

## DEVELOPMENT OF THE EUROPEAN SERVICE MODULE PROPULSION SUBSYSTEM FOR THE MULTI-PURPOSE CREW VEHICLE

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In 2013, NASA and the European Space Agency (ESA) entered into an international partnership to develop the European Service Module (ESM) for use on NASA's Multi-Purpose Crew Vehicle (MPCV), also known as Orion. The MPCV will be used as the principal spacecraft for future human space exploration missions beyond low earth orbit. The ESM Propulsion Subsystem (PSS) is a pressure-fed, bi-propellant propulsion system, being developed by Airbus Defense and Space under contract to ESA. For this effort, NASA is responsible for the traditional role of insight/oversight to ensure that the PSS delivered by Airbus meets all MPCV Program requirements. In addition, the NASA Propulsion team also has some unique responsibilities that are a result of the Implementing Agreement (IA) between NASA and ESA for development of the ESM. These responsibilities include: (1) providing the main engine and Thrust Vector Control (TVC) assembly for the PSS. This is being accomplished through the delta qualification and re-use the Space Shuttle Orbital Maneuvering System (OMS) engine and TVC assembly; (2) procurement and delivery of the Auxiliary engines (R-4Ds) for the PSS. These engines are being procured by NASA from Aerojet-Rocketdyne via Lockheed Martin, the prime contractor for the MPCV, per an Airbus-provided specification; and (3) conducting the integrated systems hot-fire test which will qualify the end-to-end PSS for flight on MPCV. This test is being conducted at the NASA White Sands Test Facility (WSTF) using an Airbus-provided test article known as the Propulsion Qualification Model (PQM).

### I. INTRODUCTION

NASA's MPCV/Orion Program is developing a new spacecraft capable of taking astronauts beyond Low Earth Orbit (LEO) and returning them safely to Earth. The major elements of the MPCV are shown in Figure 1. The Service Module (SM) consists of the European Service Module (ESM), the Crew Module Adaptor (CMA), and the Spacecraft Adaptor (SA) and Fairings. The SM mates to the Crew Module (CM) and provides in-space power and propulsion for the crew during the mission. In its launch configuration, the CM and SM are mated to the launch vehicle through the Spacecraft Adaptor (SA), the SM is encapsulated by jettisonable fairings, and the CM is encapsulated by the Launch Abort System (LAS).

NASA's prime contractor for Orion, Lockheed Martin, is responsible for the design and delivery of all elements of the Orion spacecraft with the exception of the ESM which is the responsibility of Airbus under contract to ESA. Lockheed Martin is responsible for the overall integration, operation, and performance of Orion including the ESM.

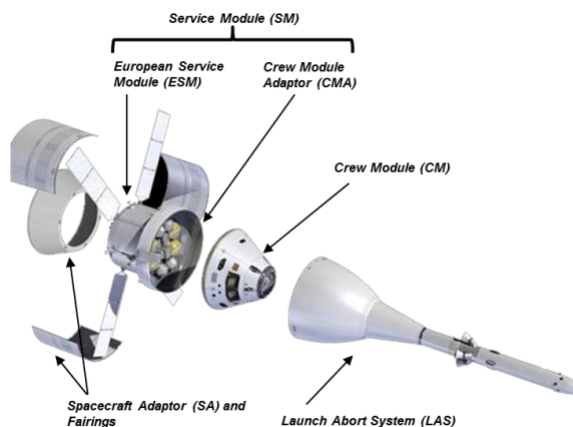


Figure 1: Major Elements of the Orion Spacecraft

The feasibility of a European-provided service module began to be studied in May 2011. At this time, Lockheed Martin service module design activities were on hold per direction from NASA. The NASA and Lockheed Martin teams were focused

on the crew module and other elements that were necessary for the upcoming Exploration Flight Test-1 (EFT-1). The study of a European-provided service module was effectively concluded in November of 2012 with the endorsement of the European development of the ESM by the ESA Ministerial Council. The design progressed with System Preliminary Design Review (PDR) in May 2014 followed by the Propulsion Subsystem (PSS) PDR in November 2014. Subsequently, the PSS Critical Design Review (CDR) was conducted in February 2016 followed by the System CDR in June 2016. After completion of assembly of the ESM, it will be delivered to NASA Kennedy Space Center (KSC) and integration with the other elements of Orion for flight will follow.

## II. PROPULSION SUBSYSTEM (PSS) DESCRIPTION

The ESM PSS design, illustrated in Fig. 2, is a pressure-fed, bi-propellant propulsion system. It utilizes Monomethylhydrazine (MMH) as the fuel and Mixed Oxides of Nitrogen - 3 (MON) as the oxidizer. The ESM PSS has a requirement for 8,602 kg (18,964 lbf) of usable propellant. Because of this requirement and packaging constraints, the propellant is stored in four tanks, two for the MMH fuel and two for the MON oxidizer, which are plumbed in a serial configuration. Liquid is displaced from the propellant tanks with gaseous helium which is stored in two high pressure bottles and delivered through independent Pressure Control Assemblies (PCA). There is a single high pressure bottle and PCA for each propellant.

The ESM PSS utilizes three types of engines/thrusters: the main engine; the auxiliary thrusters; and the reaction control system (RCS) thrusters. Major translational maneuvers are nominally conducted with the single, gimballed main engine. The eight, fixed position auxiliary thrusters are used for separation maneuvers and mid-course correction burns. Attitude control, as well as rendezvous and proximity operations, are conducted with the 24 RCS thrusters, configured in two redundant strings of twelve thrusters each. All three of these different engine systems are supplied from the same common propellant supply, resulting in a broad range of flowrate and duty cycle demands placed on the system.

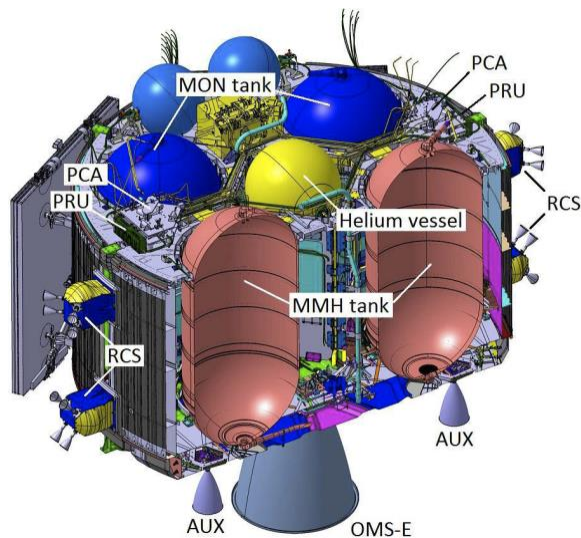


Figure 2: Cut-Away View of the ESM Propulsion Subsystem

Requirements for fault tolerance to catastrophic hazards drives numerous design features, including the need for two strings of thrusters for the RCS. Additionally, this requirement drives the need for the eight auxiliary thrusters to perform major translational maneuvers in the event of a main engine failure. In order for the eight low-thrust auxiliary engines to back-up the gimballed, high-thrust main engine, very long, continuous burn times are required. During these long contingency thruster burns, the fixed position auxiliary thrusters must be off-pulsed in order to provide control of the thrust vector.

During launch, specifically after separation of the Launch Abort System (LAS), the ESM PSS could be required to perform an abort, either sub-orbital or an Abort-to-Orbit (ATO). In the ATO scenario, the PSS must provide a total translational thrust of 29.0 kN (6,520 lbf). To do this, the main engine and all eight auxiliary thrusters must operate simultaneously. In addition, the RCS thrusters will be required for roll control. This scenario represents one of the most stressing cases for the PSS.

## III. PSS COMPONENT DESCRIPTIONS

From the onset of the ESM PSS development, schedule limitations and budget constraints made it necessary to leverage heritage hardware designs as much as possible. The primary sources of heritage hardware designs on the European side came from the Automated Transfer Vehicle (ATV) and the Ariane 5 hypergolic upper stage, the Étage à Propergols Stockables (EPS). On the US side, the

Space Shuttle Orbiter was the primary source for heritage hardware designs. In the case of the main engine and Thrust Vector Control (TVC) assembly, actual hardware from the Space Shuttle program is being reused. This includes the Orbital Maneuvering System - Engine (OMS-E), the TVC actuators, and the TVC controllers that were flown on various orbiters over the 30-year program.

To leverage heritage hardware designs, it was necessary to evaluate the qualified capability of the design relative to Orion requirements. Gaps in the need versus demonstrated capability had to be closed by delta qualification of the design. In areas of greater risk, these design gaps were first investigated through development testing, prior to a formal delta qualification. For the main engine and TVC, the flight history of the hardware was considered in addition to the qualified capability of the design.

In addition to component level development testing, targeted assembly level testing was conducted for the more complex assemblies in order to understand key features and complex dynamic interactions and also to serve as model validation/anchoring. The most significant of these assembly level test activities were a breadboard series of tests for the Electronic Pressure Regulation (EPR) pressurization system and two Hydraulic Model (HM) test campaigns. HM-1 investigated the fluidic behavior of the propellant tanks and the commonly manifolded propellant feed lines. HM-2 investigated the behavior of the gaseous helium system leveraging the prior EPR breadboard test results.

### **III.I MAIN ENGINE AND THRUST VECTOR CONTROL ASSEMBLIES**

The main engine for the ESM PSS is a reuse of the Orbital Maneuvering System (OMS) engine (OMS-E) employed on the Space Shuttle orbiter. The engines were designed, qualified and acceptance tested by Aerojet before they were delivered to NASA. During the latter portion of the 30-year Space Shuttle program, NASA's White Sands Test Facility (WSTF) acted as the depot for the OMS-E engines, servicing and refurbishing engine assemblies as required. This capability was maintained by NASA and utilized for the processing of the OMS-E for ESM.

The OMS-E, shown in Fig. 3, is a 6,000-lbf pressure-fed, bi-propellant engine. It operates at a nominal mixture ratio of 1.65. The Thrust Chamber Assembly (TCA) of the engine is regeneratively cooled with MMH. The engine has a 55:1 area ratio

nozzle which is radiatively cooled. The start and stop of fuel and oxidizer flow is controlled by a Bi-Propellant Valve (BPV) assembly. The BPV is a serially redundant ball valve for both the fuel and oxidizer. It contains two rack and pinion mechanisms that each actuate a single ball for each propellant commodity. A Pneumatic Pack assembly (PnP) stores, regulates, and supplies gaseous nitrogen to actuate the BPV and to purge the fuel from the engine upon completion of an engine firing.



Figure 3: ESM Main Engine – Shuttle OMS-E

Although it is preferred to make as few of changes as possible to the engine, there are several modifications to the heritage configuration that were required for the ESM application. A redundant combustion chamber pressure sensor and a redundant fuel temperature sensor were added to bring the engine into compliance with Orion instrumentation requirements. A heater kit was added to the TCA in order to maintain the engine within heritage qualified limits during driving cold case mission scenarios for Orion. Also, new harnesses were fabricated due to age related issues with the heritage harnesses.

The primary driver for delta qualification of the OMS-E for ESM use was the random vibration environment. Early predictions of the random vibration spectrum showed significantly greater levels over most of the spectrum. Later, refined predictions resulted in only a small increase relative to the heritage qualification spectrum, and only at a narrow range of frequencies. Although this difference was considered low risk, the planned delta qualification vibration test was still conducted.

The TVC assembly for the OMS-E is also a reuse of actual Space Shuttle hardware from various orbiters. The TVC assembly consists of two actuators (one pitch and one yaw), two controllers

(active/primary and standby/secondary), and the associated harnesses between the actuators and controllers. The TVC assembly is shown in Figure 4 as it was integrated for use on the Space Shuttle orbiter.

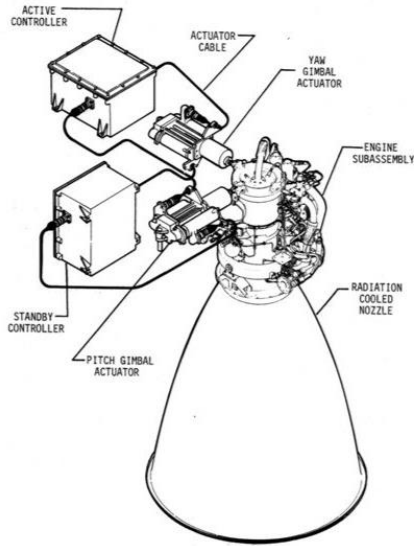


Figure 4: TVC Assembly as Installed on the OMS-E

The TVC assembly was originally designed by AIRResearch, which is now part of Honeywell. Honeywell supported all of the work associated with the reuse of this hardware for the ESM PSS. Early development vibration testing was conducted in order to investigate a more challenging random vibration environment as well as to understand risk of controller card retention, a problem encountered only one time during the 30-year history of use on the Shuttle. Based on the results of this testing, a minor design modification to the controller housing was implemented to ensure controller card engagement. The heritage harnesses were not reused for the ESM application due to age and condition concerns, as well as differences in the physical location of the controllers relative to the actuators, driving the need for longer harnesses.

### **III.II AUXILIARY THRUSTERS**

The eight auxiliary thrusters on the ESM PSS are made by Aerojet and are variants on the R-4D-11 thruster design. This thruster's design heritage goes back to the Apollo program, and it has been most recently used on the ATV and H-II Transfer Vehicle (HTV). For the ESM, each auxiliary thruster produces 465 N (105 lbf) of thrust. The thrusters are equipped with a chamber pressure transducer and a

164:1 area ratio nozzle. A single auxiliary engine is shown in Figure 5.



Figure 5: Auxiliary Engine (R-4D-11)

The auxiliary thrusters were originally intended to operate at a mixture ratio of 1.65. Development hot fire testing was conducted, primarily to investigate the thruster behavior for long duration pulsing requirements at a 50% duty cycle. Issues were encountered with the stability of the Fuel Film Cooling (FFC) during this development testing. In order to comply with the duty cycle and pulse duration requirements, the EM-1 auxiliary engines were re-orificed to operate nominally at a mixture ratio of 1.85 where FFC for the thruster was stable.

Another area of concern was the higher than heritage random vibration environment for the ESM application. A development vibration test was conducted to investigate behavior of the engine to these environments, including the potential for the valves to chatter and leak during vibration. As a result of these tests, a vibration isolation bracket was added at the thruster interface to the ESM. The bracket has heritage from ATV, although in that application its design intent was shock isolation rather than vibration isolation.

### **III.III RCS THRUSTERS**

Pitch, yaw, and roll control for the ESM is accomplished using the RCS thrusters. There are 24 thrusters, grouped in two redundant strings, each

string containing twelve thrusters. As shown in Fig. 6, the RCS thrusters are grouped into six pods, each one containing four thrusters.



Figure 6: RCS Cluster/Pod

Each thruster, shown in Fig. 7, produces 220 N (50 lbf) of thrust at a nominal mixture ratio of 1.65. The RCS thruster is produced by ArianeGroup, and the design has heritage from the ATV. The RCS thruster is equipped with a chamber pressure transducer, although it is from a different supplier than the heritage ATV application.

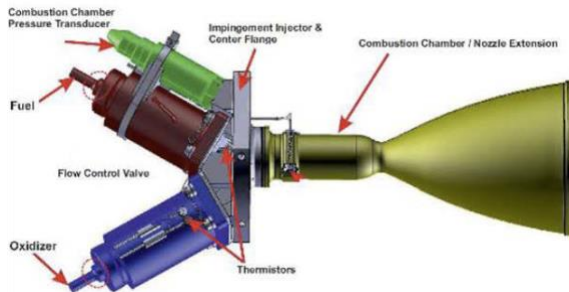


Figure 7: ESM PSS RCS Thruster

RCS thruster development hot fire testing was conducted primarily to investigate thruster behavior with a 5-Hz command frequency. The heritage capability, as qualified for the ATV, had a command frequency of 1 Hz. The thruster performed well for the pulse durations investigated. However, as longer pulse duration testing was being conducted, it was found that the chamber pressure transducer became a limiting factor due to overheating. A minor interface redesign was implemented between the thruster and the pressure transducer to improve its pulse duration capability within the needs of the EM-1 mission.

#### III.IV PRESSURANT/PROPELLANT STORAGE AND MANAGEMENT

Helium is used as a pressurant gas for the PSS and is stored in two high-pressure bottles, one for each propellant commodity. The helium bottles are

Composite Over-wrapped Pressure Vessels (COPV). They are spherical, titanium lined, with a carbon fiber over-wrap and are rated for 40 MPa (5800 psi). Aspects of COPV design are leveraged from both the ATV and the Ariane 5 hypergolic upper stage (EPS) applications.

The ESM PSS utilizes Electronic Pressure Regulation (EPR) for tank pressurization, rather than the use of mechanical regulators. This function is accomplished by using both the PCA and the Pressure Regulation Unit (PRU). The PCA contains the hardware needed to deliver helium to the propellant tanks, while the PRU contains the avionics to command the PCA hardware in order to maintain the target pressures. The PSS contains two PCA's, one for each propellant type. A cross-feed capability is included as a contingency for helium system failure.

The PSS propellant tanks are made by Airbus and leverage design heritage from previously designed surface tension tanks (i.e., Oberflächen Spannungs Tanks (OST)). The tank diameter as well as the spherical domes are heritage from the OST23 tank design. The PSS has four tanks total, two per propellant type. The tanks are serially configured relative to propellant flow, resulting in an upstream tank and a downstream tank. The shells of all four tanks for the PSS are identical however there are differences in the tank internal configurations for the upstream versus downstream positions. The tanks are made of titanium with a diameter of 1154 mm (45 inches). Each has a volume of 2100 liters (555 gallons).

The upstream tanks are required to manage tank slosh during the launch phase. This is accomplished with anti-slosh baffles which are located at the liquid/vapor interface region of the upper tank. The upstream tanks are also required to prevent liquid migration into the gaseous helium portions of the system. This is accomplished with a capillary device placed at the pressurant gas inlet of each of the upper tanks. Finally, the upstream tanks are equipped with anti-vortex baffles to reduce gas ingestion during upstream tank draining.

The downstream tanks must deliver vapor free liquid to the all of the engines and therefore require Propellant Management Devices (PMD). The PMD's are a hybrid design, leveraging heritage from several prior designs. The screen elements of the PMD's have heritage from ATV. The conical barrier of the PMD compartment has design heritage from OST1 and the vane design of the PMD has design heritage

from OST2. Development vibration testing of an engineering model PMD was conducted to develop confidence in the hybrid design as well as the need to survive vibration test environments without propellant during planned vehicle level testing for Orion.

The PSS is equipped with three different types of isolation valves, one for each of the three engine classes, for which they isolate propellant flow. The three valve types are the Main Line Isolation Valve (MLIV), the Auxiliary Branch Isolation Valve (ABIV), and the RCS Branch Isolation Valve (RBIV).

Orion requires three mechanical inhibits to prevent bulk propellant overboard leakage. The single seat thruster valves for the auxiliary and RCS thrusters act as the final/third inhibit on those branches. As such, each auxiliary and RCS branch is equipped with two additional serially redundant isolation valves. Together with the thruster valves, this provides the required three inhibits. The OMS-E bi-propellant valve counts for two of the three required inhibits. Therefore, there is only a single MLIV per commodity upstream of the OMS-E.

#### **IV. PSS QUALIFICATION TESTS**

For the PSS, components undergo qualification tests individually. For complex assemblies, such as the PCA and the RCS cluster, assembly level qualification testing is also being performed. The final, system level qualification is accomplished through testing of the Propulsion Qualification Model (PQM) test article at WSTF.

In addition to the propulsion-centric qualification tests, there are also several ESM or Orion, system-level test activities which have significant propulsion content. These tests include a Structural Test Article (STA) of the ESM and two avionics-type test activities. Airbus is conducting an avionics-type test of the ESM at the ESM-Qualification Facility (ESM-QF), and Lockheed Martin is conducting an avionics-type test at the Integrated Test Lab (ITL). ESM-QF will qualify the avionics requirements associated with the ESM. ITL will qualify the avionics and flight software requirements associated with Orion, including the ESM.

The PQM test article is being tested at WSTF in Test Stand 301. This is a sea level test stand which was augmented with a diffuser to support OMS-E firings. The diffuser is a water-cooled self-pumping

diffuser that was specifically designed and installed to support the PQM testing.

The PQM test article, shown in Fig. 8, generally has a flight-like configuration. It contains two flight-like helium bottles and four non-flight propellant tanks which are not equipped with PMD's. It has an OMS-E, eight auxiliary engines, and twelve RCS engines. The RCS engines are all on a single string, the redundant string is not represented on the PQM. The test article contains two PCA's however, only the primary string of pressurization valve and the primary PRU is included. There is partial representation of the helium cross feed system, only what is necessary to characterize its behavior by test.

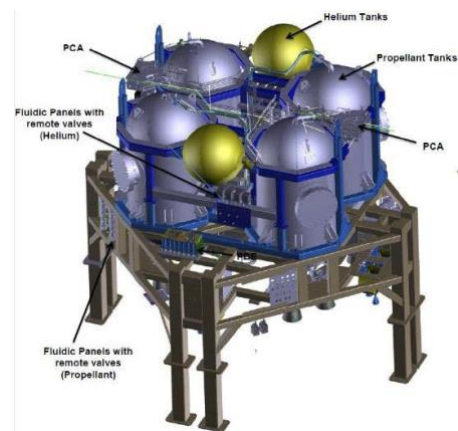


Figure 8: The Propulsion Qualification Model (PQM) Test Article

The PQM test will help to complete the PSS qualification, providing a system level test opportunity for requirements verification. In addition, the PQM will provide insight into system interactions with flight-like hardware and the appropriate propellants rather than simulants. The data from the PQM will provide the final opportunity for validation/anchoring of analytical models.

#### **VI. SUMMARY AND CONCLUSIONS**

The development of the European Service Module (ESM) Propulsion Subsystem (PSS) has been successfully completed through the Critical Design Review (CDR) milestone. In the face of budget and schedule constraints, this milestone was met by leveraging hardware designs with prior flight heritage and in some cases through the re-use of previously flown hardware from the Space Shuttle program. Targeted risk reduction was accomplished with development tests for the components with the greatest risk of non-compliance with Orion

requirements and environments. With both the System-level CDR and the PSS CDR complete, the PSS design is considered compliant with the necessary Orion requirements and mature enough to proceed with flight hardware manufacturing and assembly. After completion of assembly of the ESM, it will be delivered to NASA Kennedy Space Center (KSC) and integration with the other elements of Orion for flight will follow.

In parallel the flight model buildup, the PQM test campaign is proceeding at WSTF. This final, critical activity will provide verification by test, at the system level, of the PSS design.