Apollo Constellation Engine (ACE) krypton/xenon propulsion system

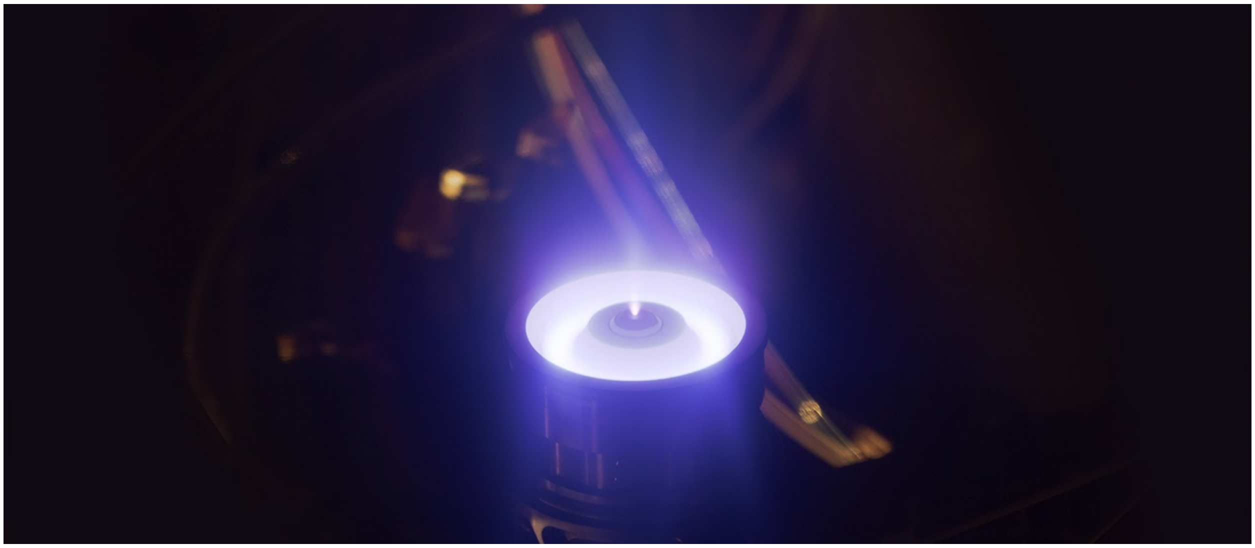

Figure 1: ACE operation with krypton

The Apollo Constellation Engine (ACE) is a Hall effect thruster propulsion system which leverages the past 50 years of Hall thruster research in a clean sheet design with major innovations, including:

- Multi-propellant capability with Krypton, Xenon, and proprietary propellants
- Heaterless, center-mounted, instant-start cathode
- Novel magnetic lensing and magnetic circuit
- Advanced high temperature materials
- 95% efficient single board PPU

Table 1: System specification summary	Krypton	Xenon
Input Power	400 W	400 W
Input Voltage (primary)	28 VDC unregulated	28 VDC unregulated
Thrust	~16 mN	~22 mN
Specific Impulse	~1,200 s	~1,300 s
Total Impulse	200 kN-s	200 kN-s
Designed & Manufactured in	USA	USA

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SUBSYSTEM COMPONENTS

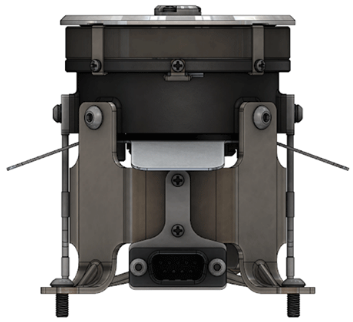

Figure 2: ACE krypton/xenon thruster v1.9

Thruster

ACE includes a thruster which has been tested from 280 W up to 600 W and is configured for operation at 400 W to the PPU.

Key features:

- Multi-propellant capability with krypton, xenon, and proprietary propellants
- Heaterless, center-mounted, instant-start cathode
- Novel magnetic lensing Advanced high temperature materials
- Designed for multi-thruster operation
- Thruster can operate between 300 W and 500 W to PPU (System optimized for 400 W operation)

Table 2: Thruster specifications	Krypton	Xenon
Power	400 W	400 W
Thrust	~16 mN	~22 mN
Specific Impulse	1,200 s	1,300 s
Total Impulse	200 kN-s	200 kN-s
Thruster Mass	1.0 kg	1.0 kg
Thrust Vector Angle	+/- 1 degree	+/- 1 degree

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PPU

The ACE PPU provides power and control to the ACE thruster, valves, regulator, and pressure transducers. Apollo has baselined two options for the PPU:

1. Radiation tolerant PPU: The PPU is designed to perform in 20 kRad TID environments. Suitable for sub 1,000 km missions in LEO for a lifetime of 5 years.
2. Radiation hardened PPU: The PPU is designed to perform in 100 kRad TID and 42MeV/u SEE environments. This PPU design prevents gate ruptures and latchups, is tolerant of transients and upsets, and is suitable for missions from LEO through the Van Allen belts to GEO for lifetimes up to 15 years.

Table 3: PPU Summary (Radiation Tolerant and Radiation Hardened PPU)

High Voltage Igniter	Regulated supply operated during thruster activation
Valve and Pressure Transducer Supplies	Regulated supplies provide power to actuate the ACE system pneumatic valves and operate the subsystem pressure transducers
Discharge Converter	Regulated main power supply to the ACE thruster
Input Voltage	28 VDC unregulated input required for thruster, feed system and housekeeping circuits
PPU Mass	1.5 kg
Efficiency	95%

Propellant Storage and Management Assembly (PSMA)

Apollo has teamed with an established space hardware manufacturer to provide xenon/krypton propellant feed systems. Apollo has baselined a Xenon/Krypton PSMA with a single string bang-bang regulator with orifice flow split for cathode anode and ignition flow.

The Xenon/Krypton PSMA was designed and is manufactured by Apollo Fusion's partner using flight heritage components and /or processes. This PSMA consists of a Propellant Management Assembly (PMA), a Xenon Flow Control (XFC), and carbon overwrapped pressure vessel (COPV) for propellant storage.

Table 4: Xenon/Krypton PSMA Summary

Propellant Management Assembly (PMA)	Service valves - Fill and drain Pressure transducers - Propellant gauging System Filter - 25 micron absolute Normally closed valve - High pressure isolation valve, primary inhibit to internal leakage (option for parallel redundancy) Latching valves - High pressure isolation valve, secondary inhibit to internal leakage
Xenon Flow Control (XFC)	Proportional control valve - Produce required mass flow for the thruster Solenoid valves - Low pressure isolation and flow control to each thruster Orifice - Restrict flow to provide required mass flow split between anode and cathode
Orifice Flow Split	Three orifices to control flow for anode, cathode and ignition flow. Ignition flow is operated for a short duration at startup using a low pressure latch valve

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Inhibits	Two inhibits that prevent propellant leak: 1) Normally closed valve and latching solenoid valves in series between tank and thruster. 2) Service valve for fill and drain of propellant. The unit has a metal to metal seat and valve cap acts as a second seal.
Pressure	High pressure side rated for MEOP of 4,000 psia at 60 °C; proof 6,000 psia; burst 10,000 psia
Redundancy	Parallel redundancy of high pressure valves and regulators within the PMA
Number of thrusters	Bang bang regulator capable of running multiple thrusters. Either through multiple XFCs or orifice flow splits (with independant low pressure latch valve inhibits). Each thruster and its associated XFC will be controlled by a single PPU.
Leakage	Internal leakage shall be less than 8.33 x 10^{-4} sccs and external leakage less than 1.0 x 10^{-6} sccs
Qualification Test	Option 1) Both PMA and XFC are flight heritage and qualified by the manufacturer for GEO applications Option 2) and 3) Use qualified valves and components in a new-space design targeted at commercial applications.
Acceptance Test	All flight assemblies shall undergo leak and proof pressure testing. Additional service valves in the PMA allow for isolated proof and leak testing of the high pressure systems

Propellant Tank

Apollo has teamed with an established space hardware manufacturer for heritage xenon/krypton propellant tanks.

Table 5: Xenon/Krypton Propellant Tank Summary

Tank Construction	COTS composite overwrap pressure vessel (COPV) with aluminum liner
Diameter	12” or 16”
Length	Custom length to meet customer requirement
MEOP	2,700 psia at 60 °C with an option for 4,000 psia at 60 °C
Proof Pressure	1.5 x MEOP
Burst Pressure	2.0 x MEOP
Qualification Test	Both burst and proof pressure shall be verified during qualification testing
Acceptance Test	All flight tanks shall undergo proof pressure testing prior to delivery
Range Safety	All flight tanks shall be proof tested to meet range safety requirements
Heritage	COPV family has flight heritage

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ELECTRICAL

Table 6: Electrical Summary

Full Power Input to PPU	400 W
Input Voltage	28 VDC unregulated
PPU efficiency	95%
Communication Interface	RS 422, RS 485, CAN bus
Component Derating Standard	ECSS-Q-ST-30-11
ESD Control Standard	ECSS-Q-ST-60-14C
Electronics Reliability Methodology	FIDES2009

RADIATION

Table 7: Radiation Approach

Radiation Tolerance Approach	Power electronics designed with the goal of reducing active components
Total Ionizing Dose and Displacement Damage	Radiation Tolerant PPU: ● >20 kRad target for parts level testing Radiation Hardened PPU: ● >50 kRad target for parts level testing
Single Event Effects	Radiation Hardened PPU: ● >37 MeV.cm^2/mg target for Destructive SEEs Not susceptibility to Non-Destructive SEEs by design

THERMAL

Table 8: Thermal Summary

Operating temperature	-20 to +60 C
Acceptance test temperature	-25 to +65 C
Qualification/survivable test temperature	-30 to +70 C
Power Dissipation	Target is 4 W from the thruster and 20 W from the PPU
Propellant Tank Thermal Control	Use of xenon or krypton propellant may require heaters for the tank and propellant feed lines. These heaters are not included in the ACE Max subsystem and will be unique to each spacecraft configuration. The PPU does not support thermal control of the tank, which will have to be provided by the satellite bus.

MECHANICAL

Table 9: Mechanical Summary

Volume requirements	CAD files are available on request
Total Dry Mass	7.6 kg (example single string krypton configuration with 3 L tank)

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