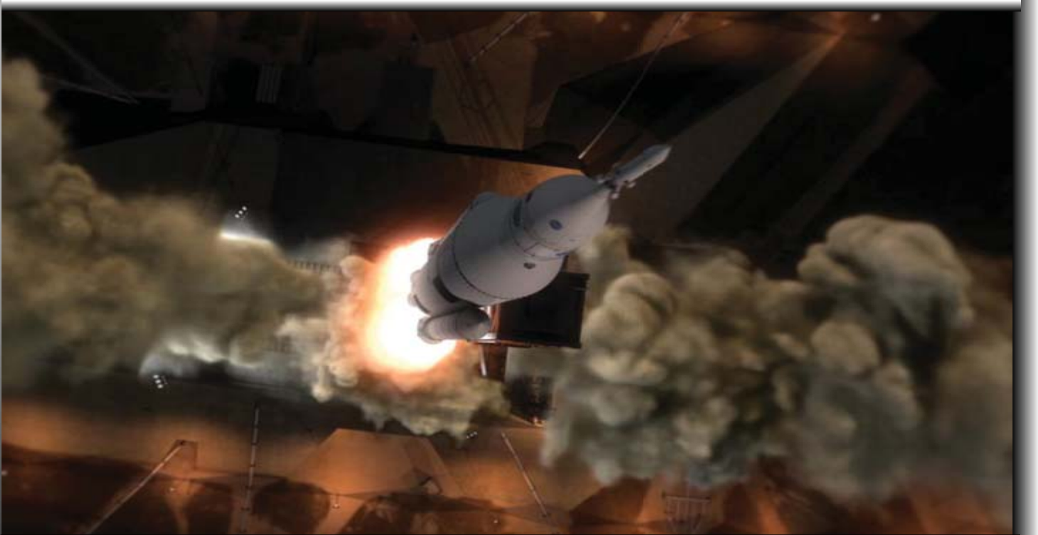

Evolution of MPCV Service Module Propulsion and GN&C Interface Requirements

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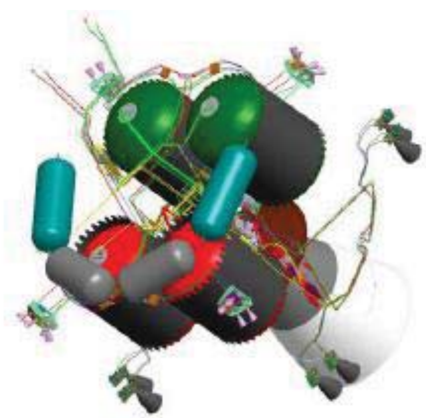
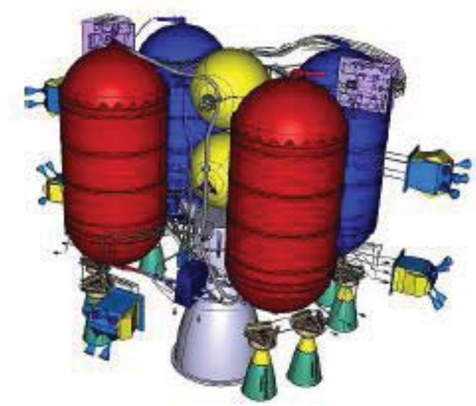
Summary

- **Introduction**
- **Mission Description**
- **ESM Propulsion Subsystem Design**
- **SM Propulsion and GNC Interfaces**
  - Main Engine and TVC
  - Auxiliary Engines
  - RCS Engines
- **Conclusions**

Introduction

- **Service Module provides propulsion, regulates heat for the spacecraft, generates electrical power, and stores commodities for life support for the Orion spacecraft**
- **Propulsion subsystem characteristics**
  - Propellant: NTO/MMH
  - Usable Propellant Load: 18964 lbm (8600 kg)
  - Single main engine with TVC, eight auxiliary engines, suite of RCS engines
- **In 2012 NASA and ESA entered into a partnership for the delivery of the ESM**
  - Prime contractor for ESM is Airbus Defense and Space
  - Prime contractor and integrator of MPCV is Lockheed Martin
- **MPCV currently has two primary missions: EM-1 and EM-2**
- **Propulsion interface requirements with GNC have been updated between CxP SM and ESM due to desired use of heritage hardware and updates in the exploration architecture**





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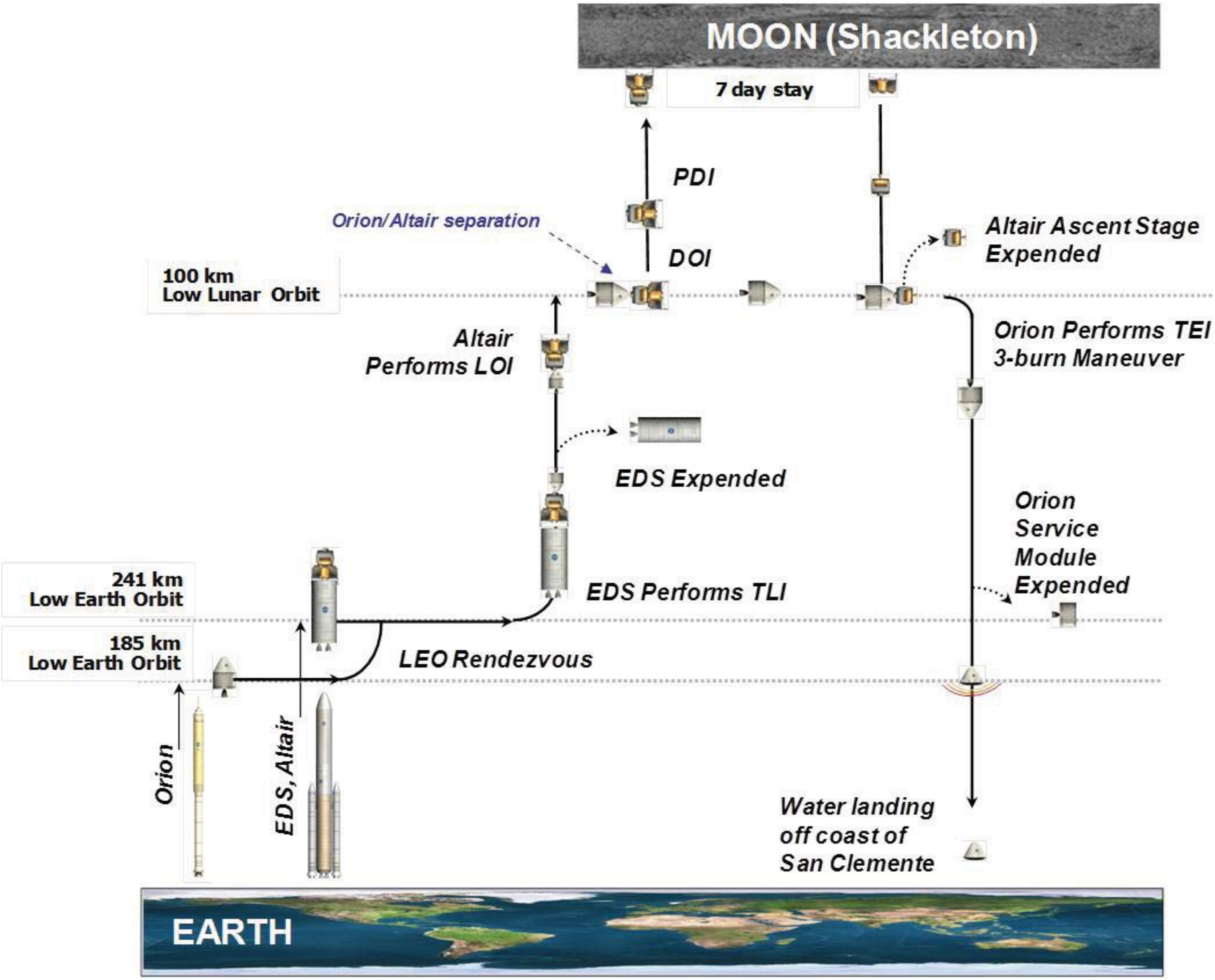
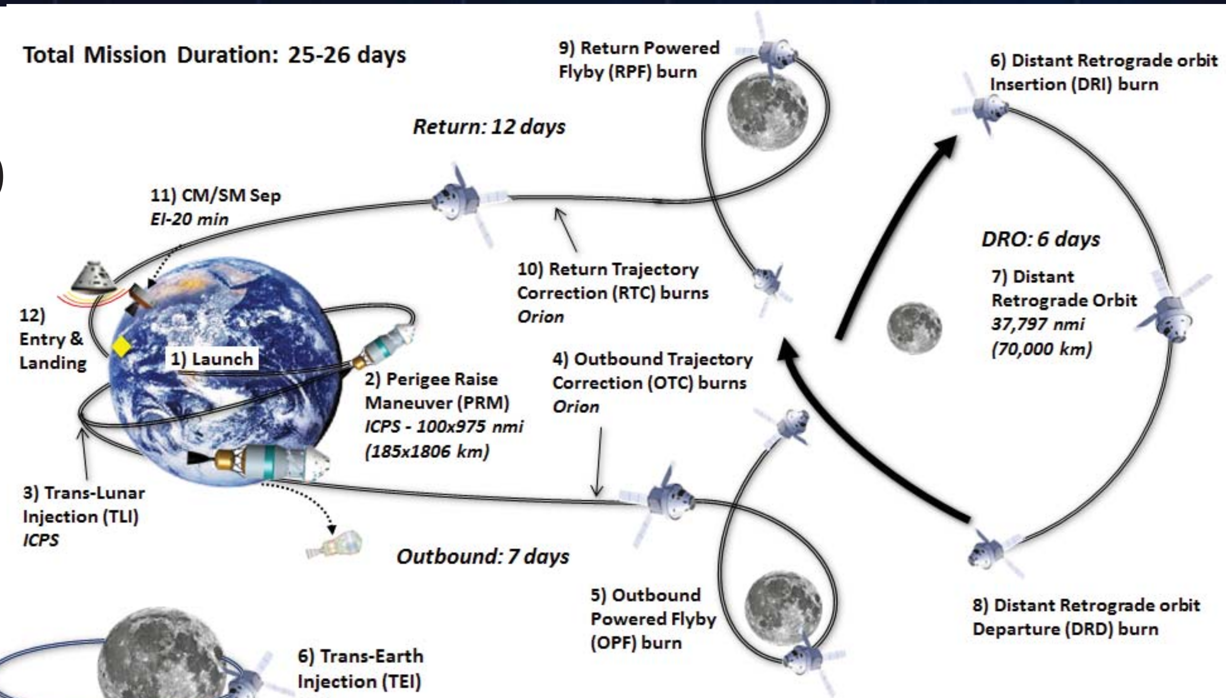
CxP LLO Sortie Mission Overview

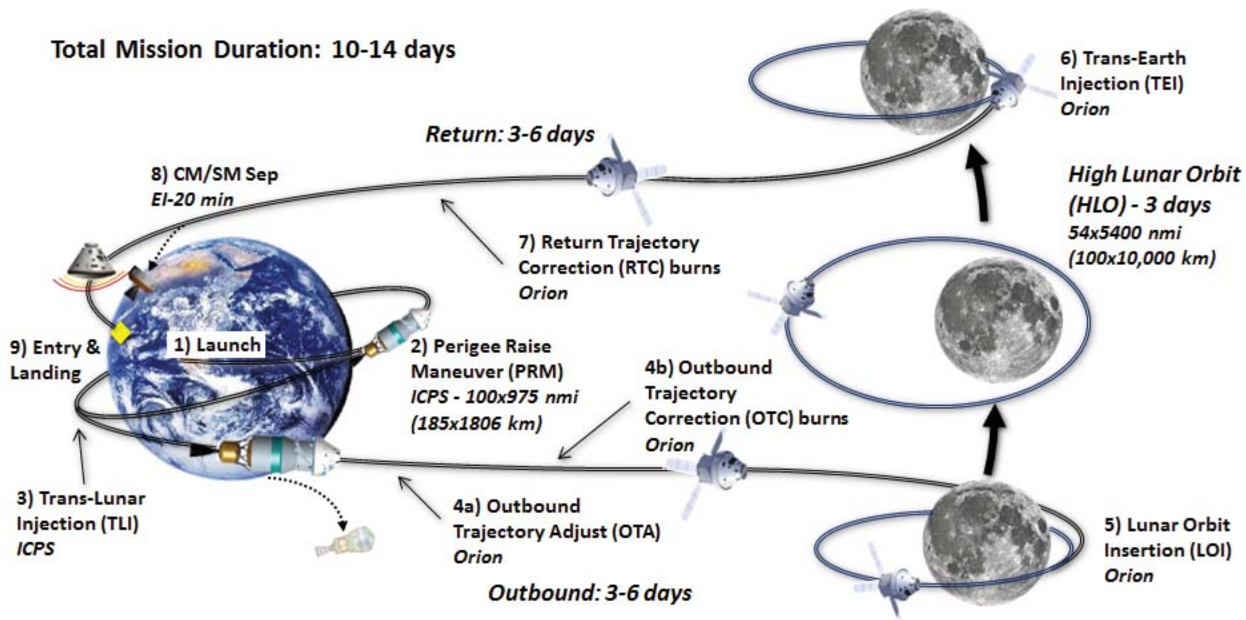


EM-1 and EM-2 Mission Overviews

EM-1: 25-26 Day DRO



EM-2: 10-14 Day HLO



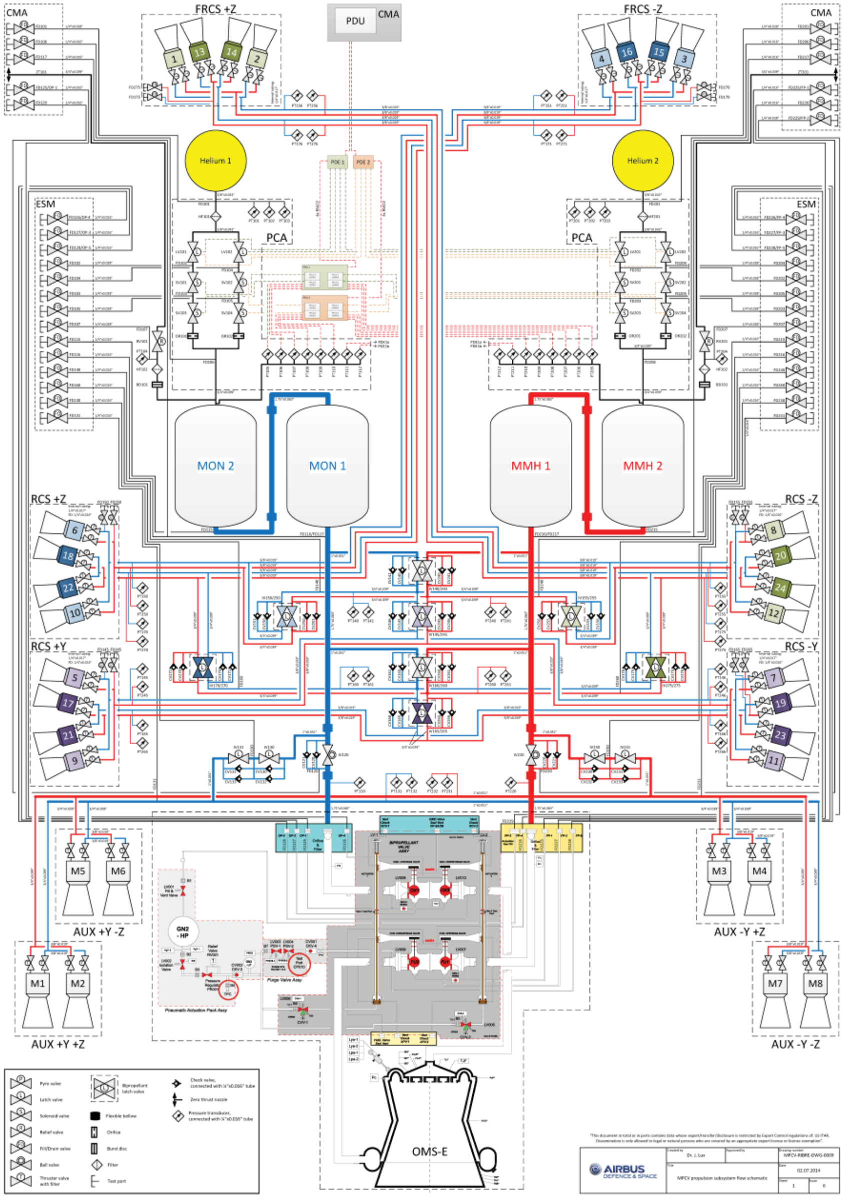
CxP LLO Sortie Mission compared to MPCV EM-2

Table 1. CxP and EM-2 HLO Comparison.

	Constellation	EM-2
Mission Type	LLO Sortie	HLO
Lunar Lander	Yes, Altair	No
Launches	Two launches, Ares I and Ares V	One SLS Launch
Mission Duration	~23 Days	9-12 Days
Rendezvous	In LEO ~315 ft/s (96 m/s)	N/A
Upper Stage Separation	From Ares I launch vehicle in LEO, Altair separated from upper stage post-TLI	From upper stage post-TLI
Outbound Trajectory Correction Burns	No, performed by Altair	Yes
Free Return Trajectory	No	Yes
OTA	N/A	Takes MPCV off of free return, ~33 ft/s (10 m/s)
LOI	No, performed by Altair ~2,786 ft/s (849 m/s)	Performed by MPCV ~1358 ft/s (414 m/s)
Time in Lunar Orbit	8 Days	3 Days
Orbit Maintenance	No, only a two-burn orbit cleanup to align orbit with lunar lander ascent ~85 ft/s (26 m/s)	Yes ~33 ft/s (10 m/s)
TEI	Three-Burn sequence ~3,500 ft/s (1,067 m/s)	One Burn ~2,133 ft/s (650 m/s)
Landing	Off the cost of California	Off the coast of California

ESM Propulsion Subsystem

- **Pressurization**
  - 5800 psi (40 Mpa) helium
  - Single COPV per commodity, ATV/EPS heritage
  - Electronic Pressure Regulation (bang-bang), BDRV
- **Propellant Storage and Distribution**
  - Four tanks, two per commodity, OST-23 heritage
  - Serial tank configuration, PMD in downstream tank
- **Main Engine**
  - Space Shuttle OMS-E with TVC (6000 lbf)
  - Isolated by mainline isolation valve
- **Auxiliary Engines**
  - Eight R-4D-11 (110 lbf)
  - Isolated into one string by Aux Engine Isolation Valve
- **Reaction Control System**
  - Twenty-four 50 lbf engines, ATV heritage
  - Isolated into two strings of twelve
  - Each string isolated into three groups of four engines

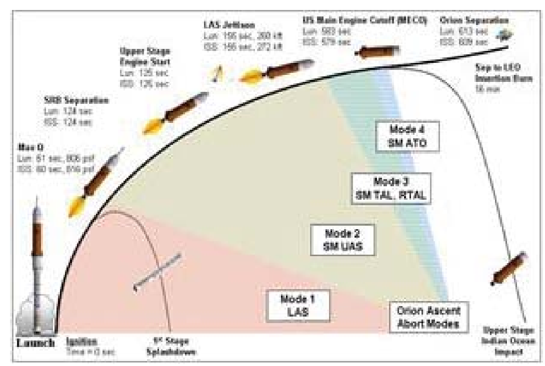


Main Engine and TVC Prop/GNC Requirements

- **CxP Main Engine: Orion Main Engine (OME)**
  - Derived key characteristics from Shuttle OMS-E
    - Increased chamber pressure, area ratio, and mixture ratio achieves higher thrust and specific impulse
  - Thrust and Isp driven by abort coverage, North Atlantic and higher delta V performance
    - RTAL/TAL overlap coverage with Ares ISS trajectories
    - 170 ft/s additional delta V performance
  - Vacuum starts driven by CxP nominal plus contingency starts
  - TVC range and slew rate driven by angular control authority for CxP missions and aborts
- **ESM Main Engine: Space Shuttle OMS-E**
  - Existing engine so performance parameters are fixed
    - Lower chamber pressure of OMS-E allows for lower system pressures
    - Lower thrust beneficial for on orbit loads on solar arrays
  - Thrust and Isp assessed to be adequate for aborts with SLS
    - 10 sec vs. 8 sec of abort overlap for MPCV vehicle configuration with SLS
  - Vacuum starts fixed, driven by OMS-E pneumatic pack, assessed to meet EM-1 and EM-2 missions
  - Space Shuttle TVC provides adequate abort and steering for EM-1 and EM-2

Table 2. Main Engine and TVC Key Performance Parameters.

	CxP SM	ESM
Nominal Thrust	7500 lbf (33.3 kN)	6000 lbf (26.6 kN)
Nominal Specific Impulse	328 s	315 s
Number of vacuum starts per mission	18	10
TVC Range	+/- 8 degrees	+/- 6 degrees
TVC Slew Rate	8-10 degrees/sec	3-6 degrees/sec

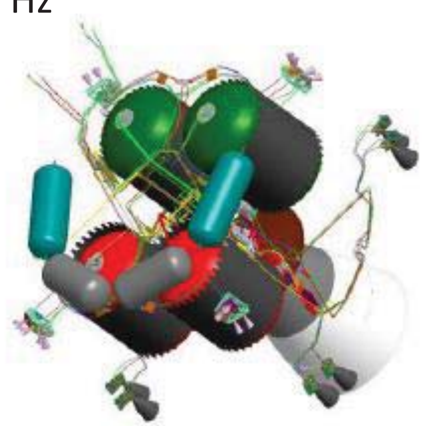


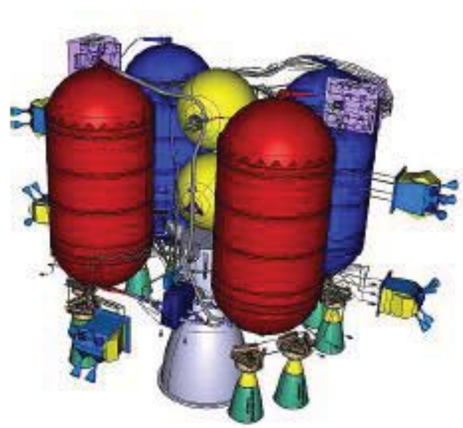
Auxiliary Engine Prop/GNC IRD Requirements

- **CxP Auxiliary Engines: Aerojet 164:1 R-4D-11**
  - Area ratio driven by accommodation , engines exterior to radiator panels
    - Lower AR Isp acceptable for CxP missions
    - Provides better duty cycle performance
  - Single burn duration driven by TEI back up
    - CxP had multi-burn TEI maneuver and longest burn is TEI-1
    - Calculated using 3 sigma low Isp and nominal thrust
  - Number of starts driven by cumulative operation at 1 Hz
- **ESM Auxiliary Engines: Aerojet 300:1 R-4D-11**
  - Area ratio driven by propellant utilization, engine interior to radiator panels
    - Higher AR can be accommodated due to smaller OMS-E
    - Provides improved delta V performance, 66 ft/s
    - Duty cycle performance still meets engine constraints
  - Single burn duration covers single burn TEI
    - Duration calculated assuming entire prop load consumed by auxiliary engine
  - Number of starts driven by cumulative operation at 1 Hz

Table 3. Auxiliary Engine Driving Key Performance Parameters

	CxP SM	ESM
Nominal Specific Impulse	311 s	315 s
Single Burn Duration	4,500 s	7,200 s
Expected Duty Cycles	> 50%	> 50%
Number of Starts	10,000	7,200



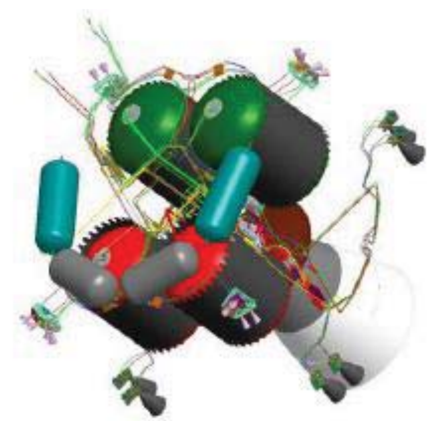


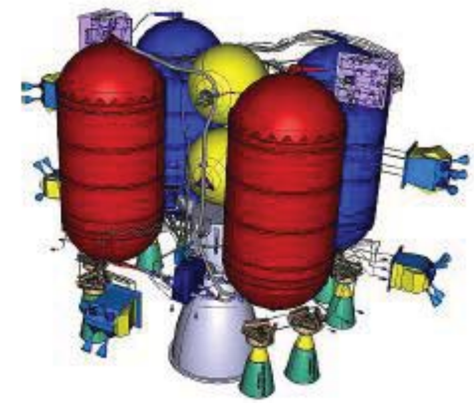
RCS Prop/GNC IRD Requirements

- **CxP RCS Engines: Aerojet R-1E**
  - Thrust, min EPW, and configuration driven by needed authority, MIB, and plume impingement
  - Iterative approach between Prop/GNC/Vehicle Configuration converged on RCS thruster requirements
    - Sixteen engines arranged in a string/pair configuration
    - Engines in canted/skewed configuration with each engine providing pitch/yaw and roll
      - Optimizes redundancy with minimum number of thrusters
      - Provides capability for very small impulses
- **ESM RCS Engines: 50 lbf engines from ATV**
  - Thrust, min EPW, and configuration driven by needed authority and MIB and plume impingement
  - Authority and precision requirements defined to allow ESA and ADS to complete RCS design
    - Twenty-four engines arranged in a string/quad configuration
    - Engines in orthogonal configuration
      - Accommodates ESM solar array configuration
      - Increased thrust allows for additional control authority, small MIB meets precision requirements

Table 4. RCS Key Performance Parameters

	CxP SM	ESM
Nominal Thrust	25 lbf (110 N)	50 lbf (220 N)
Minimum EPW	40 ms	28 ms
Number of Engines	16	24





Summary

- **Mission descriptions have evolved from CxP to MPCV**
- **The SM has maintained key functions through the implementation of MPCV and the partnership with ESA**
  - Provides propulsion for the integrated Crew and Service Module
  - Generates electrical power
  - Regulates heat for the spacecraft
  - Stores commodities for life support
- **Propulsion subsystem is a storable, pressure-fed bipropellant system feeding a main engine with TVC, eight auxiliary engines, and a suite of RCS engines**
- **Updates in the exploration architecture and the partnership with ESA have resulted in updates to the Propulsion interface requirements with GN&C**
  - Main engine thrust, Isp, starts, and TVC performance
  - Auxiliary engine Isp, single burn duration, duty cycle performance, and starts
  - RCS engine thrust, min EPW, and configuration
- **The ESM propulsion performance has been assessed to meet GNC requirements, supporting the use of hardware with heritage to the US and Europe**