Micro Propulsion System Summary

33 Systems Under Contract To-Date

Flight Proven on Nano ACE

Two MarCO MiPS on Route to Mars

Smart & Versatile w/Health Monitoring

CubeSat & Small Sat MiPS for Delta-V, ACS or Both:

- High Performance Cold Gas MiPS
- Warm Gas MiPS
- Green Monopropellant / Cold Gas Hybrid MiPS
- Green Monopropellant MiPS
- Xenon & Iodine EP Feed Systems

Small Satellite Integrated Propulsion Systems (IPS):

- Bolt-On Green Monopropellant Propulsion Modules
- Green Monopropellant Propulsion Systems

Various Propellants:

- R236fa, R134a, Isobutane, SO_2
- LMP-103S, LMP-103S/LT, AF315E, Xenon & Iodine

Materials of Construction:

- Titanium, Aluminum, CRES or Inconel

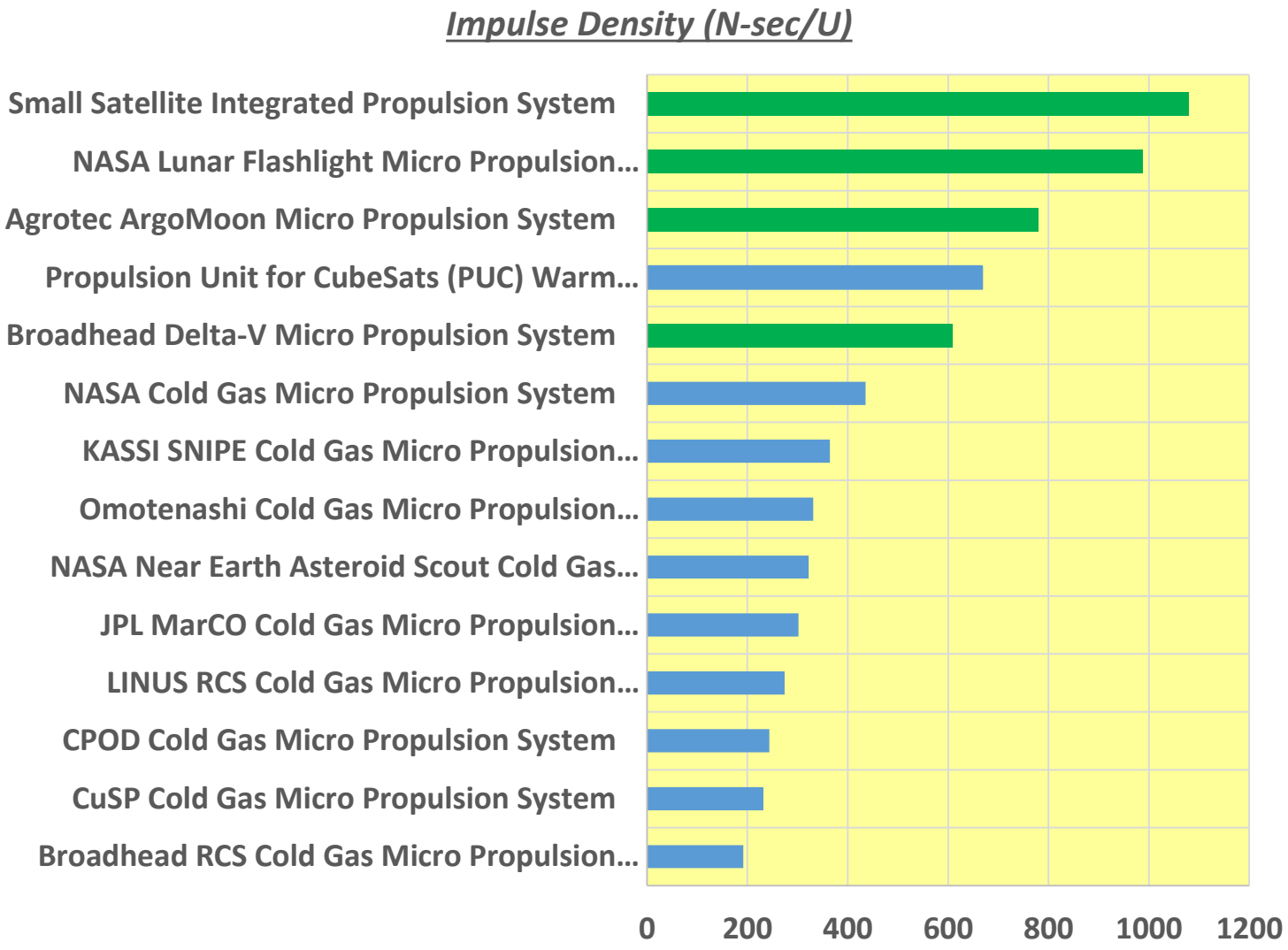
VACCO Propulsion System Overview

VACCO Product	Description	Total # Valves	# of Systems	TRL	Comments
CPOD Micro Propulsion System	**(8) 10mN Cold Gas Thrusters**	**10**	**1**	**9**	**Launched July 2017, mission complete.**
MarCO Micro Propulsion System	**(8) 25mN Cold Gas RCS Thrusters (4) Delta-V, (4) RCS**	**18**	**2**	**8**	**MarCO-A & MarCO-B, launched May 2018.**
AFRL Propulsion Unit for CubeSats (PUC)	(1) Axial 5.4mN Warm Gas Thruster	18	9	7	Delivered 2014, flight status unknown.
NASA CPOD Micro Propulsion System	(8) 10mN Cold Gas RCS Thrusters	20	2	7	Delivered November 2015, launch expected in 2019.
Omotenashi Micro Propulsion System	(8) 25mN Cold Gas Thrusters ((4) Delta-V/Pitch/Yaw, (4) Roll)	12	1	7	Delivered September 2018, launch on SLS in 2020.
SwRI CuSP Micro Propulsion System	(4) 25mN Cold Gas Thrusters (Combined Delta-V / RCS)	5	1	6	Flight unit in acceptance testing.
LunIR Cold Gas Generator	Cold Gas Generator (1) Outlet Port to Remote Thrusters	2	1	6	Flight unit in acceptance testing.
NASA Lunar Flashlight Micro Propulsion System	(4) 100mN LMP-103S/LT Thrusters (Combined Delta-V / RCS)	8	1	5	Flight unit in final assembly. Qualification Leak Before Burst test complete.
NASA Near Earth Asteroid Scout Micro Propulsion	(6) 25mN Cold Gas Thrusters ((2) Delta-V, (4) RCS)	9	1	5	Flight unit in final assembly.
Argotec ArgoMoon Micro Propulsion System	(1) 100mN LMP-103S/LT DV Thruster (4) 25mN Cold Gas RCS Thrusters	10	1	5	Flight unit in final assembly.
Broadhead Delta-V Micro Propulsion System	(1) 100mN LMP-103S/LT Delta-V Thruster	5	1	5	Flight unit in fabrication.
Broadhead RCS Cold Gas Micro Propulsion System	(4) 25mN Cold Gas RCS Thrusters	5	1	5	Flight unit in fabrication.
LINUS RCS Cold Gas Micro Propulsion System	(8) 10mN Cold Gas Thrusters (Combined Delta-V / RCS)	12	2	5	Flight unit in fabrication.
KASSI SNIPE Cold Gas Micro Propulsion System	(4) 25mN Cold Gas Thrusters (Combined Delta-V / RCS)	20	4	5	Flight units in fabrication.
Small Satellite Integrated Propulsion System	(4) 1N LMP-103S Thrusters (Combined Delta-V / RCS)	24	3	4	Flight units in design.
NASA Cold Gas Micro Propulsion Systerm	(5) 25mN Cold Gas Thrusters, (Combined Delta-V / RCS)	28	2	4	Flight units in design.
	Total:	**206**	**33**		

VACCO Propulsion System Overview

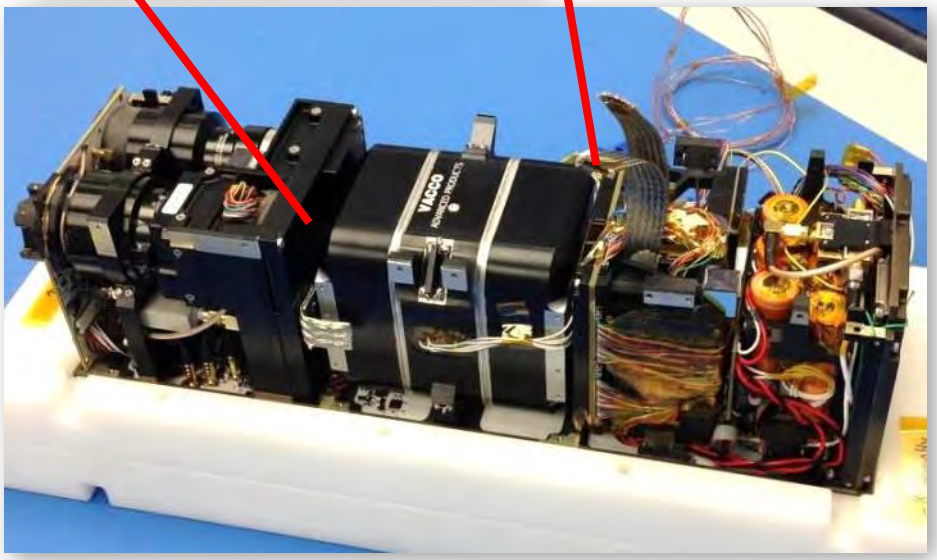
VACCO Product	Total Impulse (N-sec)	Delta-V Thrust (mN)	Delta-V (m/s)	Dry Mass (Kg)	Volume (liters or U)	Comments	Impulse Density (N-sec/U)
Broadhead RCS Cold Gas Micro Propulsion System	87	50	10	0.738	0.454		192
CuSP Cold Gas Micro Propulsion System	69.4	99.6	5	0.50	0.299		232
CPOD Cold Gas Micro Propulsion System	**174**	**8.2**	**31**	**0.81**	**0.713**		244
LINUS RCS Cold Gas Micro Propulsion System	931	23	75	2.52	3.397	RCS System not designed for delta-V.	274
JPL MarCO Cold Gas Micro Propulsion System	**755**	**100**	**58**	**1.65**	**2.500**		302
NASA Near Earth Asteroid Scout Cold Gas MiPS	500	50	38	1.26	1.553		322
Omotenashi Cold Gas Micro Propulsion System	584	100	42	1.62	1.763	Total for tandum systems.	331
KASSI SNIPE Cold Gas Micro Propulsion System	502	99.6	44	1.05	1.377		365
NASA Cold Gas Micro Propulsion System	1969	25	92	1.91	4.52		436
Broadhead Delta-V Micro Propulsion System	474	100	20	1.69	0.778	Does not include volume of Adaptor.	609
Propulsion Unit for CubeSats (PUC) Warm Gas MiPS	183	5.4	48	0.43	0.274		668
Agrotec ArgoMoon Micro Propulsion System	783	100	57	1.47	1.004	Not counting ACS Thrusters.	780
NASA Lunar Flashlight Micro Propulsion System	3220	391	248	3.00	3.261		987
Small Satellite Integrated Propulsion System	13400	3,470	287	5.3	12.42		1079

VACCO Propulsion System Impulse Density



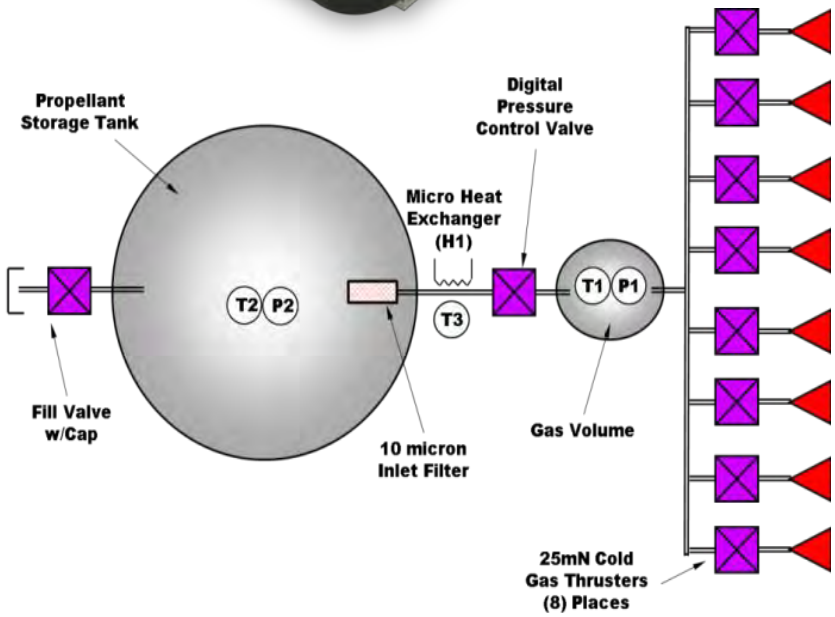
NASA/Tyvak CPOD/NanoACE Micro Propulsion System

- ***Flight proven on NanoACE (Launched 7 July 2017)***
- Contract with Tyvak Nano-Satellite Systems LLC
- CPOD: NASA Cubesat Proximity Operations Demonstration
- (3) Flight Systems Delivered
- Occupies Center 1U of 3U Cubesat
- Provides Attitude Control, Divert & Delta-V

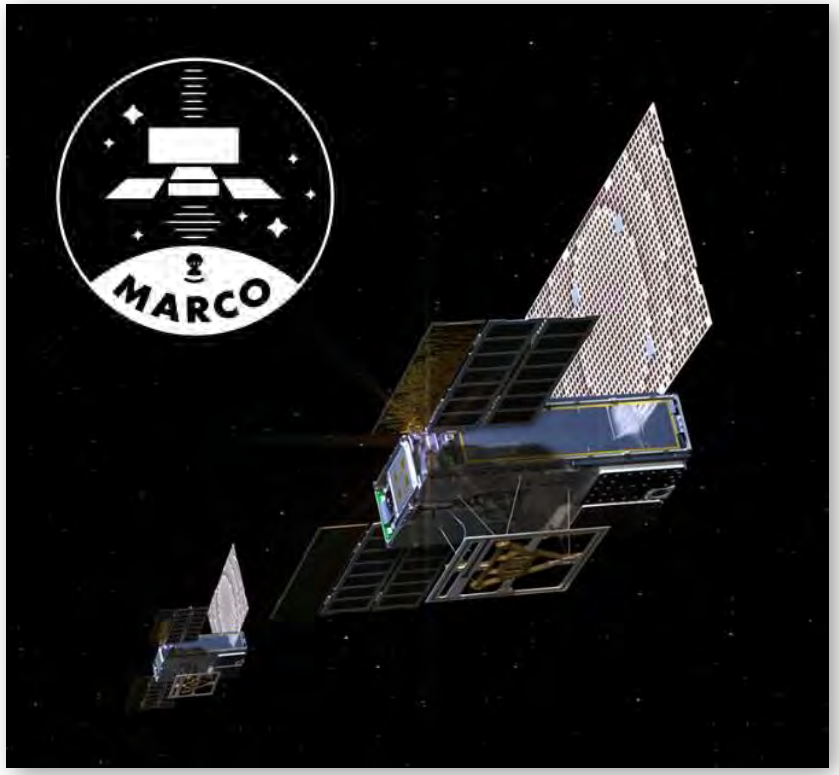


CPOD/NanoACE MiPS Overview

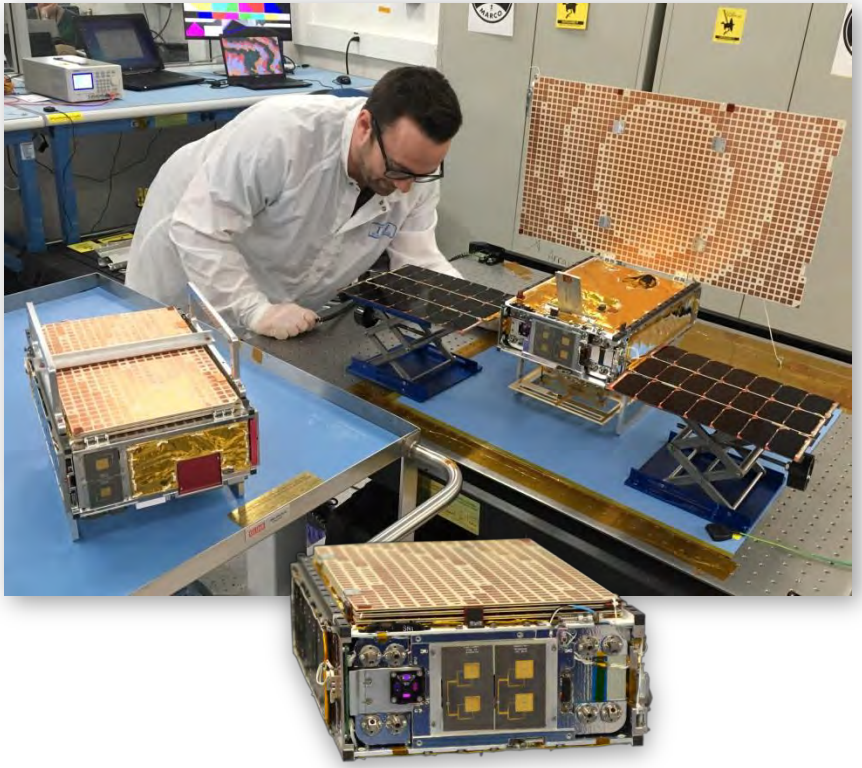
System Overview
All-Welded Aluminum Alloy Construction
Eight 10mN Cold Gas Thrusters
174 N-S Total Impulse, 31 M/S Delta-V
0.10 mN-S Minimum Impulse Bit
1U Center Manifold, Clamshell Configuration
510 grams Self-Pressurizing R236fa Green Propellant
Smart System with Integral Microcontroller
RS422 Digital Interface
Integral Sensor Suite
Total “Wet” Mass: 1270 grams



JPL Mars Cube One (MarCO) Mission

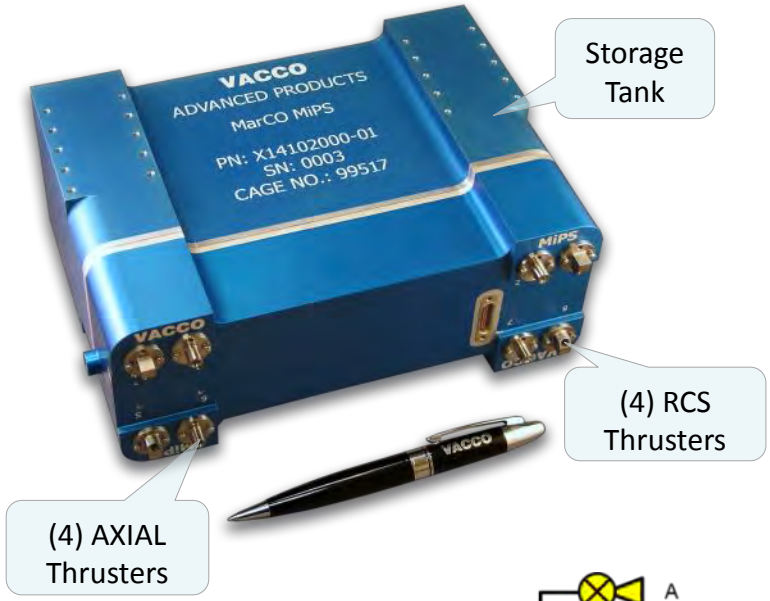


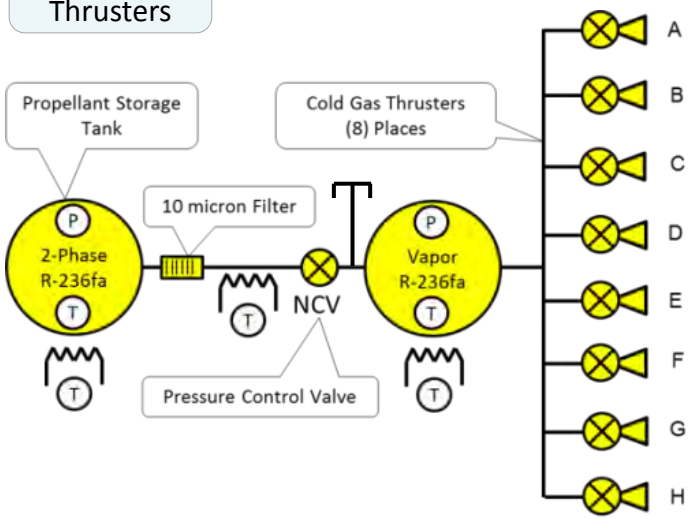
9-month program to design, build, test and deliver two flight systems.



Two Units Launched toward Mars with the InSight Mission May 5, 2018

JPL MarCO Micro Propulsion System





First Interplanetary Cubesat

Launch with InSight Lander, May 2018

Smart, Self-Contained Propulsion System:

- Contract for (2) Flight Systems
- **755 N-Sec Total Impulse**
- 1650 gram Dry Mass

System-in-a-Tank Design Including:

- Propellant Storage & Feed System
- (4) Axial & (4) RCS 25mN Thrusters
- Controller & Sensor Suite

Two Seals Against Leakage

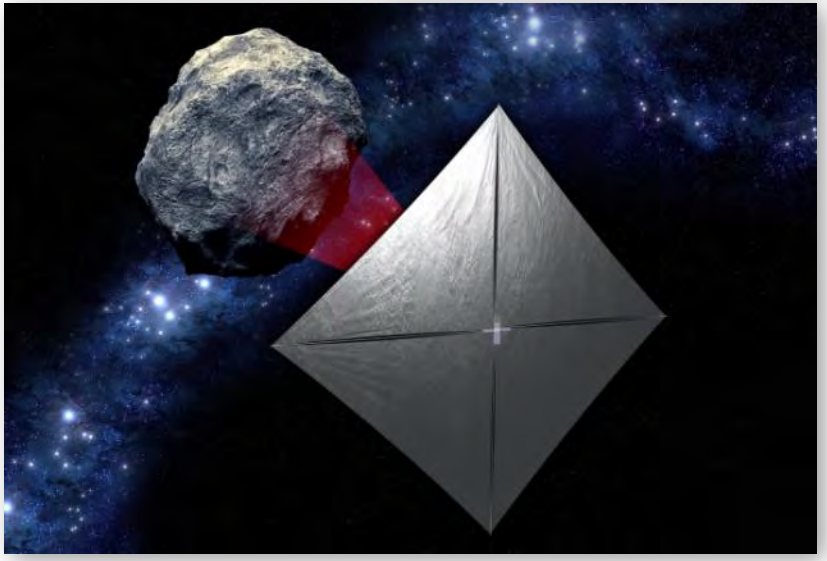
Low Power Continuous Power (<15 watts)

All-Welded Aluminum Alloy Construction

Microcontroller Driven:

- RS422 Digital Interface
- Controls Burn Type & Duration
- Closed-Loop, Variable Thrust Control
- (3) Settable Thermal Control Zones
- (3) Power Supplies, (9) Valve Drivers

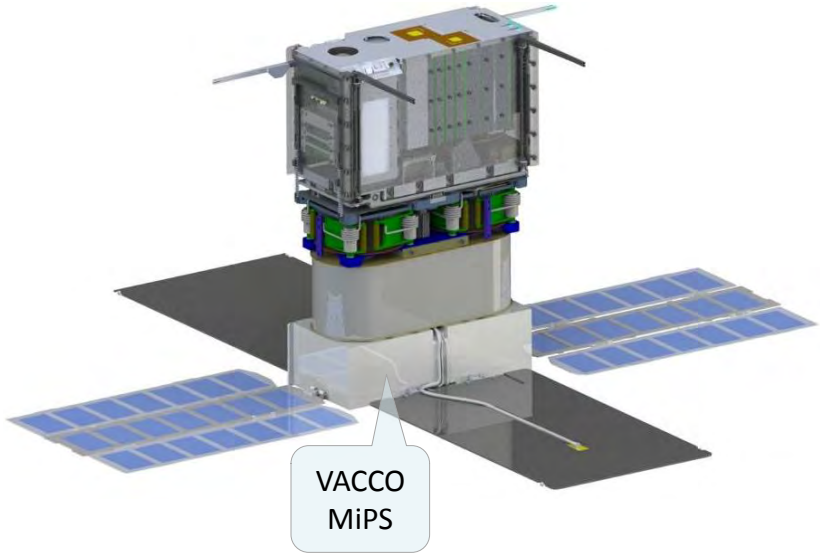
JPL/MSFC Near Earth Asteroid Scout Mission



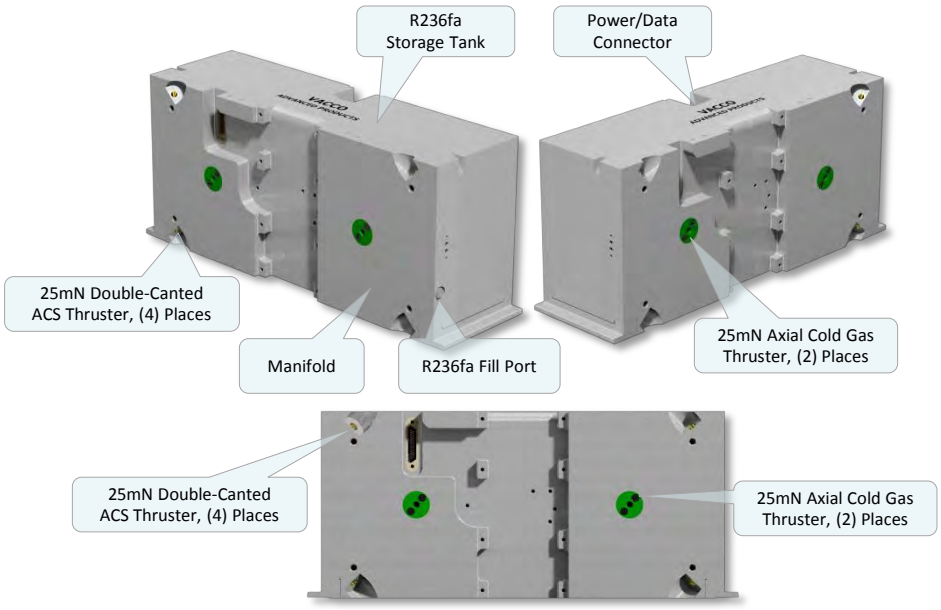
Mission Objectives:

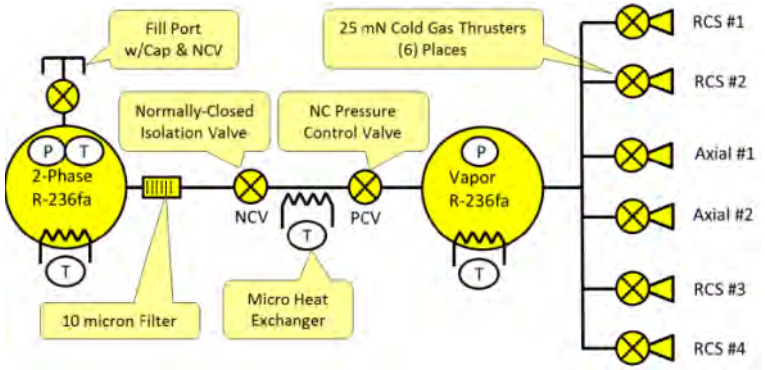
- Detect, rendezvous with and flyby a Near Earth Asteroid (NEA) target
- Characterize physical properties: volume, spectral type, spin mode and orbit
- ≥80% coverage imaging at ≤50 cm/px
- ≥30% coverage imaging at ≤10 cm/px

Main Propulsion: ~80m² Solar Sail



NEA Scout Micro Propulsion System





Smart, Self-Contained Cold Gas Propulsion System based on MarCO:

- Contract for (1) Flight System
- **500 N-Sec Total Impulse**
- 2600 gram Wet Mass

System-in-a-Tank Design Including:

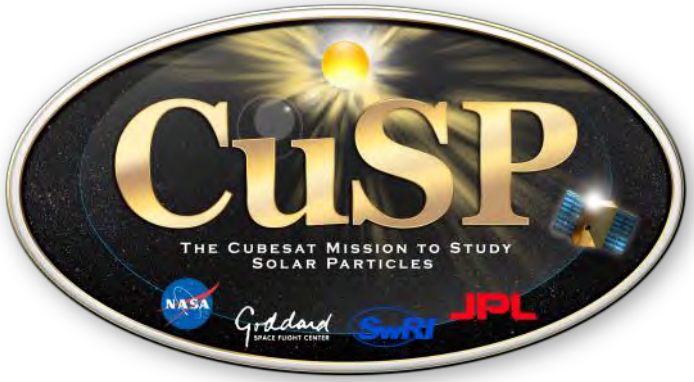
- Propellant Storage & Feed System
- (2) Axial & (4) RCS 25mN Thrusters
- Controller & Sensor Suite

Three Seals Against Leakage

Power: <9 watts while Firing

All-Welded Aluminum Alloy Construction

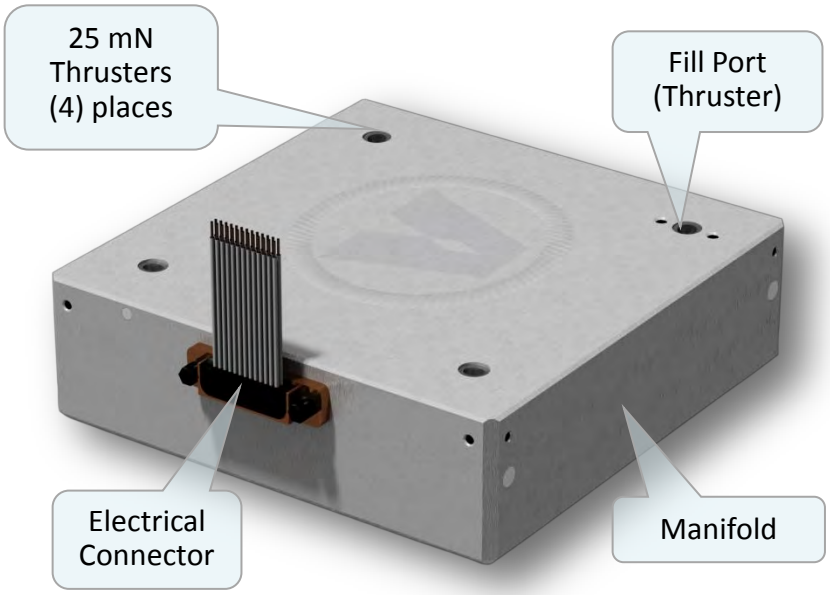
SWRI CubeSat Mission to Study Solar Particles (CuSP)



CuSP Mission Objectives:

1. Study Solar Particles in interplanetary space
2. Be a Pathfinder for creating a network of “Space Weather Stations”
3. Strengthen the case for CubeSats as a viable platform for performing ‘High Value’ Science
4. Raise the TRL of the SIS instrument for future missions

CuSP Micro Propulsion System



Smart, Self-Contained Cold Gas Propulsion System

Standardized System Based on MarCO:

- Contract for (1) Flight System

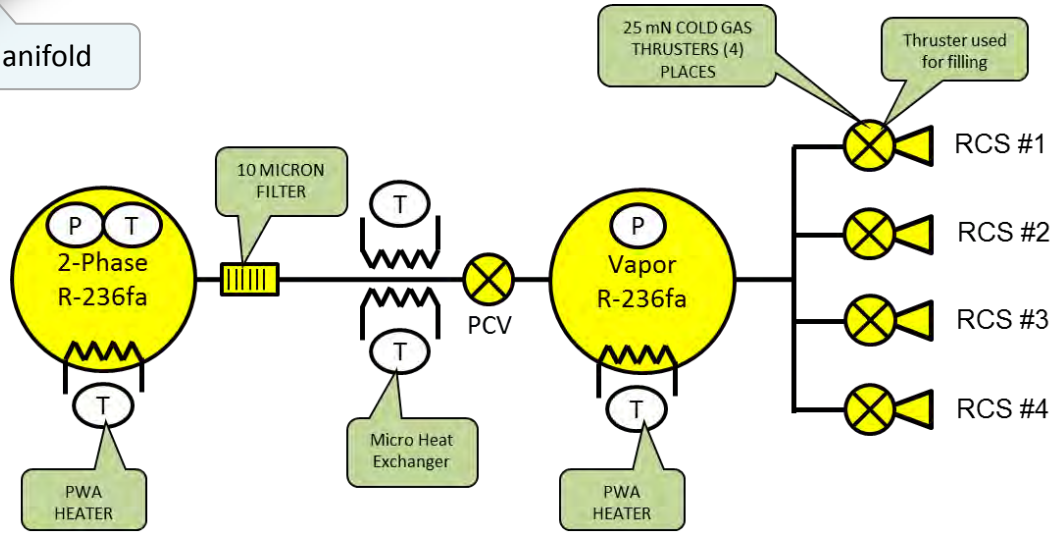
System-in-a-Tank Design Including:

- Propellant Storage & Feed System
- (4) RCS 25mN Thrusters
- Controller & Sensor Suite

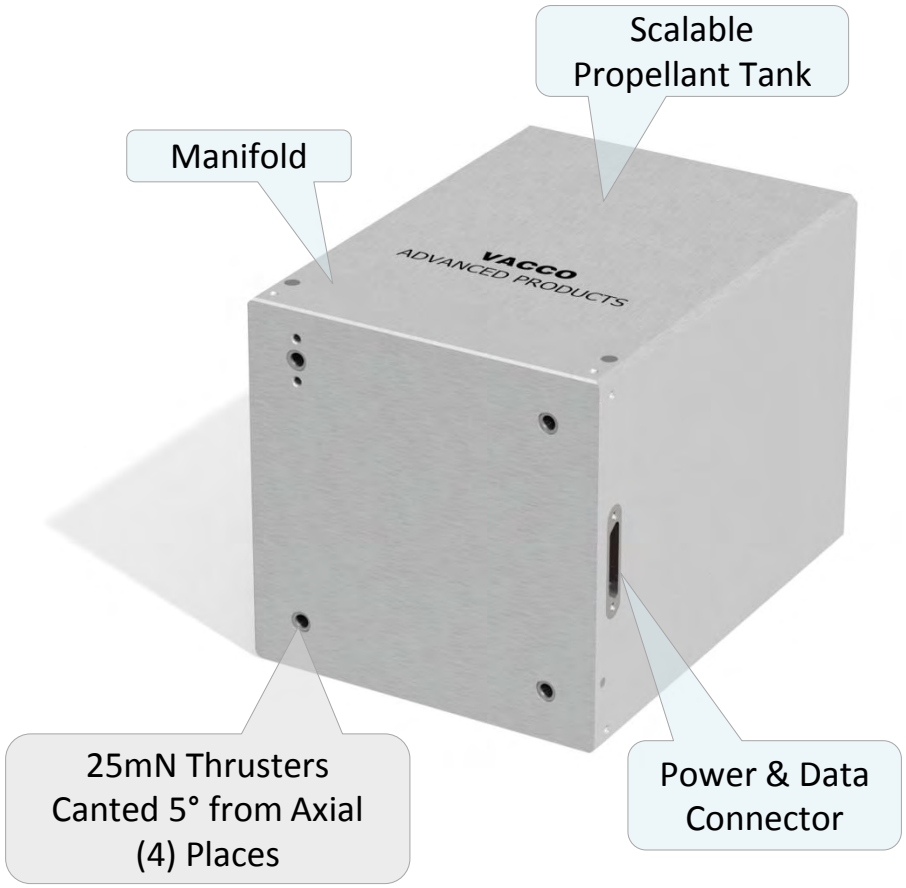
Two Seals Against Leakage

Power: <12 watts while Firing

All-Welded Aluminum Alloy Construction



Standard Cold Gas Micro Propulsion System



Four Systems Sold To-Date

Self-Contained Reaction Control System:

(4) 25mN Cold Gas Thrusters for ACS & Delta-V

All-Welded Aluminum Alloy Construction

Normally-Closed Frictionless Valves

High Reliability Pressure Control Valve

Built-In, Shielded Control Electronics

9V to 12.6V Unregulated Input Voltage

RS422 Data Bus Interface

Integral Pressure & Temperature Sensors

Minimum Impulse Bit: <2.5mN-Sec

Range Safety Features:

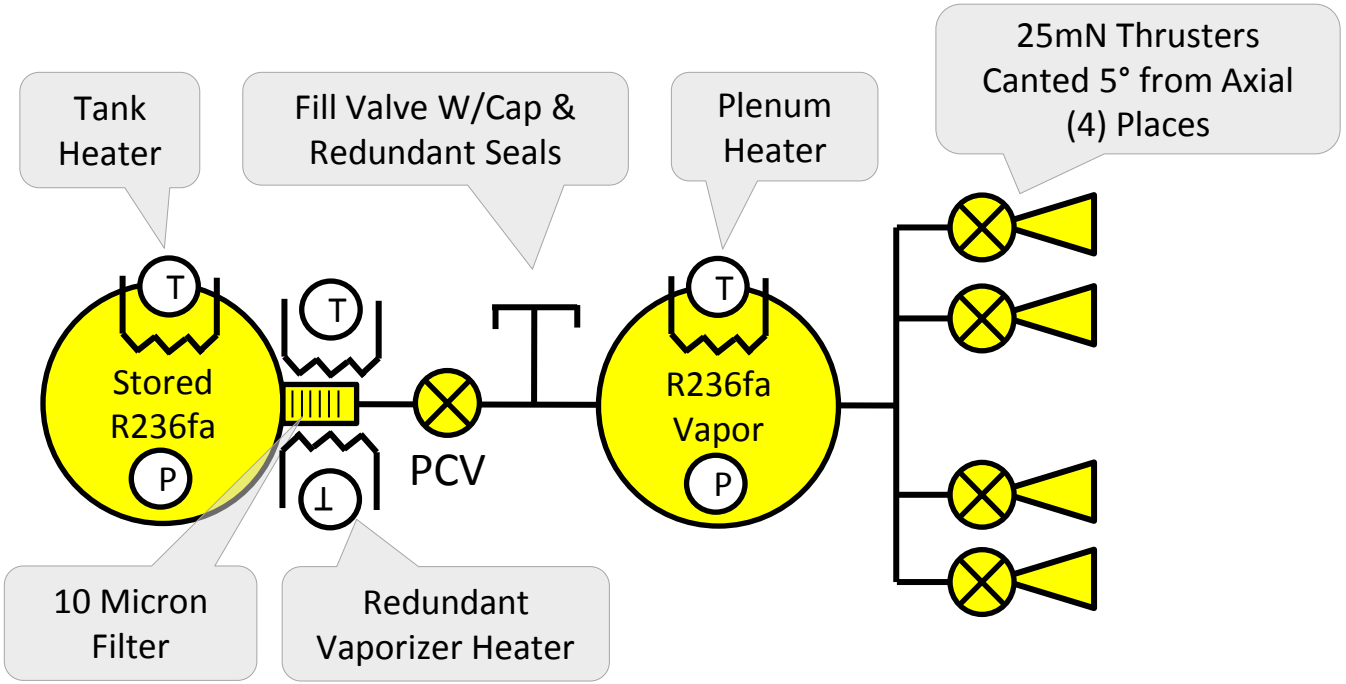
Green R236fa Propellant:

Benign Fire Extinguisher Material

Max Pressure <0.69MPa (<100 psi)

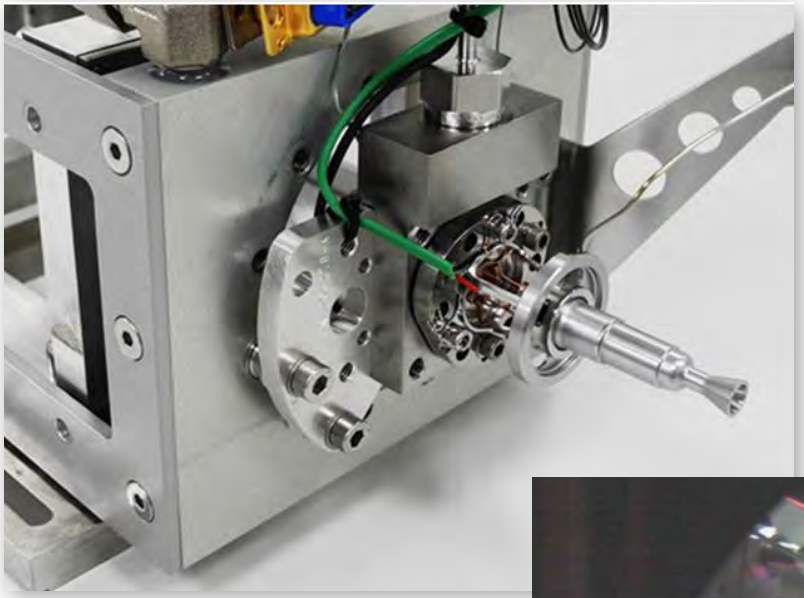
(3) Seals Against Propellant Leakage

Standard Cold Gas Micro Propulsion System

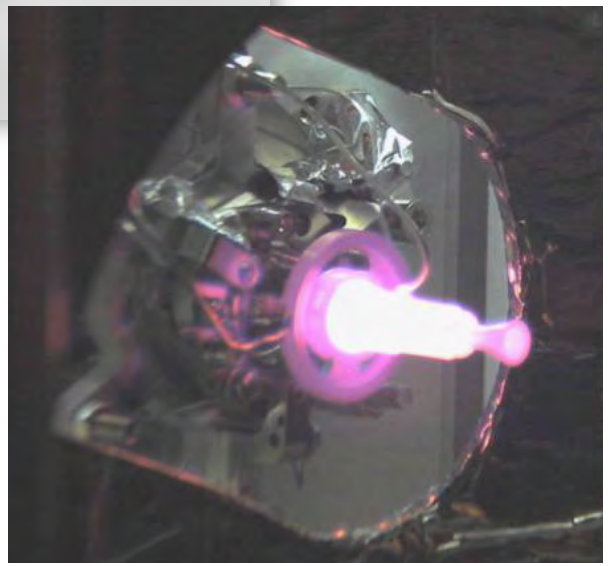


	Tank Vol. (cc)	Prop Liquid Mass (g)	Isp (sec)	Total Impulse (N-Sec)	MiPS Dry Mass (grams)	Initial Cubesat Mass (Kg)	**Axial Delta-V (M/s)**
Standard MiPS	1041	1280	40	502	963	12	**44**

Green Monopropellant Micro Propulsion Systems



ECAPS 100mN LMP-103S Thruster

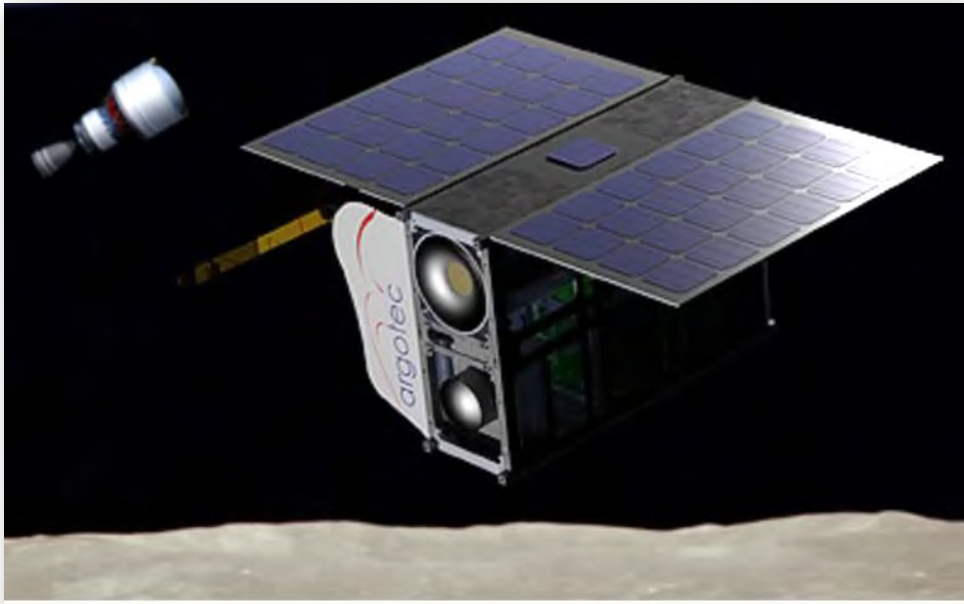


ECAPS 100mN LMP-103S Hot Fire Test

ArgoMoon Hybrid Micro Propulsion System

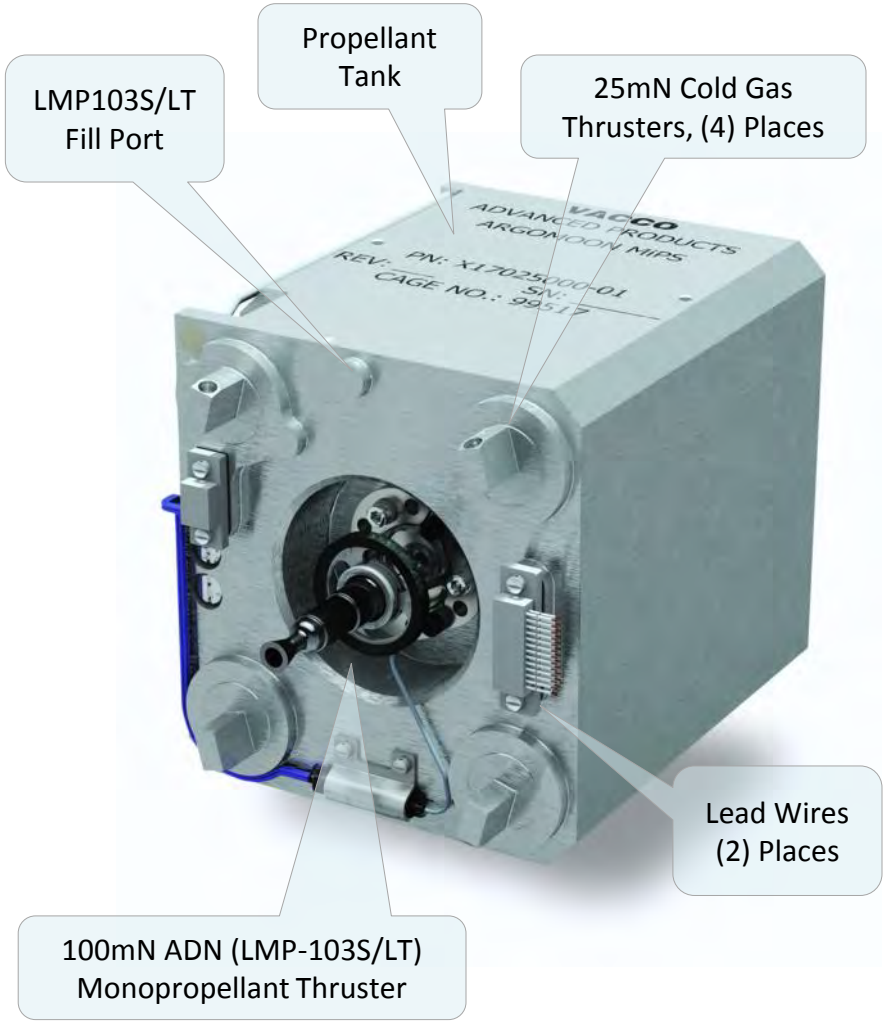
ArgoMoon

- Lunar mission designed by the Italian company Argotec for the Italian Space Agency (ASI)
- Will demonstrate proximity operations with the Interim Cryogenic Propulsion Stage (ICPS)
- Record images of the ICPS for historical documentation
- Test optical communication capabilities between the CubeSat and Earth.



ArgoMoon *[Argotec]*

ArgoMoon Hybrid Micro Propulsion System



Customer is Argotec in Italy

ArgoMoon EM-1 CubeSat

Self-Contained Propulsion System:

- (1) Axial 100mN LMP-103S/LT Delta-V Thruster
- (4) 25mN Cold Gas ACS Thrusters:
  - Double Canted 15° in Pairs
- All-Welded Titanium Alloy Construction
- High Reliability Frictionless Valves
- Built-In, Shielded Controller
- 9V to 12.6V Input Voltage
- RS422 Data Bus Interface
- ACS Minimum Impulse Bit: <1.25mN-Sec

Green LMP-130S/LT Monopropellant:

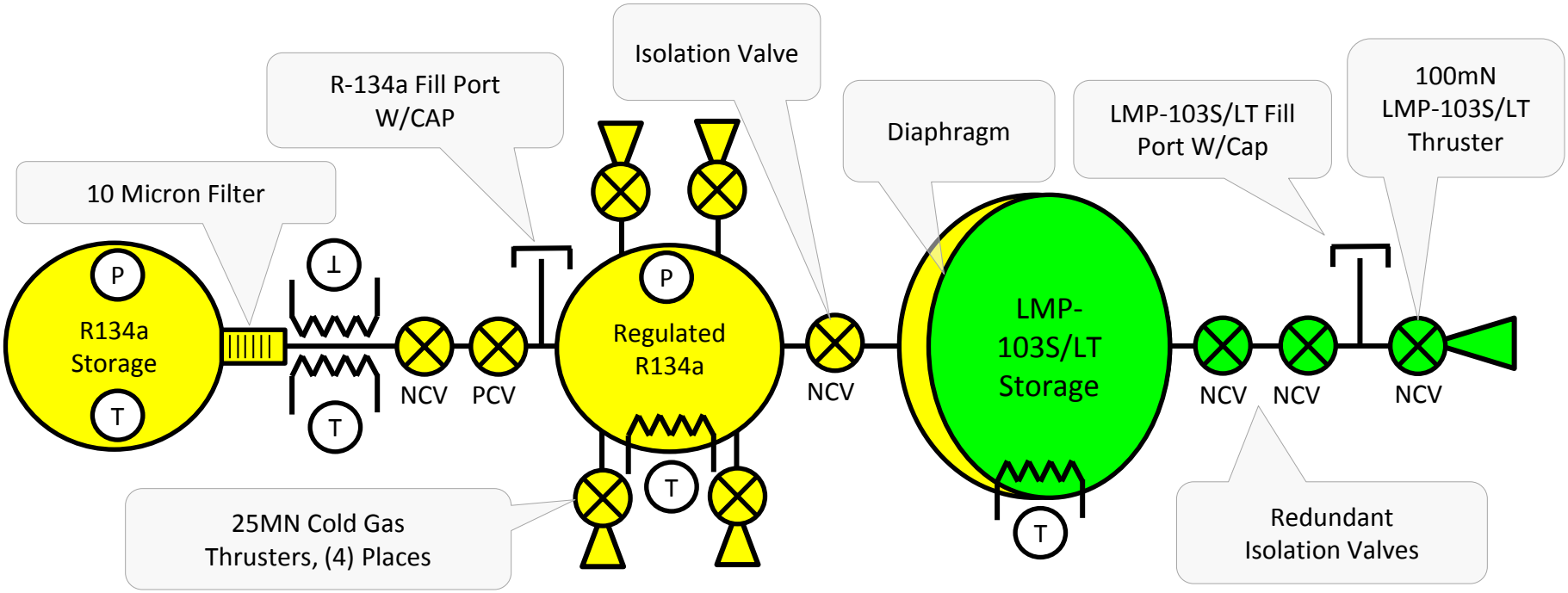
- LMP-103S Flight Proven on PRISMA
- (44) Thrusters in Orbit on SkySat Satellites
- UN / US 1.4S (Commercial Aircraft)

R134a Pressurant / ACS Propellant

(3) Seals Against LMP-103S/LT Leakage

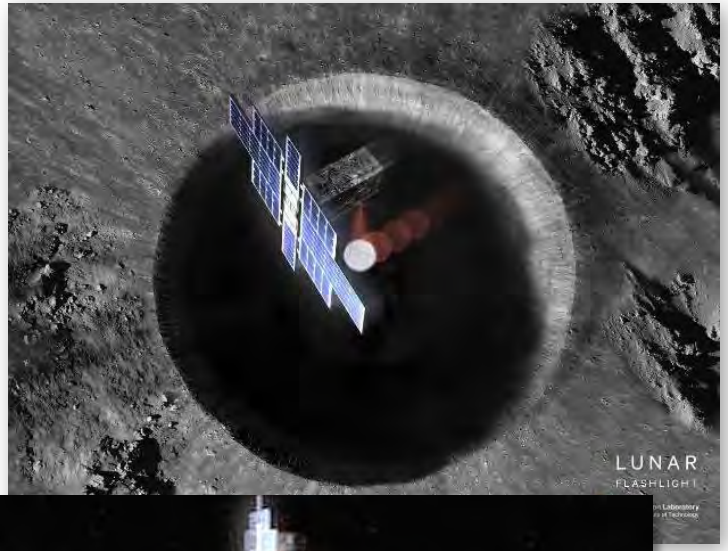
(3) Seals Against R-134a Leakage

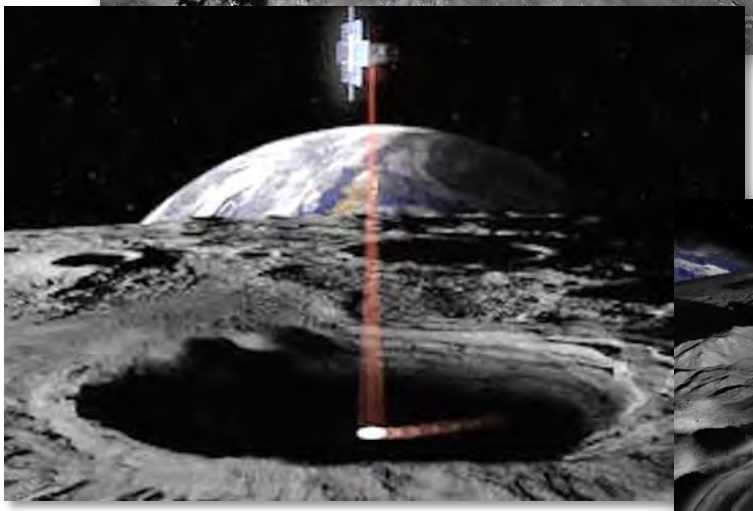
ArgoMoon Hybrid Micro Propulsion System

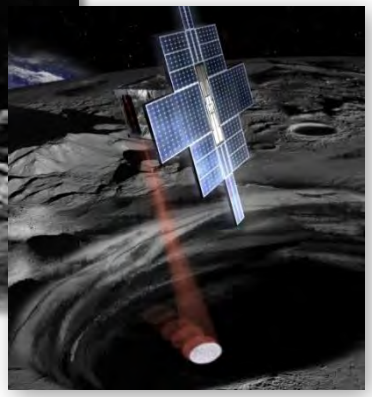


93mm x 100mm x 144mm Envelope	Prop Vol. (cc)	Prop Mass @ 60C (g)	Isp (sec)	Total Impulse (N-Sec)	MiPS Dry Mass (Kg)
LMP-103S/LT Thruster	354	420	190	783	1.47
R-134a Thrusters	241	114	40	45	

JPL/MSFC Lunar Flashlight Mission







Mission Objectives:

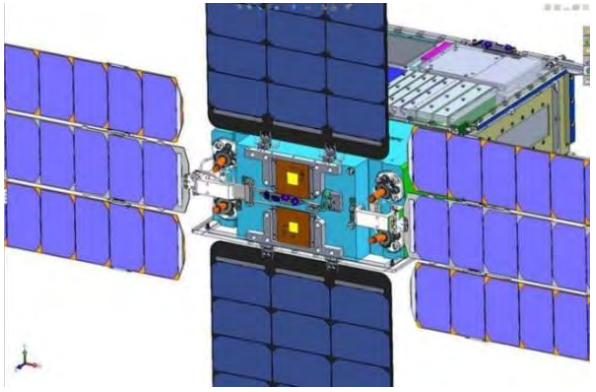
- Map surficial lunar water ice in permanently-shadowed regions

Measurements:

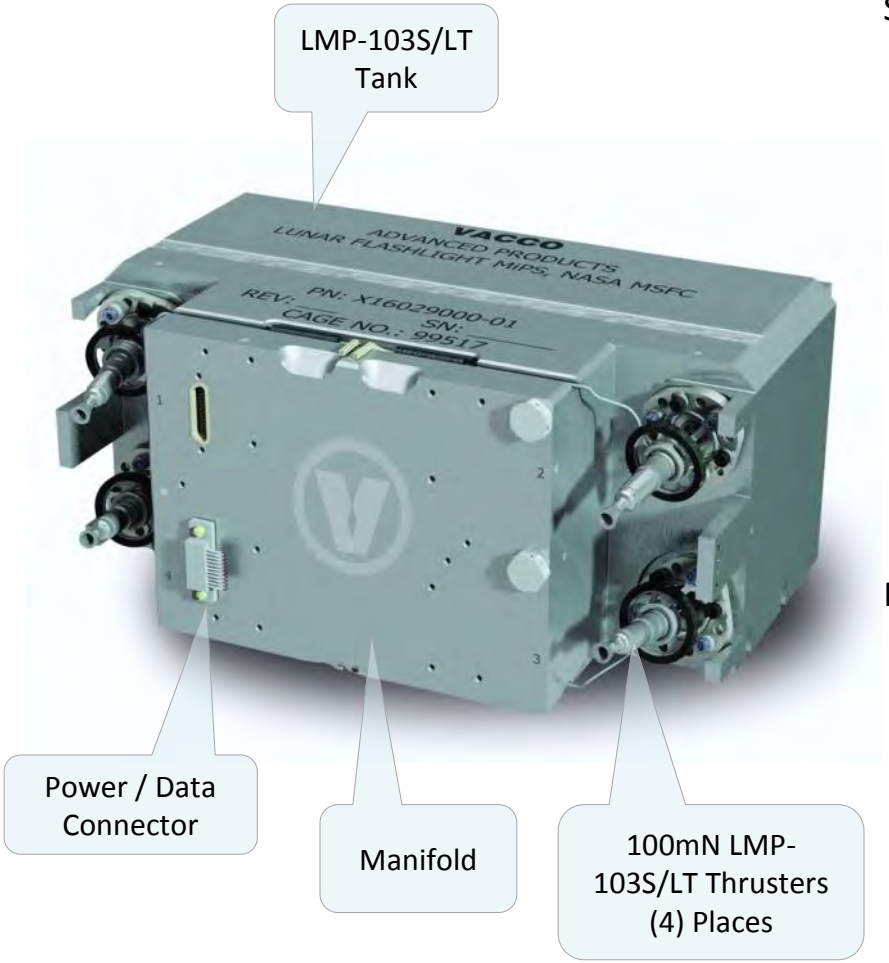
- Using the difference in reflected laser light ratios to indicate the presence and quantity of water ice
- Multiple passes over lunar south polar region with potential ice deposits.

Key Technical Constraints:

- 30 month maximum mission duration
- Solar sail acceleration limits
- Surface illumination strategies



Lunar Flashlight Micro Propulsion System



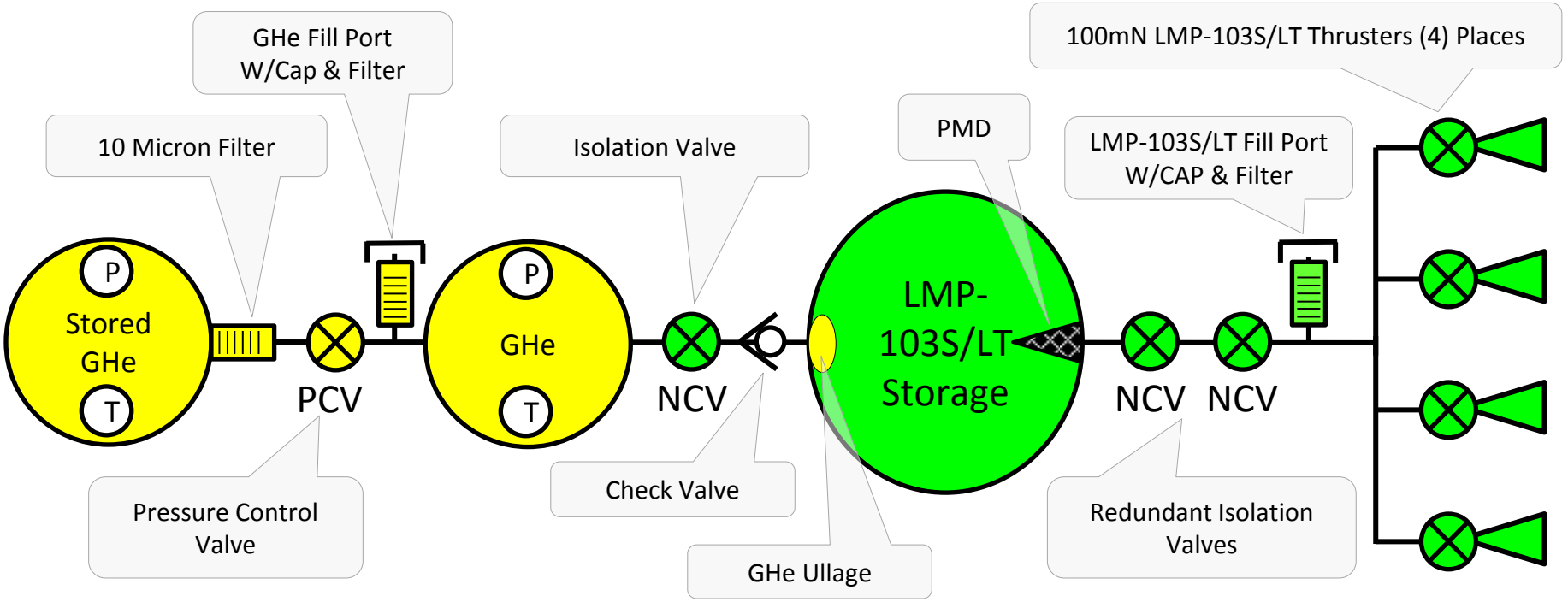
Self-Contained Delta-V Propulsion System:

- (4) 100mN LMP-103S/LT Thrusters
- Provides Pitch, Yaw, Roll and Delta-V
- All-Welded Titanium Alloy Construction
- Normally-Closed Frictionless Valves
- Built-In, Shielded Controller
- 5V & 28V Input Voltage
- 15 watts while firing
- RS422 Data Bus Interface
- Minimum Impulse Bit: <5mN-Sec

Range Safety Features:

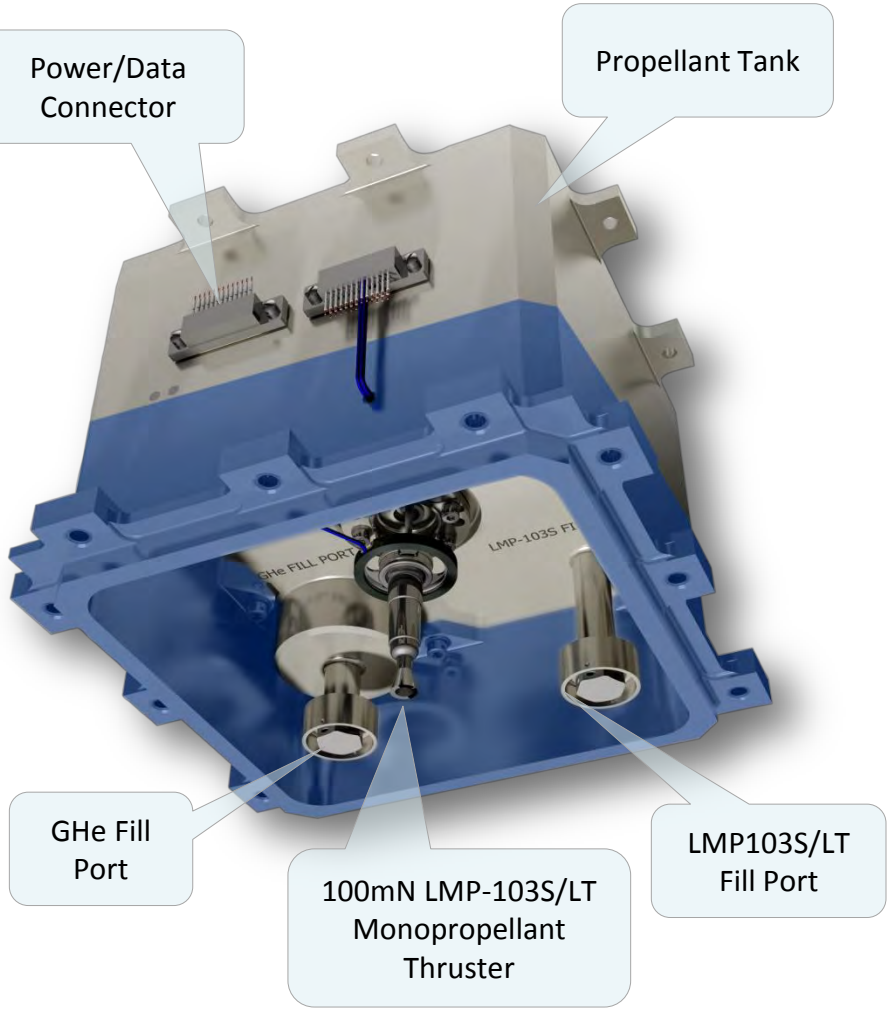
- Green LNP-103S/LT Monopropellant:
  - LMP-103S Flight Proven on PRISMA
  - (44) Thrusters in Orbit on SkySat Satellites
  - UN / US 1.4S (Commercial Aircraft)
- (3) Seals Against Leakage
- Benign GHe Pressurant
- Safe and Arm Circuit

Lunar Flashlight MiPS Schematic & Performance



	ADN Vol. (cc)	90% ADN Mass (g)	Isp (sec)	Total Impulse (N-Sec)	MiPS Dry Mass (Kg)	Initial Satellite Mass (Kg)	Delta-V (M/s)
100mN Thruster	1583	1747	190	3255	3.0	14	248

SDL Broadhead DV Micro Propulsion System



Space Dynamics Laboratory Small Sat Self-Contained Propulsion System:

(1) Axial 100mN LMP-103S/LT Delta-V Thruster

All-Welded Titanium Alloy Construction

High Reliability Frictionless Valves

Built-In, Shielded Controller

Sensor Suite

9V to 12.6V Input Voltage

RS422 Data Bus Interface

ACS Minimum Impulse Bit: <1.25mN-Sec

Green LMP-130S/LT Monopropellant:

Flight Proven on PRISMA

(44) Thrusters in Orbit on SkySat Satellites

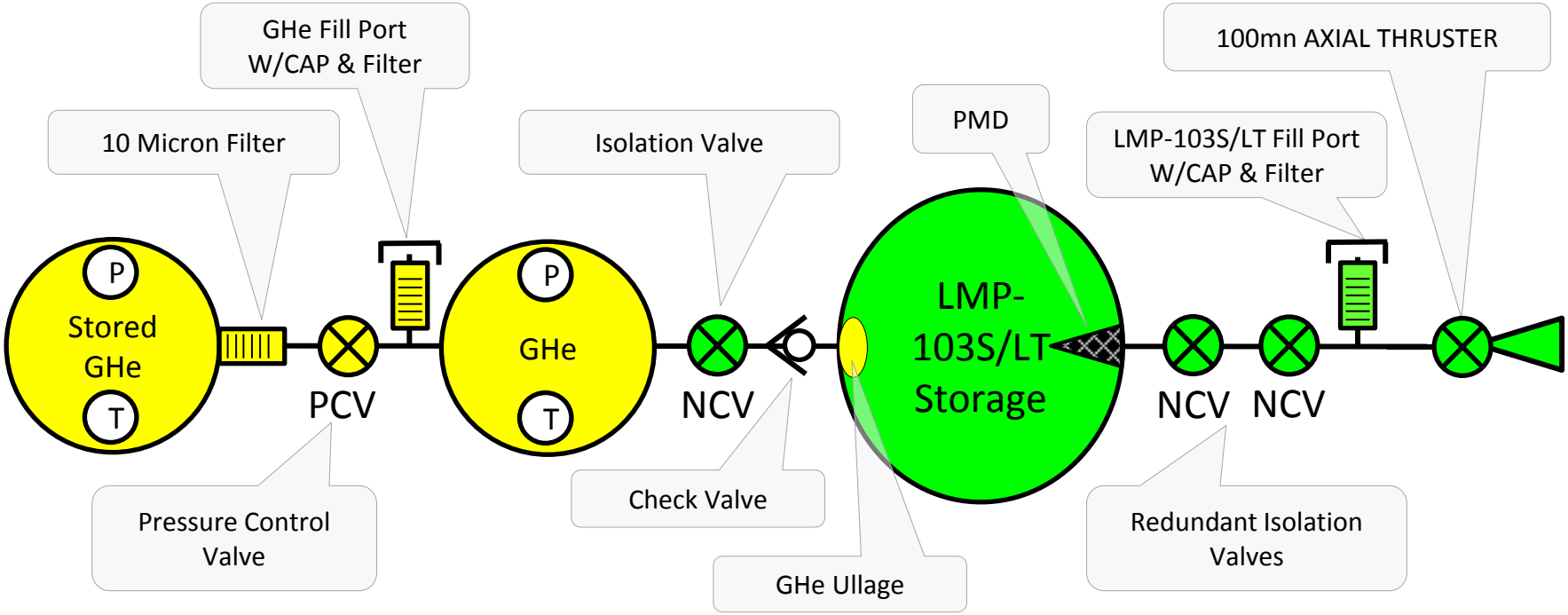
UN / US 1.4S (Commercial Aircraft)

(3) Seals Against LMP-103S/LT Leakage

GHe Pressurant

(3) Seals Against Pressurant Leakage

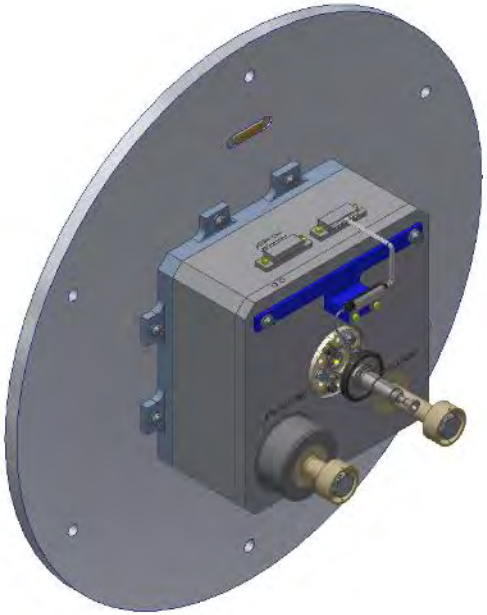
Delta-V Micro Propulsion System Schematic & Performance



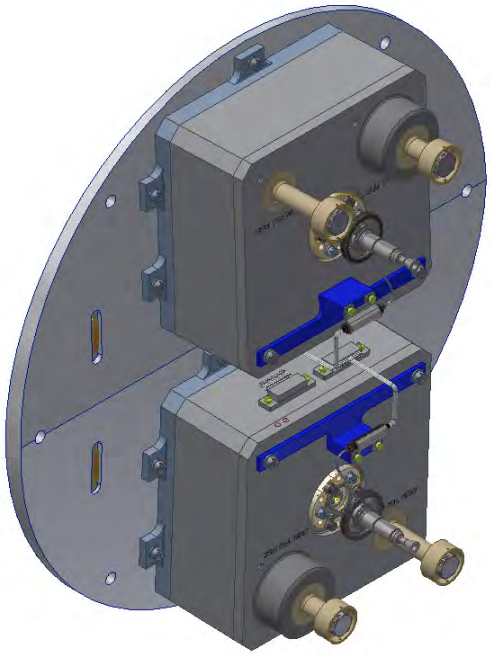
	Prop Vol. (cc)	Prop Mass (g)	Isp (sec)	Total Impulse (N-Sec)	MiPS Dry Mass (Kg)	Initial Satellite Mass (Kg)	Delta-V (M/s)
LMP-103S/LT	220	264	190	491	1.4	40	12

Green Monopropellant Micro Propulsion Systems

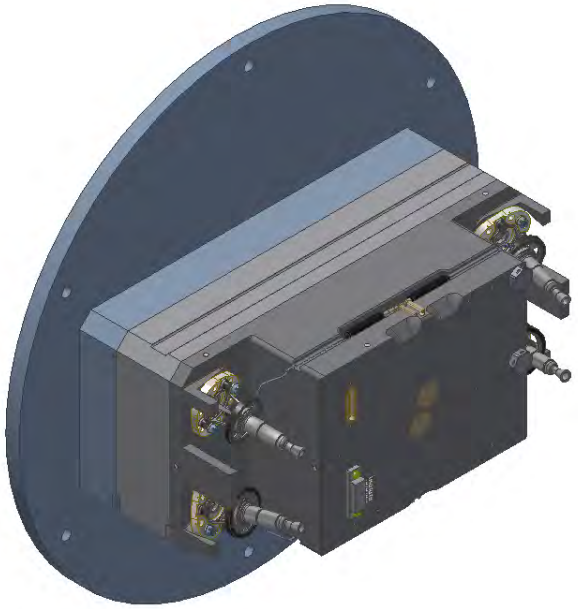
Bolt-On Modular Micro Propulsion Systems For ESPA Class Small Satellites



Single Delta-V System, Single Thruster



Redundant Delta-V Systems, Single Thruster Each



Quad Micro Propulsion System Based on Lunar Flashlight

Green Monopropellant Micro Propulsion Systems

Integrated Propulsion Subsystem for Small Satellites

Green Monopropellant Micro Propulsion Systems

VACCO Under Contract for Three Flight Systems

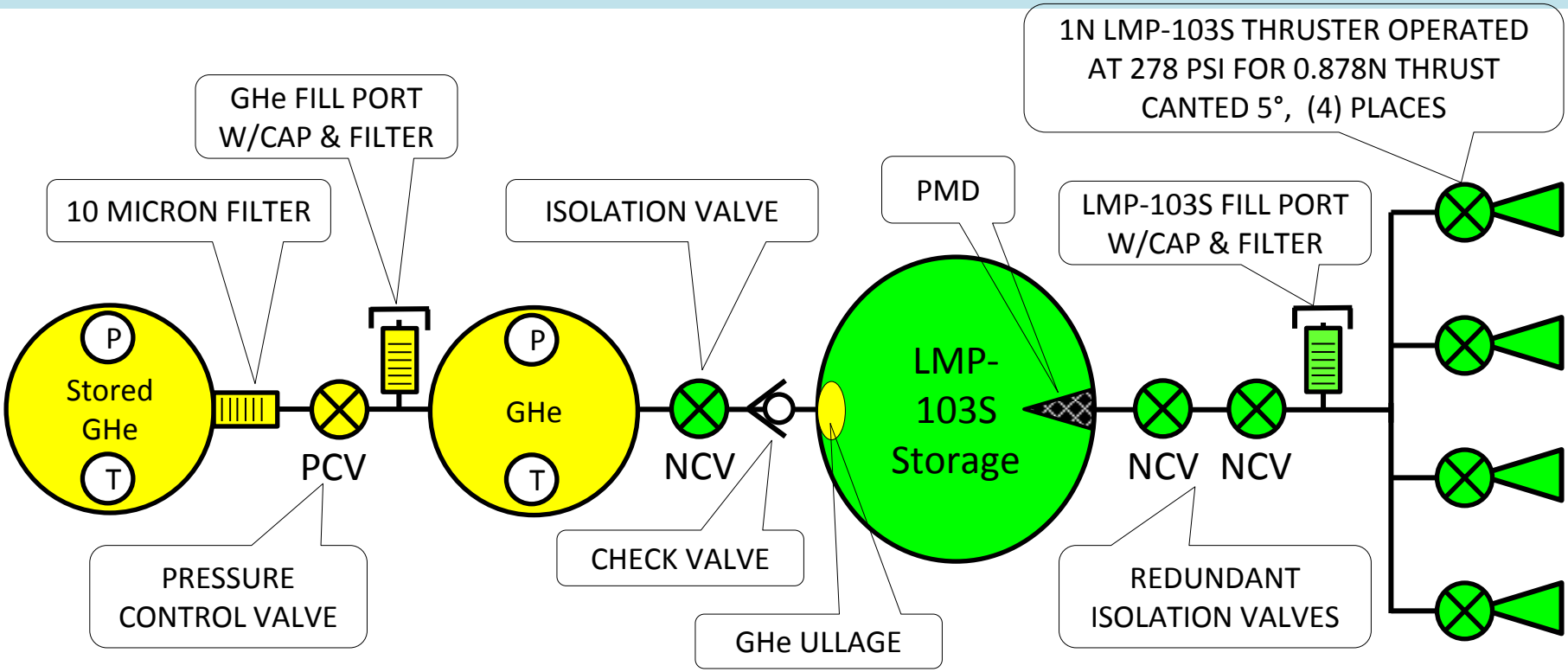
Self-Contained Integrated Propulsion Subsystem:

- (4) 1N LMP-103S Thrusters Operated at 878mN to Minimize Operating Pressure
- Thrusters canted at 5° Angle to provide Pitch, Yaw, Roll and 3.5N net Delta-V Thrust
- Total Impulse: 13,470 N-sec
- All-Welded Titanium Alloy Construction
- Frictionless High Reliability Micro Valves
- Built-In, Shielded Controller
- 5V & 28V Input Voltage, 15 watts while firing
- RS422 Data Bus Interface
- Minimum Pulse Width: 100ms

Range Safety Features:

- Green LMP-130S/LT Monopropellant:
  - LMP-103S Flight Proven on PRISMA
  - (44) Thrusters in Orbit on SkySat Satellites
  - UN / US 1.4S (Commercial Aircraft)
- (3) Seals Against Leakage
- Benign GHe Pressurant Stored at 47 bar
- Safe and Arm Circuit

Green Monopropellant Micro Propulsion Systems



	LMP-103S Vol. (cc)	LMP-103S Mass, 90% Fill (g)	Isp (sec)	Total Impulse (N-Sec)	MiPS Dry Mass (Kg)
3.5N Net Thrust	5374	6051	227	13470	5.3

MiPS Radiation Tolerance Features

1. **Electronics Shielded by Structure and Propellant –** As-proposed, all-welded aluminum alloy propellant tank shell is >=100 mil thick. Wall thickness will be adjusted as-required to meet up to 30krad requirement. Liquid R236fa propellant or pressurant surrounding Controller adds shielding.
2. **Watchdog Timer Built into Microcontroller** - Watchdog software reset. Power cycling under control of spacecraft power switching.
3. **No FLASH Memory Writing** - Corrupt settings cannot be saved to persistent memory.
4. **Designed to be Without Power Most of the Mission** - Reduces a number of single event effects (SEU, SEL, SEFI)
5. **No Voltages Above 12V** - Reduces likelihood of SEGR and SEB
6. **Radiation Testing -** JPL has conducted TID testing on select components from 0 to 30 kRAD. The electronics operate well to 13 kRAD and after that some of the circuits drift. Some components have been SEL tested.

Software Features

- **Up to 7 autonomous temperature regulation zones with manual override**
- **Over 30 commands**
  - Custom commands created at customer request
- **Customizable features adjustable on orbit:**

Heater voltage/power	Plenum pressure setpoint	PID constants	Save thrusting sequence
Maximum system power	Valve maximum voltage	Redundant PIV driver	Valve hold current
Manual heater override	Telemetry transmit rate	Plenum pressure timeout	Temperature setpoints

- **Health Monitoring data packets transmit at 10 Hz to provide continuous telemetry**