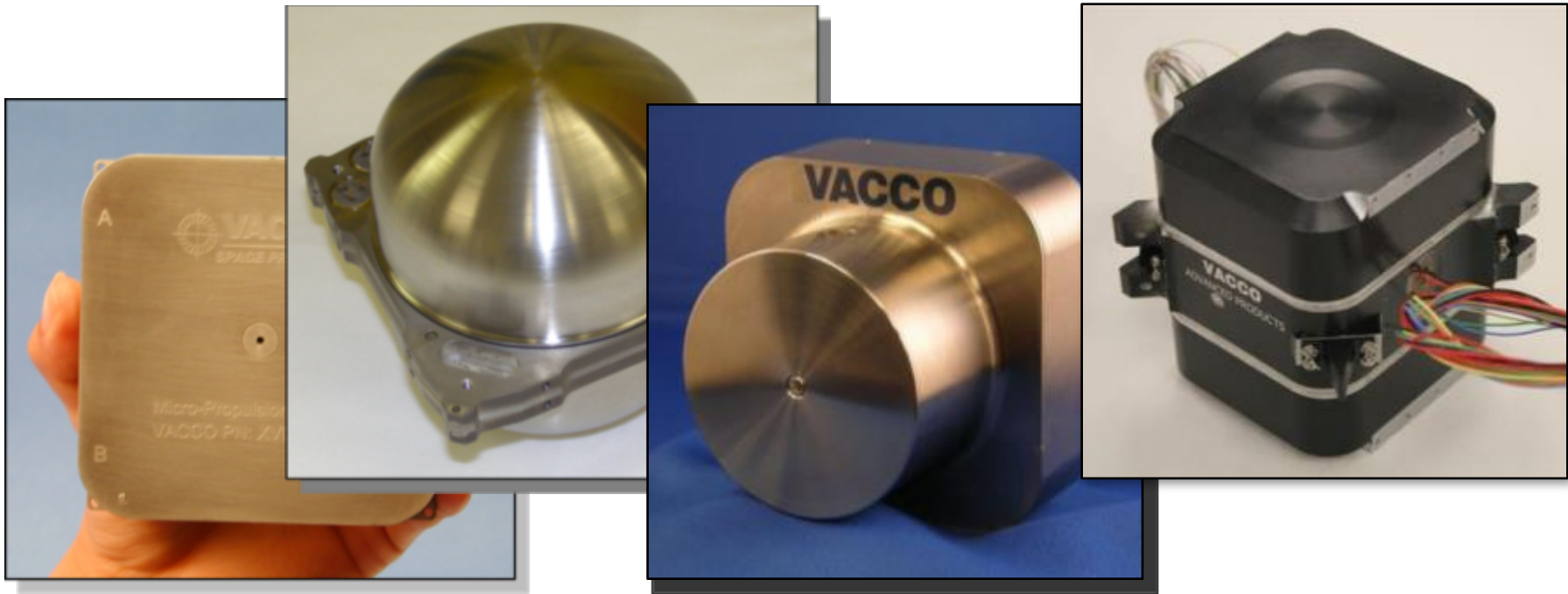


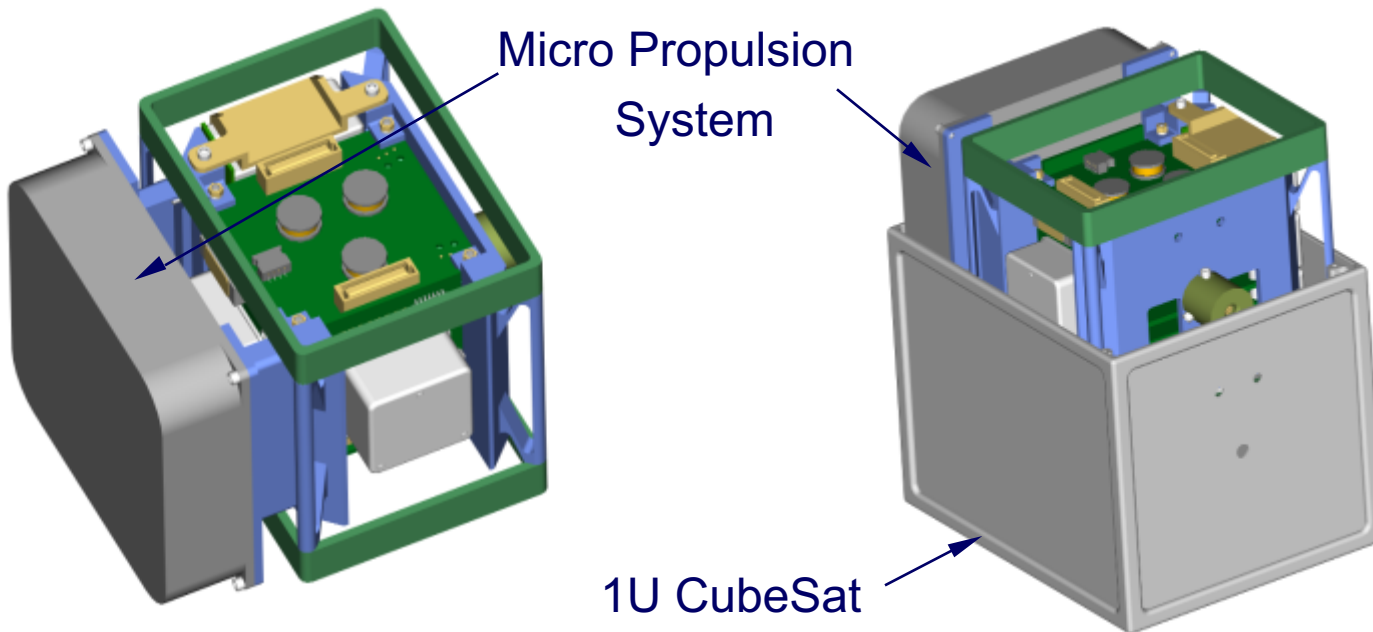
VACCO ChEMS™

Micro Propulsion Systems



14 Flight Systems and Counting...

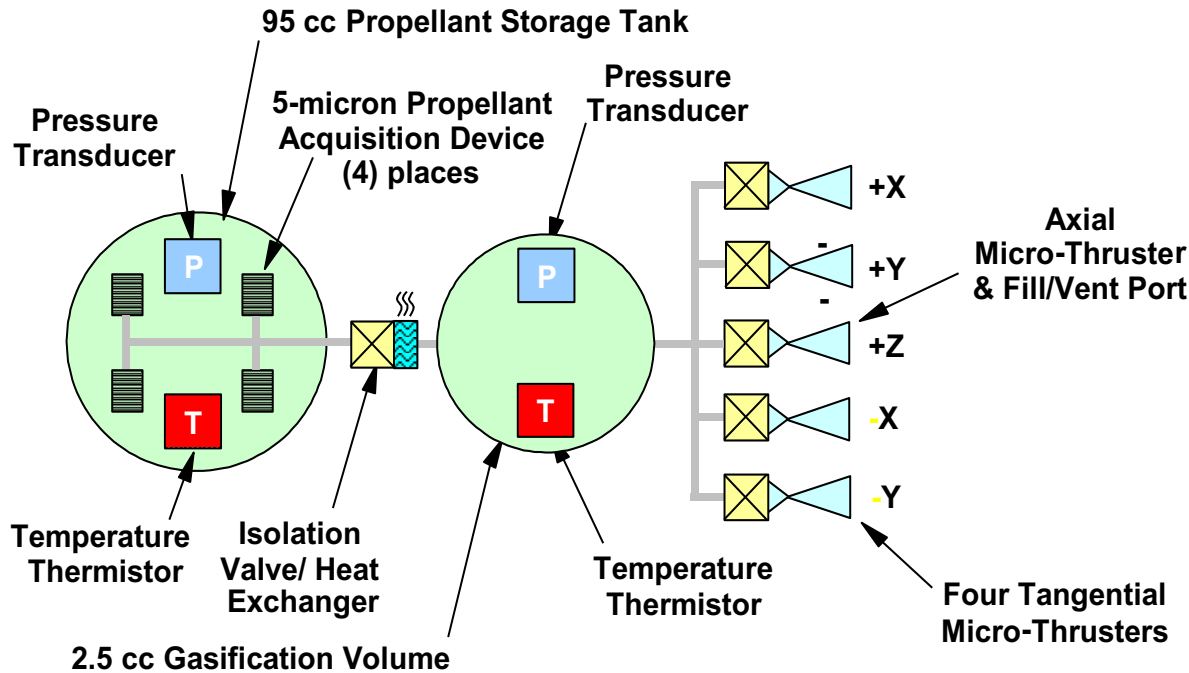
Heritage MEPSI Micro Propulsion System



Provided to AFRL for the Aerospace Corporation
MEMS Pico-Satellite Inspector (MEPSI).

(1) Unit Delivered 22 March 2004.

MEPSI MiPS Schematic



Complete System:

- (1) Storage Tank
- (2) Pressure Transducers
- (2) Temperature Sensors
- (4) 5 μ Filters
- (1) Isolation Valve
- (1) Heat Exchanger
- (1) Gasification Plenum
- (5) 55mN Thrusters



MEPSI MiPS Capability

Thrust:

- ⊕ 55 mN (40 psia Plenum Pressure)

Propulsion System Mass: 509 g

- ⊕ Dry Mass: 456 g
- ⊕ Propellant Mass: 53 g (liquid butane)

Thrust / Propulsion Densities:

- ⊕ 0.108 to 0.120 N/Kg
- ⊕ 66 N-Sec/Kg

Number of thrust cycles:

- ⊕ Up to 61,000 Minimum Impulse Bit Firings

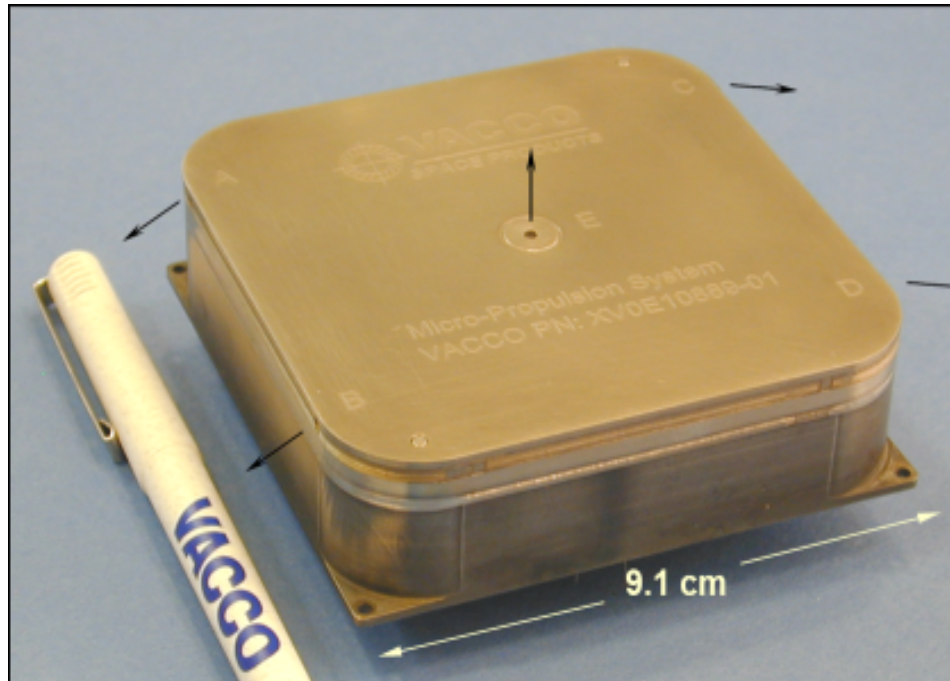
Total Impulse: 34 N-Sec

114 N-sec/Liter Performance Density

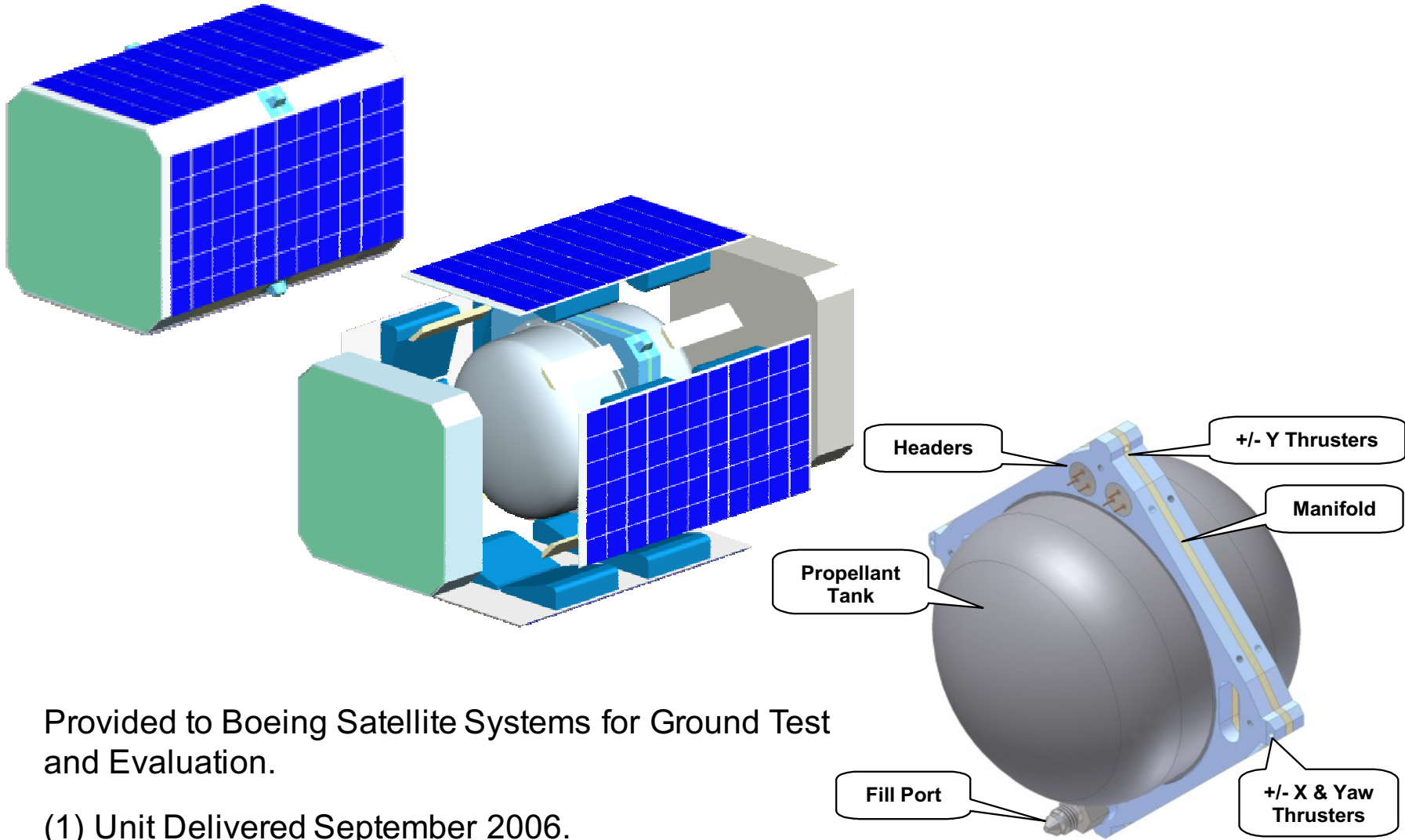
MEPSI Mass: 1.0 Kg

Total ΔV : 34 m/s

- ⊕ 26 m/s (-Z)
- ⊕ 1 m/s (+Z)
- ⊕ 3 m/s Pitch/Yaw
- ⊕ 4 m/s Roll



Heritage Boeing *Palomar* Micro Propulsion System



Provided to Boeing Satellite Systems for Ground Test and Evaluation.

(1) Unit Delivered September 2006.

Palomar MiPS Summary

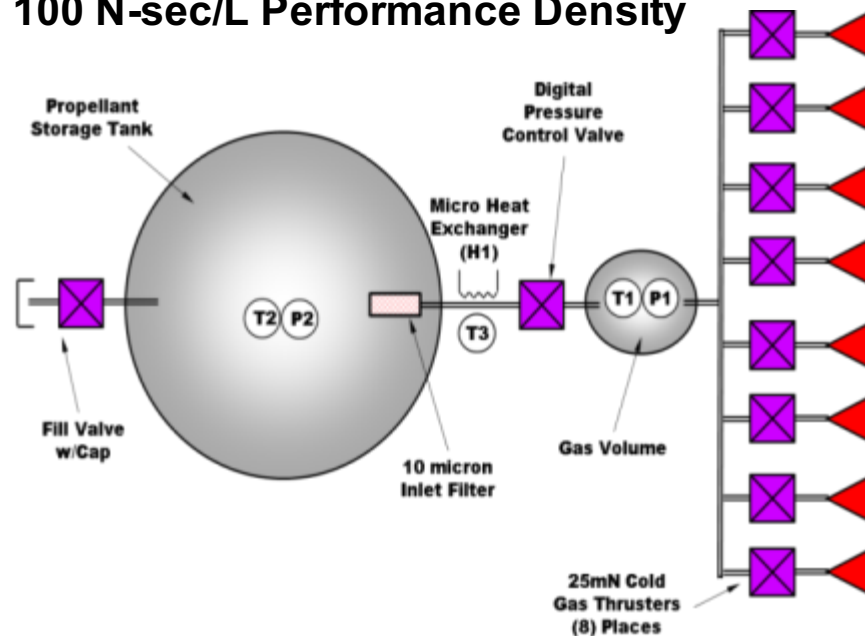


Fully Enclosed Design:

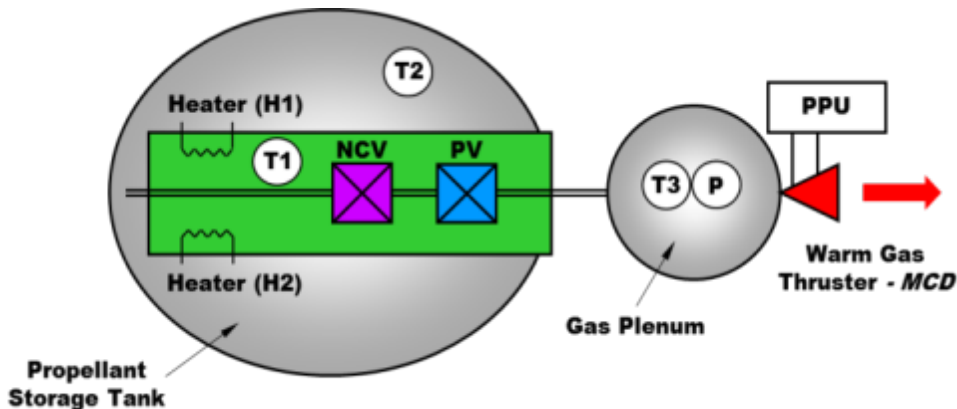
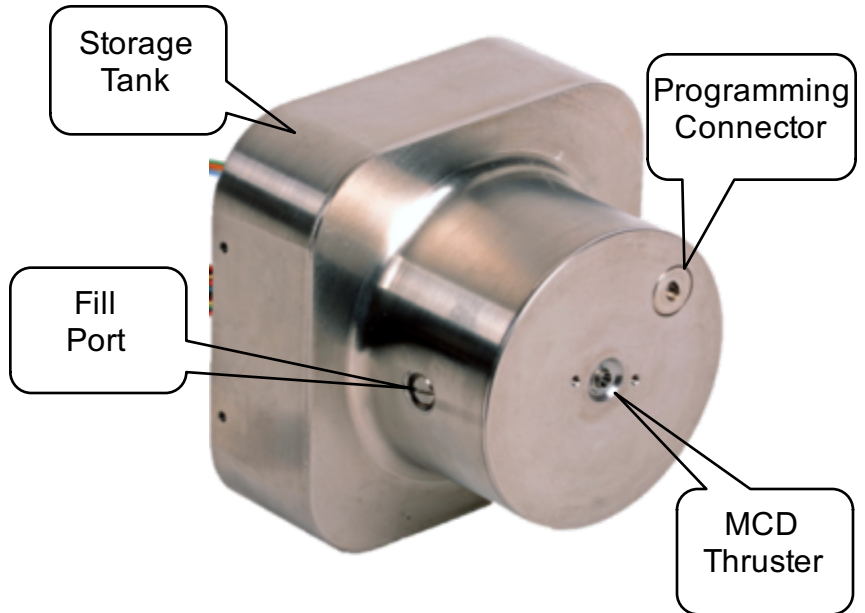
- ⊕ Isobutane Propellant
- ⊕ All-Welded Against External Leakage
- ⊕ Redundant Interrupts Against Internal Leakage
- ⊕ Reliable “Frictionless”, Soft-Seat, NC Valves
- ⊕ Simple, Self-Pressurizing Design
- ⊕ (8) 55mN Cold Gas Thrusters
- ⊕ Integral Controller, Press and Temp Sensors
- ⊕ Extensively Tested by VACCO & AFRL
- ⊕ **100 N-sec/L Performance Density**

AFRL Conclusions:

- ⊕ Highly Reliable Source for Thrust
- ⊕ Compact Combination of Fuel Storage, Sensor Feedback, Communication, Fire Control and Multiple Axis Thrust in a Robust Package
- ⊕ Average Single Thruster Values of 51 ± 6 mN Agreed Well with Predicted Values
- ⊕ Propellant Temperature Affects Thrust



AFRL Propulsion Unit for Cubesats (PUC)



Jointly developed by VACCO & CU Aerospace
Smart, Self-Contained Propulsion System:

- ⊕ (9) Flight Systems Delivered

Design Includes:

- ⊕ Propellant Storage & Feed System
- ⊕ Axial Thruster
- ⊕ Controller/PPU

Two Interrupts Against Leakage

Low Power Continuous Power (<15 watts)

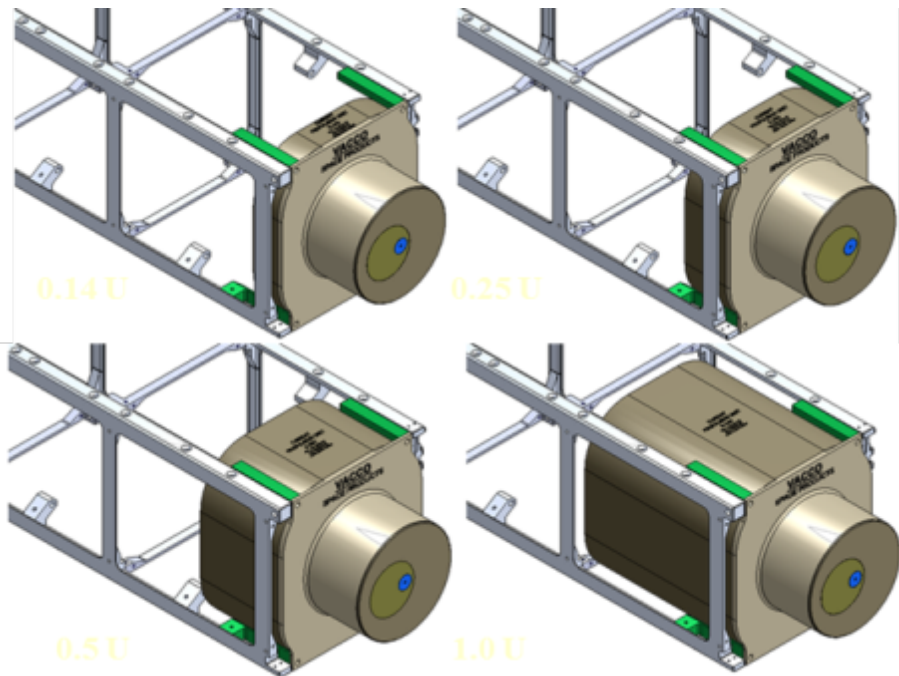
All-Welded Titanium Construction

Microcontroller Driven:

- ⊕ RS422 Digital Interface
- ⊕ Controls Burn Type & Duration
- ⊕ Closed-Loop, Variable Thrust Control
- ⊕ (2) Settable Thermal Control Zones
- ⊕ 1500 volt PPU
- ⊕ (3) Power Supplies, (2) Valve Drivers

514 to 618 N-sec/Liter Performance Density

AFRL Propulsion Unit for Cubesats (PUC)



Modular & Expandable:

- ⊕ Tank Expandable into Available Volume
- ⊕ Auxiliary Tanks Easily Accommodated

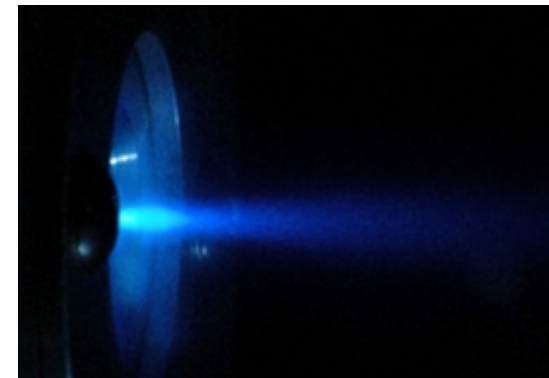
Self-Pressurizing SO₂ Green Propellant:

- ⊕ High Liquid Density
- ⊕ Critical temperature > 150° C
- ⊕ Freezing point < -75° C
- ⊕ Manageable toxicity

Micro Cavity Discharge (MCD) Thruster:

- ⊕ 4.5 mN Thrust
- ⊕ Two Modes: Warm Gas & Cold Gas

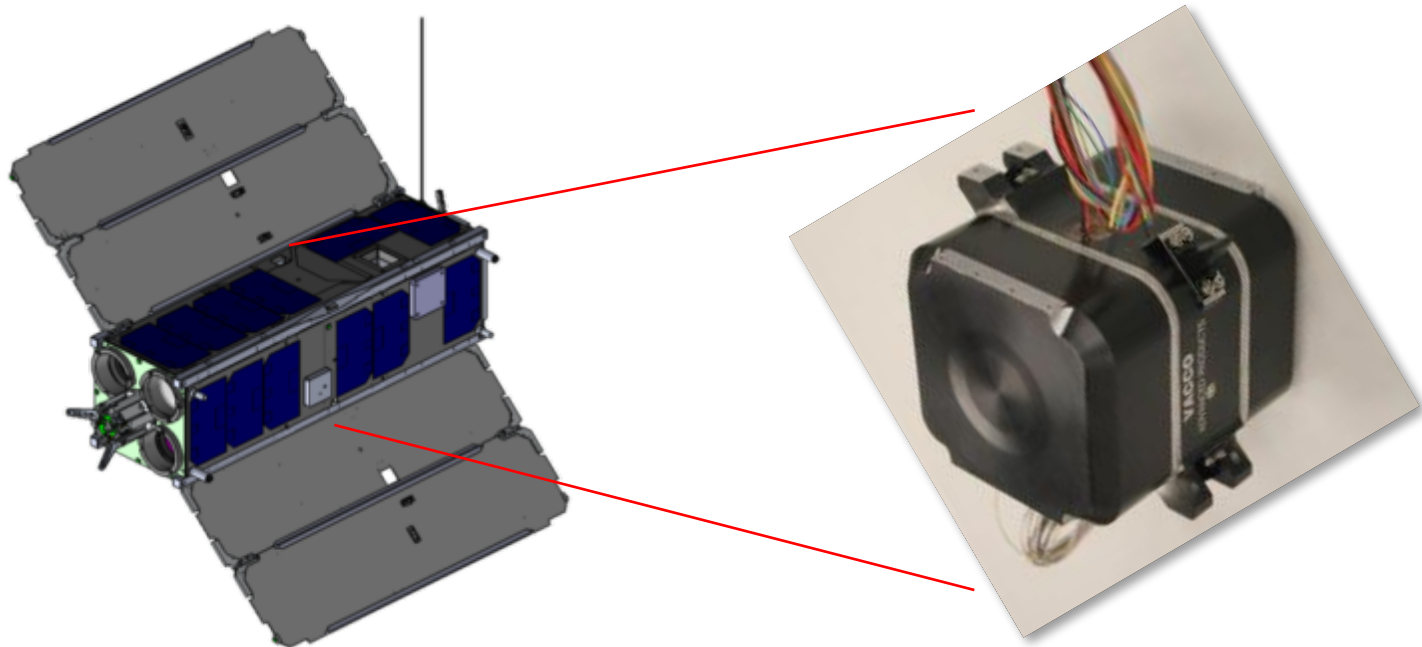
Uses 0.25 U of internal cubesat volume to deliver 184 N-Sec or 48 m/s delta-V for 4 kg CubeSat



[Courtesy of CU Aerospace]

NASA/Tyvak CPOD Micro Propulsion System

- ⊕ Contract with Tyvak Nano-Satellite Systems LLC
- ⊕ CPOD: NASA Cubesat Proximity Operations Demonstration
- ⊕ (2) Flight Systems Delivered
- ⊕ Occupies Center 0.8U of 3U Cubesat
- ⊕ Provides Attitude Control & Delta-V



CPOD MiPS Overview

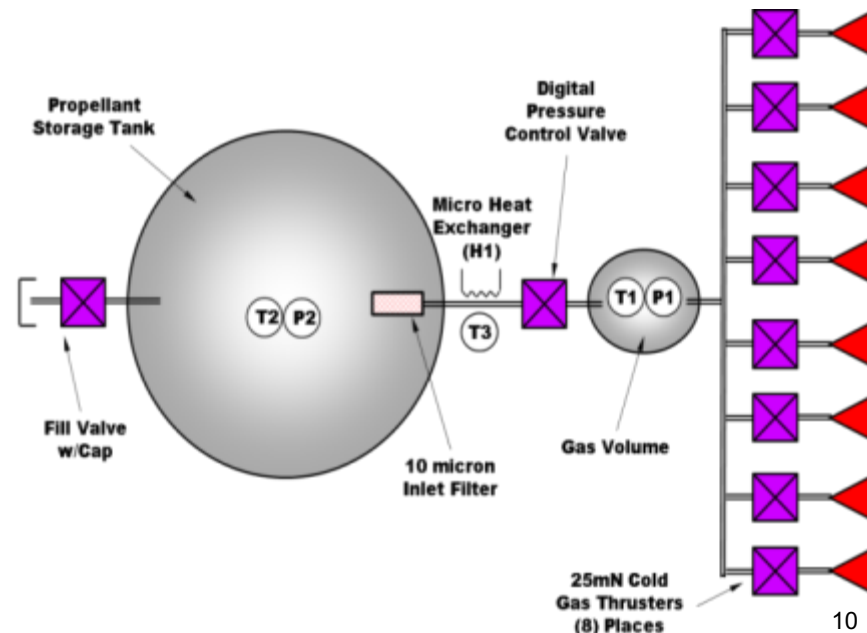
System Overview

- ⊕ All-Welded Aluminum Construction
- ⊕ Eight 25mN Cold Gas Thrusters
- ⊕ 0.20 mN-S Minimum Impulse Bit @ 3 mS Pulse Width
- ⊕ 0.8U Center Manifold, Clamshell Configuration
- ⊕ 484 grams Self-Pressurizing R134a Green Propellant
- ⊕ Smart System with Integral Microcontroller
- ⊕ RS422 Digital Interface
- ⊕ Integral Sensor Suite
- ⊕ Total "Wet" Mass: 1244 grams
- ⊕ **186 N-S Total Impulse, 33 M/S Delta-V @ 40 sec Isp**
- ⊕ **135 N-sec/Liter Performance Density**

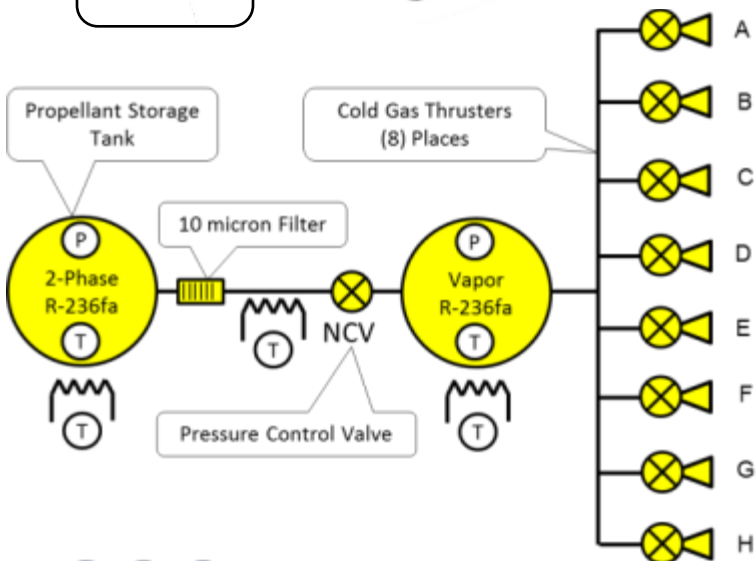
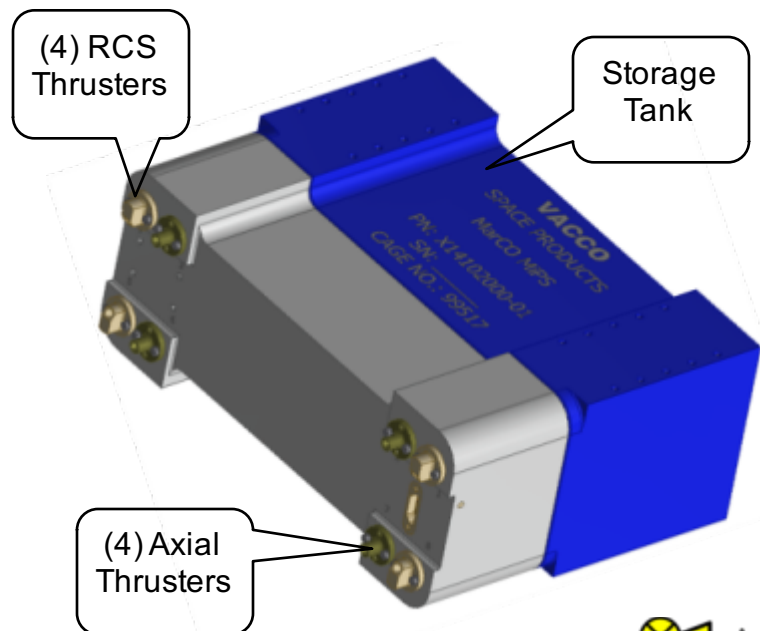


Program Complete

- ⊕ Propellant Trade Study Complete (R134a Selected)
- ⊕ Propulsion System "Flat Sat" Simulator
- ⊕ (2) Flight Units Tested & Delivered
- ⊕ Flight Expected in 2016



JPL MarCO Micro Propulsion System



First Interplanetary Cubesat

Smart, Self-Contained Propulsion System:

- ⊕ Contract for (2) Flight Systems
- ⊕ 755 N-Sec Total Impulse
- ⊕ 3490 gram Wet Mass
- ⊕ **354 N-sec/Liter Performance Density**

System-in-a-Tank Design Including:

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

Two Interrupts Against Leakage

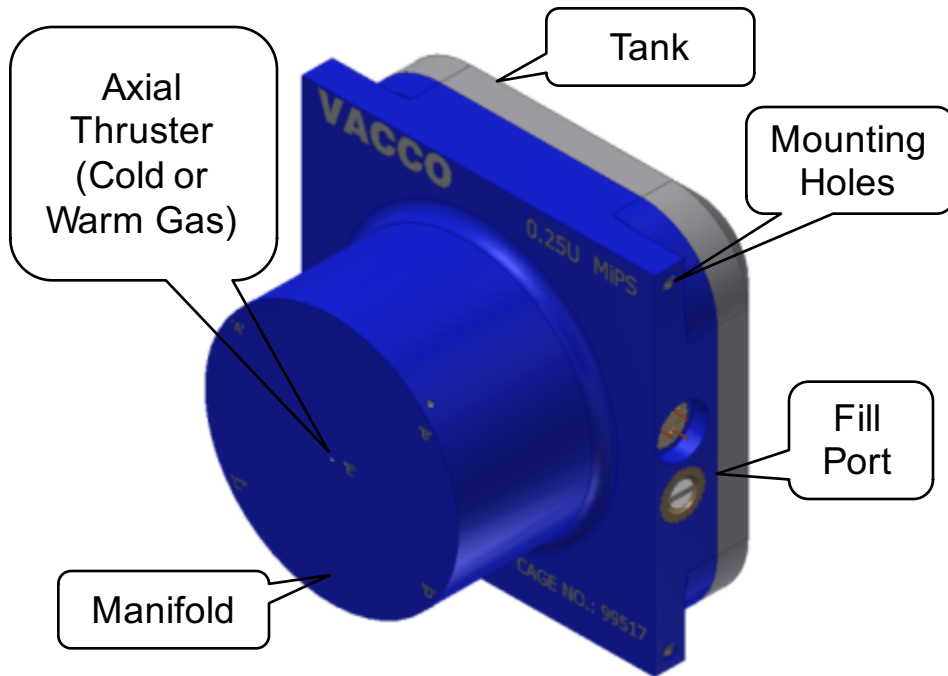
0.5 Watt Standby Power

All-Welded Aluminum Construction

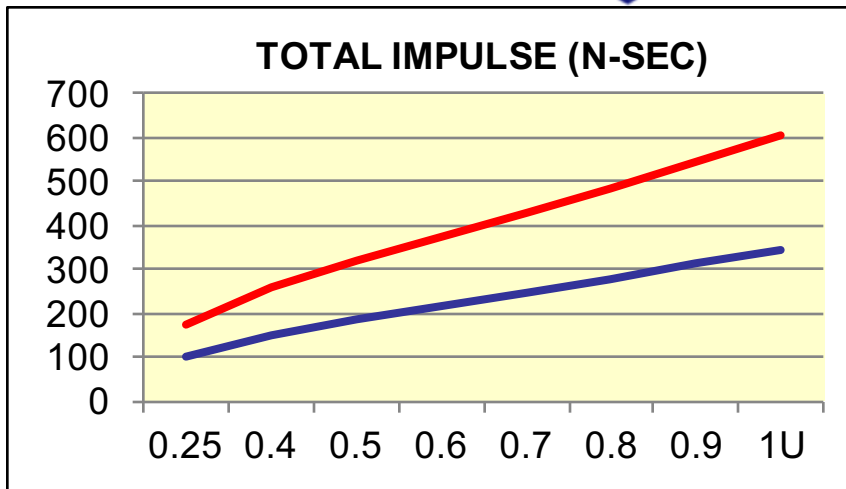
Microcontroller Driven:

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

Standard End-Mounted Cubesat MiPS

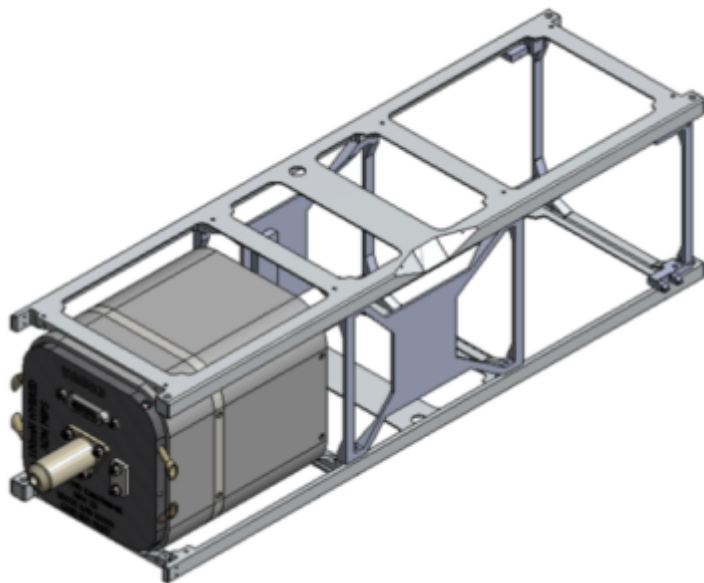


- ⊕ Low Cost, 0.25U Propulsion Module:
- ⊕ Green R236fa Propellant
- ⊕ Smart Module:
 - ⊕ Controlled via RS422 Bus
 - ⊕ Integral Sensor Suite
 - ⊕ Closed-loop Vector Pointing
 - ⊕ Closed-loop Thrust Vector Control
- ⊕ (5) 10mN Cold Gas Thrusters ($I_{sp}=40s$)
- ⊕ Min Impulse Bit: 0.05 mN-Sec.
- ⊕ Cold Gas Total Impulse: 103 N-Sec.
- ⊕ **Delta-V: 21.1 M/Sec (4.5 Kg Cubesat)**
- ⊕ **291 N-sec/Liter Cold Gas Performance Density**
- ⊕ Module Provides Delta-V and Reaction Control
- ⊕ Module Depth can be Increased from 0.25U to 1U to Maximize Total Impulse
- ⊕ Warm Gas Option: Total Impulse: 176 N-Sec
- ⊕ **Delta-V: 40.4 M/Sec (4.5 Kg Cubesat)**
- ⊕ **497 N-sec/Liter Warm Gas Performance Density**

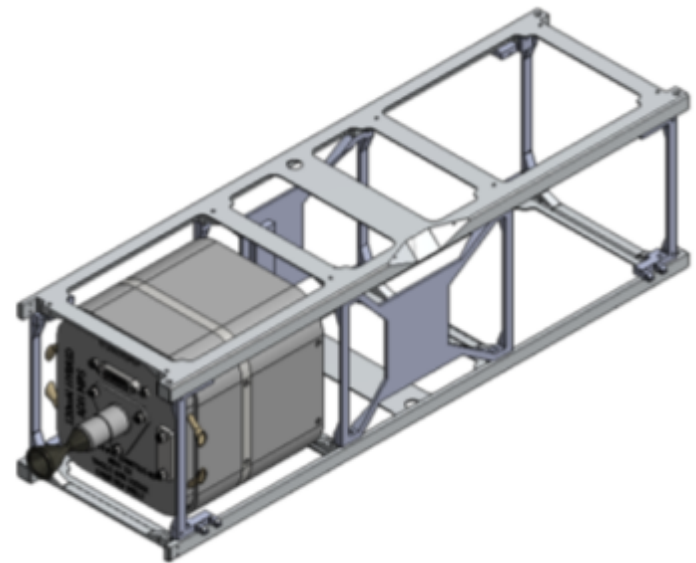


VACCO ChEMS™

High Performance Micro Propulsion Systems



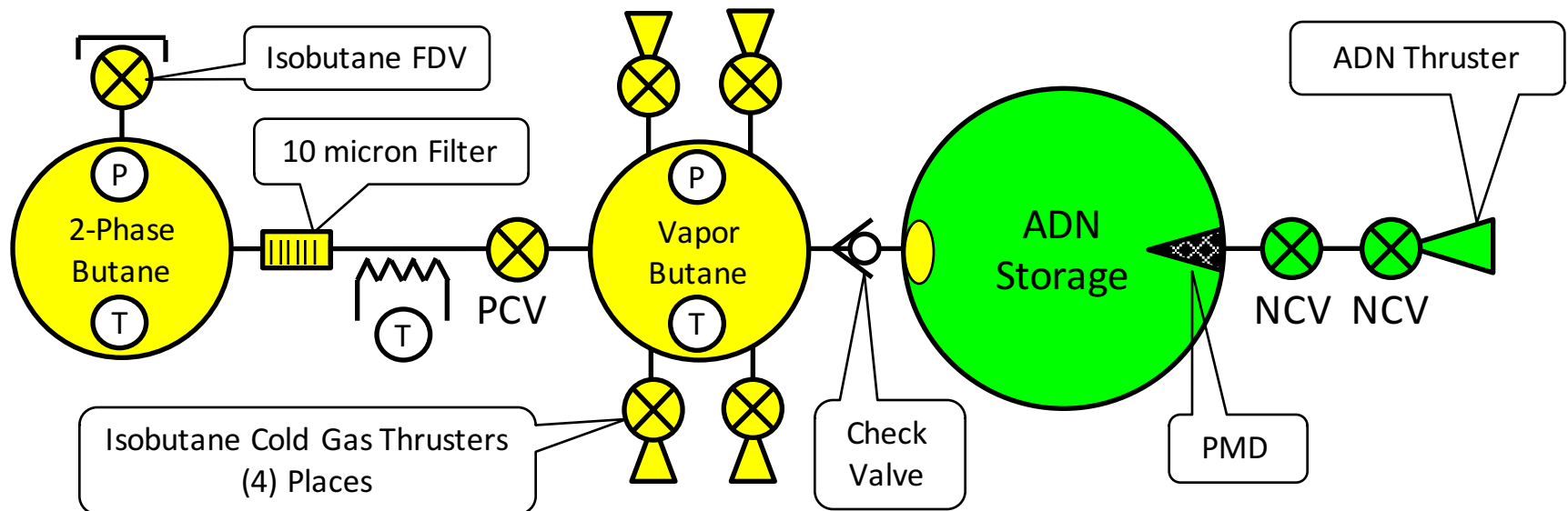
100mN / 1U Hybrid ADN MiPS



120mN / 1U Hybrid ADN MiPS

VACCO Hybrid ADN MiPS Schematic

- ⊕ Pressurant Tank w/Press & Temp Sensors
- ⊕ Pressurant Fill & Drain Valve
- ⊕ 10 micron Pressurant Filter
- ⊕ Heater Exchanger w/Temp Sensor
- ⊕ Pressurant Control Valve
- ⊕ Vapor Tank w/Press & Temp Sensors
- ⊕ (4) Isobutane Cold Gas Thrusters
- ⊕ Check Valve
- ⊕ ADN Propellant Storage Tank w/PMD
- ⊕ Normally-Closed Isolation Valve
- ⊕ Normally-Closed Thruster Valve
- ⊕ Axial ADN Thruster
- ⊕ 100mN thru 22N Versions Available



VACCO 100mN /1U Hybrid ADN MiPS

(Using New ECAPS Thruster)



100mN / 1U Hybrid ADN MiPS

Complete, Self-Contained Propulsion System.

Hybrid Delta-V and Attitude Control:

- ⊕ (1) 100mN ADN Axial Delta-V Thruster
- ⊕ (4) 10mN Butane Cold Gas ACS Thrusters
- ⊕ 1070 N-sec/Liter Performance Density

High 100mN Thrust:

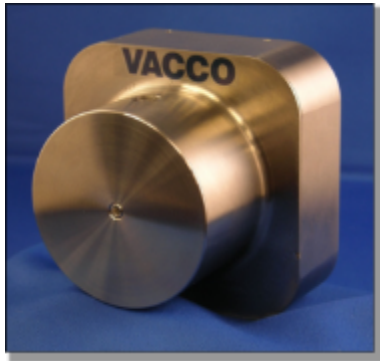
- ⊕ Derivative of 0.5N ADN Thruster
- ⊕ Hot-Fire Tested by ECAPS

Range Safety Features:

- ⊕ “Green” ADN and Isobutane Propellants
- ⊕ All-Welded against ADN External Leakage
- ⊕ (2) Interrupts against ADN Leakage
- ⊕ Low (309 psia) Max Operating Pressure
- ⊕ Safe & Arm Circuit

Cubesat Size	Cubesat Initial Mass (Kg)	MiPS Size	MiPS Dry Mass (Kg)	Prop Volume (CC)	Prop Mass (Kg)	MiPS Wet Mass (Kg)	Thruster Size (N)	Isp (sec)	Delta-V (M/s)	Total Impulse (N-Sec)	Available Volume (cc)	Specific Impulse (N-Sec/cc)	Total Burn Time (sec)	Total Power (watts)
3U	5.121	1U	1.093	426	0.528	1.621	0.1	200	214	1036	955	1.084	10361	13.6

Summary



VACCO has a Variety of Micro Propulsion Solutions for ACS and Delta-V:

- ⊕ (1) Development MEPSI MiPS,
- ⊕ (1) Development Boeing Palomar MiPS
- ⊕ (9) Flight AFRL Propulsion Unit for Cubesats
- ⊕ (3) Flight Tyvak CPOD MiPS
- ⊕ (2) Flight JPL MarCO MiPS
- ⊕ (Future) ADN Hybrid MiPS

Self-Contained Systems

Smart & Versatile

- ⊕ Wide variety of Performance Densities possible depending on available envelope and options

Various Propellants:

- ⊕ Isobutane, SO₂, R-134a, R236fa
- ⊕ ADN, AF315

Materials of Construction:

- ⊕ Titanium
- ⊕ Aluminum