Artemis I Orion ESM Propulsion System Engine Performance

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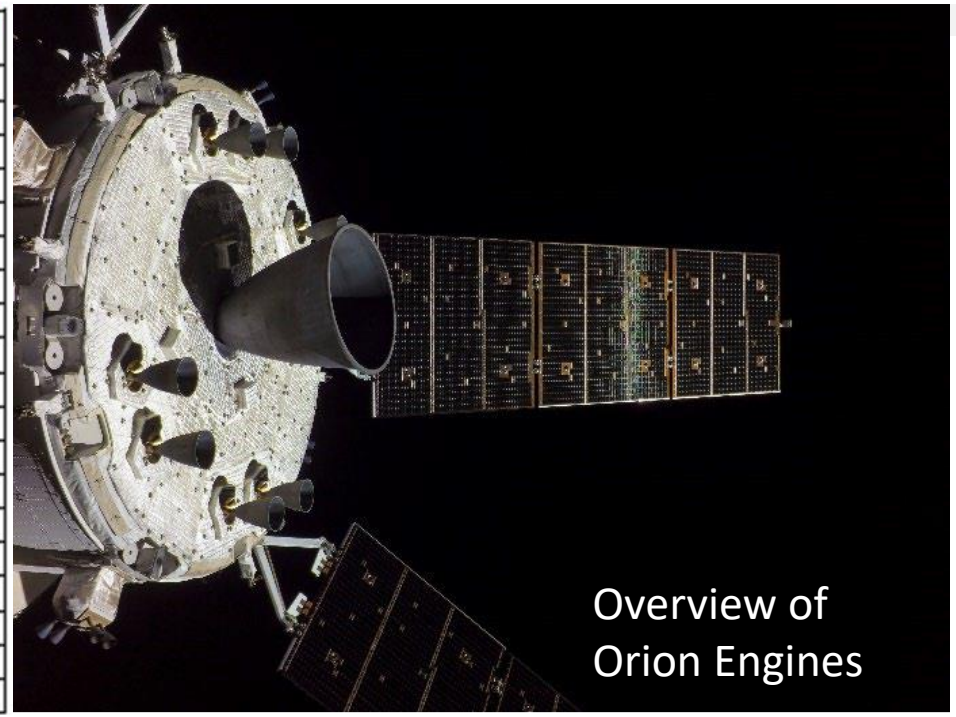
Artemis I Overview

- Artemis I was an uncrewed test flight of Orion that launched on November 16, 2022 with splashdown on December 11, 2022

- This was the first flight of European Service Module (ESM)
  - ESM provides power, propulsion, environmental control to the crew module

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

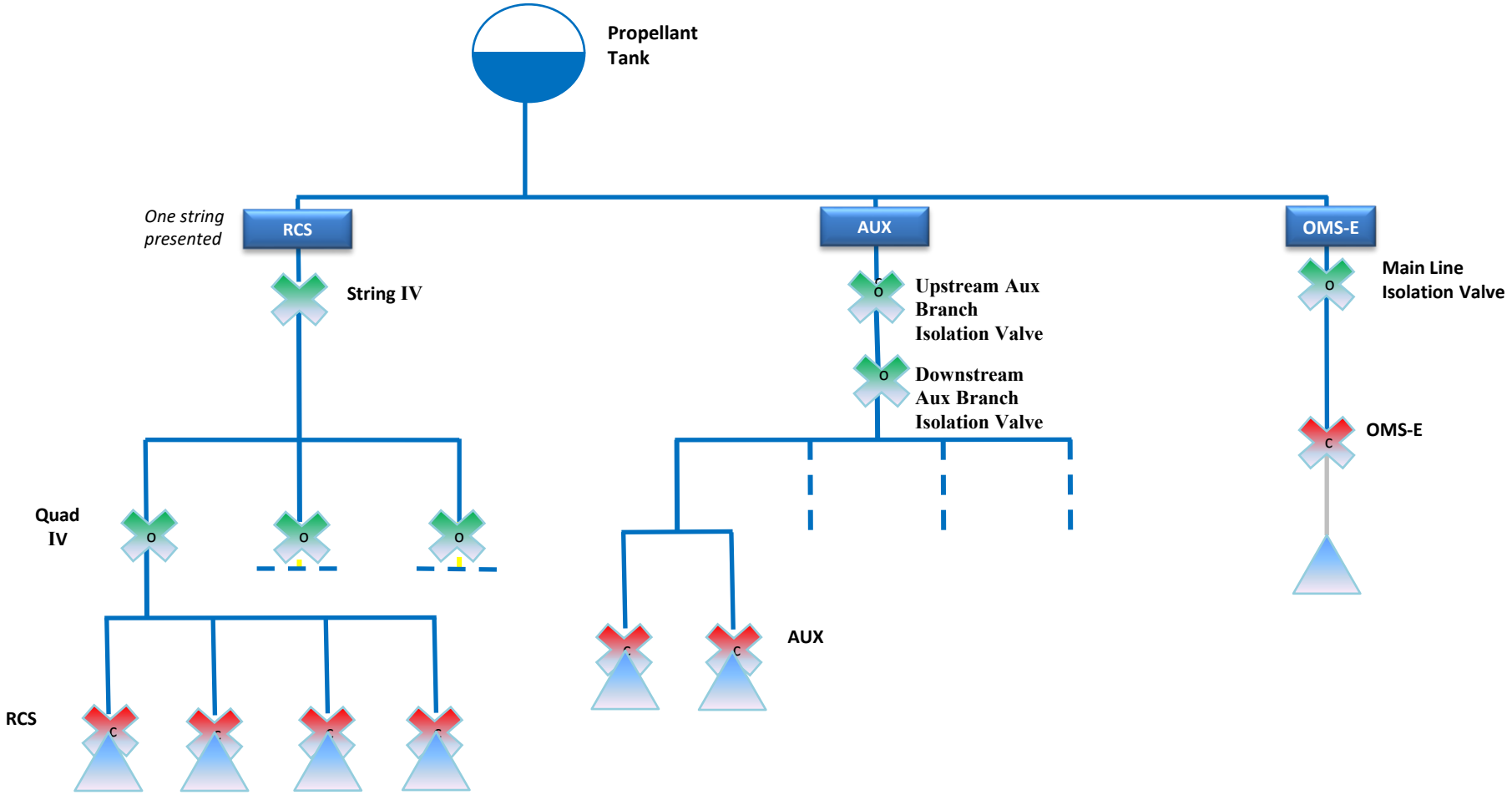

Overview of Orion Engines

ESM propulsion system is a serial bipropellant hypergolic propulsion system using monomethylhydrazine (MMH) and nitrogen tetroxide (MON-3)

There are 3 different thrust class engines on the Service Module (OMS, Auxiliary, RCS) providing both translational thrust and attitude control

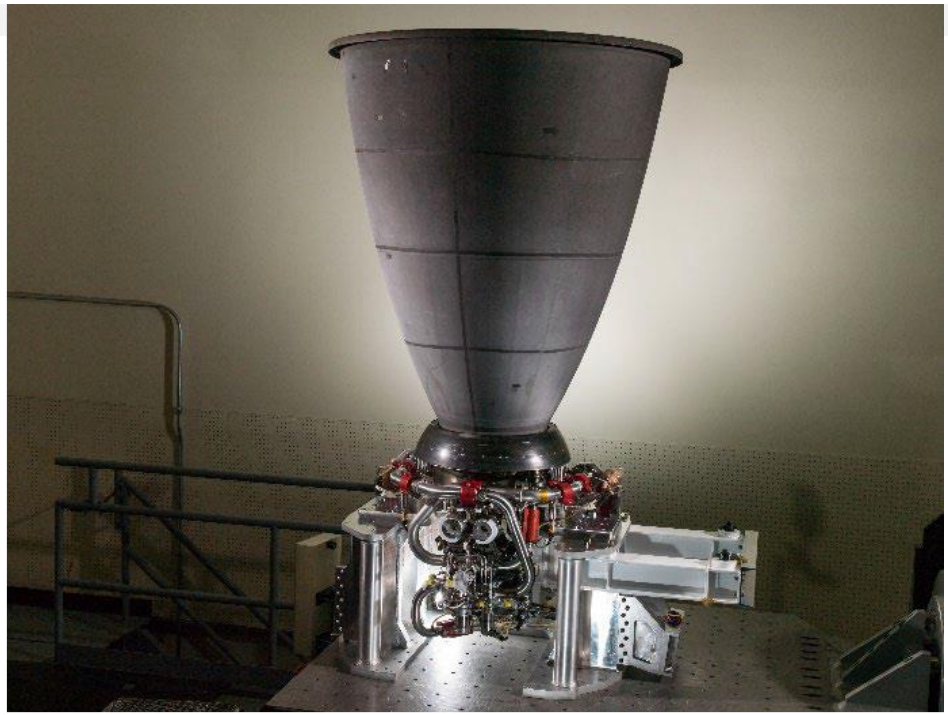
During Artemis I, the Service Module successfully executed 19 burns

System Overview (Post Priming)



OMS Engine Overview

- Main engine is refurbished previously flown hardware from the Space Shuttle program
  - Flew 19 shuttle missions between 1984 and 2002
- Engine modifications for use on Orion
  - New harnesses, additional chamber pressure & fuel injector temperature measurements
- Engine was delta-qualified for new environments

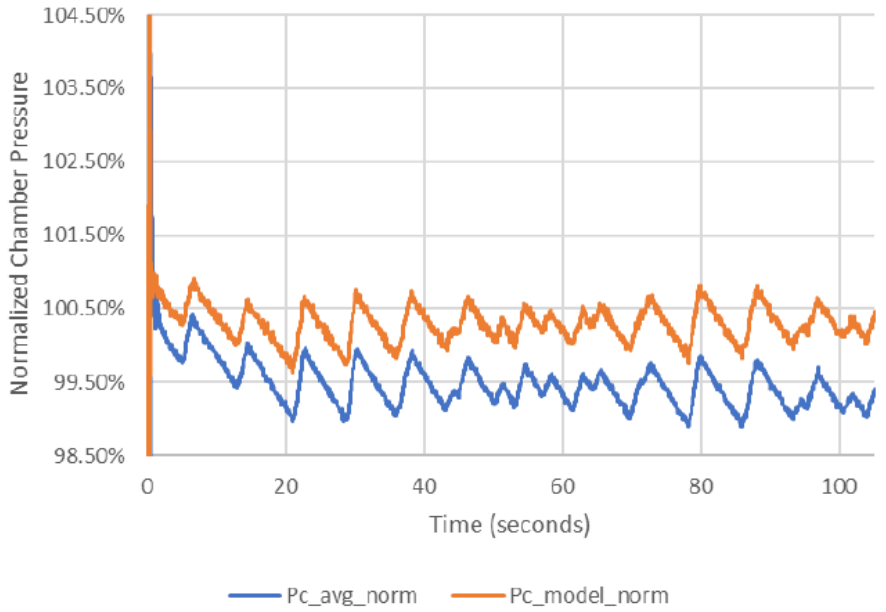


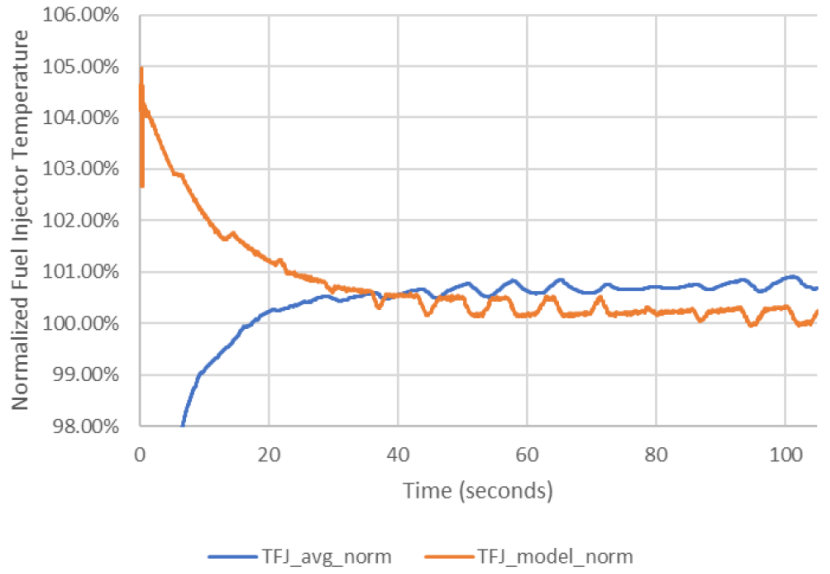
Key Parameters

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

OMS Performance

- Exemplary data shown for DRD burn
- Predicted chamber pressure tracked with measured response exactly with inlet pressure fluctuations due to bang-bang regulation system
- Bias attributable to instrumentation & model accuracy
- After start up transient, steady state equilibrium fuel injector model tracked well with in-flight telemetry (within 1%)





Auxiliary Engine Overview

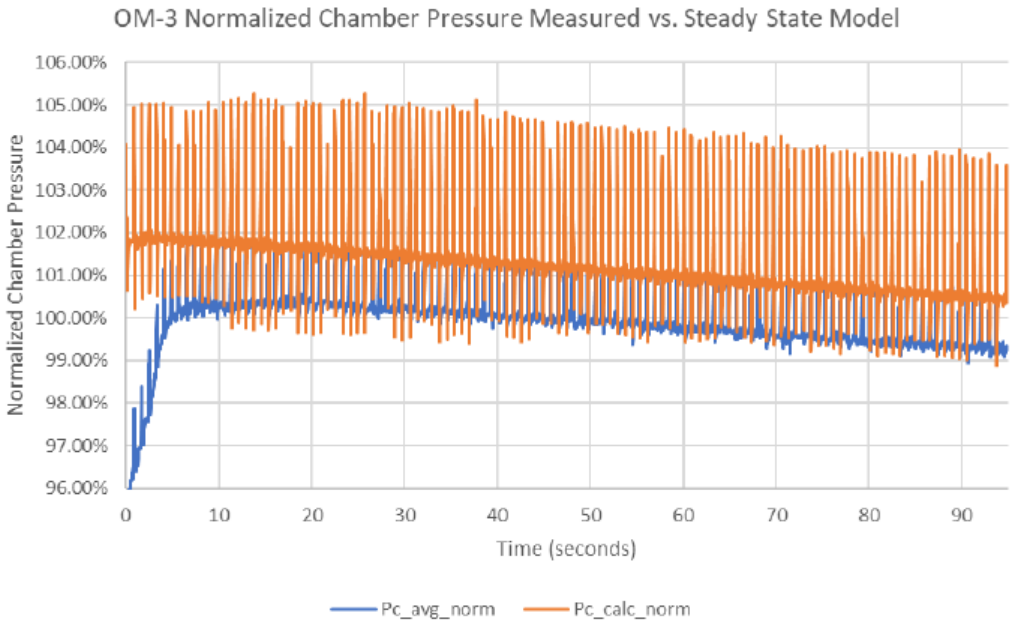
- ESM propulsion system has 8 Auxiliary (Aux) engines that provide a redundant translational thrust capability
  - Aux engines are also used nominally for upper stage separation & small trajectory correction burns
- Engines are modified Aerojet R-4D-11 engines produced specifically for the Orion program
- Off-pulsing a subset of engines provides pitch/yaw control of the spacecraft which introduced unique challenges which resulted in changes to the operating point of the engine
  - Pulse mode stability vs chug

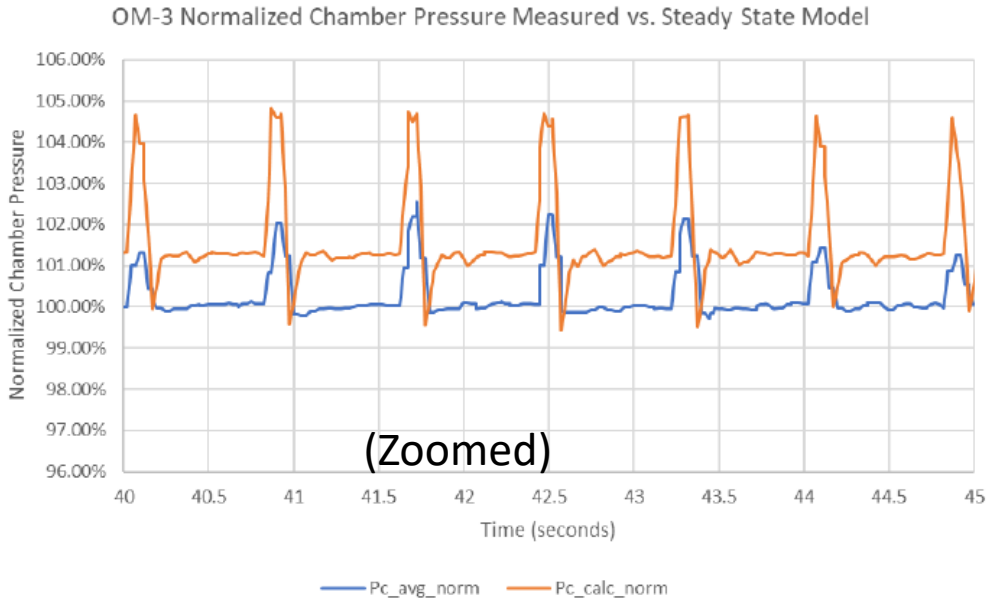
Key Parameters

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

Aux Engine Performance

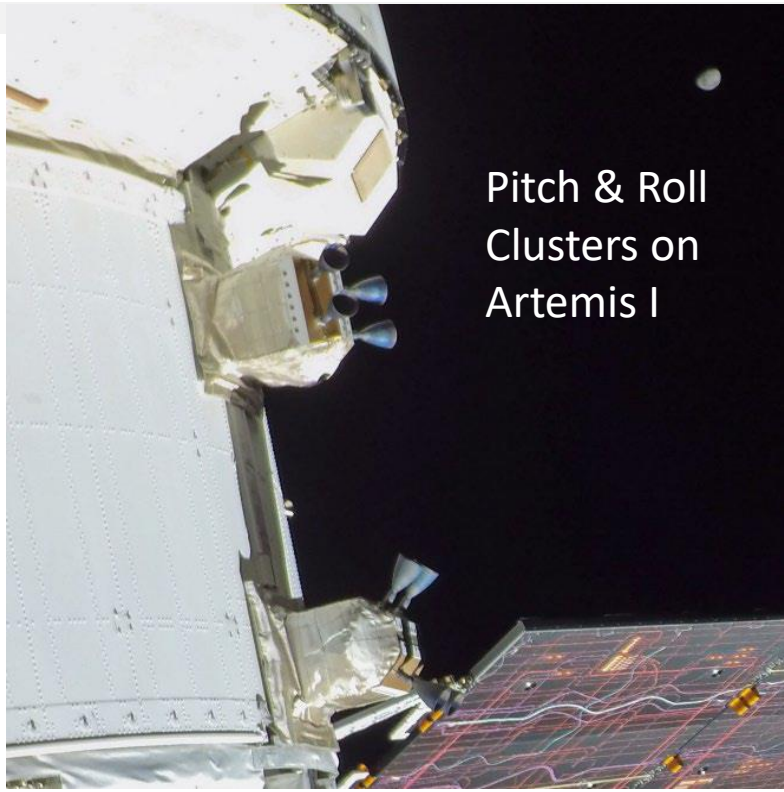
- Exemplary results shown for X2 engine during the OM-3 burn
  - Burn was 94.9 seconds utilizing 6 of 8 engines and performed in blowdown
  - 2 were deliberately turned off for the burn to achieve a development flight test objective
- Steady state model tracks performance within ~1% throughout the duration excluding the initial startup
- Aux engine X2 and three other engines fired in steady state
  - Two Aux engines were pulsing during the burn
  - Response due to pulsing engines evident in both flight telemetry and model





RCS Overview

- ESM propulsion system includes 24 RCS thrusters divided into 2 redundant strings
- Thrusters are derived from the design used on ATV
- Thruster modifications for use on Orion
  - New pulsing requirements, new chamber pressure sensor
- Thruster/cluster was delta-qualified for new environments



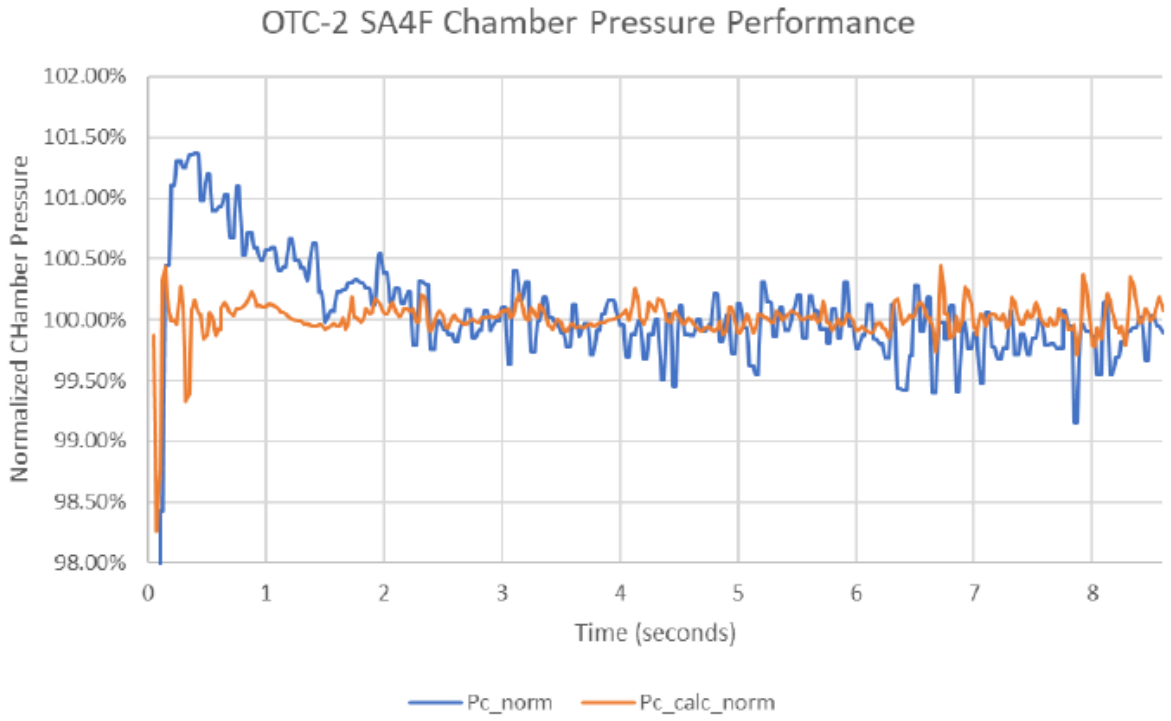
Pitch & Roll Clusters on Artemis I

Key Parameters

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

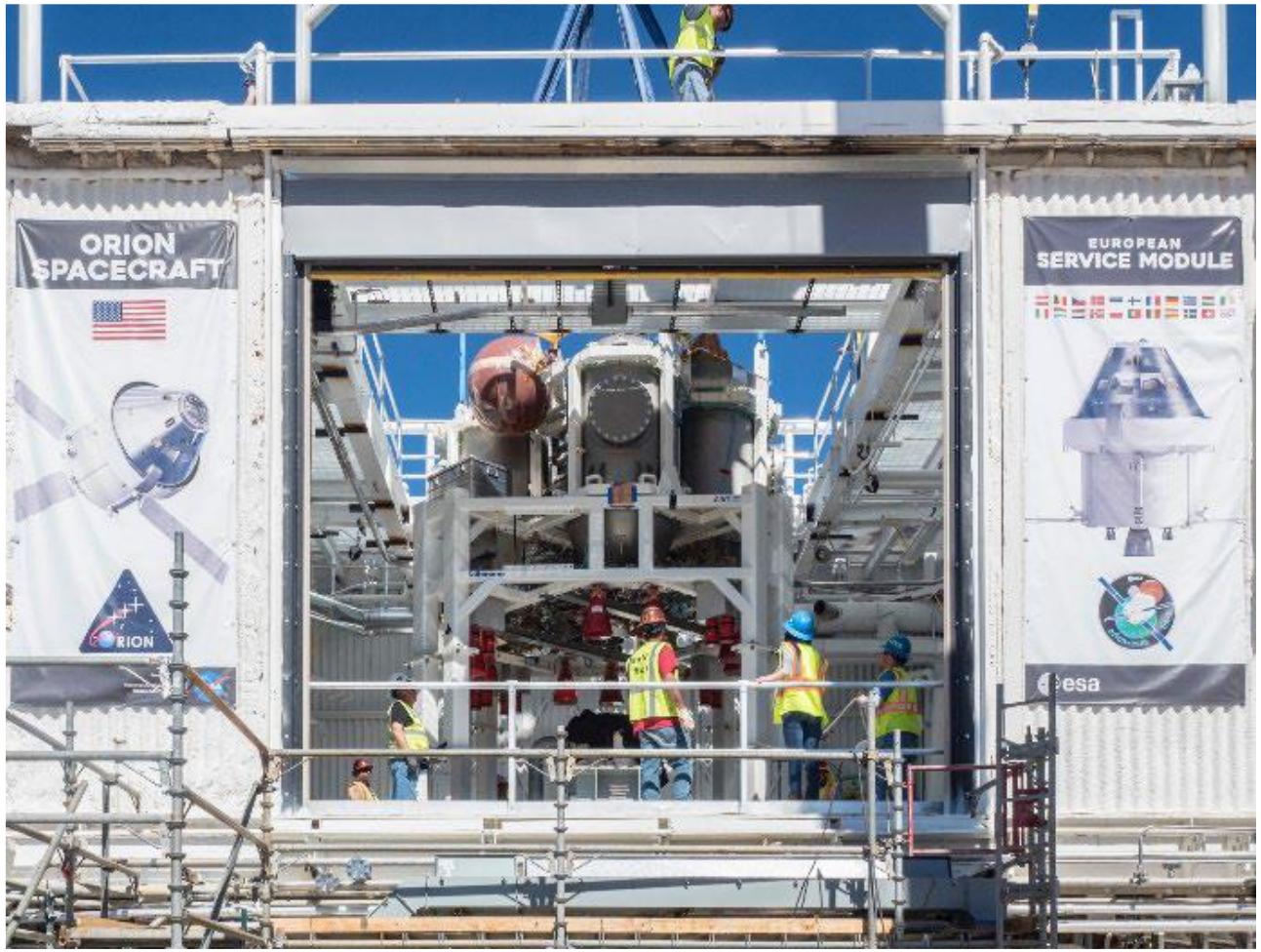
RCS Performance

- Exemplary results shown for SA4F thruster during the OTC-2 burn
  - Thruster operating in steady state to perform a small translational maneuver
- Model predicts engine performance within 1% except during engine startup transient



Qualification

- Certification was built up from engine-level tests to subsystem-level tests
- Subsystem qualification tests performed at NASA White Sands Test Facility between 2018 and 2020
- Qualification model included flight representative fluidic layout, 1 OMS engine, 8 Aux, and a subset of RCS thrusters



Future Evolutions

- OMS
  - Refurbishment of pneumatic system valves (Artemis 2+)
  - New seals in Series Valve Assembly (Artemis 3+)
  - New engine design (Artemis 7)

- Aux
  - Operational changes
    - Limiting pulse mode operations (Artemis 2+)
  - Reverting back to 1.65 mixture ratio (Artemis 3+)

- RCS
  - New chamber pressure transducer (Artemis 2+)
  - Thruster recanting within a cluster (Artemis 3+)

Summary

- The engines on the ESM propulsion system performed flawlessly throughout the Artemis I mission
- Engine performance closely matched predictions
- Design evolutions for future flights are continuing to make the system more robust and improve performance