative material is designed to disperse heat by partially vaporizing as the vehicle reenters the atmosphere and protect the crew and spacecraft from the searing heat and energy encountered during entry.

Figure 3: Heatshield

2b. Launch Abort System (LAS)

The LAS is a key crew safety feature of Orion and provides the capability to safely separate the CM from the launch vehicle stack in the event of an emergency on the launch pad or during the ascent phase. The LAS includes three solid rocket motors (the jettison motor (JM), the abort motor (AM), and the attitude control motor (ACM)) and the ogive panels that cover the CM and provide an aerodynamic surface for ascent. The jettison motor is used every mission and separates the LAS from the CM. For nominal ascents, the LAS is jettisoned at approximately 220 seconds post-launch. The AM and ACM are only used if the event of an abort. The 400,000 lbf AM fires to pull the CM away from the remainder of the stack. Simultaneously with the AM, the ACM fires to maintain control during the abort and to reorient the CM into the proper position to enable LAS jettison using the JM, after which the parachutes deploy to enable a safe landing for the CM.

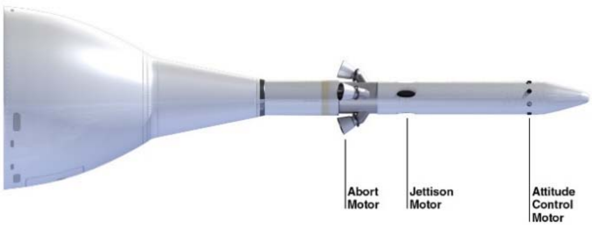

Figure 4: Launch Abort System

2c. Service Module (SM)

The SM, comprised of the two sub-elements the CMA and the ESM, provides services to the CM throughout most of the flight. The SM is jettisoned after performing the de-orbit maneuver and before the CM begins re-entry into the earth's atmosphere.

The CMA provides the structural interface between the American built CM and the European built ESM. It contains the separation mechanisms for the fairings that protect the integrated spacecraft through the launch environment as well as the pyro-technic bolt mechanisms that separate the CM from the SM prior to reentry. It contains two umbilicals. The CM-SM umbilical routes power, command, data, and consumables between the vehicles. The T-0 umbilical interfaces with the mobile launch platform to provide a gaseous purge capability and routes power, communications, commands, and data between the spacecraft and the ground support equipment prior to launch. The center of the CMA is hollow to allow protrusion of equipment located on the top surface of the ESM.

The ESM is a cylindrical unpressurized module. It is fitted with four solar wings and can carry 8.6 tons of propellant. The main functions of the ESM are to provide critical functions for the crew, such as thermal control, electrical power, and life support system consumables including water, oxygen and nitrogen for the mission. It also provides the deep space propulsion utilizing a heritage shuttle Orbital Maneuvering System Engine (OMSE), as well as 8 Auxiliary thrusters and 24 Reaction Control System (RCS) thrusters.

Figure 5: Overall View of the Service Module

2d. Spacecraft Adapter (SA) and Jettisoned Fairings (SAJs)

The SA provides structural connection to the launch vehicle from ground operations through orbital injection until separation from the upper stage. It is a conical, composite material structure that is 216 inches in diameter at the base and 77 inches tall. A key Orion mass savings measure is the SA fairings. These fairings share the liftoff and ascent loads during the initial part of ascent and jettisoned when no longer needed, approximately 200 seconds into flight. The SA fairings also provide protection for the service module components from atmospheric loads and heating during first stage flight. The fairings consist of 3-120 degree segments of composite material connected by vertical frangible joints.

3. Orion Flight Test Plan

A total of 4 test flights are planned prior to the first crewed launch of Orion. Two of these tests, Pad Abort-1 (PA-1) and Ascent Abort-2 (AA-2) validate Orion's emergency crew escape system during the most challenging abort environments. In addition to the Abort tests, two orbital/beyond earth orbit Orion flight tests, Exploration Flight Test-1 (EFT-1) and Exploration Mission-1 (EM-1) validate ascent, in-flight and entry Orion systems prior to the first flight of people on Exploration Mission-2 (EM-2).

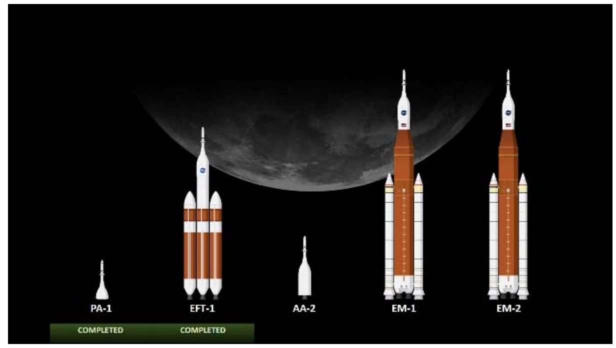

Figure 6: Orion Flight Manifest

PA-1 was successfully flown in May, 2010 and demonstrated the capability to pull the crew module away from the launch stack in the event of a pre-launch emergency while on the launch pad. In this scenario, the LAS must propel the Crew Module high enough such that the forward bay cover can be jettisoned and the parachutes successfully deployed, and far enough away from the launch pad to ensure that the crewed vehicle is not blown back into the emergency under worst case wind conditions. During PA-1, the boilerplate crew module test article was propelled from a standstill (0) to 540 mph in 2.5 seconds. The crew module reached an altitude of nearly 6,600 ft. before safely landing over 1 mile downrange from the launch pad.

Figure 7: Pad Abort 1 Flight Test

EFT-1 was successfully completed in December, 2014. The purpose of Orion's first orbital flight test was to demonstrate critical crew safety systems such as the thermal protection system, separation mechanisms, orbit and re-entry navigation and the parachute system. Systems associated with controlling 10 of the 16 top Orion risks were demonstrated during the 4 hour, 24 minute flight. A Delta IV commercial launch vehicle was utilized for this test and propelled Orion to an apogee of 3,600 nmi, the highest altitude reached by a spacecraft designed for humans since the last Apollo lunar mission in 1972. Post-landing in the Pacific Ocean off the coast of San Diego, a US Navy Well Deck ship was utilized to recover Orion as it will for future Orion flights.

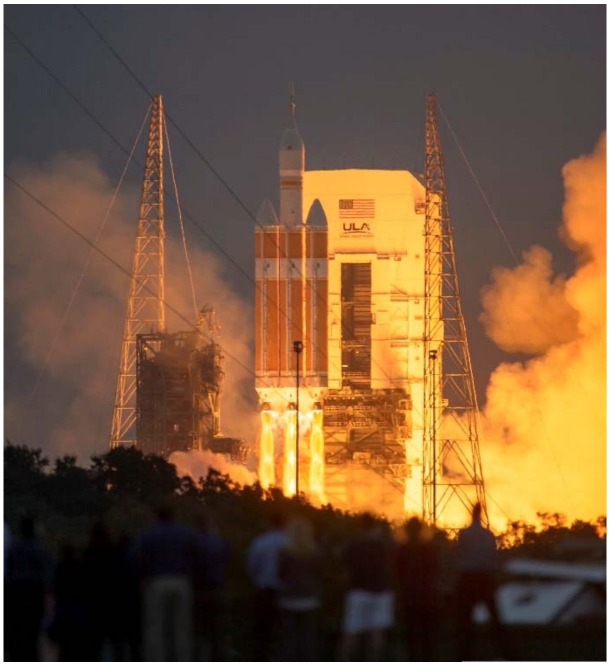

Figure 8: EFT-1 Launch

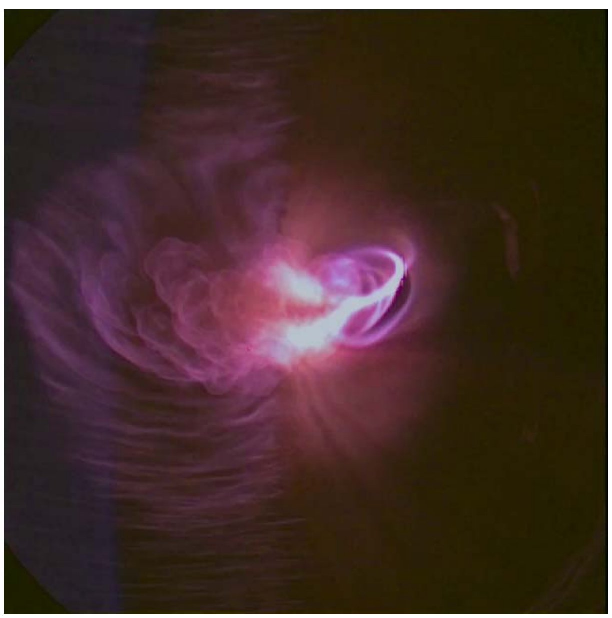

Figure 9: Plasma Stream Generated During EFT-1 Re-Entry as viewed through a CM Window

3a. AA-2

The purpose of the AA-2 mission is to demonstrate that the Orion LAS can safely separate and maneuver the CM away from a launch vehicle during an abort under highly loaded ascent conditions when atmospheric forces create a large drag and destabilizing forces during the abort. The AA-2 flight test vehicle (FTV) consists of an active production LAS, a simplified crew module with avionics, power, and instrumentation, a separation ring and an abort test booster (ATB) to launch the test article and set up the stressful initial abort conditions. Since the primary objective of this test is to validate LAS performance, and since critical systems such as the parachute system are qualified in rigorous testing outside of AA-2, the decision to include only a simple CM boilerplate, simulating the mass properties of the production CM, equipped with the avionics/instrumentation necessary to achieve test objectives was made. No parachutes or attitude control system, which are required for a nominal re-entry were included. This simplified production of the AA-2 test article, allows for the earliest possible test opportunity, providing critical abort data to inform the EM-2 vehicle.

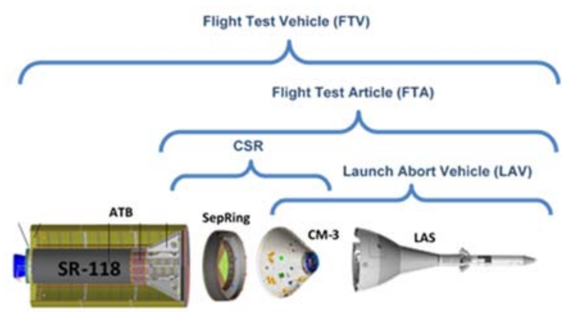

Figure 10: AA-2 Flight Test Vehicle

The test is scheduled for April 2019 and will be less than three minutes in duration. After launching on the ATB from Cape Canaveral Air Force Station pad SLC-46, the abort will be initiated at ~31,000 feet. After the abort sequence has completed and the LAS has been jettisoned, a series of recorders will begin ejecting from the spacecraft and complete prior to the CM impacting the water at 167 seconds and about 9 miles downrange from the launch site.

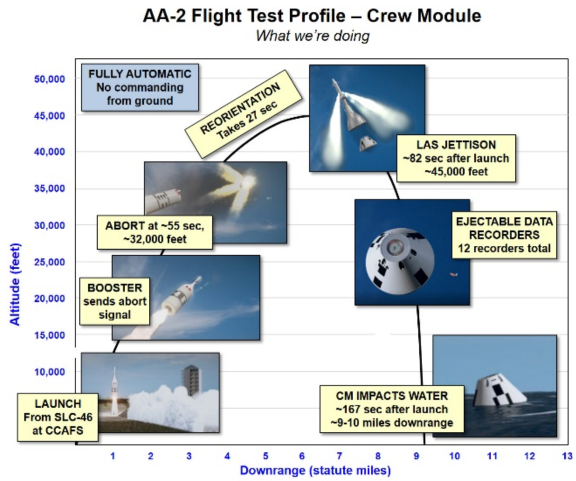

Figure 11: AA-2 Flight Test Profile

3b. EM-1

The purpose of the uncrewed EM-1 mission is to test Orion's capabilities in deep space. EM-1 is the first Orion flight on the new SLS, which will be the most powerful rocket ever built. The mission will demonstrate spacecraft systems performance and a high-speed entry (~11 km/s) validating thermal protection system performance during a BEO re-entry prior to crewed flight. The vehicle will be equipped with over 1,000 sensors to collect data for future mission extensibility, vehicle improvements, and spacecraft verification. The launch is planned for no earlier than December, 2019 and Orion will establish a Distant Retrograde Orbit around the moon. Once the Orion nears the moon, it conducts a series of two burns that puts it into an approximately 38,000 nautical mile orbit around the moon. This is a stable/repeatable orbit that can be maintained with minimal propellant until a second two burn set puts the spacecraft on a return trajectory towards Earth. The total mission duration is 21-43 days in order to ensure a landing under daylight conditions.

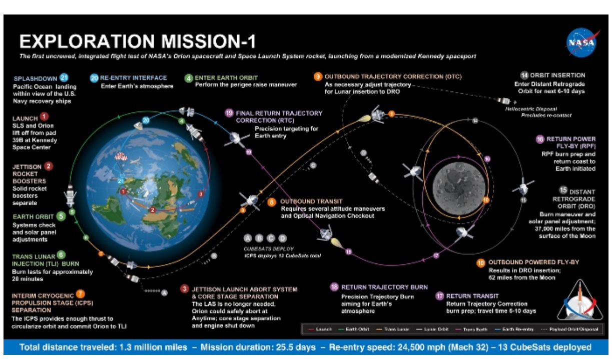

Figure 12: EM-1 Mission Profile

3c. EM-2

EM-2, the first crewed mission, is a flight of a fully functional Orion spacecraft and will demonstrate crewed flights beyond earth orbit. The mission will include a Free return trajectory, meaning no propulsive maneuvers are required to set Orion on a flight path back to earth after a single pass around the moon. This trajectory demonstrates Orion's ability to deliver crew to the moon, while minimizing risk should there be an issue on this first crewed flight. After inserting into a low earth orbit, an Apogee Raise Burn (ARB) is performed by the upper stage to place the vehicle in a highly elliptical orbit with a period of ~1 day. This provides additional time for vehicle and crew health monitoring prior to committing to the Trans-Lunar Injection (TLI) burn, the maneuver that will allow Orion to escape its earth orbit and be put on a trajectory to the moon.

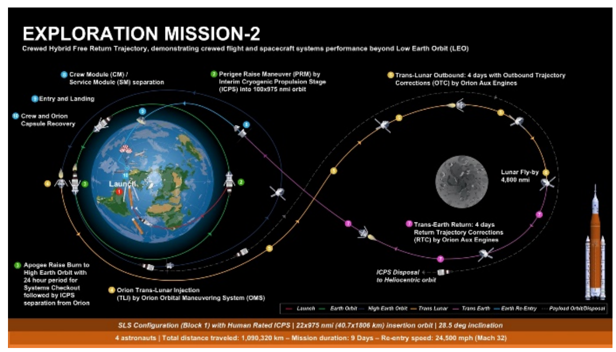

Figure 13: EM-2 Mission Profile

4. Orion Production and Testing Status

As of the writing of this paper, the Orion program has 5 major production and testing campaigns under way.

Figure 14: Orion 2018 Production Plan

The AA-2 CM test vehicle has been fully assembled and is undergoing systems level acoustic testing at Plumbrook Station in Sandusky, Ohio. LAS and ATB assembly are underway at NASA's Kennedy Space Center (KSC).

The EM-1 spacecraft modules are in final systems level testing at KSC and the Airbus Bremen site. After completion of ESM system level testing, the module will be flown to KSC where it will be integrated with the CMA, and then the SM will be mated to the CM. This Orion vehicle will be flown to Plumbrook Station in Sandusky, Ohio for systems level Thermal Vacuum and EMI/EMC testing. Upon returning from Plumbrook, Orion will be handed over to the EGS Program. EGS personnel will fuel the vehicle, mate the LAS on top of the CM, and integrate Orion with the SLS rocket.

Figure 15: EM-1 CM

Figure 16: EM-1 ESM

The EM-2 CM and ESM primary structures have been delivered to their assembly facilities at KSC and in Bremen, Germany respectively. Secondary structure and vehicle components are being installed at both locations. In support of Orion Qualification, major vehicle level integrated testing is underway at test facilities across the United States and Europe to qualify the propulsion system via hot fire testing, software and avionics, and structural systems. Finally, long lead procurement for the EM-3 vehicle has been initiated by both NASA and ESA contractors.

Figure 17: EM-2 CM Primary Structure Welding

Figure 18: EM-2 ESM Primary Structure

Figure 19: Orion Propulsion System Qualification Test Article

Figure 20: Orion Structural Test Article

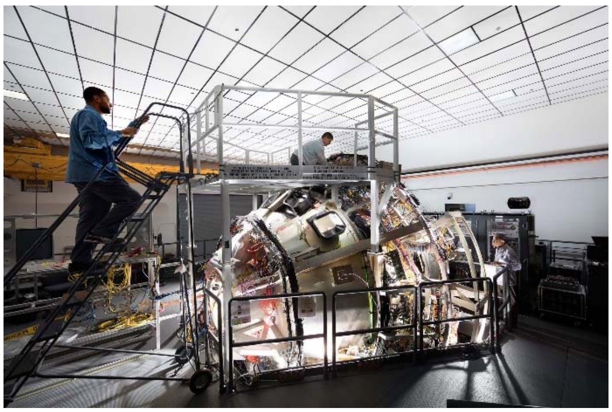

Figure 21: Orion Integrated Test Lab for Avionics Hardware/Software Integration and Validation

5. Orion and the Deep Space Gateway

Beginning with EM-3, Orion will perform key assembly and crew transportation functions for the Deep Space Gateway. The Gateway is a spaceport located in a lunar orbit that will serve as a deep space outpost, enabling human and robotic exploration activities. The first Gateway element, a Power and Propulsion element, will self-insert into the Gateway orbit. On subsequent SLS/Orion missions, Orion will retrieve Gateway elements launched underneath Orion on the SLS, transport them to the Gateway orbit and dock these new elements to the existing Gateway. Orion will also transport crew to and from the Gateway on missions ranging from 30-90 docked days.

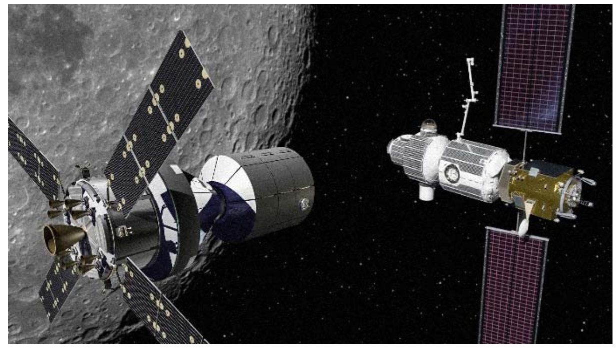

Figure 22: Orion Approaching the Deep Space Gateway with a New Gateway Module

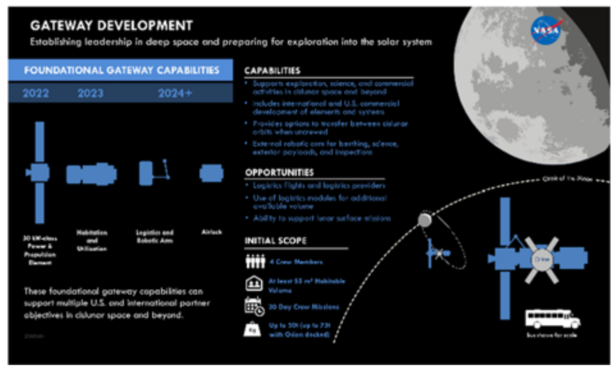

Figure 23: Deep Space Gateway Overview

6. Orion's International Collaboration

The interagency cooperation implementation between NASA and ESA is achieved through a barter agreement with no exchange of funds.

To ensure effective communication over the large geographic distance, numerous regular communication forums have been established. Personal contact and relationships between the team members is of utmost importance so major technical interchange meetings are held face to face. Local residents have been installed on both sides of the Atlantic for effective information exchange and to accelerate decision making.

6a. Cooperation Benefits

The most obvious benefits of the cooperation is that both partners benefit from the other's experience and the use of combined resources allows the project to run at a higher pace. The Orion partnership between NASA and ESA is the continuation of a long lasting fruitful cooperation from Spacelab, International Space Station (ISS), Columbus, Autonomous Transfer Vehicle (ATV), and shall pave the way for future cooperation of this kind. Even though the direct reuse of hardware from previous programs is limited, the reuse of Shuttle and ATV hardware has saved significant development cost. For example, the Orion ESM Auxiliary thrusters are derived from similar ATV thrusters. Through the close cooperation of the teams, different industrial cultures are embraced: new engineering and verification processes are used, allowing both parties to learn and to commonly define the best suitable approaches for the program. The cooperation brings US and European industries into one team allowing them to identify their own strengths and weaknesses, as well as common business potential.

6b. Cooperation Outlook

ESA and NASA have currently agreements for the procurement of ESM1 and 2, as well as for the development activities for the so-called ESM MKII or ESM evolution, increasing several performance criteria and enabling a broader mission scenario spectrum. ESM3/4 procurements are in preparation and new cooperation topics, like the Gateway in the lunar orbit, are under consideration with a firm decision planned for end of 2019.

The ESM is another extraordinary step in the history of the NASA/ESA cooperation. A non-NASA developed element is part of the critical path in a major NASA human space program. This is true sign of trust and commitment of both partner agencies in the endeavour of human exploration.

7. Conclusion

NASA and ESA are establishing a bold new human space exploration enterprise utilizing an innovative international partnership that leverages the strengths of both major Space Agencies. The first critical element of this deep space program, the Orion human exploration spacecraft is nearing the end of its design, development and testing phase. Two major flight tests, AA-2 and EM-1 will be flown in the near future, and the first crewed flight on Orion will occur in 2022.