Apollo Fusion ACE Max propulsion system

Figure 1: ACE Max krypton operation

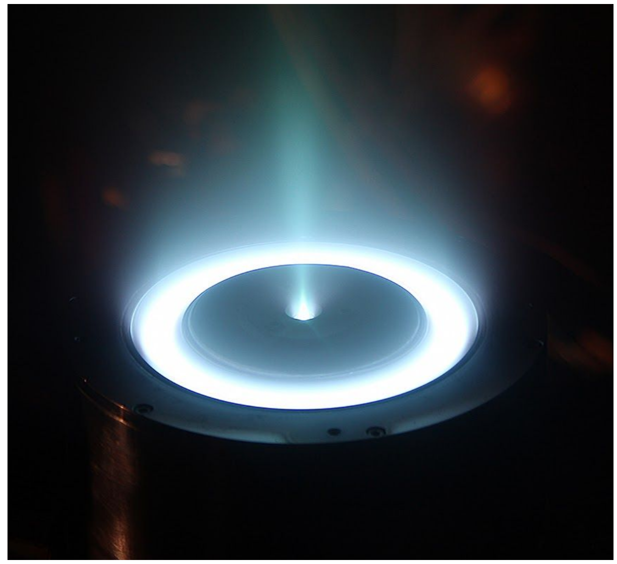

Figure 2: ACE Max xenon operation

ACE Max is a kilowatt class propulsion system using krypton or xenon propellant for missions requiring high total impulse per thruster. ACE Max is ideal for communication satellite constellations, for small GEO spacecraft, and as an enabling technology for high throughput LEO, GTO-GEO transfer, and cislunar missions. ACE Max includes a magnetically shielded thruster which is tuned to optimize performance with krypton propellant. The thruster is matched to an Apollo radiation-hardened, 95% efficient, single board PPU, a propellant management system with flight heritage components, and a COPV tank sized to fit customer mission requirements. ACE Max has been selected for programs such as a GEO mission and a commercial constellation with several hundred satellites.

Table 1: System specification summary	Krypton	Xenon
Input Power	1.4 kW	1.4 kW
Input Voltage (primary)	62-75 VDC unregulated	62V-75 VDC unregulated
Input Voltage (secondary)	28 VDC regulated	28 VDC regulated
Thrust	50 mN	60 mN
Specific Impulse	1,800 s	1,760 s
Total Impulse	1.5 MN-s	1.5 MN-s
Designed & Manufactured in	USA	USA

SUBSYSTEM COMPONENTS

Thruster

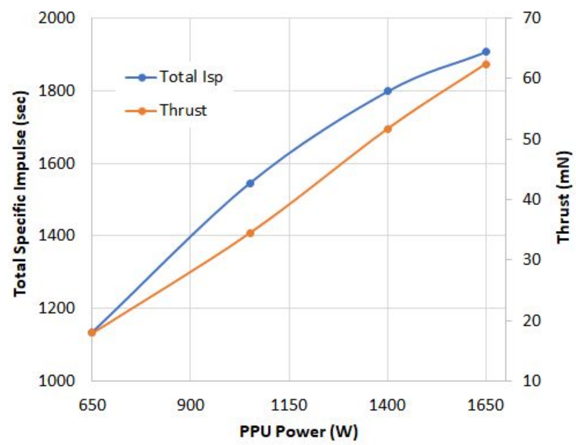

Figure 4: ACE Max test results using krypton

ACE Max includes a magnetically shielded thruster which has been tested from 650 W up to 1.8 kW to PPU and is configured for operation at 1.4 kW to the PPU.

Key features:

- Tuned to optimize performance for krypton propellant
- Designed for use with krypton or xenon propellants
- Magnetic shielding for at least 1.5 MN-s total impulse
- Consistent performance from start of life to end of mission
- Instant start, center mounted cathode
- Designed for multi-thruster operation
- Thruster can operate between 800 W and 1.8 kW to PPU (System optimized for 1.4 kW operation)

Table 2: Thruster specifications	Krypton	Xenon
Power	1.4 kW	1.4 kW
Thrust	50 mN	60 mN
Specific Impulse	1,800 s	1,760 s
Total Impulse	1.5 MN-s	1.5 MN-s
Thruster Mass	4.5 kg	4.5 kg
Thrust Vector Angle	+/- 1 degree	+/- 1 degree
Cathode Throughput	7,500+ hrs	7,500+ hrs

PPU

The ACE Max PPU provides power and control to the ACE Max thruster, valves, regulator, and pressure transducers. The PPU is designed to perform in 100 kRad TID and 42MeV/u SEE environments for a lifetime of 15 years. 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.

Table 3: PPU Summary

High Voltage Igniter	Regulated supply operated during thruster activation
Magnet Supply	Regulated supply with a peak 3.75A output
Valve and Pressure Transducer Supplies	Regulated supplies provide power to actuate the ACE Max system pneumatic valves and operate the subsystem pressure transducers
Discharge Converter	Regulated main power supply to the ACE Max thruster
Input Voltage (primary)	62-75 VDC unregulated input required for thruster
Input Voltage (secondary)	28 VDC regulated input for feed system and housekeeping circuits
PPU Mass	2.5 kg
Efficiency	95%

Propellant Storage and Management Assembly (PSMA)

Apollo has teamed with an established space hardware manufacturer to provide propellant feed systems. Apollo has baselined three options for the PSMA:

1. Flight heritage mechanical regulation assembly with series/parallel redundant pneumatic strings and a Xenon Flow Controls (XFC) for fine regulation input to each thruster
2. Single step bang-bang regulator (with parallel and serial redundant high pressure valves) and orifice flow split for cathode anode and ignition flow
3. Single step, single string bang-bang regulator with orifice flow split for cathode anode and ignition flow

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

Table 4: 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.
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 to provide heritage propellant tanks.

Table 5: 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

ELECTRICAL

Table 7: Electrical Summary

Full Power Input to PPU	1,400 W
Input Voltage (primary)	62-75 VDC unregulated input required for thruster
Input Voltage (secondary)	28V VDC regulated input required for feed system
PPU efficiency	95%
Communication Interface	RS 422, RS 485, CAN bus

RADIATION

Table 8: Radiation Approach

Radiation Tolerance Approach	Power electronics designed with the goal of reducing active components
Total Ionizing Dose and Displacement Damage	>50 kRad target for parts level testing
Single Event Effects	>37 MeV.cm^2/mg target for Destructive SEEs. No susceptibility to Non-Destructive SEEs by design.

THERMAL

Table 9: 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 20 W from the thruster and 75 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 10: Mechanical Summary

Volume requirements	CAD files are available on request
Total dry mass	19.8 kg (typical single string krypton configuration using 35 L tank)