ARTEMIS I ORION-ESM PROPULSION SYSTEM ENGINE PERFORMANCE

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ABSTRACT

NASA's Orion spacecraft transports humans and cargo into cislunar space for the Artemis program. The European Service Module (ESM), supplied by ESA and its European industry partners, provides Orion with power and in-space propulsion. The Orion-ESM propulsion system is a bipropellant hypergolic propulsion system using monomethylhydrazine (MMH) and nitrogen tetroxide (MON-3). Primary translational propulsion is provided by the Orbital Maneuvering System Engine (OMS-E), with backup translational propulsion provided by eight Auxiliary thrusters (Aux). Attitude control and small translational maneuvers are provided by twenty-four Reaction Control System (RCS) engines. The 2022 Artemis I mission was the first integrated flight test of the Orion-ESM spacecraft and its propulsion system. The OMS-E used on Artemis I was a refurbished Space Shuttle OMS-E that previously flew on nineteen missions ranging from STS-41G in 1984 to STS-112 in 2002. The Auxiliary engines are modified Aerojet Rocketdyne R4D-11 engines produced specifically for the Orion program. The RCS engines are Ariane Group engines originally used for the Automated Transfer Vehicle (ATV) program. This paper will discuss the unique operational requirements for each engine on Orion and the development and qualification efforts at both the engine and system-level that were completed to enable a successful Artemis I mission. Next the paper will evaluate the in-flight performance of the engines during the Artemis I mission showing nominal performance as expected. Additionally, comparisons to models will be presented showing very good correlation. Finally, the paper will address the plan for the engines on future Orion missions and the evolution of the system operation.

1. Overview of the Orion European Service Module Propulsion Subsystem

NASA's Orion spacecraft transports humans and cargo into cislunar space for the Artemis program. The European Service Module (ESM), supplied by ESA and its European industry partners, provides Orion with power and in-space propulsion. The Orion-ESM Propulsion Subsystem (PSS) is a bipropellant hypergolic propulsion system using monomethylhydrazine (MMH) and nitrogen tetroxide (MON-3). Primary translational propulsion is provided by the Orbital Maneuvering System Engine (OMS-E), with backup translational propulsion provided by eight Auxiliary thrusters (Aux). Attitude control and small translational maneuvers are provided by twenty-four Reaction Control System (RCS) thrusters. The RCS thrusters are divided into six clusters of four thrusters. Four clusters provide pitch and yaw control while the remaining two clusters provide roll control. An photo of the Orion engines at the aft end of the spacecraft can be seen in Fig. 1.

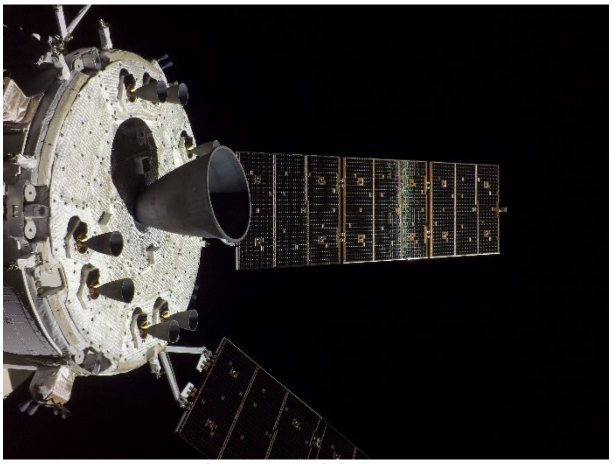

Figure 1: Overview of Orion Engines [1]

The ESM PSS utilizes two serial propellant tanks that supply all engines from a common main line branching to each engine type. The main engine, OMS-E, is supplied directly from the main line and can be isolated from the rest of the system via an isolation valve. The auxiliary engines are supplied by a single string with redundant isolation valves in order to meet ground safety requirements. The RCS is divided into two fully redundant strings that can be isolated via an isolation valve. Each RCS string is further subdivided into three manifolds that also have their own isolation valve. A simplified overview of the ESM PSS schematic is shown in Fig. 2.

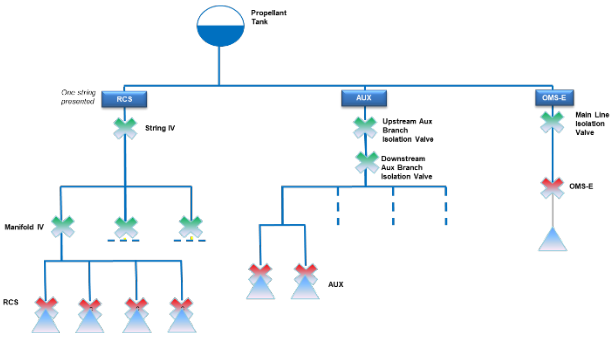

Figure 2: ESM PSS Simplified Fluid Schematic

The ESM PSS is a pressure fed system relying on high pressure helium to regulate operational propellant tank pressures. Each propellant type has its own isolated pressurization system to prevent inadvertent mixing of the hypergolic propellants. The PSS utilizes a “bang-bang” pressurization system rather than use of a conventional mechanical regulator. The vehicle flight software monitors the pressure in the propellant tank and actively commands a series of valves opened and closed based on the closed loop pressure feedback. This results in a characteristic saw tooth pressure regulation pattern as shown in Fig. 3. The regulation of each propellant is performed independently so small changes in engine thrust and mixture ratio cycle as the pressurization system responds during a burn.

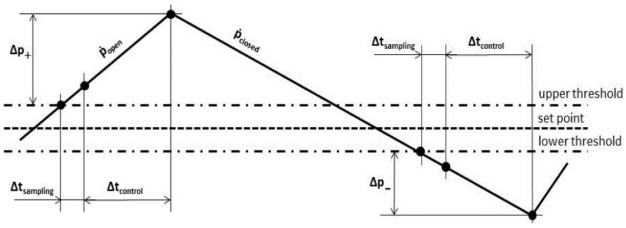

Figure 3: Bang-Bang Regulator Characteristic

2. Artemis I Mission Overview

Artemis I was the first flight of the Orion vehicle with the European Service Module. The mission was a twenty-five (25) day mission flying to the moon and inserting into a Distant Retrograde Orbit (DRO). The Artemis I mission fully tested the Orion systems including the ESM Propulsion Subsystem (PSS).

During the Artemis I mission, there were nineteen (19) discrete translational maneuvers performed using the ESM Propulsion Subsystem as summarized in Tab. 1. There were five (5) burns using the Orbital Maneuvering System Engine (OMS-E). The OMS-E was used for all four large translational maneuvers: Outbound Powered Flyby (OPF), Distant Retrograde Orbit Insertion (DRI), Distant Retrograde Orbit Departure (DRD), and Return Powered Flyby (RPF). In addition, the engine was used for the first Outbound Trajectory Correction burn (OTC-1) to provide an early indication of OMS-E performance in the ESM.

The Auxiliary engines performed six (6) burns during Artemis I. All burns completed were trajectory correction maneuvers except for the Upper Stage Separation (USS-1) burn that occurred shortly after launch. All nominal Auxiliary engine burns were relatively short with a maximum burn duration of approximately 15 seconds. Orbital Maintenance burn 3 (OM-3) was deliberately modified to perform a burn of approximately 100 seconds to provide more data on engine performance.

The remaining eight (8) translational maneuvers utilized the Reaction Control System (RCS) Engines. The RCS engine were also used for attitude control throughout the mission. The twenty-four engines accumulated a total of 41,782 pulses with a total burn time of 5739.6 seconds.

Table 1: Artemis I Engine Usage Summary

Event	Engine	GMT Day	GMT Time	Duration (sec)
USS-1	Aux	320	08:46:44	10.5
OTC-1	OMS	320	14:32:39	30.5
OTC-2	RCS	321	11:32:39	8.6
OTC-3	Aux	324	12:12:44	5.5
OTC-4	RCS	325	06:44:14	7.5
OPF	OMS	325	12:44:14	149.6
OTC-5	Aux	326	06:02:44	5.6
OTC-6	Aux	328	21:52:28	15.2
DRI	OMS	329	21:52:28	87.9
OM-1	RCS	330	21:52:28	1.23
OM-3	Aux	334	21:53:57	94.9
DRD	OMS	335	21:53:57	105.1
RTC-1	RCS	336	03:53:56	4.8
RTC-2	RCS	338	16:43:20	17
RTC-3	RCS	339	10:43:20	21.92
RPF	OMS	339	16:43:20	207.1
RTC-4	RCS	340	10:43:20	5
RTC-5	Aux	344	20:20:14	7.2
RTC-6	RCS	345	12:20:14	8.4

3. Orbital Maneuvering System Engine (OMS-E)

3.1. Overview of the OMS-E

The OMS-E used on Artemis I was a refurbished Space Shuttle OMS-E that previously flew on nineteen missions from STS-41G in 1984 to STS-112 in 2002. The OMS-E is a pressure fed, hypergolic-reacting bipropellant, regenerative and film cooled, fixed thrust engine. The engine uses monomethylhydrazine (MMH) as the fuel and nitrogen tetroxide with 3% mixed oxides of nitrogen (N_2O_4, also known as MON-3) as the oxidizer. The OMS-E gimbals to provide two-axis (pitch and yaw) thrust vector control. A summary of the main performance parameters of the OMS-E is provided in Tab. 2.

Table 2: OMS-E Nominal Performance Summary

Parameter	Nominal Value
Thrust	26.7 kN
Mixture Ratio	1.65
Specific Impulse	315.1 seconds
Fuel	MMH
Oxidizer	MON-3
Max Burn Duration	1030 seconds
Min Burn Duration	2 seconds
Number of Starts	10 max

The OMS-E fires via a pneumatically actuated series bipropellant valve. The engine carries its own supply of nitrogen to fire the engine and to perform a purge of the chamber regenerative cooling channels after engine shutdown. An image of the OMS-E installed in a vibration fixture is shown in Fig. 4.

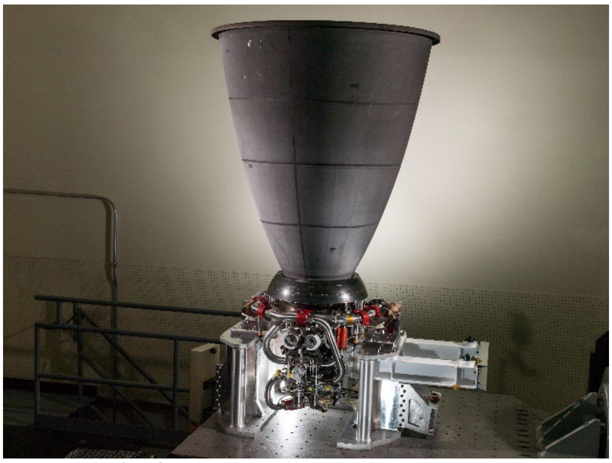

Figure 4: OMS-E Installed in a Vibration Test Fixture [2]

3.2. Path to Artemis I

The most notable changes in requirements since the OMS-E usage on the Space Shuttle Orbiter are the vibration and thermal environments. The potential exposure to deep space thermal environments led to the decision to implement a heater system on the combustion chamber to ensure temperatures remained above the minimum operational threshold. The Artemis program's vibration environments led to performing delta-qualification random vibration testing on a dedicated qualification test unit. All OMS-E disassembly, cleaning, refurbishment, and assembly processes happen at NASA's White Sands Test Facility (WSTF) in New Mexico. Fig. 5 shows WSTF technicians working on the OMS-E used for delta-qualification.

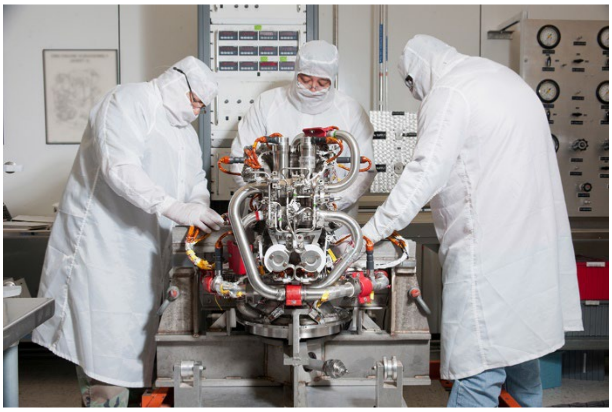

Figure 5: WSTF Technicians work on OMS-E [3]

Additional changes to the OMS-E for Artemis include the addition of redundant chamber pressure and fuel injector temperature sensors to improve engine monitoring reliability. The wiring harnesses on the engine were also replaced after inspection of the existing units showed wear due to age.

The usage of the engine in a new propulsion system required testing the engine performance in the integrated system. The vibration qualification unit was installed into the Propulsion Qualification Model (PQM) and used for a variety of engine firing tests. The PQM testing was performed at WSTF between 2018 and 2020. The test program consisted of 28 firings with over 1600 seconds of total burn time.

Figure 6: Propulsion Qualification Model at WSTF [4]

3.3. Artemis I OMS-E Performance

The OMS-E performance in flight is compared against a steady state model for the engine. The steady state model for the engine is derived from engine qualification data using specific engine parameters based on individual engine acceptance testing results. For the Artemis I engine, the performance parameters were derived based on acceptance hot fire testing performed in 1984.

Fig. 7 and 9 show the normalized engine chamber pressure and fuel injector temperature measured in flight during the Distant Retrograde Orbit Departure (DRD) burn compared to model predictions based on the inlet pressure and temperatures supplied to the engine. The normalized engine performance data indicates achieved performance relative to expected performance assuming engine operation at standard inlet conditions. Fig. 7 and 9 show that engine performance vs. modeling expectations were within 1 percent. This is remarkable considering the model is based on test data collected 28 years prior to flight. Overall, the predictions differed by less than instrumentation accuracy.

For the engine chamber pressure, the model and measured chamber pressure tracked exactly throughout the burn with inlet pressure fluctuations due to the propellant tank pressurization system as seen in Fig. 7. It appears that there was a small bias between the flight pressure transducers compared to the model predictions. This is most likely attributable to instrumentation and model accuracy. Fig. 8 looks at the difference between the chamber pressure model output and the measured flight value throughout the DRD burn. The data shows that the bias between the model output and the measured values increases throughout the burn. This trend was observed during the four long OMS-E burns and was attributed to thermal effects on pressure sensor output. Evaluation of qualification test data from PQM showed a similar trend that stabilized later in the burn. The team will continue to monitor this observation during future Artemis missions but there is no expected impact since pressure transducer performance is still within specified accuracy.

Fig. 9 shows the fuel injector temperature performance in flight compared to the modeled temperature based on inlet pressure and temperature fluctuations. The model only performs steady state evaluation so the discrepancy between measured and modeled values at the start of the burn is expected as the engine comes up to temperature. Once the engine is up to temperature, the model tracks the flight data trends within 1 percent accuracy. The model consistently predicts more rapid and sharp changes in fuel injector temperature slightly prior to the measured temperature changes. This is simply attributed to the model performing an analysis assuming the engine is operating at equilibrium at the current inlet pressure and temperature conditions. However the flight data shows there is a time constant associated with the engine temperature response. The transient thermal response of the OMS-E fuel injector temperature is not critical and there are no plans to update the performance model to consider this transient response.

In addition to the engine hot fire performance, valve response times and pneumatic system performance was evaluated to ensure results were as expected. All engine response times were within specified limits. Detailed results are not shown here in the interest of brevity.

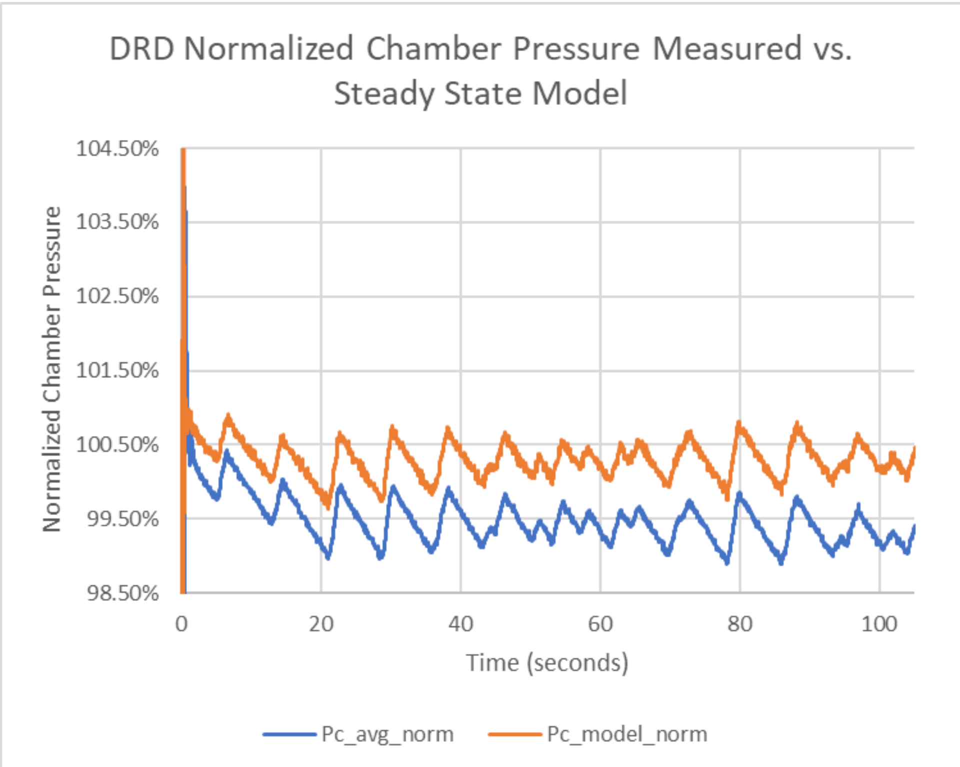

Figure 7: OMS-E Chamber Pressure Performance During DRD

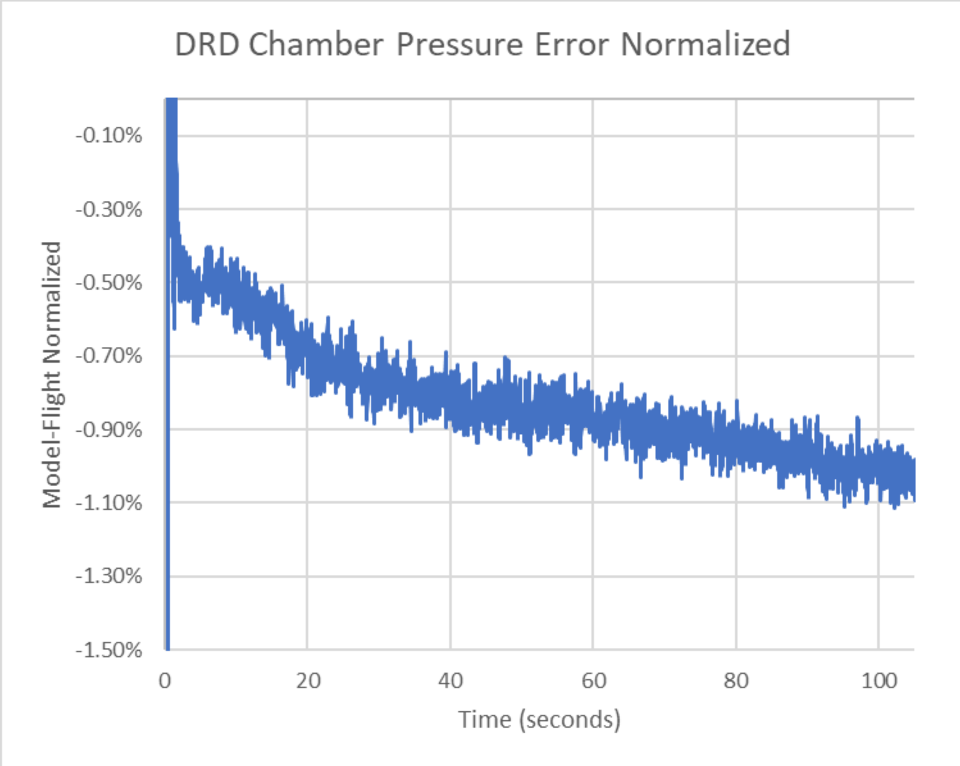

Figure 8: OMS-E Chamber Pressure Error (Model-Flight) During DRD

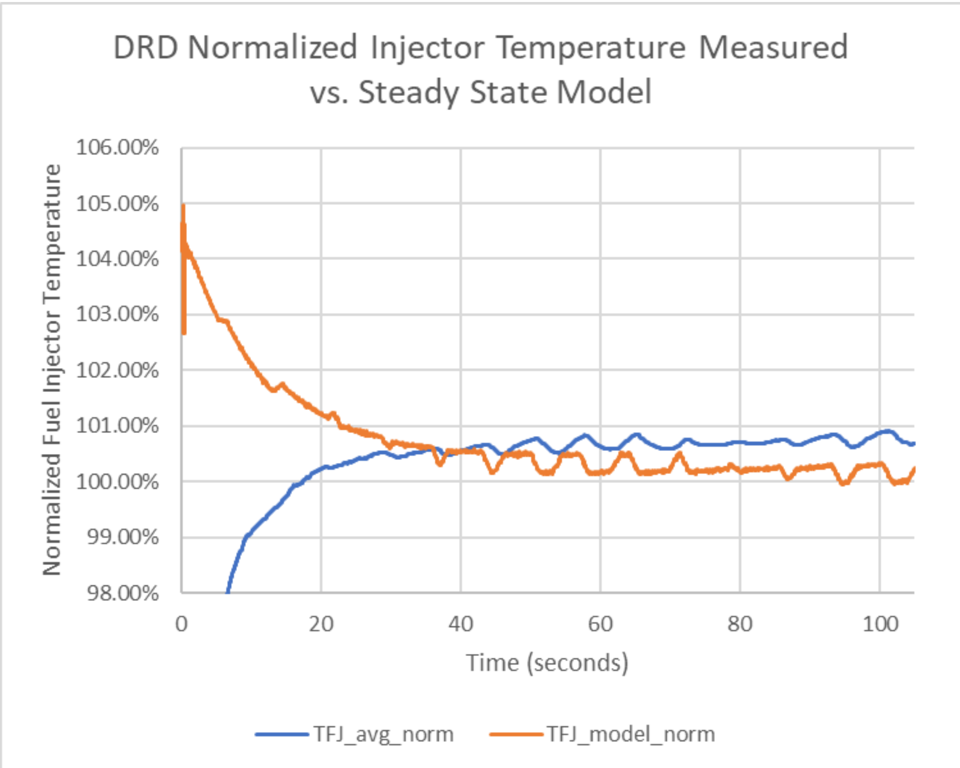

Figure 9: OMS-E Fuel Injector Temperature during DRD

4. Auxiliary Engine

4.1. Overview of Auxiliary Engine

The ESM Propulsion Subsystem has eight auxiliary engines (Aux) that provide a redundant method for translational thrust. The auxiliary engines are primarily a backup engine in the event of a failure of the OMS-E; however, the auxiliary engines are also used nominally for upper stage separation and small trajectory correction burns when it is more efficient than the RCS engines.

The auxiliary engines are modified Aerojet Rocketdyne R-4D-11 engines produced specifically for the Orion program. The auxiliary engines are a 164:1 nozzle expansion ratio variant. The requirements specific to Orion are primarily driven by the deep space thermal environment, human spaceflight requirements, and the operational requirements as backup to the main engine. Due to the deep space thermal environments, the auxiliary engines are delivered with installed valve and injector flange heaters and associated control instrumentation. The engine also comes installed with chamber pressure and temperatures sensors to support fault monitoring required for human spaceflight.

An image of the auxiliary engine is shown in Fig. 10. The key operational and performance requirements for the auxiliary engines are summarized in Tab. 3.

Figure 10: Overview of Orion Auxiliary Engine

Table 3: Artemis I Auxiliary Engine Requirements

Parameter	Value
Thrust	489 N
Mixture Ratio	1.74
Specific Impulse	310 seconds
Max Firing Time	2000 seconds
Number of Burns	40
Pulse Mode Minimum Duty Cycle	72%

4.2. Path to Artemis I

The Orion spacecraft is designed to perform pitch and yaw control during auxiliary engine burns by off pulsing a subset of the engines. This induces unique operational requirements that posed significant challenges during the development and qualification of the auxiliary engine.

The evolution of the driving auxiliary engine requirements throughout the Orion program are summarized in Tab. 4. The R-4D-11 has been widely used in steady state operation for spacecraft apogee insertion. For Orion the engine originally was intended to operate at the same mixture ratio as the OMS-E and RCS engines at a nominal thrust of 489 N and a pulse mode minimum duty cycle of 50 percent. However, early development testing of the engine showed thermal instability during pulse mode at the Orion conditions. Sensitivity testing showed a shift in mixture ratio regained engine thermal stability while maintaining the 50 percent minimum duty cycle in pulse mode. The updated performance point also resulted in a necessary change in the thrust level of the engine. This updated configuration was tested extensively during qualification and acceptance testing of the engine. However, it was discovered that at this new operational point, the engine was susceptible to chug combustion instability. Engine testing showed there were competing operating conditions that enhance chug and pulse mode thermal instability. Engine chug is prevalent at higher mixture ratios and lower thrust whereas engine pulse mode thermal instability is prevalent at lower mixture ratios and higher thrust.

To address competing issues of chug and pulse mode thermal stability, a dedicated system level effort was pursued to address the operational needs of the engine. Updated Guidance Navigation and Control analysis was performed to show that a minimum duty cycle of 72 percent could be accommodated, decreasing pulse mode thermal instability. In addition, an evaluation of the Artemis I mission profile showed that the maximum burn duration for abort burns would be 2000 seconds instead of the worst case 7200 seconds originally specified. These changes allowed for a new Aux operating point with higher nominal thrust and lower mixture ratio, represented by the final column in Tab. 4, to reduce the likelihood of chug. Additional hot fire testing was performed on a spare engine to confirm the engine met all performance requirements at the final operating point.

Table 4: Evolution of Aux Engine Requirements

Parameter	Initial	Update	Final
Thrust	489 N	467 N	489 N
Mixture Ratio	1.65	1.85	1.74
Minimum Duty Cycle	50%	50%	72%
Max Firing Time	7200 s	7200 s	2000 s

4.3. Artemis I Auxiliary Engine Performance

The auxiliary engine performance in flight is compared against a steady state model during the Orbital Maintenance Burn 3 (OM-3). The OM-3 burn was a 94.9 second burn utilizing six of the eight auxiliary engines (two were deliberately turned off for the burn as part of a development test objective). The chamber pressure performance of auxiliary engine X2 is compared against a steady state model in Fig. 11. The data has been normalized against the expected chamber pressure at nominal inlet conditions. The steady state model tracks the performance of the auxiliary engine within approximately 1 percent throughout the duration of the burn excluding initial startup. The OM-3 burn was performed in propellant tank blowdown which is evident in the steadily decreasing chamber pressure.

Auxiliary engine X2 was fired in steady state during the OM-3 burn while two of the other firing engines were operating in pulse mode and the other three engines were firing in steady state. The effect of the pulsing engines on the X2 engine can clearly be seen via temporary increase in chamber pressure. A time slice of the data is shown in Fig. 12 to better visualize the impact of the other pulsing engines on auxiliary engine X2. The increase in chamber pressure corresponds to the time periods when the pulsing engines are turned off which causes a temporary increase in engine inlet pressures due to a reduction in flow related pressure drop within the propulsion feed system. The steady state chamber pressure model generally shows a larger impact on chamber pressure due to the pulsing engines than seen in the data. This effect was also seen during the Propulsion Qualification Model testing and is believed to be due to the transient response of the engine and chamber pressure measurement.

Overall, the auxiliary engines performed well within expectations without any anomalies during the Artemis I mission.

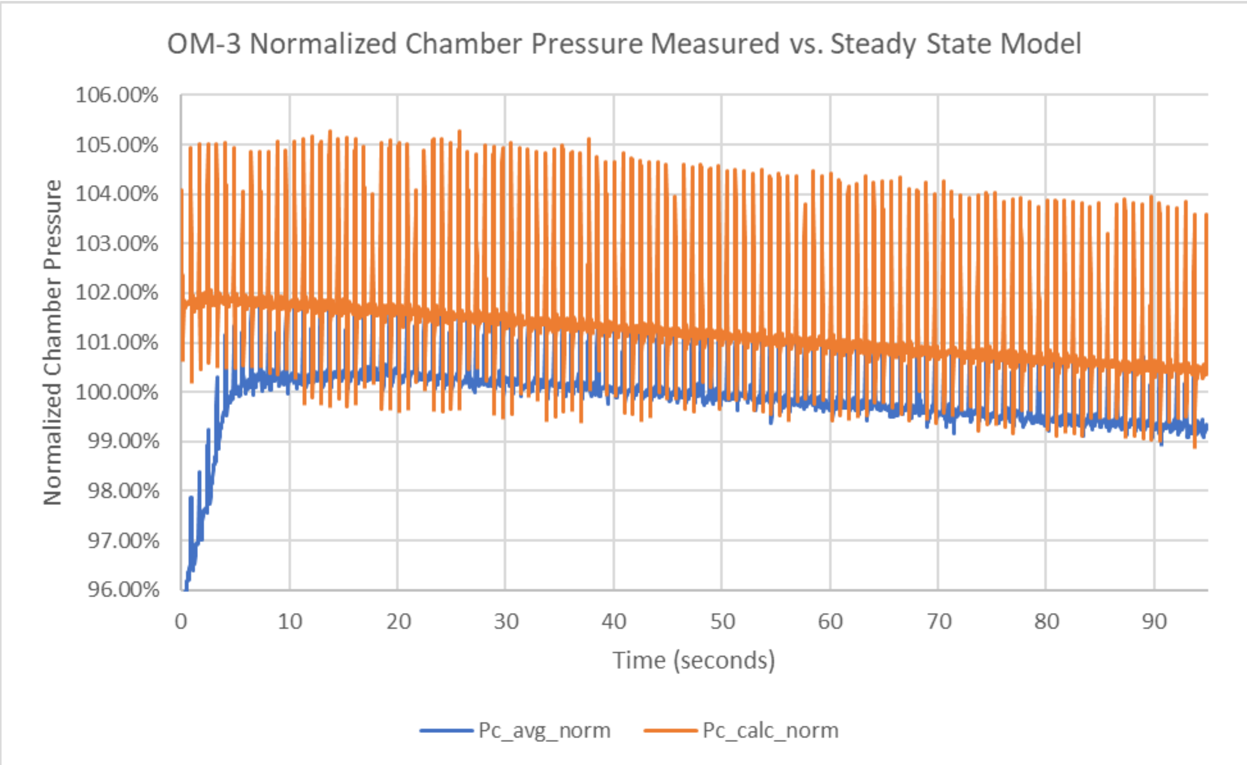

Figure 11: OM-3 Auxiliary Engine Chamber Pressure Performance

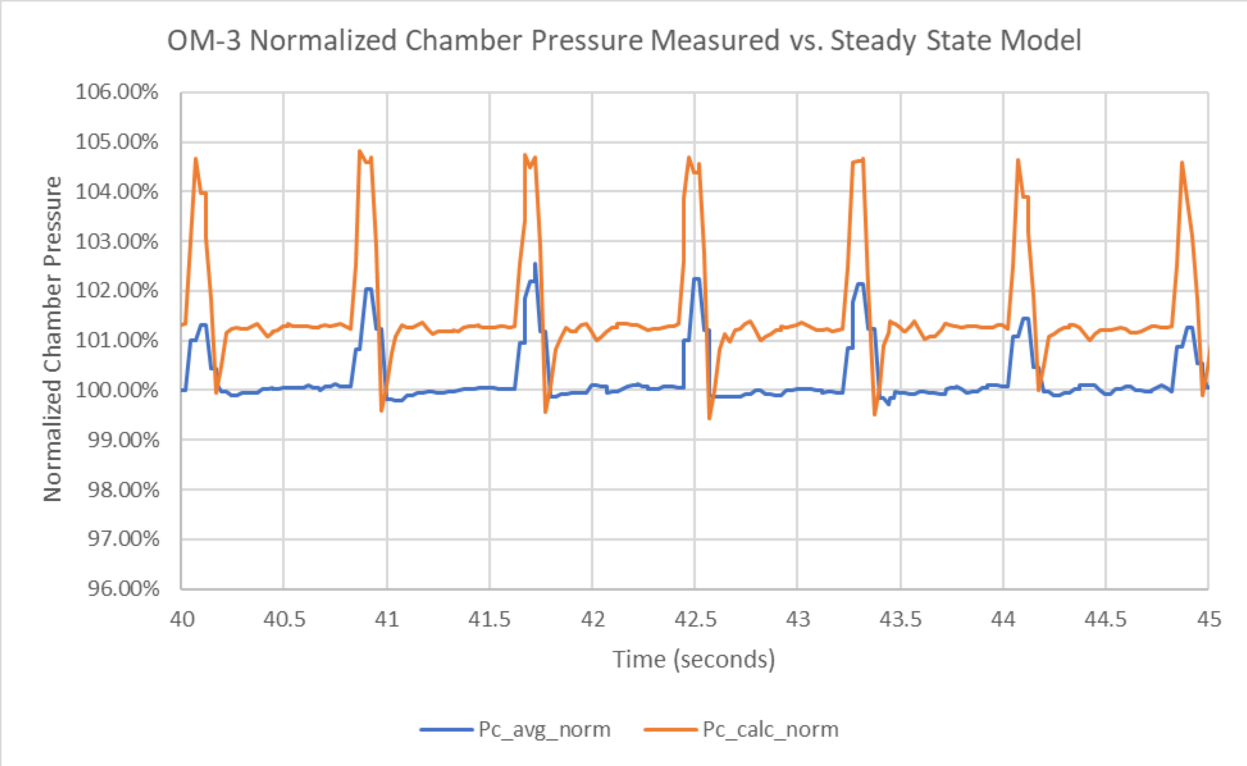

Figure 12: OM-3 Auxiliary Engine Chamber Pressure Zoomed

5. Reaction Control System (RCS) Engine

5.1. Overview of the RCS Engine

The ESM Propulsion Subsystem has twenty-four Reaction Control System (RCS) thrusters. The RCS thrusters are derived from thrusters used on the Automated Transfer Vehicle (ATV) for the same purpose. The RCS thruster and cluster is designed, manufactured, and tested by Ariane Group Gmbh in Lampoldshausen, Germany. An overview of the key performance requirements for Artemis I is given in Tab. 5.

Table 5: Artemis I RCS Engine Requirements

Parameter	**Value**
Thrust	216 N
Mixture Ratio	1.65
Specific Impulse (steady state)	>275 seconds
Minimum On Time	28 ms
Pulse Mode Frequency	5 Hz

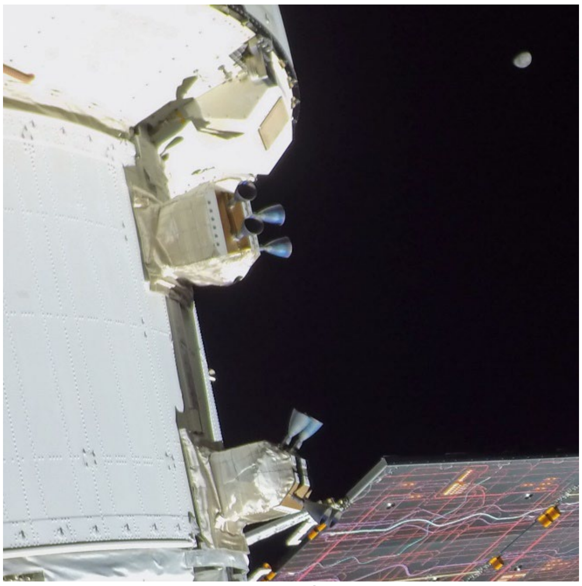

Figure 13: Pitch and Roll Cluster on Artemis I [5]

Figure 14: 200N RCS Engine Overview [6]

5.2. Path to Artemis I

The primary design changes necessary between the ATV and Orion programs for the RCS engines are due to changes in operational requirements. Due to the need for manual pilot control, the RCS engines are required to pulse at a maximum frequency of 5 Hz compared to the previously qualified 1 Hz operation for ATV. Development testing, performed to characterize any operational limitations of the thruster at 5 Hz, was followed by delta-qualification testing. The engine's chamber pressure transducer was also changed from the ATV design which required significant changes at the thruster level.

In addition to the work necessary to demonstrate compliance to mission requirements for Artemis I at the thruster level, a significant amount of design work went into designing a new cluster, the grouping of 4 thrusters into a structure. The experience from ATV was leveraged to perform the structural and thermal analysis work for the new cluster design. The RCS cluster qualification program consisted of mechanical vibration testing and thermal vacuum testing, but no hot fire testing. The objectives of the hot fire testing were fully met at the thruster level.

5.3. Artemis I RCS Engine Performance

The RCS engine performance is compared against the steady state performance model for the SA4F thruster during the OTC-2 burn. The thruster was operating in steady state to perform a small translational maneuver. The chamber pressure data has been normalized against the expected chamber pressure at nominal inlet conditions. Fig. 15 shows engine performance within 1 percent of model predictions except during the engine startup transient.

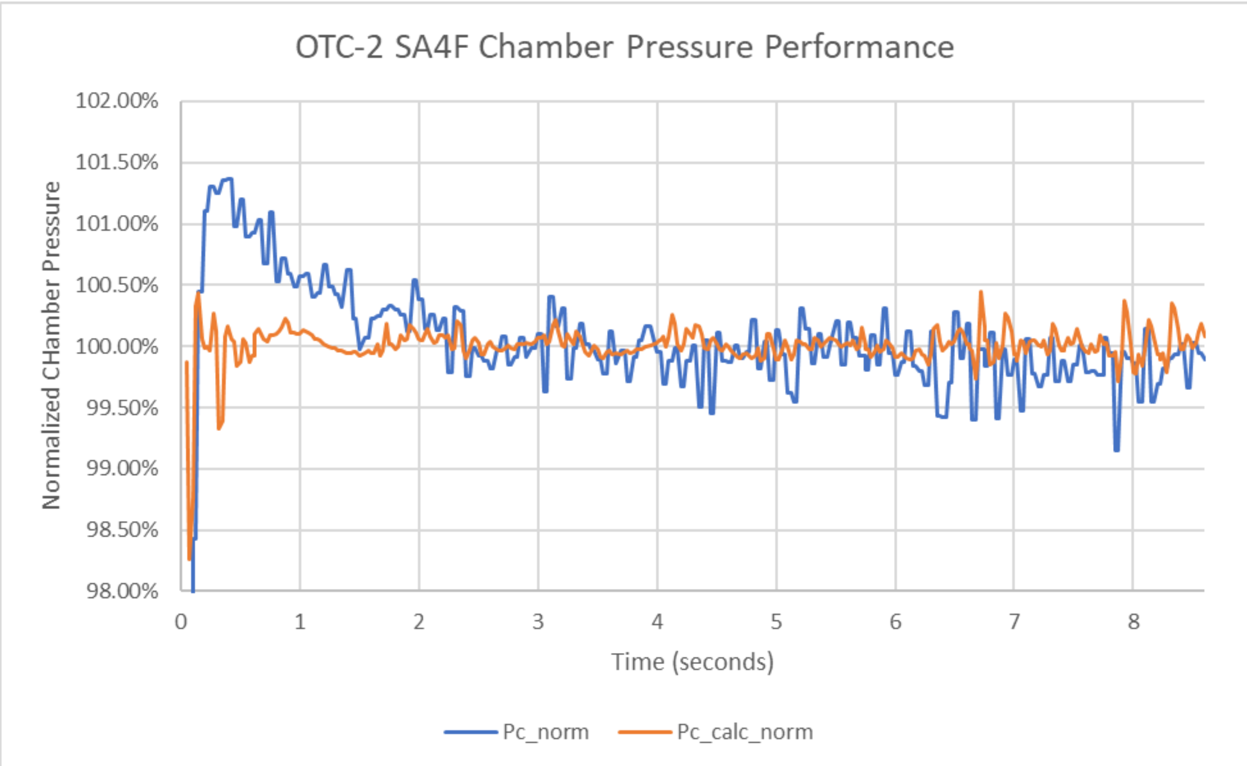

Figure 15: RCS Engine SA4F Chamber Pressure Performance During OTC-2

6. Engine Developments for Future Artemis Missions

Additional development and qualification efforts are implemented for future Artemis missions. For the main engine, the team is primarily working obsolescence issues due to the age of the hardware. On Artemis II, the pneumatic system valves are refurbished with new soft goods and delta-qualified to a higher environmental temperature. On Artemis III, the series bipropellant valve assembly is refurbished with new soft goods and delta-qualified to a higher environmental temperature. There are other small changes on future missions to replace parts that are running low on supplies with no existing supplier such as the chamber pressure transducer. In aggregate, there are no major changes in the main engine design or functionality for future mission, but finding replacement parts and qualifying the process has been a challenge. Starting on Artemis VII, a new engine will replace the heritage Space Shuttle Orbital Maneuvering System Engines currently used on Orion. The Orion Main Engine (OME), also known as the AR40, is being developed by Aerojet Rocketdyne. The design is currently between Preliminary Design Review and Critical Design Review and completed injector stability testing in 2023.

For the auxiliary engines, there are no design changes between Artemis I and II; however, there are planned operational changes for Artemis III+. Due to the challenges presented by pulse mode operation, the team has elected to remove all pulse mode operation from the auxiliary engine requirements for Artemis II except in multiple failure cases. This puts additional demand on the RCS engines which is currently under evaluation. For Artemis III+, the vehicle configuration was changed to enable steady state auxiliary engine operation. The auxiliary engine is reverting to a nominal mixture ratio of 1.65. The thermal stability problems for the engine were resolved by limiting the required maximum single burn duration in pulse mode to 300 seconds and increasing the minimum duty cycle to 80 percent. This is enabled by a redesign of the RCS clusters which will provide the primary means of pitch and yaw control during auxiliary engine burns.

For the RCS thrusters, there is a change in chamber pressure transducer between Artemis I and II+ that increases the engine capability for long pulse trains due to increased high temperature capability of the replacement transducer. As mentioned in the auxiliary engine section, the RCS clusters are redesigned for Artemis III. The RCS clusters that provide pitch and yaw control of the vehicle have been redesigned such that the aft facing thrusters point directly aft of the vehicle. This change increases the RCS capability to provide pitch and yaw control during an auxiliary engine burn.

7. Conclusion

The Artemis I mission was a success for the European Service Module Propulsion Subsystem. The engines on the vehicle performed flawlessly throughout the mission. Engine performance very closely matched predictions. The team is currently not working any issues related to engine performance during Artemis I. As we look forward to future Artemis missions, design evolutions are continuing to make the system more robust and improve the performance.

8. References

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9. List of Acronyms

ATV	Automated Transfer Vehicle
DRD	Distant Retrograde Orbit Departure
DRI	Distant Retrograde Orbit Insertion
DRO	Distant Retrograde Orbit
ESM	European Service Module
MMH	Monomethylhydrazine
MON-3	Mixed Oxides of Nitrogen
NTO	Nitrogen Tetroxide
OM	Orbital Maintenance
OMS-E	Orbital Maneuvering System Engine
OME	Orion Main Engine
OPF	Outbound Powered Flyby
OTC	Outbound Trajectory Correction
PQM	Propulsion Qualification Model
PSS	Propulsion Subsystem
RCS	Reaction Control System
RPF	Return Powered Flyby
RTC	Return Trajectory Correction
STS	Space Transportation System
USS	Upper Stage Separation
WSTF	White Sands Test Facility