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THE AEROSPACE CORPORATION

2023 Small Satellite Propulsion Technologies Compendium
The Aerospace Corporation, DISTRO A
Version 1.41

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Aerospace's role in small satellites

- Technical advisors
  - *Support for government science, engineering, and technology development*
  - *Serve as un-biased subject matter experts/knowledge base for "what's out there"*

- Laboratory capabilities
  - *Un-biased, third-party ground-testing capabilities – facilities specialized for small satellites*
    - Large vacuum facilities for direct thrust/performance characterization, plume diagnostics, life-testing, etc…
    - Chemical handling facilities for materials compatibility, hot fire, ordnance….
    - High-flow facilities, environmental testing

- Prototyping and Technology Development/Advancement Missions
  - *Aerospace's Small Satellite department builds and flies AeroCube missions (~1-2 per year).*
  - *Main motivation is technology development/TRL advancement – this is a non-profit effort, we do not produce at quantity and we do not compete with the commercial sector*

"Working to enable development of technologies that provide both immediate and long-term support to military and intelligence space programs, the commercial sector, and the public good"

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Objectives and Scope

Primary Objective: *Provide a survey of the field of small satellite propulsion systems*

Scope

Any domestic or foreign propulsion system that fell within the following targeted propulsion technologies was identified and reviewed as a credible option.

Targeted propulsion technologies:

- Generally suitable for Micro, Nano, Pico, or Cube-Satellites
    - Power: Hundreds of watts or less, with emphasis on <100W
    - Mass: Hundreds of kg or less, with emphasis on spacecraft <100kg
- TRL ≥ 2

Useful definitions:

"Commercially available", indicated by = manufacturer speculates could be ready to be delivered within ~12 months.

"Aerospace has tested", indicated by = Aerospace has tested this thruster technology. The tested unit is not necessarily a flight unit, but may be something similar, such as an engineering-model or qual-model. This does *not* equal an endorsement, only that we have test data available.

Designations for satellite names and corresponding mass for this work are defined:

Name	Mass (kg)	Power (W)
“Small-Satellite”	<500	~10,000 W
“Mini-Satellite”	100 to 500	~5,000W
“Micro-Satellite”	10 to 100	~1,000 W
“Nano-Satellite”	1 to 10	~100 W
“Pico-Satellite	0.1 to 1	~10 W
“Femto-Satellite”	<0.1	~1 W
“Cube-Satellite”*	~2	Few to tens of W

Table 1: NASA satellite mass class definitions

* Traditionally, “Cube-Satellites”, or “CubeSats” are 10 cm x 10 cm x 10 cm, defined as 1 unit, or “1U”. Each U weighs 1 kg, however, this weight definition has been extended up to approximately 2 kg/U in recent years. Satellites that are multiple-units in size are measured in U. For example, a satellite that is 20 cm x 10 cm x 10 cm is 2U.

Caution!

Most data is self-reported by manufacturer. Hence, TRL levels are estimated to the best of our ability using the manufacturer's data and available literature, with preference for public peer-reviewed journal publications and professional conference proceedings.

If you know of additional technologies that should be included or see any errors, please contact:
Andrea Hsu [*Andrea.G.Hsu@aero.org*]

This document is a living survey and is intended to be updated as technologies evolve.

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Technology Readiness Level (TRL) definitions

- Adapted from Hargus (2019, 2016).

TRL 9

Actual system "flight proven" through many repeated successful mission operations

- Micro-propulsion system is considered a routine system, not an experiment, and can be operated without specialized technologist support. Fully mature hardware and software interfaces.

TRL 8

System reaches the end of system development

- Proto-flight demonstration anomalies have been mitigated
- Final system design is implemented and flight-verified
- Repeatable system production and performance demonstrated and documented
- System ready for operational deployment and no longer deemed an experiment with specialized support
- No further technology development occurs

TRL 7

Proto-flight system has been demonstrated in an operational environment

- Protoflight hardware developed and flown
- Performance verification completed on orbit and compared to ground test results, results are published and archived
- Proto-flight anomalies traced to root cause and verified with ground tests

Continued…

[1] Hargus, W., Singleton, J., "Application of Technology Readiness Levels (TRLs) to Micro-Propulsion Systems," 52nd AIAA/SAE/ASEE JPC, 2016.
[2] Hargus, W., "JANNAF Guidelines for the Application of Technology Readiness Levels (TRLs) to Micro-Propulsion Systems," JANNAF Spacecraft Propulsion Subcommittee, JANNAF 2019. DISTRO A.

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Technology Readiness Level (TRL) definitions

➢ Adapted from Hargus (2019, 2016).

TRL 6

Prototype (i.e. qualification model) successfully passed "proto-flight" ground tests.

- "Proto-flight" tests represent a family of tests that lower risks to a customer-accepted level and may not be equivalent to a full-suite of environmental testing as defined for larger, heritage spacecraft. It may include tests that are specific to a customer's defined mission. Test results have been documented/published.
- System demonstrated to be fully compatible with the anticipated space and launch environments, including relevant radiation, thermal-vacuum, corona discharge, and launch vibrational levels
- Software interfaces fully identified, developed, and verified at prototype-level fidelity
- System lifetime is directly measured
- Recommended: Peer review to verify entry into TRL 6

TRL 5

System is reaching readiness for technical demonstration

- Thruster head design finalized as appropriate for flight
- Unit as finalized has been tested for nominal performance and lifetime
- All subsystem breadboard designs, including control interfaces to main spacecraft, at engineering model (EM)
- Entire system laboratory-verified in simulated flight environment, and ground test results are clearly documented
- System impact (thermal soak-back, EMI, plume contamination, etc.) on host spacecraft is quantified

TRL 4

Focus shift from thruster head to overall system performance

- Representative thruster system is assembled from breadboard subsystems and includes (at a minimum) a thruster head, propellant management subsystem, and rudimentary command and control.
- System requirements are formulated from a design reference mission (DRM)
- System is demonstrated at breadboard level of fidelity in representative environment
- Thruster lifetime directly measured (with performance measurements at BoL and EoL) and significant portion of thruster head lifetime demonstrated
- Ground test results clearly documented

Continued…

[1] Hargus, W., Singleton, J., "Application of Technology Readiness Levels (TRLs) to Micro-Propulsion Systems," 52nd AIAA/SAE/ASEE JPC, 2016.
[2] Hargus, W., "JANNAF Guidelines for the Application of Technology Readiness Levels (TRLs) to Micro-Propulsion Systems," JANNAF Spacecraft Propulsion Subcommittee, JANNAF 2019. DISTRO A.

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TRL Definitions (cont.)

- Adapted from Hargus (2019, 2016).

TRL 3

Active research initiated

- Thruster head hardware developed
- Performance is experimentally measured using laboratory surrogate subsystems. Performance defined as thrust, Isp, or impulse bit, and thruster head power efficiency (for EP devices). Measurement uncertainties are identified.
- Lifetime is estimated via analytical tools, and lifetime-limiting mechanisms identified
- Thruster system impact on host spacecraft explored

TRL 2

Practical invention begins

- Propellant acceleration mechanism observed directly or from literature
- Notional sub-systems (propellant storage, propellant feed, power sources, etc. are identified
- Thruster performance estimated parametrically or from first principles

TRL 1

Thruster and propellant acceleration mechanisms conceptualized

- Limited to paper studies or observations of other work
- Extrapolation to a concept with thrust generation capability

[1] Hargus, W., Singleton, J., "Application of Technology Readiness Levels (TRLs) to Micro-Propulsion Systems," 52nd AIAA/SAE/ASEE JPC, 2016.
[2] Hargus, W., "JANNAF Guidelines for the Application of Technology Readiness Levels (TRLs) to Micro-Propulsion Systems," JANNAF Spacecraft Propulsion Subcommittee, JANNAF 2019. DISTRO A.

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Executive Summary

2023 Outlook

Number of emerging propulsion technologies identified as credible options with TRL ≥ 2

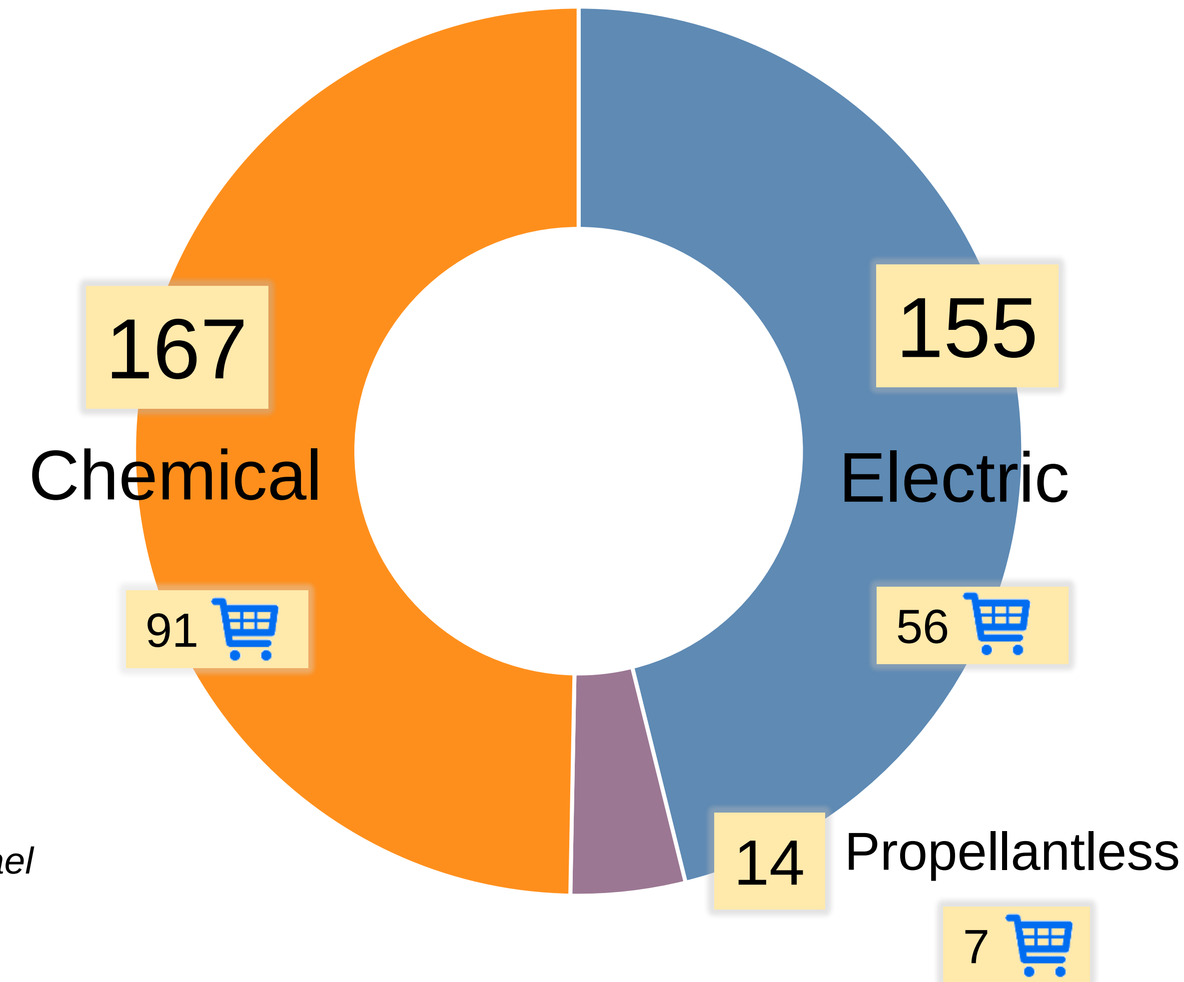
336

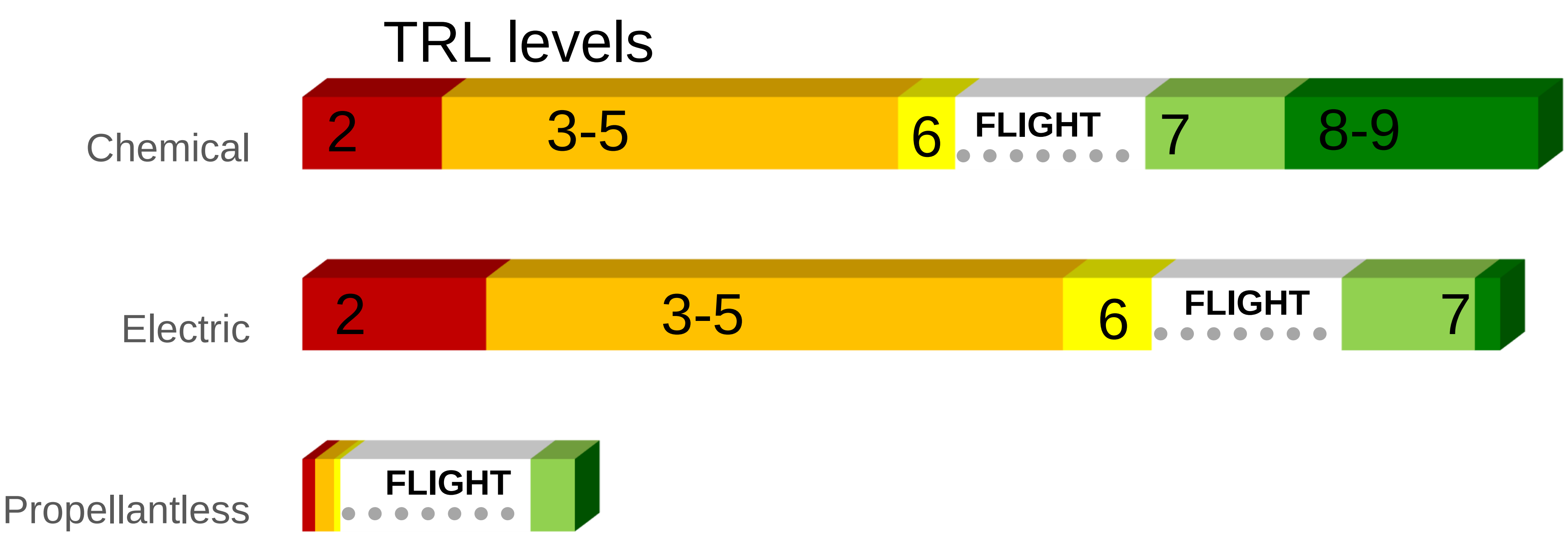
154 **are considered commercially available**

- *Cost data is very limited and depends on SmallSat mission requirements*
- *Commercially available ≠ COTS. Understood to be deliverable within approx. 1 yr.*

195 **are domestic, followed closely Europeans**

- *Notable domestic vendors: Aerojet Rocketdyne, Moog, Busek, VACCO*
- *Notable foreign vendors: Ariane Group, Ecaps, and Enpulsion, Sitael, Rafael*





Chemical systems have more flight heritage than electrical systems

37% vs. 16%

with TRL 7 or higher

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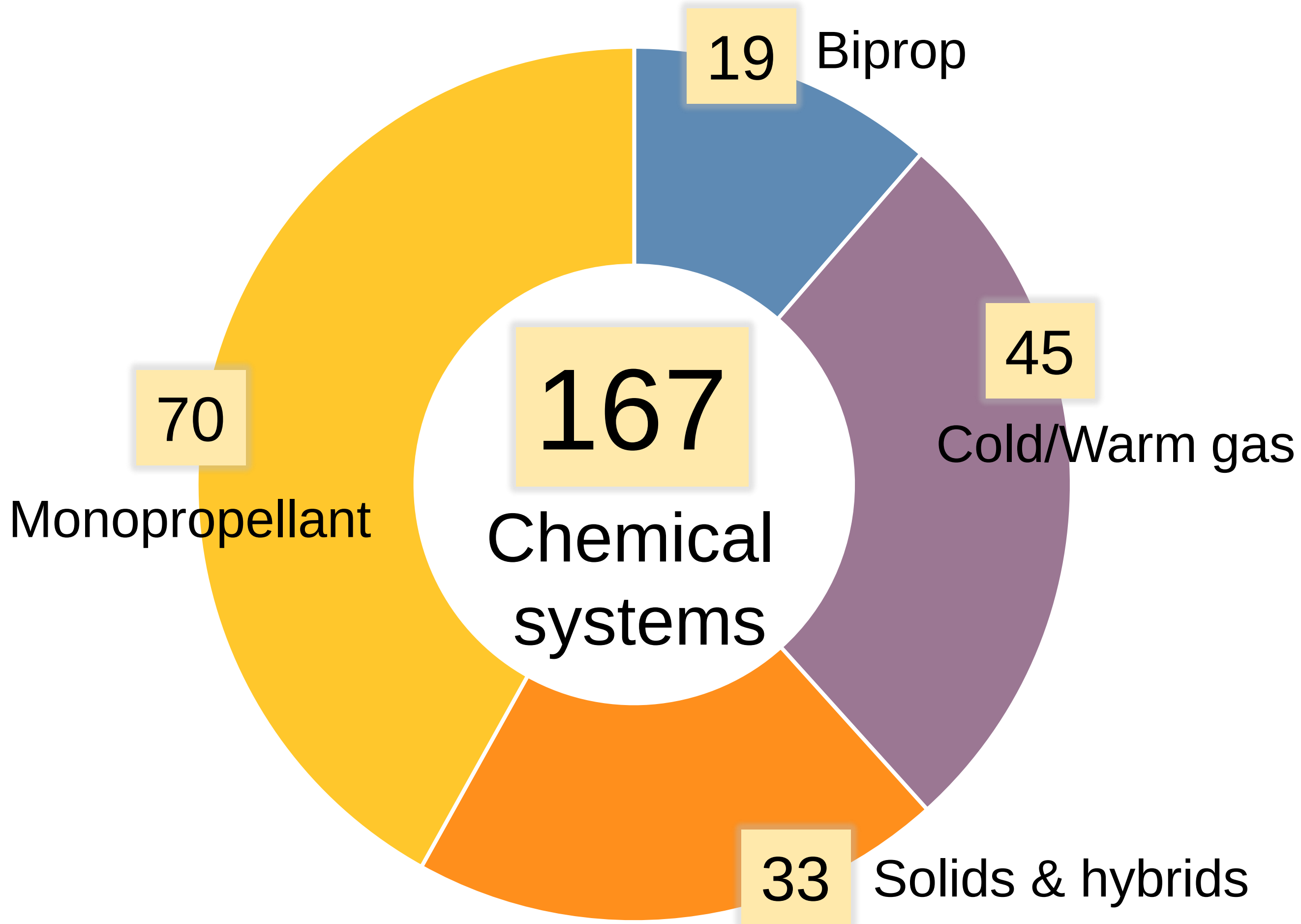
Chemical Propulsion Options - Summary

2023 Outlook



Typical propellant types

- Hydrazine
- AF-M315E (ASCENT)
- LMP-103S
- Refrigerants (R134a/R236fa)
- Inert gas
- Water
- AP/HTPB
- 3-D printed plastics

124 are domestic, followed closely European commercial space companies

- *Notable domestic vendors: Aerojet Rocketdyne, Moog, NGC, VACCO, Busek, Stellar Explorations*
- *Notable foreign vendors: Ariane Group, ECAPS, Surrey Satellite Technologies*

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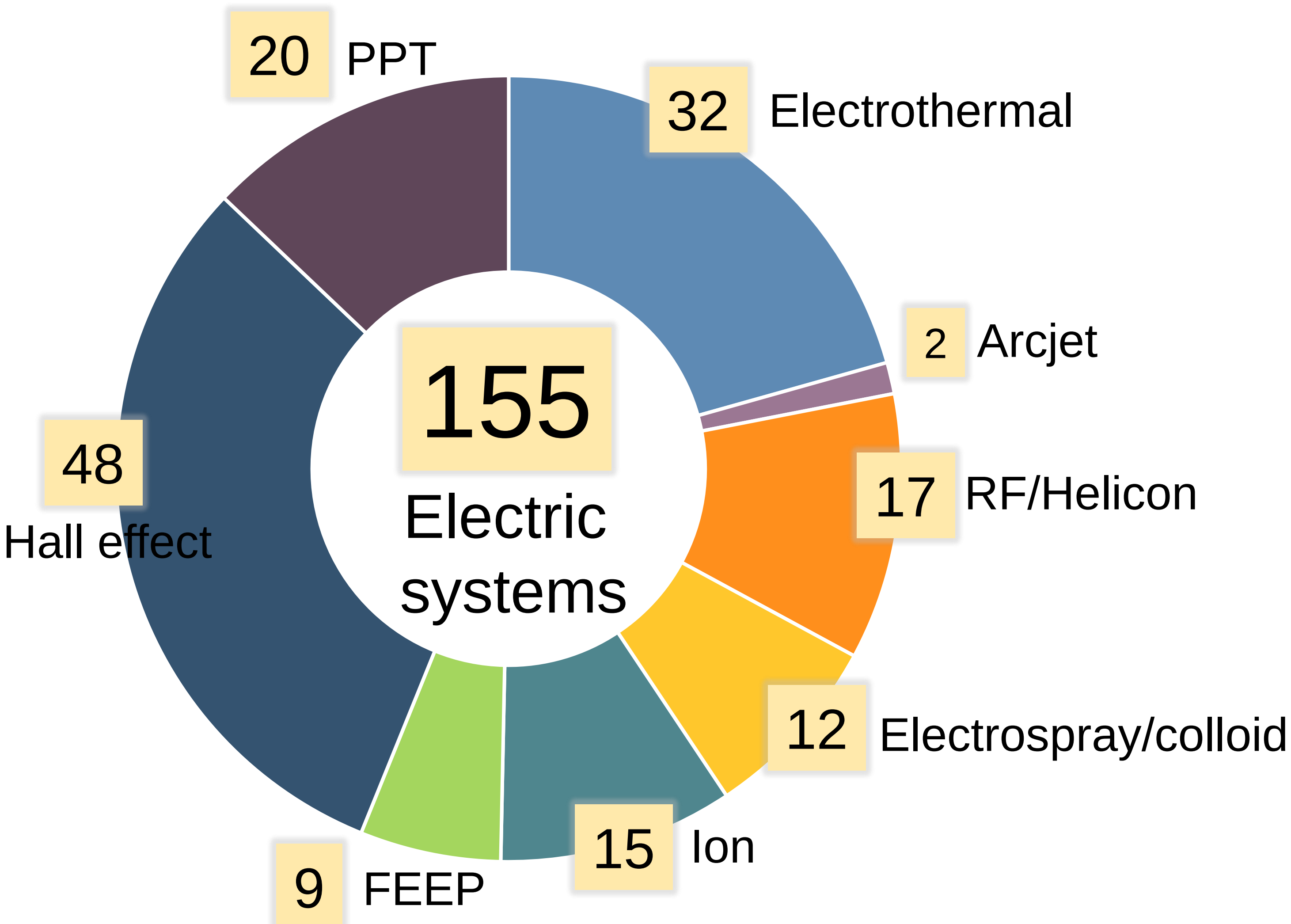
Electric Propulsion Options - Summary

2023 Outlook



Typical propellant types

- Inert gases (Xe, Ar, Kr)
- Iodine
- Teflon
- Indium
- Ionic liquids

⋮

64 are domestic, followed closely European commercial space companies

– *Notable domestic vendors: Busek, PhaseFour, Orbion, Exoterra*

– *Notable foreign vendors: Ariane Group, ThrustMe, Enpulsion, Rafael, Fakel, Pale Blue*

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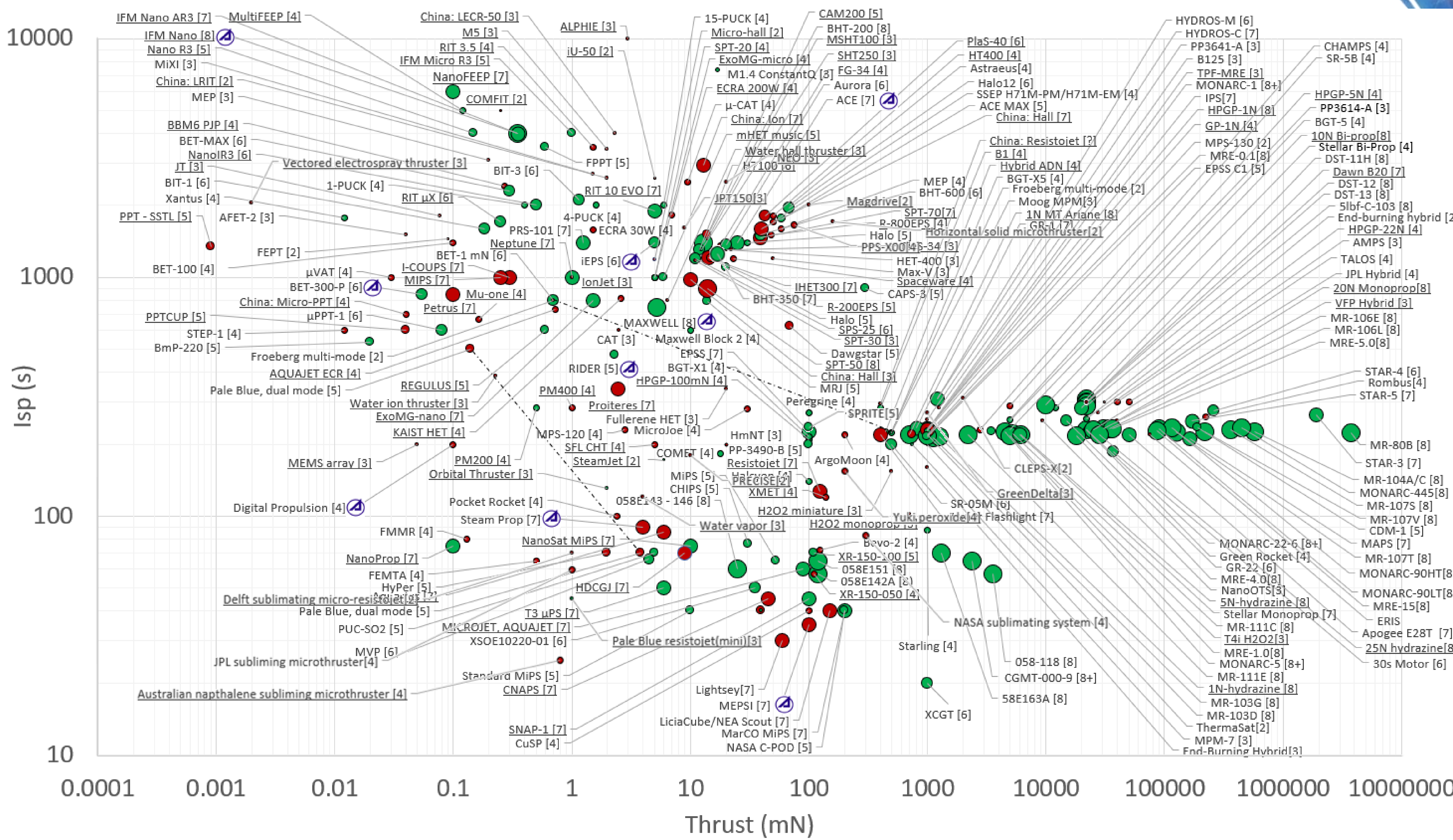
*Specific Impulse vs. Thrust**

- Commercially available
- Unavailable
- Aerospace has tested, ≠ endorsement
- ABCD Foreign manufacturer
- ----- Dual mode systems

*Only systems with published Isp and Thrust values are plotted

Size of marker indicates TRL level



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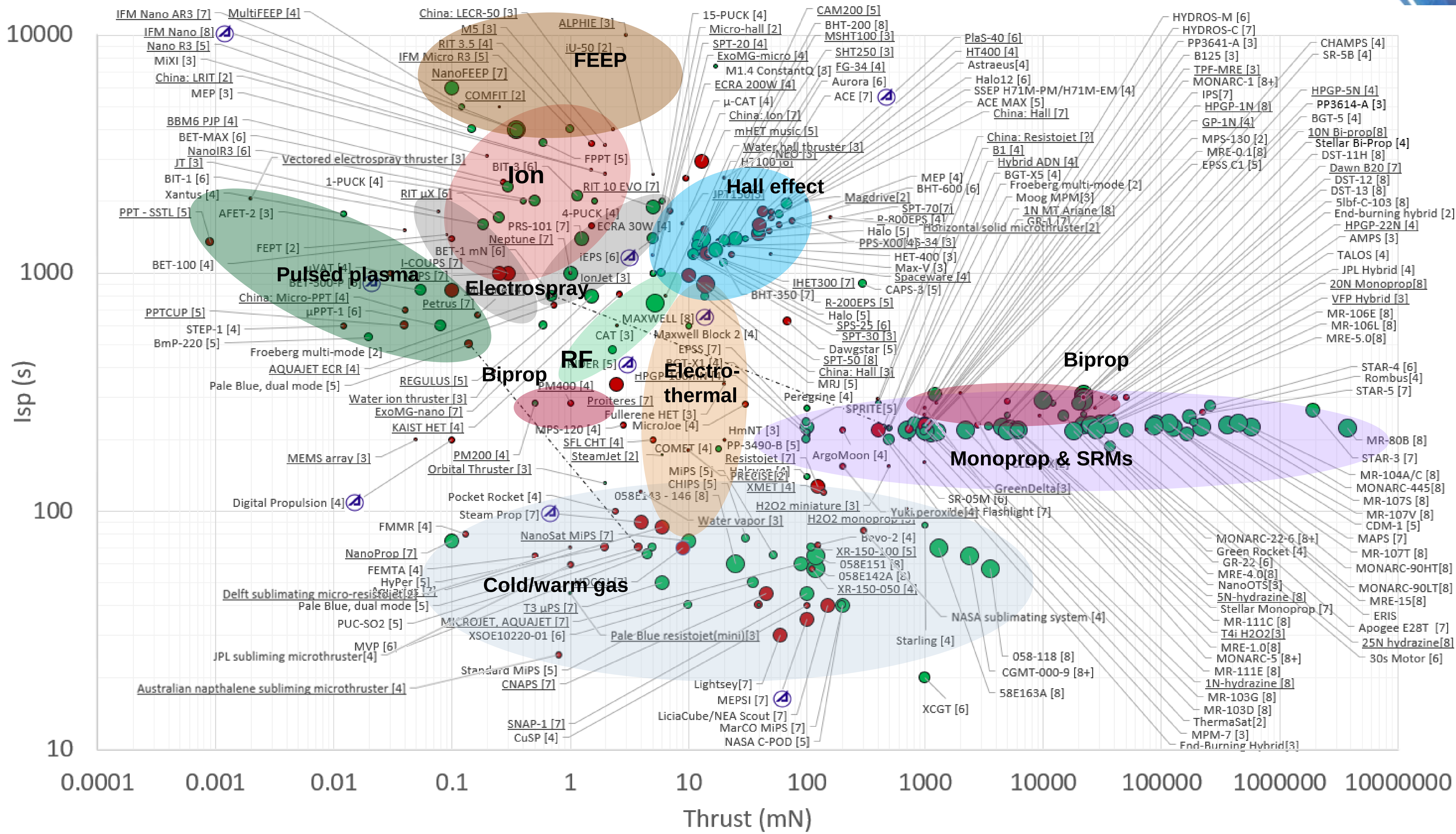
*Specific Impulse vs. Thrust, by propulsion technology**

*Only systems with published Isp and Thrust values are plotted

- Commercially available
- Unavailable
- Aerospace has tested, ≠ endorsement
- ABCD Foreign manufacturer
- Dual mode systems

Size of marker indicates TRL level



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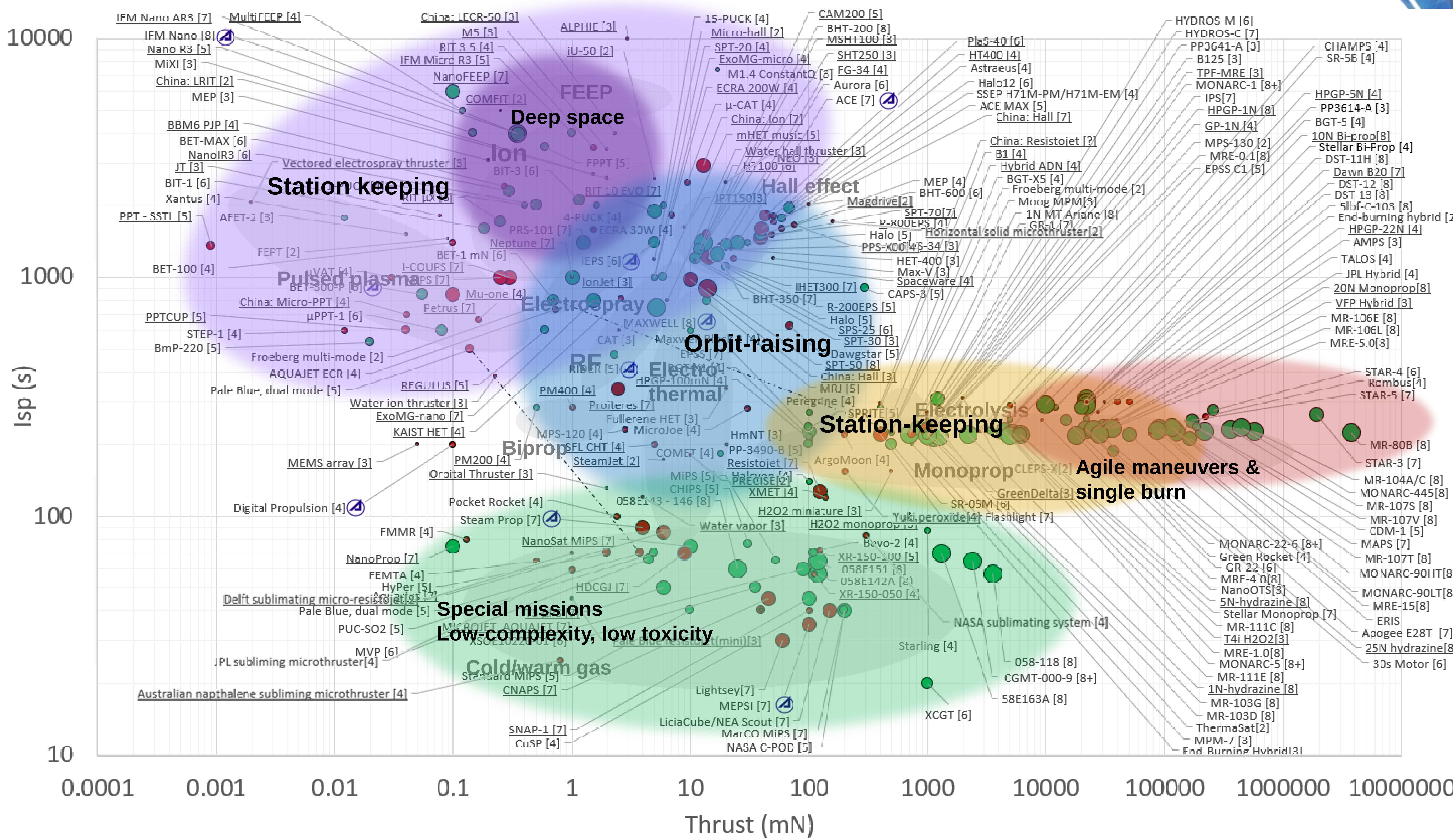
*Specific Impulse vs. Thrust, by mission**

*Only systems with published Isp and Thrust values are plotted

Commercially available
Unavailable
Aerospace has tested, ≠ endorsement
ABCD Foreign manufacturer
Dual mode systems

Size of marker indicates TRL level



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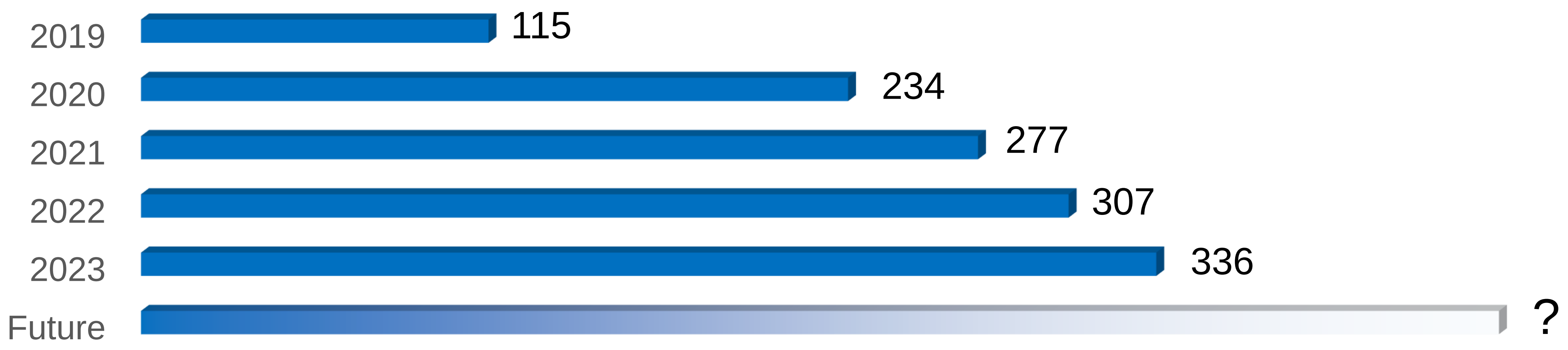
Trends, observations, and thoughts

The number of propulsion systems has increased over the last 5 years



- How to best account for systems suspected to be no longer in production?
- How to better track progress? Current system utilizes an organic approach
- How to more accurately gauge technologies which have limited publications/publicly available news?

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Trends, observations, and thoughts

Trends from this year…

- **Growth and turbulence in the electric propulsion industry has resulted in an increase in the number and variety of thrusters**
  - Hall thrusters: many models and manufacturers have emerged, perished, been acquired, renamed, redesigned, etc.
  - FEEPs and Metal PPTs are emerging, as they offer integration simplicity (no moving parts and solid propellant storage)
  - Foreign vendors making headway – two-thirds of new systems found this year were not domestic, mostly European
  - Fraction of EP systems reaching flight is higher this year than last year, indicating push for launch
  - Growing interest in alternative propellants due to high price of xenon
- **Chemical systems proceed with steady growth**
  - Heritage large manufacturers continue to lead with very high TRL systems, but there is increased competition from small companies in two main areas:
    - Miniaturization of hydrazine systems, due to a growing acceptance of hydrazine on small satellites combined with successful first flight demonstrations
    - Adoption of "Green" propellants (hydrazine alternatives), including ionic liquids, ammonium dinitramide blends, peroxide, water, N2O blends
  - Novel technologies such as ultra-low SWAP solid arrays, small biprops, novel propellants, additive manufacturing, and MEMs systems are emerging.
  - Need for agile, high thrust systems still apparent

More observations for discussion…

- There is an (over) - abundance of available propulsion systems
  - Many duplicates of similar technologies being manufactured at multiple vendors
  - Major commercial players develop their own propulsion (e.g., Starlink, Kuiper)
  - Venture capital appears to be driving a significant portion of R&D rather than market demand to satisfy mission needs
    - Venture capital seeks a profitable market exit that may not result in COTS hardware available to NSS on the open market
- Commercial TRLs are self-reported with minimal third-party validation
  - Different TRL systems exist which can make self-reported maturity levels confusing to customers
- Start-ups face challenges advancing systems to TRL > 6
  - Establishing in-house test facilities is expensive and flights are difficult to procure
- Lack of qualification and acceptance standards tailored to small satellites
  - 'Proto-qual' system is specific to individual missions and customers
    - SMC standards (such as SMC-S-025, SMC-S005, SMC-S-016 may not encompass all customer needs, or may be too much, incurring extra cost and schedule)
    - Agile missions require rapid technology development or COTS options, but standards for qualification of COTS hardware by flight and ground test are not well established
- Lack of mission requirements standards for guiding technology development
  - Evolution from one-off deep-pocketed missions to small agile missions requires a change in industry and customer mindset
    - Traditionally, mission needs drive technology development and requirements, but this is too time consuming and costly in the new space era
  - Mission needs are increasingly confined to high side, leaving commercial developers in the dark
  - NASA and NSS mission requirements often have little overlap, causing tech development to be unaligned

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PROPULSION SYSTEMS….

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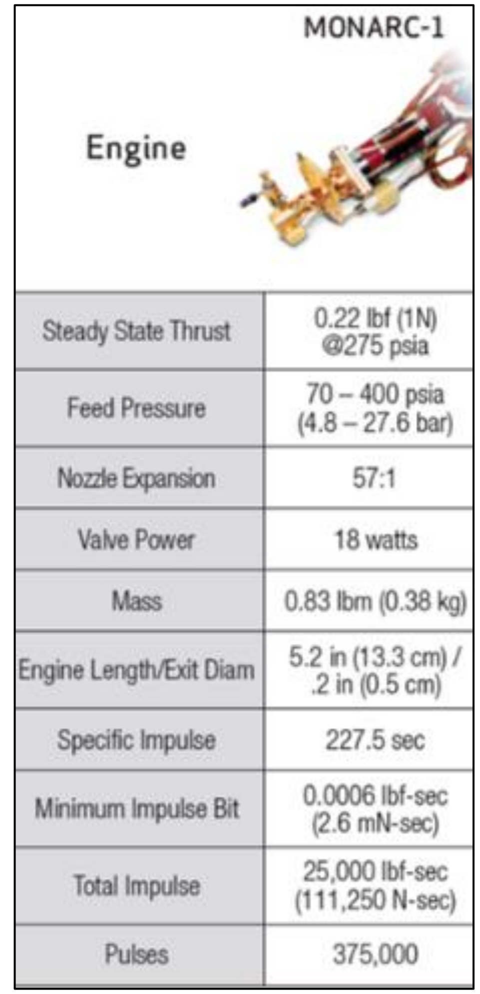
MONARC-1 MOOG

Propulsion Technology	Hydrazine monopropellant
Manufacturer/Country	Moog (USA) (formerly AMPAC In-Space Propulsion, ISP)
TRL	8+
Size (including PPU)	14 cm L x 0.5 cm D (~1.5U)
Design satellite size	>6U
Isp (s)	227.5
Thrust type/magnitude	1N (0.22 lbf) (thrust, nominal) 25,000 lbf*s (impulse, total) 0.0006 lbf*s (impulse, min)
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	18W (valve)
Flight heritage (if any)	Extensive (although could not find if any were small satellites).
Commercially available	YES
Last updated	*01/2019*



Engine	MONARC-1
Steady State Thrust	0.22 lbf (1N) @275 psia
Feed Pressure	70 – 400 psia (4.8 – 27.6 bar)
Nozzle Expansion	57:1
Valve Power	18 watts
Mass	0.83 lbm (0.38 kg)
Engine Length/Exit Diam	5.2 in (13.3 cm) / .2 in (0.5 cm)
Specific Impulse	227.5 sec
Minimum Impulse Bit	0.0006 lbf-sec (2.6 mN-sec)
Total Impulse	25,000 lbf-sec (111,250 N-sec)
Pulses	375,000

Additional comments:

[Reference 1-3][Jan 2019][General thruster info]

Feed pressure = 70 - 400 psia, mass is 0.4 kg, and pulses are 375,000. System has extensive history on conventional satellites. From Moog's website, "The MONARC line of monopropellant thrusters provides a simple and reliable propulsion solution and are particularly suited for ACS applications. Higher-thrust engines can be used for main (delta-v) engine applications or flight vehicle attitude control. These engines can be used in a monopropellant or dual-mode system. Engines range from a nominal 0.2 lbf (1 N) to 100 lbf (445 N) and over 3000 have been delivered. Missions: Galileo (ENSS), ORBCOMM Generation 2 (OG2), BepiColombo, MMS, Worldview, Landsat 8 (LDCM), GOES-R/S, LCROSS."
However, the authors could not find any small satellite missions that have flown these.

References:
[1] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html
[2] http://www.moog.com/content/dam/moog/literature/Space_Defense/Spacecraft/Monopropellant_Thrusters_Rev_0613.pdf
[3] History of Liquid Propellant Rocket Engines, by George Sutton, 2006.

8+ | NO

Comm. avail. | TRL | Aerospace-tested

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MONARC-5 MOOG

Propulsion Technology	Hydrazine monopropellant
Manufacturer/Country	Moog (USA) (formerly AMPAC In-Space Propulsion, ISP)
TRL	8+
Size (including PPU)	42 cm L x 3 cm D (~4.5U)
Design satellite size	>6U
Isp (s)	226.1
Thrust type/magnitude	4.5N (1 lbf) (thrust, nominal) 138,000 lbf*s (impulse, total) 0.0007 lbf*s (impulse, min)
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	18W (valve)
Flight heritage (if any)	Yes. Extensive on conventional spacecraft. For small satellites, Soil Moisture Active Passive (SMAP, 2015) [4]
Commercially available	YES
Last updated	*06/2020*

Engine	MONARC-5 
Steady State Thrust	1.0 lbf (4.5 N) @325 psia
Feed Pressure	80 – 420 psia (5.5 – 29.0 bar)
Nozzle Expansion	135:1
Valve Power	18 watts
Mass	1.08 lbm (0.49 kg)
Engine Length/Exit Diam	9.4 in (41.8 cm) /1 in (2.5 cm)
Specific Impulse	226.1 secs
Minimum Impulse Bit	0.0007 lbf-sec (3.1 mN-sec)
Total Impulse	138,000 lbf-sec (613,852 N-sec)
Pulses	205,000

Additional comments:

[Reference 1-5][Jan 2019][General thruster info]

Feed pressure = 80-420 psia, mass is 0.5 kg, and pulses are 205,000.

System has been reviewed by George Sutton's book and has a long flight heritage on conventional spacecraft. Moog's website says, "The MONARC-5 has a long heritage, dating back more than 30 years, with flight heritage on a range of commercial and exploration missions, including Worldview, LCROSS and MMS. Nearly 600 MONARC-5 hydrazine monopropellant thrusters have been delivered and flown."

From the AIAA paper on the catalyst, "The MONARC-5 thrusters have a successful heritage with the Shell 405 catalyst substrate. However, with the dwindling supply of Shell 405, Moog-ISP now manufactures the MONARC 5 with Heraeus catalyst manufactured in Germany."

The only small satellite mission to our knowledge that has launched Monarc-5 thrusters is NASA/JPL's Soil Moisture Active Passive (SMAP) satellite, launched 2014. Moog delivered nine MONARC-5 thrusters and one qualification thruster to JPL. Thrusters were integrated onto SMAP and activated soon after separation from the Delta II second stage to de-tumble the spacecraft and initiate sun acquisition after solar array deployment.

The NASA report claims flight demonstrations aboard SMAP were successful and that the thruster demonstrated 4.5 N thrust on orbit

References:

[1] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html

[2] History of Liquid Propellant Rocket Engines, by George Sutton, 2006.

[3] http://www.moog.com/news/operating-group-news/2015/moog-supports-ula-delta-ii-launch-with-nasa-spacecraft-for-enhanced-understing-of-weather-climate/

[4] NASA survey of small-satellite propulsion, 2018. https://sst-soa.arc.nasa.gov/04-propulsion

[5] Gatto, C., Nakazono, B., "Life test results of a MONARC-5 1 lbf monopropellant thruster with Heraeus catalyst," AIAA, 2014.

Comm. avail.	TRL	Aerospace-tested
	8+	NO

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MONARC-22-6 MOOG

Propulsion Technology	Hydrazine monopropellant
Manufacturer/Country	Moog (USA) (formerly AMPAC In-Space Propulsion, ISP)
TRL	8+
Size (including PPU)	20 cm L x 4 cm Dia (~2U)
Design satellite size	>6U
Isp (s)	229.5
Thrust type/magnitude	22N (5 lbf) (thrust, nominal) 120,000 lbf*s (impulse, total) 0.07 lbf*s (impulse, min)
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	30W (valve)
Flight heritage (if any)	Yes. Extensive on conventional spacecraft. No small sat missions found.
Commercially available	YES
Last updated	*01/2019*

Engine	MONARC-22-6	MONARC-22-12
Steady State Thrust	5 lbf (22N) @275 psia	5 lbf (22N) @190 psia
Feed Pressure	70 – 400 psia (4.8 – 27.6 bar)	70 – 400 psia (4.8 – 27.6 bar)
Nozzle Expansion	60:1	40:1
Valve Power	30 watts	30 watts
Mass	1.58 lbm (0.72 kg)	1.51 lbm (0.69 kg)
Engine Length/Exit Diam	8 in (20.3 cm) / 1.5 in (3.8 cm)	9 in (22.9 cm) / 1.2 in (5.3 cm)
Specific Impulse	229.5 secs	228.1 secs
Minimum Impulse Bit	0.07 lbf-sec (312m N-sec)	0.12 lbf-sec (526m N-sec)
Total Impulse	120,000 lbf-sec (533,784 N-sec)	263,720 lbf-sec (1,173,085 N-sec)
Pulses	230,000	160,000

Additional comments:

[Reference 1-4][Jan 2019][General thruster info]

Feed pressure = 70-400 psia, mass is 0.7 kg, and pulses are 230,000 (MONARC-22-6). System has extensive history on conventional satellites. From Moog's website, "The MONARC line of monopropellant thrusters provides a simple and reliable propulsion solution and are particularly suited for ACS applications. Higher-thrust engines can be used for main (delta-v) engine applications or flight vehicle attitude control. These engines can be used in a monopropellant or dual-mode system. Engines range from a nominal 0.2 lbf (1 N) to 100 lbf (445 N), and over 3000 have been delivered. Missions: Galileo (ENSS), ORBCOMM Generation 2 (OG2), BepiColombo, MMS, Worldview, Landsat 8 (LDCM), GOES-R/S, LCROSS." However, the authors could not find any small satellite missions that have flown these.

References:

[1] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html

[2] http://www.moog.com/content/dam/moog/literature/Space_Defense/Spacecraft/Monopropellant_Thrusters_Rev_0613.pdf

[3] History of Liquid Propellant Rocket Engines, by George Sutton, 2006.

[4] NASA survey of small-satellite propulsion, 2018. https://sst-soa.arc.nasa.gov/04-propulsion

Comm. avail.	TRL	Aerospace-tested
	8+	NO

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MONARC-22-12 MOOG

Propulsion Technology	Hydrazine monopropellant
Manufacturer/Country	Moog (USA) (formerly AMPAC In-Space Propulsion, ISP)
TRL	8+
Size (including PPU)	23 cm L x 6 cm Dia (~2.5U)
Design satellite size	>6U
Isp (s)	228.1
Thrust type/magnitude	22N (5 lbf) (thrust, nominal) 263,720 lbf*s (impulse, total) 0.12 lbf*s (impulse, min)
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	30W (valve)
Flight heritage (if any)	Yes. Extensive on conventional spacecraft. No small sat missions found.
Commercially available	YES
Last updated	*01/2019*

Engine	MONARC-22-6	MONARC-22-12
Steady State Thrust	5 lbf (22N) @275 psia	5 lbf (22N) @190 psia
Feed Pressure	70 – 400 psia (4.8 – 27.6 bar)	70 – 400 psia (4.8 – 27.6 bar)
Nozzle Expansion	60:1	40:1
Valve Power	30 watts	30 watts
Mass	1.58 lbm (0.72 kg)	1.51 lbm (0.69 kg)
Engine Length/Exit Diam	8 in (20.3 cm) / 1.5 in (3.8 cm)	9 in (22.9 cm) / 1.2 in (5.3 cm)
Specific Impulse	229.5 secs	228.1 secs
Minimum Impulse Bit	0.07 lbf-sec (312m N-sec)	0.12 lbf-sec (526m N-sec)
Total Impulse	120,000 lbf-sec (533,784 N-sec)	263,720 lbf-sec (1,173,085 N-sec)
Pulses	230,000	160,000

Additional comments:

[Reference 1-4][Jan 2019][General thruster info]

Feed pressure = 70-400 psia, mass is 0.7 kg, and pulses are 160,000 (MONARC-22-12). System has extensive history on conventional satellites. From Moog's website, "The MONARC line of monopropellant thrusters provides a simple and reliable propulsion solution and are particularly suited for ACS applications. Higher-thrust engines can be used for main (delta-v) engine applications or flight vehicle attitude control. These engines can be used in a monopropellant or dual mode system. Engines range from a nominal 0.2 lbf (1 N) to 100 lbf (445 N) and over 3000 have been delivered. Missions: Galileo (ENSS), ORBCOMM Generation 2 (OG2), BepiColombo, MMS, Worldview, Landsat 8 (LDCM), GOES-R/S, LCROSS."
However, the authors could not find any small satellite missions that have flown these.

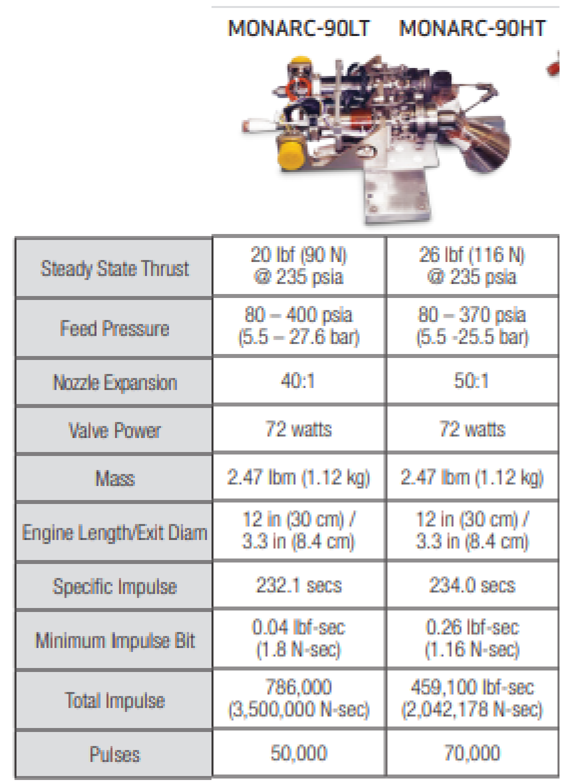
References:
[1] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html
[2] http://www.moog.com/content/dam/moog/literature/Space_Defense/Spacecraft/Monopropellant_Thrusters_Rev_0613.pdf
[3] History of Liquid Propellant Rocket Engines, by George Sutton, 2006.
[4] NASA survey of small-satellite propulsion, 2018. https://sst-soa.arc.nasa.gov/04-propulsion

Comm. avail.	TRL	Aerospace-tested
	8+	NO

DISTRO A: Approved for public release. OTR-2024-00338

MONARC-90LT MOOG

Propulsion Technology	Hydrazine monopropellant
Manufacturer/Country	Moog (USA) (formerly AMPAC In Space Propulsion, ISP)
TRL	8+
Size (including PPU)	30 cm L x 8.4 cm D (~3U)
Design satellite size	
Isp (s)	232.1
Thrust type/magnitude	90N (20 lbf) (thrust, nominal) 786,000 lbf*s (impulse, total) 0.04 lbf*s (impulse, min)
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	30W (valve)
Flight heritage (if any)	
Commercially available	YES
Last updated	07/2020



	MONARC-90LT	MONARC-90HT
Steady State Thrust	20 lbf (90 N) @ 235 psia	26 lbf (116 N) @ 235 psia
Feed Pressure	80 – 400 psia (5.5 – 27.6 bar)	80 – 370 psia (5.5 -25.5 bar)
Nozzle Expansion	40:1	50:1
Valve Power	72 watts	72 watts
Mass	2.47 lbm (1.12 kg)	2.47 lbm (1.12 kg)
Engine Length/Exit Diam	12 in (30 cm) / 3.3 in (8.4 cm)	12 in (30 cm) / 3.3 in (8.4 cm)
Specific Impulse	232.1 secs	234.0 secs
Minimum Impulse Bit	0.04 lbf-sec (1.8 N-sec)	0.26 lbf-sec (1.16 N-sec)
Total Impulse	786,000 (3,500,000 N-sec)	459,100 lbf-sec (2,042,178 N-sec)
Pulses	50,000	70,000

Additional comments:

[Reference 1][July 2020][General info]
Feed pressure = 70-400 psia, mass is 1.2 kg. System has extensive history on conventional satellites. From Moog's website, "The MONARC line of monopropellant thrusters provides a simple and reliable propulsion solution and are particularly suited for ACS applications. Higher-thrust engines can be used for main (delta-v) engine applications or flight vehicle attitude control. These engines can be used in a monopropellant or dual mode system. Engines range from a nominal 0.2 lbf (1 N) to 100 lbf (445 N) and over 3000 have been delivered. Missions: Galileo (ENSS), ORBCOMM Generation 2 (OG2), BepiColombo, MMS, Worldview, Landsat 8 (LDCM), GOES-R/S, LCROSS."

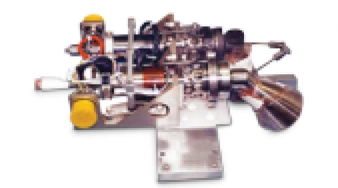
However, the authors could not find any small satellite missions that have flown these.

References:
[1] https://www.moog.com/products/propulsion-controls.html

Comm. avail.	8+	NO
	TRL	Aerospace-tested

MONARC-90HT MOOG

Propulsion Technology	Hydrazine monopropellant
Manufacturer/Country	Moog (USA) (formerly AMPAC In Space Propulsion, ISP)
TRL	8+
Size (including PPU)	30 cm L x 8.4 cm D (~3U)
Design satellite size	
Isp (s)	234.0
Thrust type/magnitude	116N (26 lbf) (thrust, nominal) 459,100 lbf*s (impulse, total) 0.26 lbf*s (impulse, min)
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	72W (valve)
Flight heritage (if any)	
Commercially available	YES
Last updated	07/2020



	MONARC-90LT	MONARC-90HT
Steady State Thrust	20 lbf (90 N) @ 235 psia	26 lbf (116 N) @ 235 psia
Feed Pressure	80 – 400 psia (5.5 – 27.6 bar)	80 – 370 psia (5.5 -25.5 bar)
Nozzle Expansion	40:1	50:1
Valve Power	72 watts	72 watts
Mass	2.47 lbm (1.12 kg)	2.47 lbm (1.12 kg)
Engine Length/Exit Diam	12 in (30 cm) / 3.3 in (8.4 cm)	12 in (30 cm) / 3.3 in (8.4 cm)
Specific Impulse	232.1 secs	234.0 secs
Minimum Impulse Bit	0.04 lbf-sec (1.8 N-sec)	0.26 lbf-sec (1.16 N-sec)
Total Impulse	786,000 (3,500,000 N-sec)	459,100 lbf-sec (2,042,178 N-sec)
Pulses	50,000	70,000

Additional comments:

[Reference 1][July 2020][General info]
Feed pressure = 70-400 psia, mass is 1.2 kg. System has extensive history on conventional satellites. From Moog's website, "The MONARC line of monopropellant thrusters provides a simple and reliable propulsion solution and are particularly suited for ACS applications. Higher-thrust engines can be used for main (delta-v) engine applications or flight vehicle attitude control. These engines can be used in a monopropellant or dual mode system. Engines range from a nominal 0.2 lbf (1 N) to 100 lbf (445 N) and over 3000 have been delivered. Missions: Galileo (ENSS), ORBCOMM Generation 2 (OG2), BepiColombo, MMS, Worldview, Landsat 8 (LDCM), GOES-R/S, LCROSS."

However, the authors could not find any small satellite missions that have flown these.

References:
[1] https://www.moog.com/products/propulsion-controls/spacecraft/thrusters.html

8+ NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

MONARC-445 MOOG

Propulsion Technology	Hydrazine monopropellant
Manufacturer/Country	Moog (USA) (formerly AMPAC In Space Propulsion, ISP)
TRL	8+
Size (including PPU)	41 cm L x 14.8 cm W
Design satellite size	
Isp (s)	234.0
Thrust type/magnitude	445N (100 lbf) (thrust, nominal) 1,25,000 lbf*s (impulse, total) 2.59 lbf*s (impulse, min
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	58W (valve)
Flight heritage (if any)	
Commercially available	YES
Last updated	07/2020

Additional comments:

[Reference 1][July 2020][General info]
Feed pressure = 70-400 psia, mass is 1.2 kg. System has extensive history on conventional satellites. From Moog's website, "The MONARC line of monopropellant thrusters provides a simple and reliable propulsion solution and are particularly suited for ACS applications. Higher-thrust engines can be used for main (delta-v) engine applications or flight vehicle attitude control. These engines can be used in a monopropellant or dual mode system. Engines range from a nominal 0.2 lbf (1 N) to 100 lbf (445 N) and over 3000 have been delivered. Missions: Galileo (ENSS), ORBCOMM Generation 2 (OG2), BepiColombo, MMS, Worldview, Landsat 8 (LDCM), GOES-R/S, LCROSS."

However, the authors could not find any small satellite missions that have flown these.

References:
[1] https://www.moog.com/products/propulsion-controls/spacecraft/thrusters.html

8+ NO

Comm. avail. TRL Aerospace-tested

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Cold Gas MicroThruster (CGMT-000-9)
Marotta

Propulsion Technology	Cold gas
Manufacturer/Country	Marotta (USA) with UK branch (Marotta UK) (UK)
TRL	8+
Size (including PPU)	Very small, <70g (~0.25U)
Design satellite size	1U or larger
Isp (s)	~65
Thrust type/magnitude	2.4N at 154bar GN2 (beginning of life) 0.05N at end of life due to pressure decrease 44 mN*s (impulse bit, min)
Delta-V (m/s)	
Propellant	GHe, GN2
Power consumption (W)	<1W peak power consumption
Flight heritage (if any)	NASA ST-5
Commercially available	YES
Last updated	*01/2019*

CGMT-000-9

Additional comments:
[Reference 1-3][Jan 2019][General info]
Marotta Controls developed and qualified the Cold Gas Micro Thruster (CGMT) as part of the NMP ST5 program. The effort was managed and delivered to NASA GSFC. When coupled with its control electronics, this thruster achieves < 1 Watt Peak Power consumption using a low voltage 3.3 or 5 VDC supply bus. The design began as, and achieved operation with, a 3.3 VDC spacecraft supply bus voltage [13], though during the ST5 efforts it was adjusted to 5 VDC to accommodate a change in bus voltage at the system level. Interface mounting was also modified to accommodate system configuration requirements. The updated version was used in performing component qualification testing. The ST5 program involves three spacecraft, each using a single thruster per craft in a blow-down cold gas system. Thrust begins at ~2.36 N Thrust @ 154 bar GN2 then becomes ~105 mN Thrust @ 7 bar GN2 at near-exhaustion after blowdown. Minimum impulse bit is 44 mN-sec. Flight hardware has been delivered and integrated and is awaiting the demonstration flight. This hardware has been included in NASA Tech Briefs (8/2004), Aviation Week & Space Technology (3/22/2004), and Aerospace Engineering (12/2003) publications.
The thruster has been tested to 6000 open/close cycles.
Marotta UK is extensively involved in a variety of SSTL propulsion platforms. SSTL spacecraft with propulsion systems in orbit, in build, or in development include: SNAP-1, Alsat-1, UK-DMC, BilSat-1, PROBA 2.

References:
[1] https://www.prweb.com/releases/2006/04/prweb363198.htm
[2] Schappell, D., Scarduffa, E., Smith, P., Solway, N., “Advances in Marotta electric and small satellite propulsion fluid control activities,” AIAA-2005-4055.
[3] Spektor, R., Fathi, G., Brady, B., Moore, T., “2011 Review of Propulsion Options for the Aerospace CubeSat Project,” Aerospace report TOR-2011(8582)-6

(cart icon)	8+	NO
Comm. avail.	TRL	Aerospace-tested

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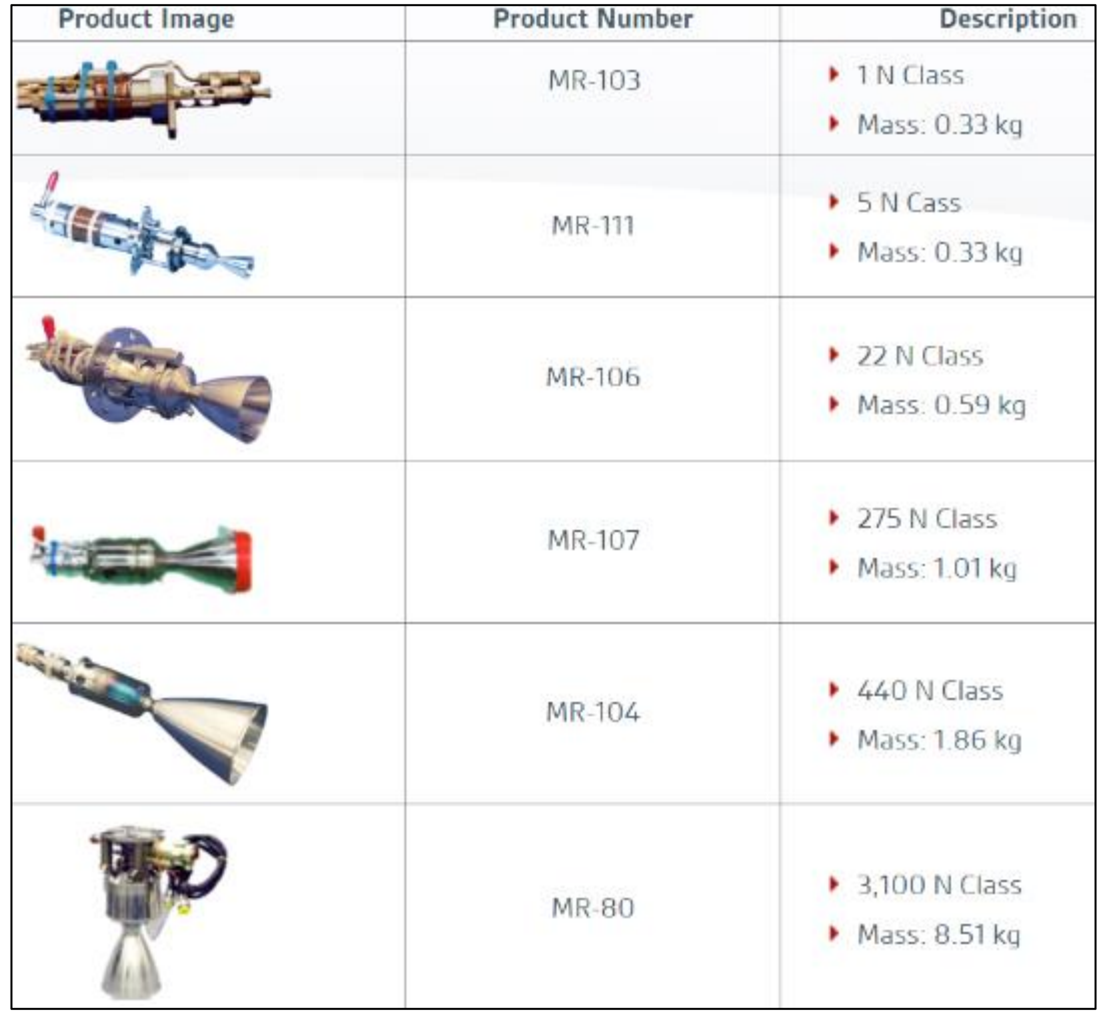
MR-XXX Hydrazine Monopropellant Thruster Family
Aerojet Rocketdyne (1 of 13)

Propulsion Technology	On next slides
Manufacturer/Country	
TRL	
Size (including PPU)	
Design satellite size	
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	
Power consumption (W)	
Flight heritage (if any)	
Commercially available	
Last updated	*01/2019*



Product Image	Product Number	Description
	MR-103	1 N Class Mass: 0.33 kg
	MR-111	5 N Cass Mass: 0.33 kg
	MR-106	22 N Class Mass: 0.59 kg
	MR-107	275 N Class Mass: 1.01 kg
	MR-104	440 N Class Mass: 1.86 kg
	MR-80	3,100 N Class Mass: 8.51 kg

Aerojet's family of hydrazine thrusters

Additional comments:
[Reference 1][Jan 2019][Thruster info]
The manufacturer's website has extensive specifications.
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).

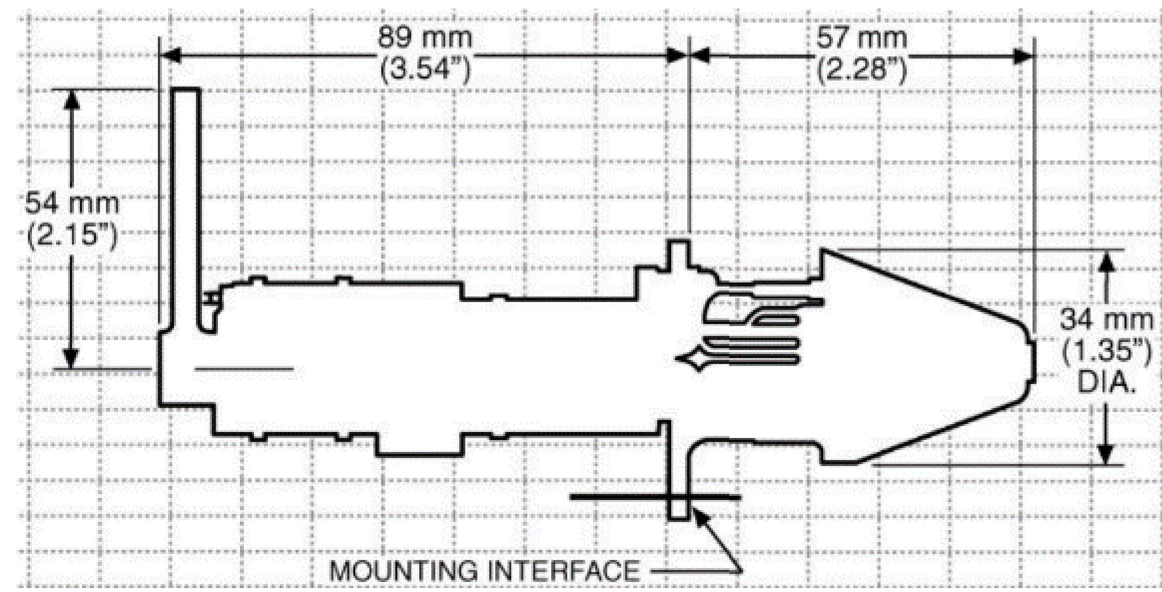
References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets

Comm. avail.	TRL	Aerospace-tested
	8+	NO

DISTRO A: Approved for public release. OTR-2024-00338

MR-103D 1N
Aerojet Rocketdyne (2 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~1.5U
Design satellite size	
Isp (s)	224 – 209 s
Thrust type/magnitude	1.02 – 0.22 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	~14 W
Flight heritage (if any)	Extensive A version of the MR-103 was flown on the NASA New Horizons mission [3]
Commercially available	YES
Last updated	*06/2020*



Additional comments:

[Reference 1-2][Jan 2019][Thruster info]
The manufacturer's website has extensive specifications.
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).

[Reference 3][Jun 2020][Flight info]
Aerojet Rocketdyne has leveraged existing designs with flight heritage from large spacecraft that may be applicable to small buses, such as the MR-103 thruster used on New Horizons for attitude control application. Other Aerojet Rocketdyne thrusters potentially applicable to small spacecraft include the MR-111 and the MR-106. These systems have successfully flown on a number of missions.

References:

[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf
[3] NASA 2020 SOA for Small Satellites (POC Gabriel Benavides). https://www.nasa.gov/smallsat-institute/sst-soa-2020/in-space-propulsion

Comm. avail.	TRL	Aerospace-tested
	8+	NO

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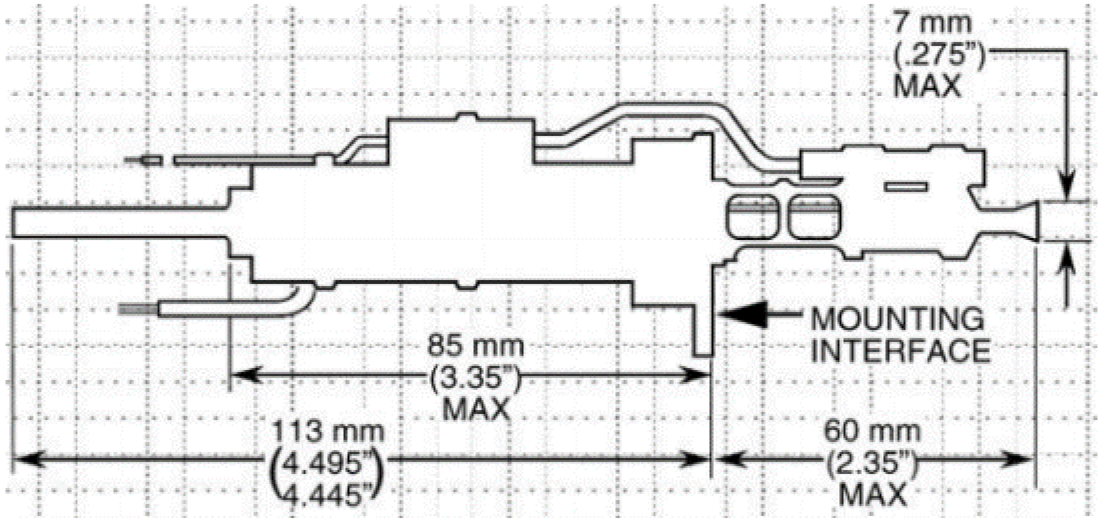
MR-103G 1N
Aerojet Rocketdyne (3 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~1.75U
Design satellite size	
Isp (s)	224 – 202 s
Thrust type/magnitude	1.13 – 0.19 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	~14 .5 W
Flight heritage (if any)	Extensive
Commercially available	YES
Last updated	*04/2023*



Additional comments:
[Reference 1-2][Jan 2019][General info]
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).
The manufacturer's website has extensive specifications, specified in the references.

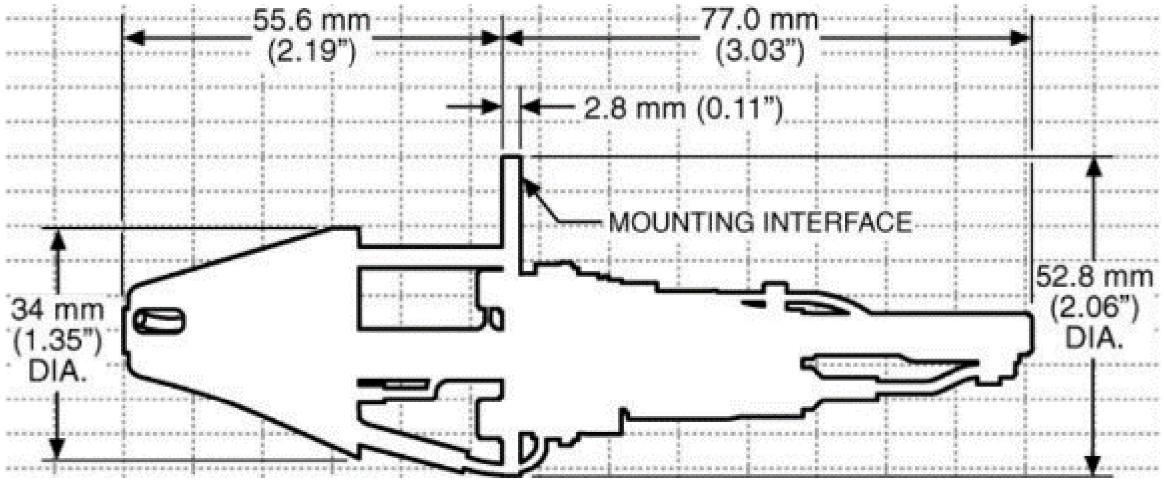
References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf

DISTRO A: Approved for public release. OTR-2024-00338

8+ NO
Comm. avail. TRL Aerospace-tested

MR-103M 1N
Aerojet Rocketdyne (4 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~1.25U
Design satellite size	
Isp (s)	221 – 206 s
Thrust type/magnitude	0.99 – 0.28 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	~11 W
Flight heritage (if any)	Extensive
Commercially available	YES
Last updated	*01/2019*



Additional comments:
[Reference 1-2][Jan 2019][General info]
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).
The manufacturer's website has extensive specifications.

References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf

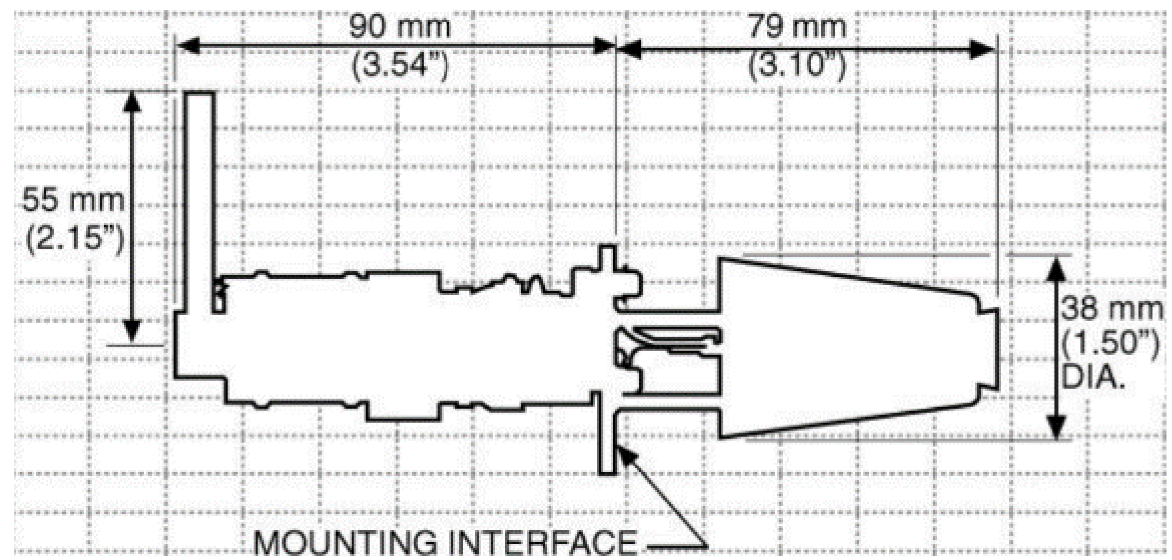
8+ NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

MR-111C 4N
Aerojet Rocketdyne (5 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~1.70U
Design satellite size	
Isp (s)	229 – 215 s
Thrust type/magnitude	5.3 – 1.3 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	~13.6 W
Flight heritage (if any)	Extensive
Commercially available	YES
Last updated	*01/2019*



Additional comments:
[Reference 1-2][Jan 2019][General info]
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).
The manufacturer's website has extensive specifications.

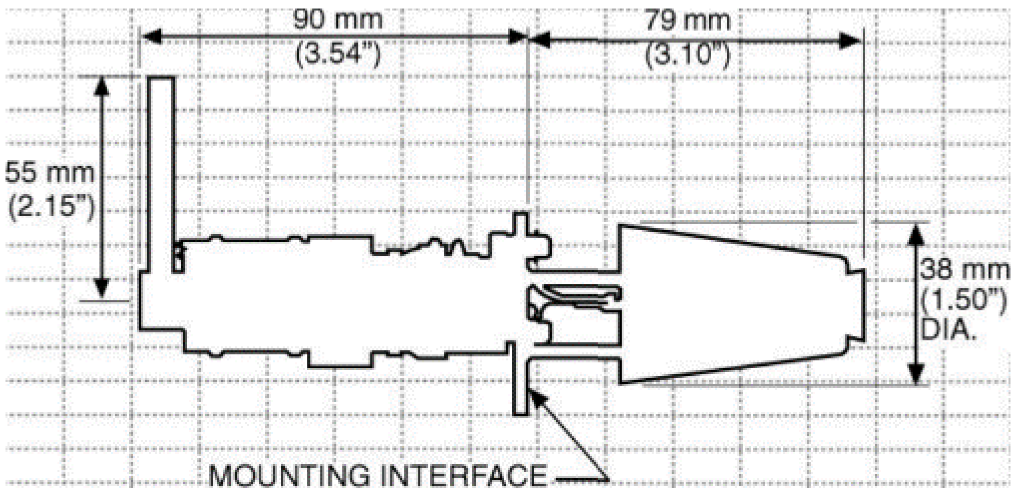
References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf

8+ NO
Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

MR-111E 2N
Aerojet Rocketdyne (6 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~1.70U
Design satellite size	
Isp (s)	224 – 213 s
Thrust type/magnitude	2.2 – 0.5 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	~13.6 W
Flight heritage (if any)	Extensive
Commercially available	YES
Last updated	*01/2019*



Additional comments:
[Reference 1-2][Jan 2019][General info]
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).
The manufacturer's website has extensive specifications.

References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf

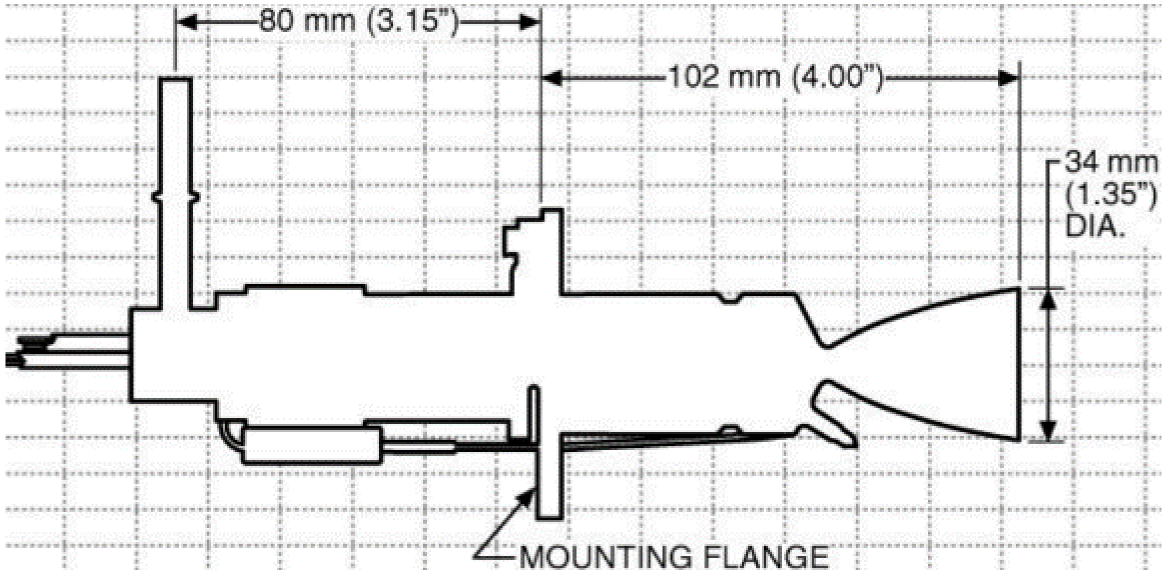
Comm. avail.	8+ TRL	NO Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

MR-106E 22N
Aerojet Rocketdyne (7 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~1.8U
Design satellite size	
Isp (s)	235 – 229 s
Thrust type/magnitude	30.7 – 11.6 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	~35 W
Flight heritage (if any)	Extensive
Commercially available	YES
Last updated	*01/2019*



Additional comments:
[Reference 1-2][Jan 2019][General info]
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).
The manufacturer's website has extensive specifications.

References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf

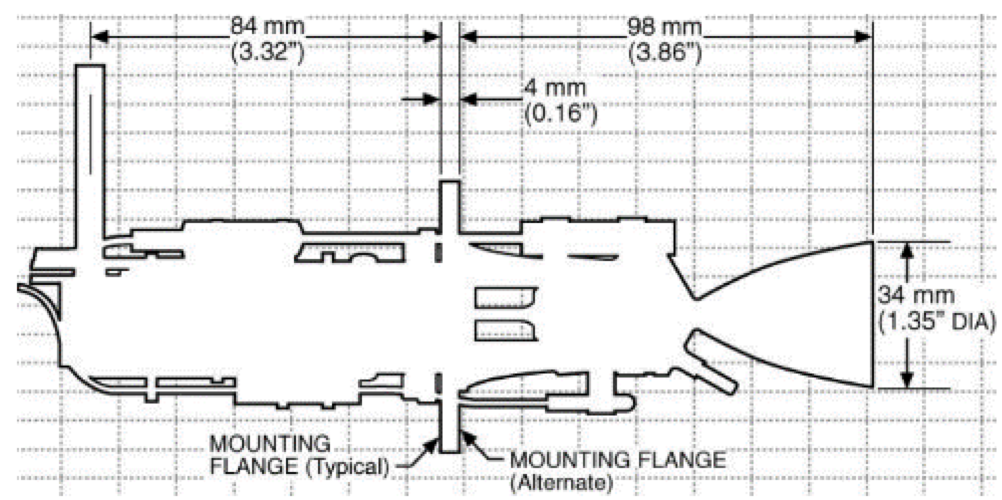
Comm. avail.	8+ TRL	NO Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

MR-106L 22N
Aerojet Rocketdyne (8 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~2U
Design satellite size	
Isp (s)	235 – 229 s
Thrust type/magnitude	34 – 10 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	~42 W
Flight heritage (if any)	Extensive
Commercially available	YES
Last updated	*01/2019*



Additional comments:
[Reference 1-2][Jan 2019][General info]
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).
The manufacturer's website has extensive specifications.

References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf

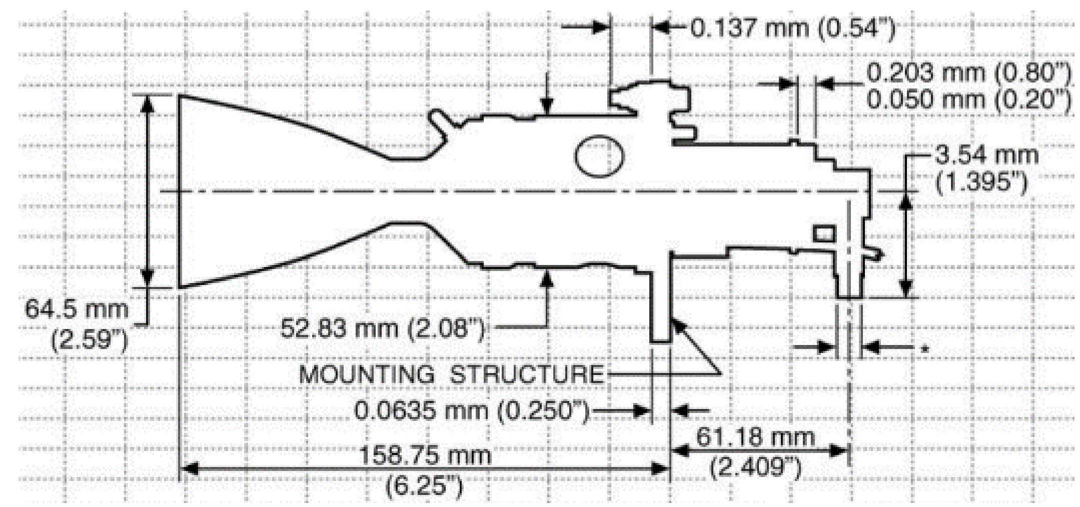
8+ NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

MR-107S 275N
Aerojet Rocketdyne (9 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~2.25U
Design satellite size	
Isp (s)	225 – 236 s
Thrust type/magnitude	360 – 85 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	<34.8 W
Flight heritage (if any)	Extensive
Commercially available	YES
Last updated	*01/2019*



Additional comments:
[Reference 1-2][Jan 2019][General info]
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).
The manufacturer's website has extensive specifications.

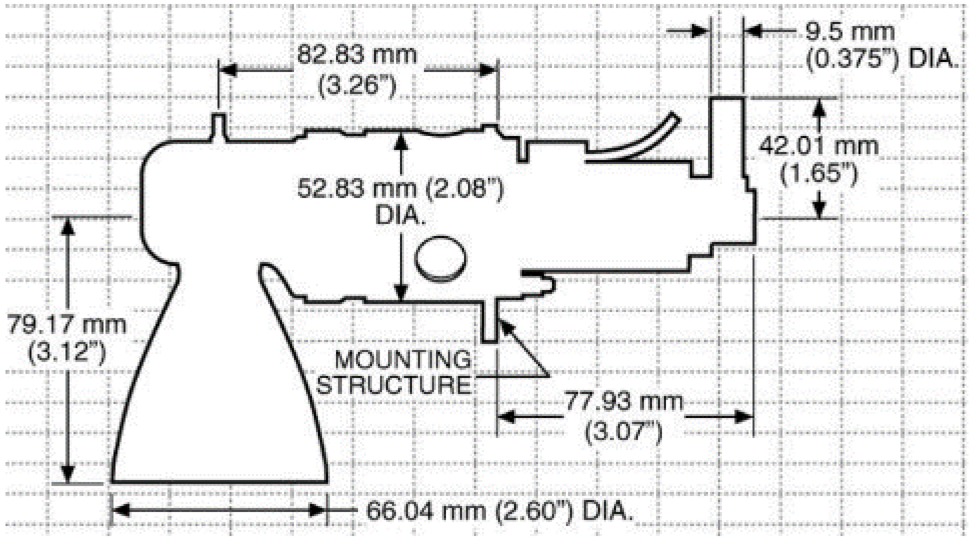
References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf

Comm. avail.	8+ TRL	NO Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

MR-107T 110N
Aerojet Rocketdyne (10 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~2U
Design satellite size	
Isp (s)	222 – 228 s
Thrust type/magnitude	125 – 54 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	<34.8 W
Flight heritage (if any)	Extensive
Commercially available	YES
Last updated	*01/2019*



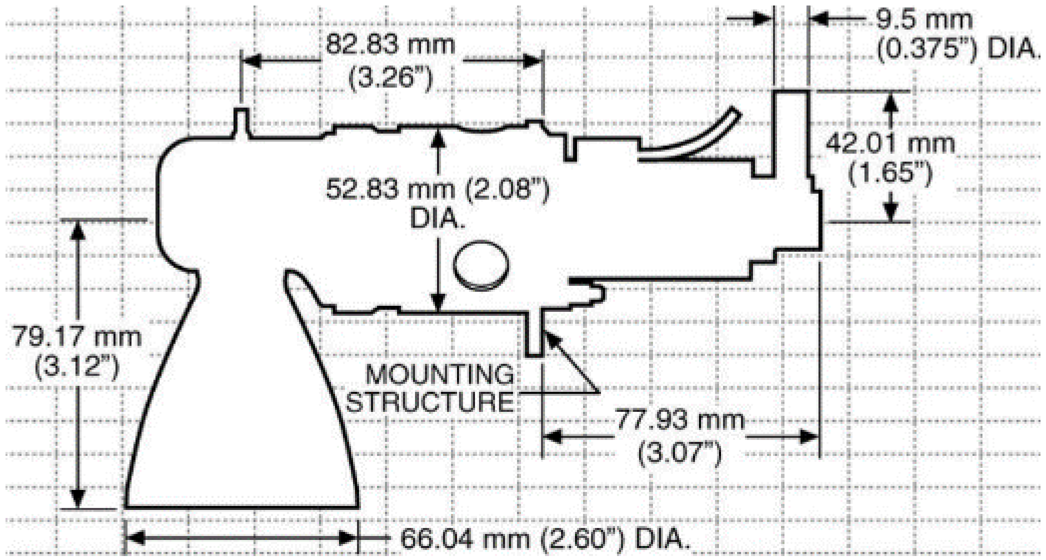
Additional comments:
[Reference 1-2][Jan 2019][General info]
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).
The manufacturer's website has extensive specifications.

References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf

8+ NO
Comm. avail. TRL Aerospace-tested

MR-107V 220N
Aerojet Rocketdyne (11 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~2U
Design satellite size	
Isp (s)	229 – 223 s
Thrust type/magnitude	220 – 67 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	<34.8 W
Flight heritage (if any)	Extensive
Commercially available	YES
Last updated	*01/2019*



Additional comments:
[Reference 1-2][Jan 2019][General info]
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).
The manufacturer's website has extensive specifications.

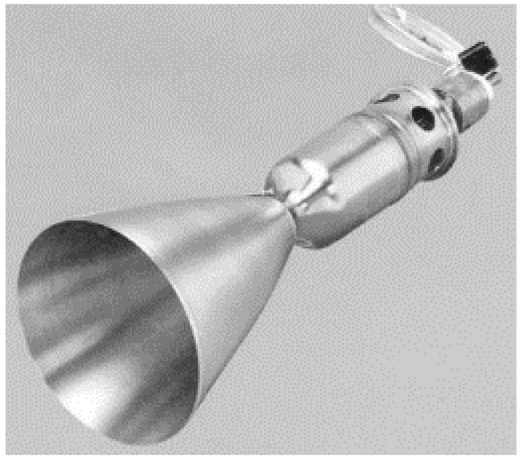
References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf

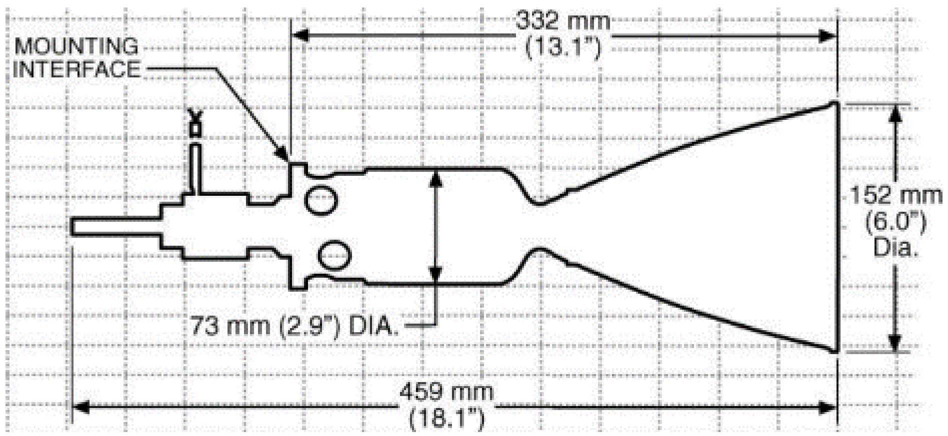
	8+	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

MR-104A/C 440N
Aerojet Rocketdyne (12 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~4.6U
Design satellite size	
Isp (s)	223 – 239 s
Thrust type/magnitude	572.5 – 204.6 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	~47 W
Flight heritage (if any)	Extensive
Commercially available	YES
Last updated	*01/2019*





Additional comments:
[Reference 1-2][Jan 2019][General info]
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).
The manufacturer's website has extensive specifications.

References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf

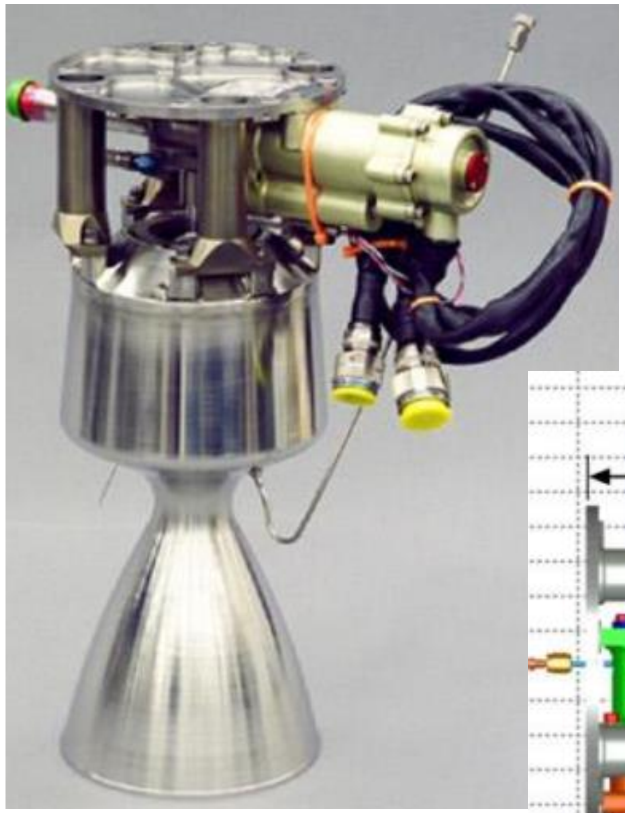
Comm. avail.	8+ TRL	NO Aerospace-tested

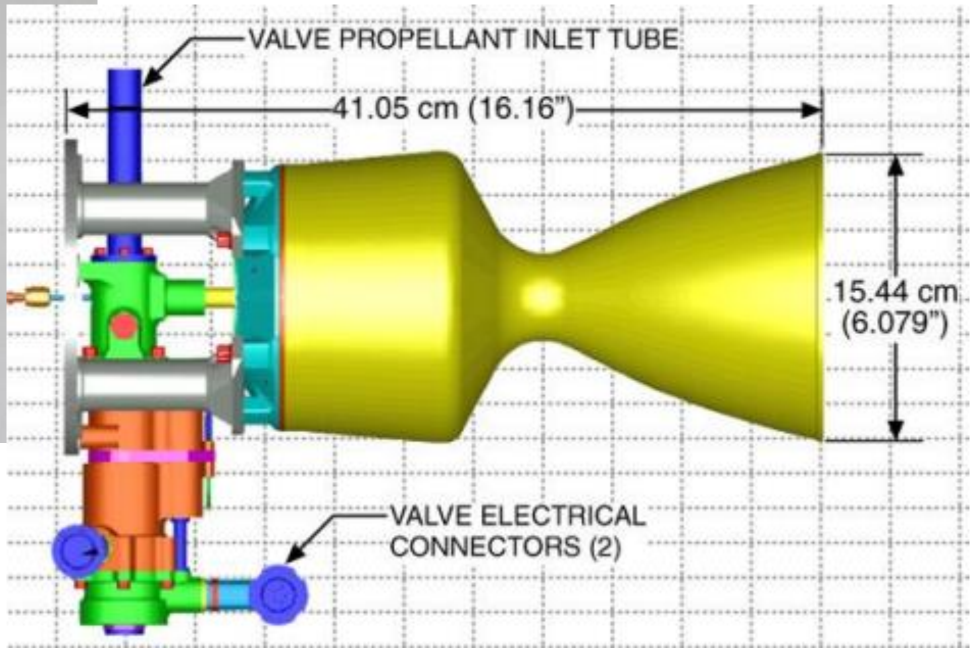
DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

MR-80B 3100N
Aerojet Rocketdyne (13 of 13)

Propulsion Technology	Monopropellant (Hydrazine)
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	8+
Size (including PPU)	~4.1U
Design satellite size	
Isp (s)	200 – 225 s
Thrust type/magnitude	3780 – 31 N @ Steady State
Delta-V (m/s)	
Propellant	Hydrazine (N2H4)
Power consumption (W)	~168 W
Flight heritage (if any)	Extensive
Commercially available	YES
Last updated	*01/2019*





Additional comments:
[Reference 1-2][Jan 2019][General info]
Aerojet Rocketdyne has delivered more than 1,500 flight hydrazine monopropellant rocket engines over the past 40 years, and their products cover the full thrust range from 1 N to 4,000 N (0.2 lbf to 900 lbf).
The manufacturer's website has extensive specifications.

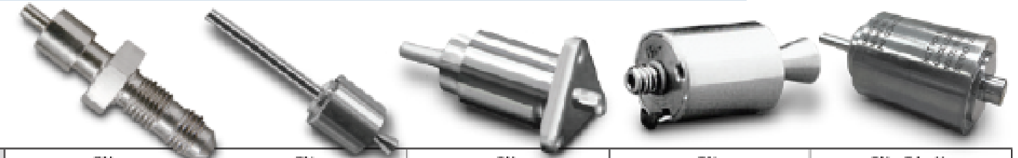
References:
[1] http://www.rocket.com/propulsion-systems/monopropellant-rockets
[2] http://www.rocket.com/files/aerojet/documents/Capabilities/PDFs/Monopropellant%20Data%20Sheets.pdf

8+ NO
Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Cold Gas Thruster Model No. 058E143/058E145/058E146 (MOOG)

Propulsion Technology	Cold gas
Manufacturer/Country	Moog (USA) (formerly AMPAC In-Space Propulsion, ISP)
TRL	8+
Size (including PPU)	14 mm diameter x 57 mm long, mass = 40g [valve hardware only, does not include tank or PPU]
Design satellite size	Variable (flown on CHAMP and GRACE, both large spacecraft: 400 to 500 kg)
Isp (s)	60 s
Thrust type/magnitude	10 to 40 mN (continuous, variable) at 22 psia
Delta-V (m/s)	35 m/s for a 500 kg spacecraft, calculated
Propellant	Gaseous Nitrogen
Power consumption (W)	10W valve open, 1W holding
Flight heritage (if any)	CHAMP (2000), GRACE (2002)
Commercially available	YES
Last updated	*01/2019*



Parameter					
Propellant	GN_2	GN_2	GN_2	GN_2	GN_2, GAr, Xe
Material	Stainless Steel, Fluorosilicone	Stainless Steel, Nylon	Stainless Steel, AFE411	Stainless Steel, Nylon	Stainless Steel, Vespel
Nominal Thrust	10 mN (0.0022 lbf), 16 mN (0.0036 lbf), 40 mN (0.0090 lbf) @ 1.5 bar (21.75 psia) GN_2	120 mN (0.027 lbf) @ 6.9 bar (100 psia) GN_2	120 mN (0.027 lbf) @ 6.9 bar (100 psia) GN_2	3.6 N (0.8 lbf) @ 15.7 bar (230 psia) GN_2	1.3 N @ 90 bar (1300 psia) Xe inlet, 0.9N @ 90 bar (1300 psia) GN_2 and GAr inlet
Specific Impulse (Nom)	> 60 sec	> 57 sec	65 sec	57 sec	21 sec Xe 70 sec GN2 54 sec GAr
MEOP	10.0 bar (145 psia)	20.7 bar (300 psia)	27.6 bar (400 psia)	15.7 bar (230 psia)	186 bar (2700 psia)
Proof	20.0 bar (290 psia)	41.4 bar (600 psia)	70.0 bar (1015 psia)	76.9 bar (1115 psia)	279 bar (4050 psia)
Burst	40.0 bar (580 psia)	82.7 bar (1200 psia)	111.4 bar (1615 psia)	155 bar (2250 psia)	465 bar (6750 psia)
Leakage - Internal	< 0.1 scch GN_2 @ 2.5 bar (36 psid)	< 0.1 sccm GN_2 @ 13.8 bar (200 psid)	< 2.8×10^{-4} scc/s GHe	< 2.0 sccm GN_2 @ 4.1 bar (60 psig)	< 1.0×10^{-4} sccs GHe @ MEOP
Leakage – External	< 1.0×10^{-4} su/s GHe	< 1.0×10^{-6} scc/s GHe @ 27.6 bar (400 psid)	< 1.0×10^{-6} scc/s GHe	< 1.0 sccm GN_2 @ 4.1 bar (60 psig)	< 1.0×10^{-5} sccs GHe @ MEOP
Operating Voltage	22-32 Vdc, 28 Vdc Nominal, 10 Vdc Holding	27-29 Vdc, 28 Vdc Nominal	22-34 Vdc, 28 Vdc Nominal	27-29 Vdc, 28 Vdc Nominal	28 Vdc nominal, 10 Vdc hold
Power	10 W open, 1 W holding	< 35 W @ 28 Vdc, 20°C	< 10.5 W @ 28 Vdc, 20°C 1.5 W @ 10 Vdc (holding)	30 W @ 28 Vdc, 20°C	10.5 W nominal @ 28 Vdc @ 21°C, 1.3W @ 10 VDc holding voltage
Coil Resistance	86 Ohms at 20°C (68°F)	26.8 Ohms at 20°C (68°F)	75 Ohms at 20°C (68°F)	28 Ohms at 20°C (68°F)	74.5 Ohms nominal at 21°C (68°F)
Response – Opening	< 2.5 msec	< 3.5 msec @ 28 Vdc, 13.8 bar (200 psia)	< 5 msec	< 4 msec	< 10 msec
Response – Closing	< 2.5 msec	< 3.5 msec @ 28 Vdc, 13.8 bar (200 psia)	< 3 msec	< 4 msec	< 10 msec
Life (Cycles)	500,000 – 2,000,000	20,000	1,000,000	> 10,000	> 100,000
Operating Temperature	-50°C to +60°C (-58°F to +140°F)	-40°C to +60°C (-40°F to +140°F)	-25°C to +75°C (-13°F to +167°F)	-40°C to +60°C (-40°F to +140°F)	-70°C to +60°C (-94°F to +140°F)
Inlet Filtration	none	10 micron Absolute	40 micron Absolute	10 micron Absolute	25 micron Absolute
Dimensions	Ø14 mm x 57 mm long (Ø0.55" x 2.25")	Ø14 mm x 20.3 mm long (Ø0.55" x 0.8")	Ø19.1 mm x 41 mm long (Ø0.75" x 1.6")	Ø6.6 mm x 25.4 mm long (Ø0.26" x 1.0")	Ø23.8 x 53.1 mm long (Ø0.94" x 2.1")
Mass	40 grams (0.09 lbm)	16 grams (0.035 lbm)	70 grams (0.15 lbm)	23 grams (0.05 lbm)	115 grams max (0.25 lbm)
Heritage	CHAMP and GRACE	SIRTF	SIRTF, Classified Mission	SAFER, SCIT, Pluto Fast Flyby	GEO applications
Model No.	058E143 058E145 058E146	058E142A	058E151	058-118	58E163A

Additional comments:

[Reference 1-4][Jan 2019][General info]

CHAMP was a three-axis stabilized (Earth pointing) spacecraft with three magnetorquers and cold gas propulsion for attitude and orbit change maneuvers. The spacecraft weighed 522 kg (including 30 kg of propellant). GRACE is an international cooperative US-German dual-minisatellite SST (Satellite-to-Satellite Tracking) geodetic mission with the overall objective of obtaining long-term data with unprecedented accuracy for global (high-resolution) models of the mean and the time-variable components of the Earth's gravity field (a new model of the Earth's gravity field every 30 days for five years). GRACE is also part of NASA's ESSP (Earth System Science Pathfinder) program. The spacecraft weighed 432 kg, with 34 kg propellant.

The manufacturer claims 500,000 to 2 million life cycles. From the manufacturer's website:

"Moog cold gas thruster valves are direct-acting, solenoid actuated devices with a nylon poppet which is integrated in the armature/poppet assembly. In the de-energized closed position, the armature/poppet assembly is held against the seat by a conical spiral spring. The valve is opened when the electromagnetic force of the coil overcomes the spring pre-load and the armature/poppet assembly lifts from the seat allowing gas to flow. De-energizing the coil causes the magnetic field to decay and the spring preload forces returns the armature assembly to its seat providing leak tight gas shut off. Moog produces cold gas thrusters in a variety of thrust ranges to meet mission requirements. Typical thrusts range from 10mN to 4N. Moog cold gas thrusters have flown on SAFER, SIRTF, CHAMP, GRACE, Pluto Fast Flyby, and DOD classified missions."

References:

[1] Bzibziak, R., "Update of Cold Gas Propulsion at Moog," Spacecraft Propulsion, Third International Conference held 10-13 October, 2000 at Cannes, France.
[2] https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/champ
[3] https://directory.eoportal.org/web/eoportal/satellite-missions/g/grace
[4] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html

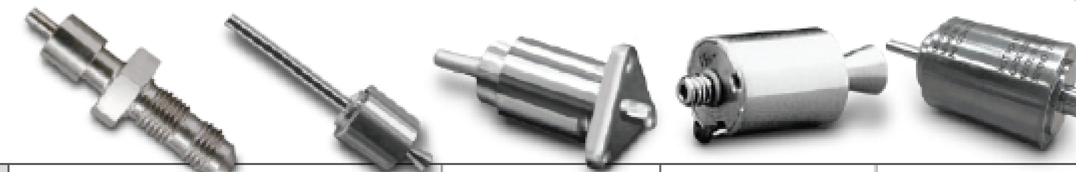
8+ | NO
Comm. avail. | TRL | Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

Cold Gas Thruster Model No. 058E142A (MOOG)

Propulsion Technology	Cold gas
Manufacturer/Country	Moog (USA) (formerly AMPAC In-Space Propulsion, ISP)
TRL	8+
Size (including PPU)	14 mm diameter x 20 mm long, mass = 16g [valve hardware only, does not include tank or PPU]
Design satellite size	Variable (flown on SIRTF, large spacecraft)
Isp (s)	57s
Thrust type/magnitude	120 mN at 100 psia
Delta-V (m/s)	~40 m/s for 500 kg spacecraft, calculated
Propellant	Gaseous nitrogen
Power consumption (W)	<35W at 28 VDC
Flight heritage (if any)	SIRTF aka Spitzer Space Telescope (SST) (2003)
Commercially available	YES
Last updated	*01/2019*



Parameter					
Propellant	GN_2	GN_2	GN_2	GN_2	GN_2, GAr, Xe
Material	Stainless Steel, Fluorosilicone	Stainless Steel, Nylon	Stainless Steel, AFE411	Stainless Steel, Nylon	Stainless Steel, Vespel
Nominal Thrust	10 mN (0.0022 lbf), 16 mN (0.0036 lbf), 40 mN (0.0090 lbf) @ 1.5 bar (21.75 psia) GN_2	120 mN (0.027 lbf) @ 6.9 bar (100 psia) GN_2	120 mN (0.027 lbf) @ 6.9 bar (100 psia) GN_2	3.6 N (0.8 lbf) @ 15.7 bar (230 psia) GN_2	1.3 N @ 90 bar (1300 psia) Xe inlet, 0.9N @ 90 bar (1300 psia) GN_2 and GAr inlet
Specific Impulse (Nom)	> 60 sec	> 57 sec	65 sec	57 sec	21 sec Xe 70 sec GN2 54 sec GAr
MEOP	10.0 bar (145 psia)	20.7 bar (300 psia)	27.6 bar (400 psia)	15.7 bar (230 psia)	186 bar (2700 psia)
Proof	20.0 bar (290 psia)	41.4 bar (600 psia)	70.0 bar (1015 psia)	76.9 bar (1115 psia)	279 bar (4050 psia)
Burst	40.0 bar (580 psia)	82.7 bar (1200 psia)	111.4 bar (1615 psia)	155 bar (2250 psia)	465 bar (6750 psia)
Leakage - Internal	< 0.1 scch GN_2 @ 2.5 bar (36 psid)	< 0.1 sccm GN_2 @ 13.8 bar (200 psid)	< $2.8x10^{-4}$ scc/s GHe	< 2.0 sccm GN_2 @ 4.1 bar (60 psig)	< 1.0 x 10^{-4} sccs GHe @ MEOP
Leakage – External	< $1.0x10^{-4}$ su/s GHe	< $1.0x10^{-6}$ scc/s GHe @ 27.6 bar (400 psid)	< $1.0x10^{-6}$ scc/s GHe	< 1.0 sccm GN_2 @ 4.1 bar (60 psig)	<1.0 x 10^{-6} sccs GHe @ MEOP
Operating Voltage	22-32 Vdc, 28 Vdc Nominal, 10 Vdc Holding	27-29 Vdc, 28 Vdc Nominal	22-34 Vdc, 28 Vdc Nominal	27-29 Vdc, 28 Vdc Nominal	28 Vdc nominal, 10 Vdc hold
Power	10 W open, 1 W holding	< 35 W @ 28 Vdc, 20°C	< 10.5 W @ 28 Vdc, 20°C 1.5 W @ 10 Vdc (holding)	30 W @ 28 Vdc, 20°C	10.5 W nominal @ 28 Vdc @ 21°C, 1.3W @ 10 VDc holding voltage
Coil Resistance	86 Ohms at 20°C (68°F)	26.8 Ohms at 20°C (68°F)	75 Ohms at 20°C (68°F)	28 Ohms at 20°C (68°F)	74.5 Ohms nominal at 21°C (68°F)
Response – Opening	< 2.5 msec	< 3.5 msec @ 28 Vdc, 13.8 bar (200 psia)	< 5 msec	< 4 msec	< 10 msec
Response – Closing	< 2.5 msec	< 3.5 msec @ 28 Vdc, 13.8 bar (200 psia)	< 3 msec	< 4 msec	< 10 msec
Life (Cycles)	500,000 – 2,000,000	20,000	1,000,000	> 10,000	> 100,000
Operating Temperature	-50°C to +60°C (-58°F to +140°F)	-40°C to +60°C (-40°F to +140°F)	-25°C to +75°C (-13°F to +167°F)	-40°C to +60°C (-40°F to +140°F)	-70°C to +60°C (-94°F to +140°F)
Inlet Filtration	none	10 micron Absolute	40 micron Absolute	10 micron Absolute	25 micron Absolute
Dimensions	Ø14 mm x 57 mm long (Ø0.55" x 2.25")	Ø14 mm x 20.3 mm long (Ø0.55" x 0.8")	Ø19.1 mm x 41 mm long (Ø0.75" x 1.6")	Ø6.6 mm x 25.4 mm long (Ø0.26" x 1.0")	Ø23.8 x 53.1 mm long (Ø0.94" x 2.1")
Mass	40 grams (0.09 lbm)	16 grams (0.035 lbm)	70 grams (0.15 lbm)	23 grams (0.05 lbm)	115 grams max (0.25 lbm)
Heritage	CHAMP and GRACE	SIRTF	SIRTF, Classified Mission	SAFER, SCIT, Pluto Fast Flyby	GEO applications
Model No.	058E143 058E145 058E146	058E142A	058E151	058-118	58E163A

Additional comments:

[Reference 1-4][Jan 2019][General info]

The Spitzer Space Telescope (SST), formerly the Space Infrared Telescope Facility (SIRTF), is an infrared space telescope launched in 2003 and still operating as of 2018. It is the fourth and final of the NASA Great Observatories program. SIRTF had a launch mass of 950 kg, of which ~70 kg was propellant.

The manufacturer claims 20,000 life cycles. From the manufacturer's website:

"Moog cold gas thruster valves are direct-acting, solenoid actuated devices with a nylon poppet which is integrated in the armature/poppet assembly. In the de-energized closed position, the armature/poppet assembly is held against the seat by a conical spiral spring. The valve is opened when the electromagnetic force of the coil overcomes the spring pre-load and the armature/poppet assembly lifts from the seat allowing gas to flow. De-energizing the coil causes the magnetic field to decay and the spring preload forces returns the armature assembly to its seat providing leak tight gas shut off. Moog produces cold gas thrusters in a variety of thrust ranges to meet mission requirements. Typical thrusts range from 10mN to 4N. Moog cold gas thrusters have flown on SAFER, SIRTF, CHAMP, GRACE, Pluto Fast Flyby, and DOD classified missions."

References:

[1] Bzibziak, R., "Update of Cold Gas Propulsion at Moog," Spacecraft Propulsion, Third International Conference held 10-13 October, 2000 at Cannes, France.
[2] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html
[3] https://en.wikipedia.org/wiki/Spitzer_Space_Telescope

	8+	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Cold Gas Thruster Model No. 058E151 (MOOG)

Propulsion Technology	Cold gas
Manufacturer/Country	Moog (USA) (formerly AMPAC In-Space Propulsion, ISP)
TRL	8+
Size (including PPU)	19 mm diameter x 41 mm long, mass = 70g [valve hardware only, does not include tank or PPU]
Design satellite size	Variable (flown on SIRTF, large spacecraft)
Isp (s)	65s
Thrust type/magnitude	120 mN at 100 psia
Delta-V (m/s)	~40 m/s for 500 kg spacecraft
Propellant	Gaseous nitrogen, Xenon
Power consumption (W)	<10.5W at 28 VDC, 1.5W (holding)
Flight heritage (if any)	SIRTF aka Spitzer Space Telescope (SST) (2003) + classified mission
Commercially available	YES
Last updated	*01/2019*

Parameter					
Propellant	GN_2	GN_2	GN_2	GN_2	GN_2, GAr, Xe
Material	Stainless Steel, Fluorosilicone	Stainless Steel, Nylon	Stainless Steel, AFE411	Stainless Steel, Nylon	Stainless Steel, Vespel
Nominal Thrust	10 mN (0.0022 lbf), 16 mN (0.0036 lbf), 40 mN (0.0090 lbf) @ 1.5 bar (21.75 psia) GN_2	120 mN (0.027 lbf) @ 6.9 bar (100 psia) GN_2	120 mN (0.027 lbf) @ 6.9 bar (100 psia) GN_2	3.6 N (0.8 lbf) @ 15.7 bar (230 psia) GN_2	1.3 N @ 90 bar (1300 psia) Xe inlet, 0.9N @ 90 bar (1300 psia) GN_2 and GAr inlet
Specific Impulse (Nom)	> 60 sec	> 57 sec	65 sec	57 sec	21 sec Xe 70 sec GN2 54 sec GAr
MEOP	10.0 bar (145 psia)	20.7 bar (300 psia)	27.6 bar (400 psia)	15.7 bar (230 psia)	186 bar (2700 psia)
Proof	20.0 bar (290 psia)	41.4 bar (600 psia)	70.0 bar (1015 psia)	76.9 bar (1115 psia)	279 bar (4050 psia)
Burst	40.0 bar (580 psia)	82.7 bar (1200 psia)	111.4 bar (1615 psia)	155 bar (2250 psia)	465 bar (6750 psia)
Leakage - Internal	< 0.1 scch GN_2 @ 2.5 bar (36 psid)	< 0.1 sccm GN_2 @ 13.8 bar (200 psid)	< 2.8×10^{-4} scc/s GHe	< 2.0 sccm GN_2 @ 4.1 bar (60 psig)	< 1.0×10^{-4} sccs GHe @ MEOP
Leakage – External	< 1.0×10^{-4} scc/s GHe	< 1.0×10^{-6} scc/s GHe @ 27.6 bar (400 psid)	< 1.0×10^{-6} scc/s GHe	< 1.0 sccm GN_2 @ 4.1 bar (60 psig)	< 1.0×10^{-6} sccs GHe @ MEOP
Operating Voltage	22-32 Vdc, 28 Vdc Nominal, 10 Vdc Holding	27-29 Vdc, 28 Vdc Nominal	22-34 Vdc, 28 Vdc Nominal	27-29 Vdc, 28 Vdc Nominal	28 Vdc nominal, 10 Vdc hold
Power	10 W open, 1 W holding	< 35 W @ 28 Vdc, 20°C	< 10.5 W @ 28 Vdc, 20°C 1.5 W @ 10 Vdc (holding)	30 W @ 28 Vdc, 20°C	10.5 W nominal @ 28 Vdc @ 21°C, 1.3W @ 10 VDc holding voltage
Coil Resistance	86 Ohms at 20°C (68°F)	26.8 Ohms at 20°C (68°F)	75 Ohms at 20°C (68°F)	28 Ohms at 20°C (68°F)	74.5 Ohms nominal at 21°C (68°F)
Response – Opening	< 2.5 msec	< 3.5 msec @ 28 Vdc, 13.8 bar (200 psia)	< 5 msec	< 4 msec	< 10 msec
Response – Closing	< 2.5 msec	< 3.5 msec @ 28 Vdc, 13.8 bar (200 psia)	< 3 msec	< 4 msec	< 10 msec
Life (Cycles)	500,000 – 2,000,000	20,000	1,000,000	> 10,000	> 100,000
Operating Temperature	-50°C to +60°C (-58°F to +140°F)	-40°C to +60°C (-40°F to +140°F)	-25°C to +75°C (-13°F to +167°F)	-40°C to +60°C (-40°F to +140°F)	-70°C to +60°C (-94°F to +140°F)
Inlet Filtration	none	10 micron Absolute	40 micron Absolute	10 micron Absolute	25 micron Absolute
Dimensions	Ø14 mm x 57 mm long (Ø0.55" x 2.25")	Ø14 mm x 20.3 mm long (Ø0.55" x 0.8")	Ø19.1 mm x 41 mm long (Ø0.75" x 1.6")	Ø6.6 mm x 25.4 mm long (Ø0.26" x 1.0")	Ø23.8 x 53.1 mm long (Ø0.94" x 2.1")
Mass	40 grams (0.09 lbm)	16 grams (0.035 lbm)	70 grams (0.15 lbm)	23 grams (0.05 lbm)	115 grams max (0.25 lbm)
Heritage	CHAMP and GRACE	SIRTF	SIRTF, Classified Mission	SAFER, SCIT, Pluto Fast Flyby	GEO applications
Model No.	058E143 058E145 058E146	058E142A	058E151	058-118	58E163A

Additional comments:

[Reference 1-3][Jan 2019][General info]

The Spitzer Space Telescope (SST), formerly the Space Infrared Telescope Facility (SIRTF), is an infrared space telescope launched in 2003 and still operating as of 2018. It is the fourth and final of the NASA Great Observatories program. SIRTF had a launch mass of 950 kg, of which ~70kg was propellant.

The manufacturer claims 20,000 life cycles. From the manufacturer's website:

"Moog cold gas thruster valves are direct-acting, solenoid actuated devices with a nylon poppet which is integrated in the armature/poppet assembly. In the de-energized closed position, the armature/poppet assembly is held against the seat by a conical spiral spring. The valve is opened when the electromagnetic force of the coil overcomes the spring pre-load and the armature/poppet assembly lifts from the seat allowing gas to flow. De-energizing the coil causes the magnetic field to decay and the spring preload forces returns the armature assembly to its seat providing leak tight gas shut off. Moog produces cold gas thrusters in a variety of thrust ranges to meet mission requirements. Typical thrusts range from 10mN to 4N. Moog cold gas thrusters have flown on SAFER, SIRTF, CHAMP, GRACE, Pluto Fast Flyby, and DOD classified missions."

References:

[1] Bzibziak, R., "Update of Cold Gas Propulsion at Moog," Spacecraft Propulsion, Third International Conference held 10-13 October, 2000 at Cannes, France.
[2] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html
[3] https://en.wikipedia.org/wiki/Spitzer_Space_Telescope

Comm. avail.	TRL	Aerospace-tested
	8+	NO

Cold Gas Thruster Model No. 058-118 (MOOG)

Propulsion Technology	Cold gas
Manufacturer/Country	Moog (USA) (formerly AMPAC In-Space Propulsion, ISP)
TRL	8+
Size (including PPU)	6.6 mm diameter x 25.4 mm long, mass = 70g, valve only
Design satellite size	Variable (flown on large spacecraft)
Isp (s)	65s
Thrust type/magnitude	3.6N at 230 psia
Delta-V (m/s)	~40 m/s for 500 kg spacecraft
Propellant	Gaseous nitrogen
Power consumption (W)	30W at 28 VDC
Flight heritage (if any)	SAFER, SCIT, Pluto Fast Flyby (aka Pluto Kuiper Express and Pluto Express)
Commercially available	YES
Last updated	*01/2019*

Parameter					
Propellant	GN_2	GN_2	GN_2	GN_2	GN_2, GAr, Xe
Material	Stainless Steel, Fluorosilicone	Stainless Steel, Nylon	Stainless Steel, AFE411	Stainless Steel, Nylon	Stainless Steel, Vespel
Nominal Thrust	10 mN (0.0022 lbf), 16 mN (0.0036 lbf), 40 mN (0.0090 lbf) @ 1.5 bar (21.75 psia) GN_2	120 mN (0.027 lbf) @ 6.9 bar (100 psia) GN_2	120 mN (0.027 lbf) @ 6.9 bar (100 psia) GN_2	3.6 N (0.8 lbf) @ 15.7 bar (230 psia) GN_2	1.3 N @ 90 bar (1300 psia) Xe inlet, 0.9N @ 90 bar (1300 psia) GN_2 and GAr inlet
Specific Impulse (Nom)	> 60 sec	> 57 sec	65 sec	57 sec	21 sec Xe 70 sec GN2 54 sec GAr
MEOP	10.0 bar (145 psia)	20.7 bar (300 psia)	27.6 bar (400 psia)	15.7 bar (230 psia)	186 bar (2700 psia)
Proof	20.0 bar (290 psia)	41.4 bar (600 psia)	70.0 bar (1015 psia)	76.9 bar (1115 psia)	279 bar (4050 psia)
Burst	40.0 bar (580 psia)	82.7 bar (1200 psia)	111.4 bar (1815 psia)	155 bar (2250 psia)	465 bar (6750 psia)
Leakage - Internal	< 0.1 scch GN_2 @ 2.5 bar (36 psid)	< 0.1 sccm GN_2 @ 13.8 bar (200 psid)	< 2.8x10^{-4} scc/s GHe	< 2.0 sccm GN_2 @ 4.1 bar (60 psig)	< 1.0 x 10^{-4} sccs GHe @ MEOP
Leakage – External	< 1.0x10^{-5} scc/s GHe	< 1.0x10^{-6} scc/s GHe @ 27.8 bar (400 psid)	< 1.0x10^{-6} scc/s GHe	< 1.0 sccm GN_2 @ 4.1 bar (60 psig)	<1.0 x 10^{-5} sccs GHe @ MEOP
Operating Voltage	22-32 Vdc, 28 Vdc Nominal, 10 Vdc Holding	27-29 Vdc, 28 Vdc Nominal	22-34 Vdc, 28 Vdc Nominal	27-29 Vdc, 28 Vdc Nominal	28 Vdc nominal, 10 Vdc hold
Power	10 W open, 1 W holding	< 35 W @ 28 Vdc, 20°C	< 10.5 W @ 28 Vdc, 20°C 1.5 W @ 10 Vdc (holding)	30 W @ 28 Vdc, 20°C	10.5 W nominal @ 28 Vdc @ 21°C, 1.3W @ 10 VDc holding voltage
Coil Resistance	86 Ohms at 20°C (68°F)	26.8 Ohms at 20°C (68°F)	75 Ohms at 20°C (68°F)	28 Ohms at 20°C (68°F)	74.5 Ohms nominal at 21°C (68°F)
Response – Opening	< 2.5 msec	< 3.5 msec @ 28 Vdc, 13.8 bar (200 psia)	< 5 msec	< 4 msec	< 10 msec
Response – Closing	< 2.5 msec	< 3.5 msec @ 28 Vdc, 13.8 bar (200 psia)	< 3 msec	< 4 msec	< 10 msec
Life (Cycles)	500,000 – 2,000,000	20,000	1,000,000	> 10,000	> 100,000
Operating Temperature	-50°C to +60°C (-58°F to +140°F)	-40°C to +60°C (-40°F to +140°F)	-25°C to +75°C (-13°F to +167°F)	-40°C to +60°C (-40°F to +140°F)	-70°C to +60°C (-94°F to +140°F)
Inlet Filtration	none	10 micron Absolute	40 micron Absolute	10 micron Absolute	25 micron Absolute
Dimensions	Ø14 mm x 57 mm long (Ø0.55" x 2.25")	Ø14 mm x 20.3 mm long (Ø0.55" x 0.8")	Ø19.1 mm x 41 mm long (Ø0.75" x 1.6")	Ø6.6 mm x 25.4 mm long (Ø0.26" x 1.0")	Ø23.8 x 53.1 mm long (Ø0.94" x 2.1")
Mass	40 grams (0.09 lbm)	16 grams (0.035 lbm)	70 grams (0.15 lbm)	23 grams (0.05 lbm)	115 grams max (0.25 lbm)
Heritage	CHAMP and GRACE	SIRTF	SIRTF, Classified Mission	SAFER, SCIT, Pluto Fast Flyby	GEO applications
Model No.	058E143 058E145 058E146	058E142A	058E151	058-118	58E163A

Additional comments:

[Reference 1-2][Jan 2019][General info]

Simplified Aid For EVA Rescue (SAFER) is a small, self-contained, propulsive backpack system (jet pack) worn during spacewalks to be used in case of emergency only. If an untethered astronaut were to lose physical contact with the vessel, it would provide free-flying mobility to return to it. It is worn on spacewalks outside the International Space Station (ISS) and was worn on spacewalks outside the Space Shuttle. So far, there has not been an emergency in which it was needed. SAFER is a small, simplified version of the Manned Maneuvering Unit (MMU), which was used for regular maneuvering. EVA stands for extravehicular activities. SAFER was first flown on STS-64 September 9, 1994, when an untethered flight test was performed first by astronaut Mark Lee and then Carl Meade. Both astronauts flew the SAFER up and around the Shuttle's Robotic Arm along with a demonstration test of the SAFER's automatic attitude hold feature. This feature arrests uncontrolled rotation of a detached crewmember expected in an accidental separation. SAFER has a mass of approximately 83 lbs (38 kg) and can provide a total change in velocity (delta-v) of at least 10 ft/s (3 m/s). It was also tested during flight STS-92 when astronauts Wisoff and Lopez-Alegria performed test maneuvers, flying up to 50 feet while remaining tethered to the spacecraft.

Originally conceived as *Pluto Fast Flyby*, and later briefly named *Pluto Express*, the mission was inspired by a 1991 United States Postal Service stamp that branded Pluto as "Not Yet Explored". While the project was initiated in 1992, the project's development phase was lengthy, spending nearly a decade in the proposal and funding stage. During planning, the mission was changed to include a Kuiper belt object flyby and re-christened the *Pluto Kuiper Express*, after the discovery of numerous such objects beyond Neptune in the mid-to-late 1990s. NASA ultimately decided to cancel the mission in 2000, however, citing the project's expanding budget as the ultimate reason for the cancellation. After the mission's cancellation, most of the *Pluto Fast Flyby* team, including Stern, went on to develop *New Horizons*, a mission nearly identical to *Pluto Kuiper Express*, for NASA's New Frontiers program. The spacecraft was successfully launched in January 2006, after a financial standoff with NASA and additional delays, and went on to perform the first ever flyby of the Pluto-Charon system in July 2015.

The manufacturer claims 10,000 life cycles. From the manufacturer's website:

"Moog cold gas thruster valves are direct-acting, solenoid actuated devices with a nylon poppet which is integrated in the armature/poppet assembly. In the de-energized closed position, the armature/poppet assembly is held against the seat by a conical spiral spring. The valve is opened when the electromagnetic force of the coil overcomes the spring pre-load and the armature/poppet assembly lifts from the seat allowing gas to flow. De-energizing the coil causes the magnetic field to decay and the spring preload forces returns the armature assembly to its seat providing leak tight gas shut off. Moog produces cold gas thrusters in a variety of thrust ranges to meet mission requirements. Typical thrusts range from 10mN to 4N. Moog cold gas thrusters have flown on SAFER, SIRTF, CHAMP, GRACE, Pluto Fast Flyby, and DOD classified missions."

References:

[1] Bzibziak, R., "Update of Cold Gas Propulsion at Moog," Spacecraft Propulsion, Third International Conference held 10-13 October, 2000 at Cannes, France.
[2] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html

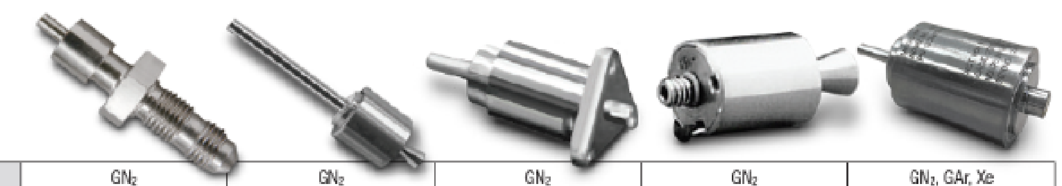
8+ | NO

Comm. avail. | TRL | Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Cold Gas Thruster Model No. 58E163A (MOOG)

Propulsion Technology	Cold gas
Manufacturer/Country	Moog (USA) (formerly AMPAC In-Space Propulsion, ISP)
TRL	8
Size (including PPU)	23.8 mm diameter x 53.1 mm long, mass = 115g [valve hardware only, does not include tank/PPU]
Design satellite size	Variable
Isp (s)	21s (Xe), 70s (GN2), 54s (Ar)
Thrust type/magnitude	1.3N at 90 bar
Delta-V (m/s)	
Propellant	Gaseous nitrogen, Xenon, Argon
Power consumption (W)	<10.5W at 28 VDC, 1.3W (holding)
Flight heritage (if any)	GEO applications
Commercially available	YES
Last updated	*02/2019*



Parameter					
Propellant	GN_2	GN_2	GN_2	GN_2	GN_2, GAr, Xe
Material	Stainless Steel, Fluorosilicone	Stainless Steel, Nylon	Stainless Steel, AFE411	Stainless Steel, Nylon	Stainless Steel, Vespel
Nominal Thrust	10 mN (0.0022 lbf), 16 mN (0.0036 lbf), 40 mN (0.0090 lbf) @ 1.5 bar (21.75 psia) GN_2	120 mN (0.027 lbf) @ 6.9 bar (100 psia) GN_2	120 mN (0.027 lbf) @ 6.9 bar (100 psia) GN_2	3.6 N (0.8 lbf) @ 15.7 bar (230 psia) GN_2	1.3 N @ 90 bar (1300 psia) Xe inlet, 0.9N @ 90 bar (1300 psia) GN_2 and GAr inlet
Specific Impulse (Nom)	> 60 sec	> 57 sec	65 sec	57 sec	21 sec Xe 70 sec GN2 54 sec GAr
MEOP	10.0 bar (145 psia)	20.7 bar (300 psia)	27.6 bar (400 psia)	15.7 bar (230 psia)	186 bar (2700 psia)
Proof	20.0 bar (290 psia)	41.4 bar (600 psia)	70.0 bar (1015 psia)	76.9 bar (1115 psia)	279 bar (4050 psia)
Burst	40.0 bar (580 psia)	82.7 bar (1200 psia)	111.4 bar (1615 psia)	155 bar (2250 psia)	465 bar (6750 psia)
Leakage - Internal	< 0.1 scch GN_2 @ 2.5 bar (36 psid)	< 0.1 sccm GN_2 @ 13.8 bar (200 psid)	$< 2.8x10^{-4}$ scc/s GHe	< 2.0 sccm GN_2 @ 4.1 bar (60 psig)	$< 1.0 \times 10^{-4}$ sccs GHe @ MEOP
Leakage – External	$< 1.0x10^{-5}$ su/s GHe	$< 1.0x10^{-6}$ scc/s GHe @ 27.6 bar (400 psid)	$< 1.0x10^{-6}$ scc/s GHe	< 1.0 sccm GN_2 @ 4.1 bar (60 psig)	$<1.0 \times 10^{-4}$ sccs GHe @ MEOP
Operating Voltage	22-32 Vdc, 28 Vdc Nominal, 10 Vdc Holding	27-29 Vdc, 28 Vdc Nominal	22-34 Vdc, 28 Vdc Nominal	27-29 Vdc, 28 Vdc Nominal	28 Vdc nominal, 10 Vdc hold
Power	10 W open, 1 W holding	< 35 W @ 28 Vdc, 20°C	< 10.5 W @ 28 Vdc, 20°C 1.5 W @ 10 Vdc (holding)	30 W @ 28 Vdc, 20°C	10.5 W nominal @ 28 Vdc @ 21°C, 1.3W @ 10 VDc holding voltage
Coil Resistance	86 Ohms at 20°C (68°F)	26.8 Ohms at 20°C (68°F)	75 Ohms at 20°C (68°F)	28 Ohms at 20°C (68°F)	74.5 Ohms nominal at 21°C (68°F)
Response – Opening	< 2.5 msec	< 3.5 msec @ 28 Vdc, 13.8 bar (200 psia)	< 5 msec	< 4 msec	< 10 msec
Response – Closing	< 2.5 msec	< 3.5 msec @ 28 Vdc, 13.8 bar (200 psia)	< 3 msec	< 4 msec	< 10 msec
Life (Cycles)	500,000 – 2,000,000	20,000	1,000,000	> 10,000	> 100,000
Operating Temperature	-50°C to +60°C (-58°F to +140°F)	-40°C to +60°C (-40°F to +140°F)	-25°C to +75°C (-13°F to +167°F)	-40°C to +60°C (-40°F to +140°F)	-70°C to +60°C (-94°F to +140°F)
Inlet Filtration	none	10 micron Absolute	40 micron Absolute	10 micron Absolute	25 micron Absolute
Dimensions	Ø14 mm x 57 mm long (Ø0.55" x 2.25")	Ø14 mm x 20.3 mm long (Ø0.55" x 0.8")	Ø19.1 mm x 41 mm long (Ø0.75" x 1.6")	Ø6.6 mm x 25.4 mm long (Ø0.26" x 1.0")	Ø23.8 x 53.1 mm long (Ø0.94" x 2.1")
Mass	40 grams (0.09 lbm)	16 grams (0.035 lbm)	70 grams (0.15 lbm)	23 grams (0.05 lbm)	115 grams max (0.25 lbm)
Heritage	CHAMP and GRACE	SIRTF	SIRTF, Classified Mission	SAFER, SCIT, Pluto Fast Flyby	GEO applications
Model No.	058E143 058E145 058E146	058E142A	058E151	058-118	58E163A

Additional comments:

[Reference 1][Feb 2019][General info]
"Moog cold gas thruster valves are direct-acting, solenoid actuated devices with a nylon poppet which is integrated in the armature/poppet assembly. In the de-energized closed position, the armature/poppet assembly is held against the seat by a conical spiral spring. The valve is opened when the electromagnetic force of the coil overcomes the spring pre-load and the armature/poppet assembly lifts from the seat allowing gas to flow. De-energizing the coil causes the magnetic field to decay and the spring preload forces returns the armature assembly to its seat providing leak tight gas shut off. Moog produces cold gas thrusters in a variety of thrust ranges to meet mission requirements. Typical thrusts range from 10mN to 4N. Moog cold gas thrusters have flown on SAFER, SIRTF, CHAMP, GRACE, Pluto Fast Flyby, and DOD classified missions."

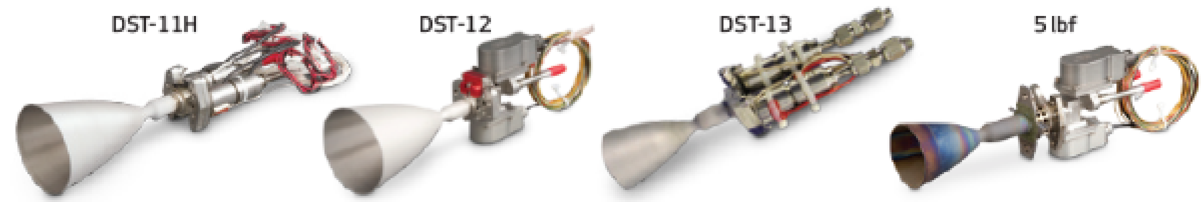
References:
[1] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html

	8+	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DST-11H MOOG

Propulsion Technology	Bi-prop
Manufacturer/Country	MOOG (USA)
TRL	8
Size (including PPU)	10.3” length
Design satellite size	27U+
Isp (s)	310s
Thrust type/magnitude	22N (continuous)
Delta-V (m/s)	
Propellant	Hydrazine/MON
Power consumption (W)	41 W (valve)
Flight heritage (if any)	Extensive. Intelsat, BepiColombo, Wild Geese, Tenacious, GOES-R
Commercially available	YES
Last updated	02/2019



Design	DST-11H	DST-12	DST-13	5 lbf
Propellant	Hydrazine/MON	MMH/MON	MMH/MON	MMH/MON
Nominal Steady State Thrust	5 lbf (22N)	5 lbf (22N)	5 lbf (22N)	5 lbf (22N)
Feed Pressure	80 – 400 psia (5.5 – 27.6 bar)	60 – 400 psia (4.1 - 27.6 bar)	80 – 400 psia (5.5 - 27.6 bar)	39 - 320 psia (2.8 - 22.1 bar)
Nozzle Expansion	300:1	300:1	300:1	150:1/300:1
Nominal Mixture Ratio	0.85	1.61	1.65	1.61/1.65
Valve	Solenoid	Latching Torque Motor	Solenoid	Latching Torque Motor or Solenoid
Valve Power	41 watts max (2 coils wired in series)	6 watts max (Latch) 7 watts max (primary) 9 watts max (secondary	41 watts max (2 coils wired in series)	6 watts max (Latch) 7 watts max (primary) 9 watts max (secondary) (Torque Motor) 15.6 watts max (solenoid)
Mass	1.7 lbm (0.77 kg)	1.4 lbm (0.64 kg)	1.5 lbm (0.68 kg)	1.4 – 2.0 lbm (0.64 – 0.91 kg)
Length	10.3 in (262 mm)	9.6 in (244 mm)	10.4 in (264 mm)	9.7-13.5 in (248 - 343 mm)
Chamber Material	Platinum/Rhodium Alloy	Platinum/Rhodium Alloy	Platinum/Rhodium Alloy	C-103

Performance	DST-11H	DST-12	DST-13	5 lbf
Specific Impulse	310 secs	302 secs	298 secs	288 secs/292 secs
Throughput	907 kg (2000 lbm)	1073 kg (2365 lbm)	637 kg (1404 lbm)	484 kg (1068 lbm)
Programs	Intelsat, BepiColombo, Wild Geese, Tenacious, GOES-R	AsiaSat 5, Telstar, Himawari, Turksat	NASA SDO	ETS-8, QZSS, Superbird-7, ST-2, WGS, Intelsat
Highlights	DST-11H provides highest performance available in a hydrazine/ MON ACS Thruster	DST-12/13 Provides highest performance available in MMH/MON ACS Thruster		Engine has been in production for more than 30 years, with > 2000 delivered and flown

Additional comments:

[Reference 1][Feb 2019][General info]

Moog is a world leader in Bipropellant attitude control propulsion for commercial and defense satellites. Our DST family of 5 lbf thrusters combines a high performance injector design with a high temperature Platinum/Rhodium chamber to provide industry leading performance in both steady state and pulse mode operation. We also supply our heritage 5 lbf and 2 lbf thrusters, which have been providing reliable attitude control for more than twenty years. Moog ACS engines have been the industry standard with more than 2,000 delivered.

DST-11H provides highest performance available in a hydrazine/MON ACS thruster.

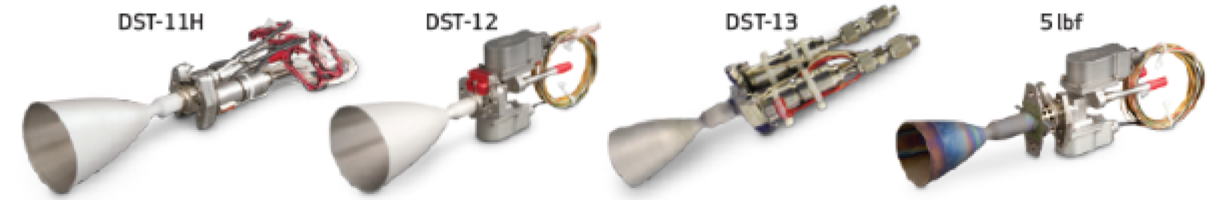
References:

[1] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html

Comm. avail.	8+	NO
Comm. avail.	TRL	Aerospace-tested

DST-12 MOOG

Propulsion Technology	Bi-prop
Manufacturer/Country	MOOG (USA)
TRL	8
Size (including PPU)	9.6” length
Design satellite size	27U+
Isp (s)	302s
Thrust type/magnitude	22N (continuous)
Delta-V (m/s)	
Propellant	MMH/MON
Power consumption (W)	9W max
Flight heritage (if any)	Extensive. AsiaSat5, Telstar, Himawari, Turksat.
Commercially available	YES
Last updated	02/2019



Design	DST-11H	DST-12	DST-13	5 lbf
Propellant	Hydrazine/MON	MMH/MON	MMH/MON	MMH/MON
Nominal Steady State Thrust	5 lbf (22N)	5 lbf (22N)	5 lbf (22N)	5 lbf (22N)
Feed Pressure	80 – 400 psia (5.5 – 27.6 bar)	60 – 400 psia (4.1 - 27.6 bar)	80 – 400 psia (5.5 - 27.6 bar)	39 - 320 psia (2.8 - 22.1 bar)
Nozzle Expansion	300:1	300:1	300:1	150:1/300:1
Nominal Mixture Ratio	0.85	1.61	1.65	1.61/1.65
Valve	Solenoid	Latching Torque Motor	Solenoid	Latching Torque Motor or Solenoid
Valve Power	41 watts max (2 coils wired in series)	6 watts max (Latch) 7 watts max (primary) 9 watts max (secondary	41 watts max (2 coils wired in series)	6 watts max (Latch) 7 watts max (primary) 9 watts max (secondary) (Torque Motor) 15.6 watts max (solenoid)
Mass	1.7 lbm (0.77 kg)	1.4 lbm (0.64 kg)	1.5 lbm (0.68 kg)	1.4 – 2.0 lbm (0.64 – 0.91 kg)
Length	10.3 in (262 mm)	9.6 in (244 mm)	10.4 in (264 mm)	9.7-13.5 in (248 - 343 mm)
Chamber Material	Platinum/Rhodium Alloy	Platinum/Rhodium Alloy	Platinum/Rhodium Alloy	C-103

Performance	DST-11H	DST-12	DST-13	5 lbf
Specific Impulse	310 secs	302 secs	298 secs	288 secs/292 secs
Throughput	907 kg (2000 lbm)	1073 kg (2365 lbm)	637 kg (1404 lbm)	484 kg (1068 lbm)
Programs	Intelsat, BepiColombo, Wild Geese, Tenacious, GOES-R	AsiaSat 5, Telstar, Himawari, Turksat	NASA SDO	ETS-8, QZSS, Superbird-7, ST-2, WGS, Intelsat
Highlights	DST-11H provides highest performance available in a hydrazine/ MON ACS Thruster	DST-12/13 Provides highest performance available in MMH/MON ACS Thruster		Engine has been in production for more than 30 years, with > 2000 delivered and flown

Additional comments:

[Reference 1][Feb 2019][General info]

Moog is a world leader in Bipropellant attitude control propulsion for commercial and defense satellites. Our DST family of 5 lbf thrusters combines a high performance injector design with a high temperature Platinum/Rhodium chamber to provide industry leading performance in both steady state and pulse mode operation. We also supply our heritage 5 lbf and 2 lbf thrusters, which have been providing reliable attitude control for more than twenty years. Moog ACS engines have been the industry standard with more than 2,000 delivered.

DST-12/13 provides highest performance available in MMH/MON ACS thruster.

References:

[1] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html

8+	NO
Comm. avail.	TRL	Aerospace-tested

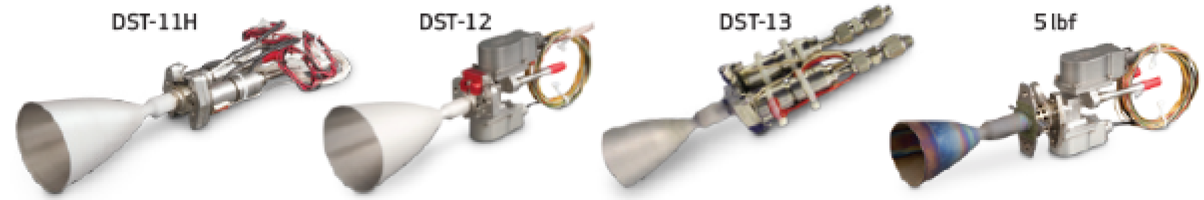
DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

DST-13 MOOG

Propulsion Technology	Bi-prop
Manufacturer/Country	MOOG (USA)
TRL	8
Size (including PPU)	10.4” length
Design satellite size	27U+
Isp (s)	298s
Thrust type/magnitude	22N (continuous)
Delta-V (m/s)	
Propellant	MMH/MON
Power consumption (W)	41W max (valve)
Flight heritage (if any)	NASA SDO
Commercially available	YES
Last updated	02/2019

Design	DST-11H	DST-12	DST-13	5 lbf



Propellant	Hydrazine/MON	MMH/MON	MMH/MON	MMH/MON
Nominal Steady State Thrust	5 lbf (22N)	5 lbf (22N)	5 lbf (22N)	5 lbf (22N)
Feed Pressure	80 – 400 psia (5.5 – 27.6 bar)	60 – 400 psia (4.1 - 27.6 bar)	80 – 400 psia (5.5 - 27.6 bar)	39 - 320 psia (2.8 - 22.1 bar)
Nozzle Expansion	300:1	300:1	300:1	150:1/300:1
Nominal Mixture Ratio	0.85	1.61	1.65	1.61/1.65
Valve	Solenoid	Latching Torque Motor	Solenoid	Latching Torque Motor or Solenoid
Valve Power	41 watts max (2 coils wired in series)	6 watts max (Latch) 7 watts max (primary) 9 watts max (secondary	41 watts max (2 coils wired in series)	6 watts max (Latch) 7 watts max (primary) 9 watts max (secondary) (Torque Motor) 15.6 watts max (solenoid)
Mass	1.7 lbm (0.77 kg)	1.4 lbm (0.64 kg)	1.5 lbm (0.68 kg)	1.4 – 2.0 lbm (0.64 – 0.91 kg)
Length	10.3 in (262 mm)	9.6 in (244 mm)	10.4 in (264 mm)	9.7-13.5 in (248 - 343 mm)
Chamber Material	Platinum/Rhodium Alloy	Platinum/Rhodium Alloy	Platinum/Rhodium Alloy	C-103

Performance	DST-11H	DST-12	DST-13	5 lbf
Specific Impulse	310 secs	302 secs	298 secs	288 secs/292 secs
Throughput	907 kg (2000 lbm)	1073 kg (2365 lbm)	637 kg (1404 lbm)	484 kg (1068 lbm)
Programs	Intelsat, BepiColombo, Wild Geese, Tenacious, GOES-R	AsiaSat 5, Telstar, Himawari, Turksat	NASA SDO	ETS-8, QZSS, Superbird-7, ST-2, WGS, Intelsat
Highlights	DST-11H provides highest performance available in a hydrazine/ MON ACS Thruster	DST-12/13 Provides highest performance available in MMH/MON ACS Thruster		Engine has been in production for more than 30 years, with > 2000 delivered and flown

Additional comments:

[Reference 1][Feb 2019][General info]

Moog is a world leader in Bipropellant attitude control propulsion for commercial and defense satellites. Our DST family of 5 lbf thrusters combines a high performance injector design with a high temperature Platinum/Rhodium chamber to provide industry leading performance in both steady state and pulse mode operation. We also supply our heritage 5 lbf and 2 lbf thrusters, which have been providing reliable attitude control for more than twenty years. Moog ACS engines have been the industry standard with more than 2,000 delivered.

DST-12/13 provides highest performance available in MMH/MON ACS thruster.

References:

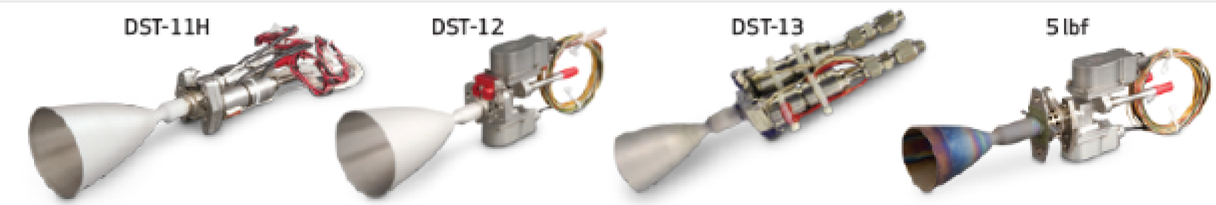
[1] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html

Comm. avail.	8+ TRL	NO Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

5LBF C-103 MOOG

Propulsion Technology	Bi-prop
Manufacturer/Country	MOOG (USA)
TRL	8
Size (including PPU)	13.5" length
Design satellite size	27U+
Isp (s)	288 to 292s
Thrust type/magnitude	22N (continuous)
Delta-V (m/s)	
Propellant	MMH/MON
Power consumption (W)	15.6W max (valve)
Flight heritage (if any)	Extensive. ETS-8, QZSS, Superbird-7, ST-2, WGS, Intelsat
Commercially available	YES
Last updated	02/2019



Design	DST-11H	DST-12	DST-13	5 lbf
Propellant	Hydrazine/MON	MMH/MON	MMH/MON	MMH/MON
Nominal Steady State Thrust	5 lbf (22N)	5 lbf (22N)	5 lbf (22N)	5 lbf (22N)
Feed Pressure	80 – 400 psia (5.5 – 27.6 bar)	60 – 400 psia (4.1 - 27.6 bar)	80 – 400 psia (5.5 - 27.6 bar)	39 - 320 psia (2.8 - 22.1 bar)
Nozzle Expansion	300:1	300:1	300:1	150:1/300:1
Nominal Mixture Ratio	0.85	1.61	1.65	1.61/1.65
Valve	Solenoid	Latching Torque Motor	Solenoid	Latching Torque Motor or Solenoid
Valve Power	41 watts max (2 coils wired in series)	6 watts max (Latch) 7 watts max (primary) 9 watts max (secondary	41 watts max (2 coils wired in series)	6 watts max (Latch) 7 watts max (primary) 9 watts max (secondary) (Torque Motor) 15.6 watts max (solenoid)
Mass	1.7 lbm (0.77 kg)	1.4 lbm (0.64 kg)	1.5 lbm (0.68 kg)	1.4 – 2.0 lbm (0.64 – 0.91 kg)
Length	10.3 in (262 mm)	9.6 in (244 mm)	10.4 in (264 mm)	9.7-13.5 in (248 - 343 mm)
Chamber Material	Platinum/Rhodium Alloy	Platinum/Rhodium Alloy	Platinum/Rhodium Alloy	C-103

Performance	DST-11H	DST-12	DST-13	5 lbf
Specific Impulse	310 secs	302 secs	298 secs	288 secs/292 secs
Throughput	907 kg (2000 lbm)	1073 kg (2365 lbm)	637 kg (1404 lbm)	484 kg (1068 lbm)
Programs	Intelsat, BepiColombo, Wild Geese, Tenacious, GOES-R	AsiaSat 5, Telstar, Himawari, Turksat	NASA SDO	ETS-8, QZSS, Superbird-7, ST-2, WGS, Intelsat
Highlights	DST-11H provides highest performance available in a hydrazine/ MON ACS Thruster	DST-12/13 Provides highest performance available in MMH/MON ACS Thruster		Engine has been in production for more than 30 years, with > 2000 delivered and flown

Additional comments:

[Reference 1][Feb 2019][General info]

Moog is a world leader in Bipropellant attitude control propulsion for commercial and defense satellites. Our DST family of 5 lbf thrusters combines a high performance injector design with a high temperature Platinum/Rhodium chamber to provide industry leading performance in both steady state and pulse mode operation. We also supply our heritage 5 lbf and 2 lbf thrusters, which have been providing reliable attitude control for more than twenty years. Moog ACS engines have been the industry standard with more than 2,000 delivered.

Engine has been in production for more than 30 years, with >2000 delivered and flown.

References:

[1] https://www.moog.com/products/propulsion-controls/spacecraft/spacecraft-propulsion-components/thrusters.html

8+ NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

NGC Monopropellant thrusters series MRE-0.1

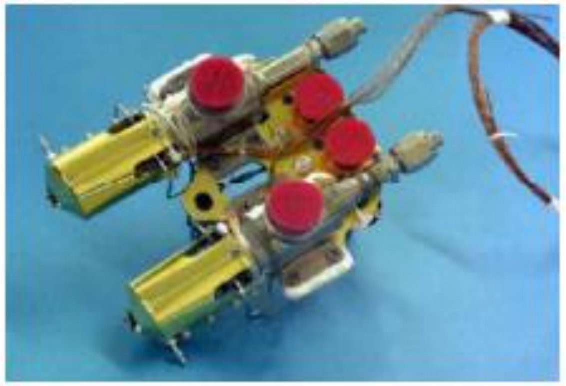
Propulsion Technology	Monopropellant Thruster
Manufacturer/Country	Northrop Grumman (USA)
TRL	8+
Size (including PPU)	114 mm (width), 175 mm (length), 0.5/0.9 kg (STM/DTM mass)
Design satellite size	
Isp (s)	216
Thrust type/magnitude	1.0 N
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	15 W
Flight heritage (if any)	Chandra W-ray Observatory, DSP, STEP4
Commercially available	Yes
Last updated	07/2020

Technical Data

Propellant	Hydrazine
Thrust at maximum operating pressure	1.0 N at 350 psia
Thrust at 275 psia inlet pressure	0.8 N
Steady state specific impulse at 275 psia inlet pressure	216 seconds
Operating pressure range	5-600 psia
Life (demonstrated)	
• Maximum throughput	34 kg
• Maximum cycles	370,000
Thrust valve power at 28 Vdc	15 W
Weight (STM/DTM)	0.5 kg/0.9 kg
Envelope (width x length)	114 mm x 175 mm

Spacecraft Programs

Chandra X-ray Observatory, DSP, STEP4



[1]

Additional comments:

[Reference 1][July 2020][Thruster and general information]
Northrop Grumman has developed, qualified and flown nearly 1,000 monopropellant thrusters, gas generators and gas thrusters, ranging from 30 millipounds to 8 lbs. We have also developed and tested 15-pound class and larger monopropellant thrusters. In all cases, Northrop Grumman thrusters have exceeded design goals and outlived the useful spacecraft lives on a wide range of myriad of programs, including Pioneer 10 and 11, DSP, TDRS, FSC, Chandra X-ray Observatory, SOHO, EOS, TOMS, STEP, ROCSAT, KOMPSAT, and HEAO.

The authors could not find whether these thrusters had flown on small sat missions.

References:
[1] https://www.northropgrumman.com/space-old/propulsion-products-and-services/

8+ NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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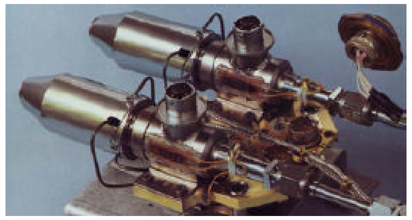
NGC Monopropellant thrusters series
MRE-1.0

Propulsion Technology	Monopropellant Thruster
Manufacturer/Country	Northrop Grumman (USA)
TRL	8+
Size (including PPU)	114 mm (width), 188 mm (length), 0.5/1.0 kg (STM/DTM)
Design satellite size	
Isp (s)	218
Thrust type/magnitude	5.0 N
Delta-V (m/s)	Not listed
Propellant	Hydrazine
Power consumption (W)	15 W
Flight heritage (if any)	Dtm – Pioneer, HEAO, TDRSS, FLTSATCOM, EOS SSTI, SOHO TOMS, KOMPSAT, ROCSAT, STEP4, STEP1
Commercially available	Yes
Last updated	07/2020

MRE-1.0 Monopropellant Thruster

For satellite attitude and velocity control.



Technical Data

Propellant	Hydrazine
Thrust at maximum operating pressure	5.0 N at 400 psia
Thrust at 275 psia inlet pressure	3.4 N
Steady state specific impulse at 275 psia inlet pressure	218 sec
Operating pressure range	8-565 psia
Life (demonstrated)	
• Maximum throughput	544 kg
• Maximum cycles	457,849
Thrust valve power at 28 Vdc	15 W
Weight (STM/DTM)	0.5 kg/1.0 kg
Envelope (width x length)	114mm x 188mm

Spacecraft Programs

DTM - Pioneer, HEAO, TDRSS, FLTSATCOM, EOS, SSTI, SOHO TOMS, KOMPSAT, ROCSAT, STEP4, STEP1

Additional comments:

[Reference 1][July 2020][Thruster and general information]
Northrop Grumman has developed, qualified and flown nearly 1,000 monopropellant thrusters, gas generators and gas thrusters, ranging from 30 millipounds to 8 lbs. We have also developed and tested 15-pound class and larger monopropellant thrusters. In all cases, Northrop Grumman thrusters have exceeded design goals and outlived the useful spacecraft lives on a wide range of myriad of programs, including Pioneer 10 and 11, DSP, TDRS, FSC, Chandra X-ray Observatory, SOHO, EOS, TOMS, STEP, ROCSAT, KOMPSAT, and HEAO.

The authors could not find whether these thrusters had flown on small sat missions.

References:
[1] https://www.northropgrumman.com/space-old/propulsion-products-and-services/

8+ | NO

Comm. avail. | TRL | Aerospace-tested

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NGC Monopropellant thrusters series
MRE-4.0

Propulsion Technology	Monopropellant Thruster
Manufacturer/Country	Northrop Grumman (USA)
TRL	8+
Size (including PPU)	61 mm (width), 206 mm (length), 0.5 kg
Design satellite size	
Isp (s)	217
Thrust type/magnitude	18 N
Delta-V (m/s)	Not listed
Propellant	Hydrazine
Power consumption (W)	30 W
Flight heritage (if any)	Intelsat III, DSCS III, STEP0, ISEE-C, DSP, ATMOS, Explorer
Commercially available	Yes
Last updated	07/2020

MRE-4.0 Monopropellant Thruster

For satellite attitude and velocity control.

Technical Data

Propellant	Hydrazine
Thrust at maximum operating pressure	18 N at 600 psia
Thrust at 275 psia inlet pressure	9.8 N
Steady state specific impulse at 275 psia inlet pressure	217 sec
Operating pressure range	50-600 psia
Life (demonstrated)	
• Maximum throughput	249 kg
• Maximum cycles	507,000
Thrust valve power at 28 Vdc	30 W
Weight (STM/DTM)	0.5 kg/-
Envelope (width x length)	61mm x 206mm

Spacecraft Programs

Intelsat III, DSCS III, STEP0, ISEE-C, DSP, Atmos, Explorer

Additional comments:

[Reference 1][July 2020][Thruster and general information]
Northrop Grumman has developed, qualified and flown nearly 1,000 monopropellant thrusters, gas generators and gas thrusters, ranging from 30 millipounds to 8 lbs. We have also developed and tested 15-pound class and larger monopropellant thrusters. In all cases, Northrop Grumman thrusters have exceeded design goals and outlived the useful spacecraft lives on a wide range of myriad of programs, including Pioneer 10 and 11, DSP, TDRS, FSC, Chandra X-ray Observatory, SOHO, EOS, TOMS, STEP, ROCSAT, KOMPSAT, and HEAO.

The authors could not find whether these thrusters had flown on small sat missions.

References:
[1] https://www.northropgrumman.com/space-old/propulsion-products-and-services/

Comm. avail.	8+	NO
	TRL	Aerospace-tested

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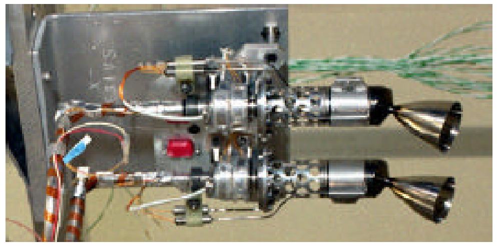
NGC Monopropellant thrusters series
MRE-5.0

Propulsion Technology	Monopropellant Thruster
Manufacturer/Country	Northrop Grumman (USA)
TRL	8+
Size (including PPU)	145 mm (width), 264 mm (length), 1.5 kg (DTM)
Design satellite size	
Isp (s)	232
Thrust type/magnitude	36 N
Delta-V (m/s)	Not listed
Propellant	Hydrazine
Power consumption (W)	30 W
Flight heritage (if any)	GRO
Commercially available	Yes
Last updated	07/2020

MRE-5.0 Monopropellant Thruster



For satellite attitude and velocity control.

Technical Data

Propellant	Hydrazine
Thrust at maximum operating pressure	36 N at 400 psia
Thrust at 275 psia inlet pressure	28 N
Steady state specific impulse at 275 psia inlet pressure	232 sec
Operating pressure range	70-475 psia
Life (demonstrated) • Maximum throughput • Maximum cycles	 456 kg 28,512
Thrust valve power at 28 Vdc	30 W
Weight (STM/DTM)	-/1.5 kg
Envelope (width x length)	145mm x 264mm

Spacecraft Programs

GRO

Additional comments:

[Reference 1][July 2020][Thruster and general information]
Northrop Grumman has developed, qualified and flown nearly 1,000 monopropellant thrusters, gas generators and gas thrusters, ranging from 30 millipounds to 8 lbs. We have also developed and tested 15-pound class and larger monopropellant thrusters. In all cases, Northrop Grumman thrusters have exceeded design goals and outlived the useful spacecraft lives on a wide range of myriad of programs, including Pioneer 10 and 11, DSP, TDRS, FSC, Chandra X-ray Observatory, SOHO, EOS, TOMS, STEP, ROCSAT, KOMPSAT, and HEAO.

The authors could not find whether these thrusters had flown on small sat missions.

References:
[1] https://www.northropgrumman.com/space-old/propulsion-products-and-services/

8+ NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

NGC Monopropellant thrusters series MRE-15/MRE-1.5

Propulsion Technology	Monopropellant Thruster
Manufacturer/Country	Northrop Grumman (USA)
TRL	8+
Size (including PPU)	119 mm (width), 318 mm (length), 1.1 kg (STM)
Design satellite size	
Isp (s)	228
Thrust type/magnitude	86 N
Delta-V (m/s)	Not listed
Propellant	Hydrazine
Power consumption (W)	72 W
Flight heritage (if any)	None listed, but assumed to have flown
Commercially available	Yes
Last updated	07/2020

MRE-15 Monopropellant Thruster

For satellite attitude and velocity control.

Technical Data

Propellant	Hydrazine
Thrust at maximum operating pressure	86 N at 400 psia
Thrust at 275 psia inlet pressure	66 N
Steady state specific impulse at 275 psia inlet pressure	228 sec
Operating pressure range	138-430 psia
Life (demonstrated)	
• Maximum throughput	970 kg
• Maximum cycles	105,561
Thrust valve power at 28 Vdc	72 W
Weight (STM/DTM)	1.1 kg/-
Envelope (width x length)	119mm x 318 mm

Additional comments:

[Reference 1][July 2020][Thruster and general information]
Northrop Grumman has developed, qualified and flown nearly 1,000 monopropellant thrusters, gas generators and gas thrusters, ranging from 30 millipounds to 8 lbs. We have also developed and tested 15-pound class and larger monopropellant thrusters. In all cases, Northrop Grumman thrusters have exceeded design goals and outlived the useful spacecraft lives on a wide range of myriad of programs, including Pioneer 10 and 11, DSP, TDRS, FSC, Chandra X-ray Observatory, SOHO, EOS, TOMS, STEP, ROCSAT, KOMPSAT, and HEAO.

The authors could not find whether these thrusters had flown on small sat missions.

References:
[1] https://www.northropgrumman.com/space-old/propulsion-products-and-services/

8+ NO

Comm. avail. TRL Aerospace-tested

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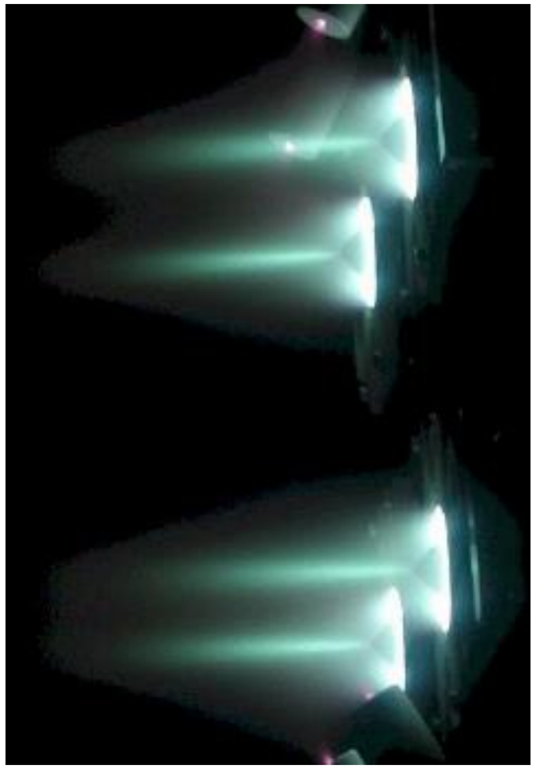
BHT-200 (Xenon)/BHT-200-I (Iodine) [1 of 2]
Busek

Propulsion Technology	Hall effect thruster
Manufacturer/Country	Busek (USA)
TRL	8
Size (including PPU)	~2 to 3U (estimated)
Design satellite size	Small sat
Isp (s)	1400s
Thrust type/magnitude	13 mN (at 200W)
Delta-V (m/s)	
Propellant	Xenon, Iodine, Krypton
Power consumption (W)	100 to 300W, 250 VDC
Flight heritage (if any)	TACSAT-2 (2006), FalconSat-5 (2010), FalconSat-6 (2018) MFC iSAT (iodine, 2 units delivered) [4, 5, 6, 7]
Commercially available	YES
Last updated	*01/2021*



Multiple BHT-200's in a cluster

Additional comments:

[Reference 1-4, 7][Jan 2019][General info]

The BHT-200 is the first US-designed and US-built Hall Effect thruster used in-space on operational satellites, and is subject of numerous technical papers and journal publications. The BHT-200 is a patented design covered under "Tandem Hall Field Plasma Accelerator," US Patent No. 6,150,764. Over 20 units of the BHT-200 have been built and delivered for broad range of characterization, plume studies, and clustering and modeling efforts, including three flight systems: TacSat-2, FalconSat-5, and FalconSat-6. Busek has a pending flight order for two iodine compatible versions of the thruster for MSFC iSat mission. iSAT is a 12U CubeSat intended as a rapid orbital demonstration of the iodine Hall thruster technology.

A key advantage to using iodine as a propellant is that it provides a high density times specific impulse, it is three times as fuel efficient as the commonly flown xenon, it may be stored in the tank as an unpressurized solid, and it is not a hazardous propellant. 1U with 5 kg of iodine on a 12U vehicle can provide a change of velocity of 4 km/s ΔV, perform a 20,000km altitude change, 30° inclination change from LEO, or an 80° inclination change from GEO. During operations, the tank is heated to vaporize the propellant. The thruster then ionizes the vapor and accelerates it via magnetic and electrostatic fields, resulting in high specific impulse. The satellite has full three-axis attitude control capability by using momentum wheels and magnetic torque rods to rotate. iSat also counts with a passive thermal control system. The cathode is the BHC-1500, and is external. Cathode mass is 0.2 kg.

On December 16, 2006 the AFRL TacSat-2 satellite was launched with Busek's 200W Hall Thruster for primary propulsion. This thruster is the first US-designed and US-built Hall thruster in space and represents a significant milestone not only for Busek but also for the US space industry. The primary objective was to demonstrate improved microsat maneuverability. Plume measurements and on-board diagnostics verified performance. AFRL and the USAF Academy integrated Busek's HET system on the FalconSat-5 satellite, which launched aboard DoD Space Test Program's S26 mission on an Orbital Sciences Minotaur-IV rocket from Kodiak Island in November 2010.

References:

[1] Nakles, M., Brieda, L., Reed, G., Hargus, W., Spicer, R., "Experimental and Numerical Examination of the BHT-200 hall Thruster Plume," Presented at the 43rd AIAA JPC, 2007. AFRL Report AFRL-PR-ED-TP-2007-331.
[2] Krejci, D., Lozano, P., "Space Propulsion Technology for Small Spacecraft," Proceedings of the IEEE, 2018.
[3] https://en.wikipedia.org/wiki/Iodine_Satellite
[4] http://www.busek.com/index_htm_files/70000700%20BHT-200%20Data%20Sheet%20Rev-.pdf
[5] Kamhawi, H., Haag, T., Benavides, G., Hickman, T., Smith, T., Williams, G., Myers, J., Polzin, K., Dankanich, J., Byrne, L., Szabo, J., and Lee, L., "Overview of Iodine Propellant Hall Thruster Development Activities at NASA Glenn Research Center," 52nd AIAA Joint Propulsion Conference, Salt Lake City, Utah, 2016.
[6] https://techport.nasa.gov/view/91492
[7] Hruby, P., Demmons, N., Courtney, D., Tsay, M., Szabo, J., and Hruby, V., "Overview of Busek Electric Propulsion," 36th IEPC, Vienna, Austria, 2019.

Comm. avail.	TRL	Aerospace-tested
	8	NO

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BHT-200 (Xenon)/BHT-200-I (Iodine) [2 of 2]
Busek

Additional comments:

[Reference 1][June 2020][Iodine development]
Low-power Hall thruster tests at Busek Co. Inc. found that Hall thruster performance with iodine is very similar to its performance with xenon; however, iodine stores three times as dense as xenon and at sub-atmospheric pressures. The increase in storage density and reduction in tank pressure can lead to improved spacecraft volume utilization, which can translate to a significant ΔV increase relative to xenon propellant for a given electric propulsion system volume.
NASA continues to develop iodine Hall thrusters due to mission benefits for small spacecraft. The team of NASA GRC, NASA MSFC, and Busek Co. Inc. are working on both a flight mission and technology development activity. The Busek BHT-200-I will be qualified for flight on the iSAT mission. The BHT-600-I development activity will culminate in the delivery of an engineering model, BHT-600-I Hall thruster propulsion system. To date, extended duration tests have been conducted at NASA GRC on the EM BHT-200-I and BHT-600-I Hall thrusters. In each test the thruster performance was consistent with previous observed results and in-line with operation on xenon. Post inspection of the thrusters did not show any significant physical changes after operation with iodine. Future activities will focus on flight qualification of the BHT-200-I system, including integrated system testing with the iodine feed system, cathode, and power processing unit. Technology development will continue with the BHT-600-I to examine iodine operation at 600 W and to perform extended duration testing of an engineering model propulsion system after the delivery of the 600 W PPU.

[Reference 2][June 2020][Iodine development]
The Iodine Satellite (iSat) spacecraft was to be the first CubeSat to demonstrate high change in velocity from a secondary payload launch safe propulsion system using a Hall thruster modified to use iodine as a propellant. The mission was to demonstrate CubeSat maneuverability, including plane change, altitude change and change in its closest approach to Earth to ensure atmospheric reentry in less than 90 days.
It was determined during the course of this project that additional development related to iodine compatible cathodes was required before conducting an in space demonstration of the technology at this scale of thruster.

[Reference 3][Jan 2021][Missions for iodine thruster]
Busek recently delivered two iodine compatible versions of the thruster for MSFC iSAT mission.

References:
[1] Kamhawi, H., Haag, T., Benavides, G., Hickman, T., Smith, T., Williams, G., Myers, J., Polzin, K., Dankanich, J., Byrne, L., Szabo, J., and Lee, L., “Overview of Iodine Propellant Hall Thruster Development Activities at NASA Glenn Research Center,” 52nd AIAA Joint Propulsion Conference, Salt Lake City, Utah, 2016.
[2] https://techport.nasa.gov/view/91492
[3] http://busek.com/index_htm_files/70000700A%20BHT-200.pdf

Comm. avail.	TRL	Aerospace-tested
	8	NO

DISTRO A: Approved for public release. OTR-2024-00338

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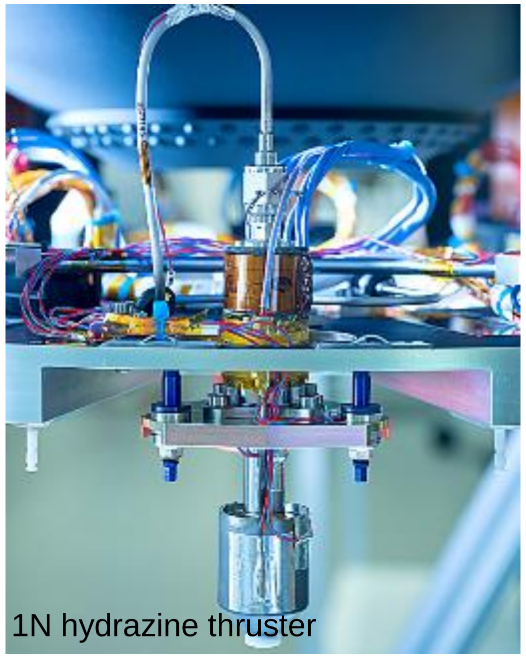
1N Monopropellant Thruster
Ariane Group

Propulsion Technology	Hydrazine monopropellant
Manufacturer/Country	Ariane Group (Airbus/Safran) (FRANCE/GERMANY)
TRL	8
Size (including PPU)	300g (150mm x 30 mm x 30 mm, ~0.5U)
Design satellite size	1U and larger
Isp (s)	220s
Thrust type/magnitude	0.32 to 1.1 N (continuous, nominal) 0.01 to 0.043N (impulse bit, min) 135,000 N*s (impulse, total)
Delta-V (m/s)	Not reported but likely similar to Busek's ~150 to 200 m/s for 4 kg spacecraft. For ALSAT-2, it had a delta V=70m/s for a 120 kg spacecraft.
Propellant	Hydrazine
Power consumption (W)	Not reported but likely 10's of W. (catalyst pre-heat main contributor)
Flight heritage (if any)	Many. Roughly 30 flights since 2000, including Elisa 1 to 4, and most recently CSO-1 (2016). ALSAT-2 (2016)
Commercially available	YES
Last updated	*06/2020*


1N hydrazine thruster

Additional comments:

[Reference 1-2][Jan 2019][General info]

The 1N monopropellant hydrazine thruster is used for attitude, trajectory and orbit control of small and mid-size satellites and spacecraft. The thruster is typically used in our own propulsion systems and is also available separately for use in our customers' propulsion systems. More than 500 units of this thruster operate successfully in space. The 1N thruster was derived from the space proven 0.5N thruster, of which some 165 units were flown on OTS-2, ECS, Marecs, Telecom-1, Skynet 4 and NATO-IV. Since these applications, the thruster has undergone multiple refinements, especially in achieving a minimum possible production cost. Today, this unit may be regarded as a low-cost thruster. Propellant supply to the thruster is provided by a two stage flow control valve comprising two identical monostable, normally closed valves placed in series within a single housing. Additionally each thruster is equipped with an internal redundant catalyst bed heater and with thermal insulation to guarantee optimum start-up. All materials used in the valve and thrust chamber assembly have been selected for compatibility with hydrazine propellant. Thrust is generated when the control valve is commanded to open, causing propellant to be fed to the thrust chamber where a decomposition reaction takes place within the catalyst bed. The thruster is qualified for multiple cold starts.
This thruster has been qualified to more than 50,000 cycles.
5N and 20N versions are also available, but likely require too much power.

[Reference 3-4][Jan 2019][Flight info]

A NASA report says that these thrusters were used on the ALSAT-2 satellite, built by Airbus. ALSAT-2 is a 120 kg spacecraft with a design life of 5 years. The hydrazine system has a delta v= 70 m/s.

References:

[1] https://www.ariane.group/en/equipment-and-services/satellites-and-spacecraft/1-n/
[2] http://www.space-propulsion.com/brochures/hydrazine-thrusters/hydrazine-thrusters.pdf
[3] NASA survey of small-satellite propulsion, 2018. https://sst-soa.arc.nasa.gov/04-propulsion
[4] https://directory.eoportal.org/web/eoportal/satellite-missions/a/alsat-2

(cart icon)	8+	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

10N Bi-Propellant Thruster
Ariane Group

Propulsion Technology	Monomethylhydrazine (MMH) and di-nitrogen-tetroxide (N2O4)/ mixed oxides of nitrogen (MON-1, MON-3) bipropellant
Manufacturer/Country	Ariane Group (Airbus/Safran) (FRANCE/GERMANY)
TRL	8
Size (including PPU)	350 g (single seat) 650 g (dual seat) 35 mm (diameter)
Design satellite size	
Isp (s)	292 s
Thrust type/magnitude	10 N (nominal), 6.0-12.5 N (range)
Delta-V (m/s)	Not reported
Propellant	MMH (fuel), N2O4, MON-1, MON-3 (oxidizer)
Power consumption (W)	Not reported
Flight heritage (if any)	Many, roughly 60 since 2010. See [1] for full list.
Commercially available	Yes
Last updated	07/2020

10N Bi-Propellant Thruster Key Technical Characteristics	
Thrust Nominal	10 N (2.2 lbf)
Thrust Range	6.0 ... 12.5 N
Specific Impulse at Nominal Point	292 s
Flow Rate Nominal	3.50 g/s
Flow Rate Range	2.30 ... 4.20 g/s
Mixture Ratio Nominal	1.60 ... 1.65
Mixture Ratio Range	1.20 ... 2.10
Chamber Pressure Nominal	9 bar
Inlet Pressure Range	10 ... 23 bar
Throat Diameter (inner)	2.85 mm
Nozzle End Diameter (inner)	35 mm
Nozzle Expansion Ratio (by area)	150
Mass, Thruster with Valve	350 g (single seat) 650 g (dual seat)
Chamber Nozzle Material	Platinum/Rhodium Alloy
Fuel	MMH
Oxidizer	N_2O_4, MON-1, MON-3
Valve Single Seat	Bi-propellant torque motor valve
Valve Dual Seat	Bi-propellant torque or linear motor valves
Mounting I/F to S/C	Valve flange with 3 through-holes of 6.4 mm (1/4") diameter
Tubing I/F	Per SAE AS4395E02 or welded
Valve Lead Wires	24 AWG per MIL-W-81381
Thruster Heater and Thermal Sensor	On request
Qualified longest single burn	8 hours
Qualified accumulated burn life	69 hours
Qualified cycle life	1.100.000 cycles

[1]

Flight heritage [1]

Spacecraft	Launch Year	Spacecraft	Launch Year	Spacecraft	Launch Year
Arabsat 5A	2010	YAHSAT 1B	2012	DirecTV 15	2015
Arabsat 5B	2010	AMOS 4	2013	Hispasat 1 AG	2015
Astra 3B	2010	Alphasat PFM	2013	TELSTAR 12V	2015
COMS	2010	Astra 2E	2013	AMU-1	2015
KA-SAT	2010	W3D	2013	Eutelsat 8WB	2015
MILSAT-B	2010	SES-6	2013	AMOS 6	2015
Nilesat 201	2010	GAIA	2013	SkyBrasil	2015
Rascom-2	2010	AthenaFidus	2014	AMOS 6 R	2016
W3B	2010	Astra 2G	2014	Bepi Colombo	2016
Arabsat 5C	2011	Astra 5B	2014	EDRS-C	2016
Astra 1N	2011	ARSAT 1	2014	SES-10	2016
Atlantic Bird 7	2011	Ekspress-AM4R	2014	SGDC	2016
Ekspress AM4	2011	Eutelsat 3B	2014	Koreasat 7	2016
W3C	2011	MEASAT 3B	2014	Exomars Orbiter	2016
Yahsat 1A	2011	Arabsat 6B	2015	Echostar 105	2017
Apstar7	2012	ARSAT 2	2015	Eutelsat 172B	2017
Astra 2F	2012	Eutelsat 9B	2015	SES-12	2017
MSG FM3	2012	LISA-Pathfinder	2015	Solar Orbiter	2017
SK5D	2012	MSG FM4	2015	MTG	2019
W5A	2012	Ekspress-AM7	2015		
W6A	2012	Sicral2	2015		

Additional comments:

[Reference 1][July 2020][General info]
The 10N and 400N thrusters are part of Ariane's chemical propulsion systems mainly flying in commercial GEO programs. Also recently, missions like Rosetta and Gaia, Bepi Colombo, Lisa Pathfinder, and Solar Orbiter have flown the 10N and 400 N workhorse thrusters.
The 10N thrusters have been flying since 1974.
However, the authors have not found any small satellites that have flown this system as a primary propulsion system.

References:
[1] https://www.space-propulsion.com/brochures/bipropellant-thrusters/bipropellant-thrusters.pdf

8+ NO
Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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20N Monopropellant Thruster
Ariane Group

Propulsion Technology	Monopropellant Thruster
Manufacturer/Country	Ariane Group
TRL	9
Size (including PPU)	33 mm (diameter), 196 mm (length), 650 g
Design satellite size	
Isp (s)	222 - 230
Thrust type/magnitude	7.9 - 24.6N vac
Delta-V (m/s)	Not reported
Propellant	Hydrazine
Power consumption (W)	Not reported
Flight heritage (if any)	Many large satellites, since 1982, including NGSAR (2018), Planck (2009), Herschel (2009), METOP 1-3 (2006-2018), SMM (1999), Integral (2002), EURECA (1982).
Commercially available	Yes
Last updated	07/2020

Additional comments:

[Reference 1][July 2020][Thruster info]
The 20N monopropellant hydrazine thruster is used for attitude, trajectory, and orbit control of satellites, spacecraft, and platforms. The flow of propellant is controlled by a flow control valve, comprising two independent consecutive monostable, normally closed valve stages. When the valve is activated, propellant is supplied through a fuel supply pipe, mounted within the heat barrier, to the injection plate. The flow rate is adjusted by an orifice within the fuel pipe to ensure that the delivered thrust is within the specified limits.

The authors could not find any small satellite missions that have flown this thruster.

References:
[1] https://www.space-propulsion.com/spacecraft-propulsion/hydrazine-thrusters/20n-hydrazine-thruster.html

8+ | NO
Comm. avail. | TRL | Aerospace-tested

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1N Hydrazine thruster

Propulsion Technology	Hydrazine Monopropellant
Manufacturer/Country	Rafael (Israel)
TRL	8
Size (including PPU)	Small (<310 g)
Design satellite size	
Isp (s)	215s @ 22 bar feed pressure [1] 205s @ 5.5 bar feed pressure [1]
Thrust type/magnitude	0.27 to 1.25 N (continuous) [1] 60,000 to 120,000 N*s (impulse, total) [1]
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	9.2W at 28VDC
Flight heritage (if any)	VENUS/VENµS (2017), GlobalStar-2 (many since 2012), Galileo, OFEQ, EROS [2] O3B, Sentinel-1, NEOSAT, Venus, PRISMA, SAC-D [3]
Commercially available	YES
Last updated	*12/2023*

Parameter	Characteristics		
Propellant:	Hydrazine (N_2H_4)		
Feed Pressure (bar abs):	OFEQ	GB*2	Galileo
	27 to 5.5	25 to 5.5	24.7 to 5.5
Thrust, Steady State (N): (BOL)	1.25 to 0.27		
SSF Specific Impulse (sec):	>215 @ 22 bar		
	>205 @ 5.5 bar		
Minimum Impulse Bit (N-s):	0.008 @ 5.5 bar @ 0.02 sec/1 sec		
Nominal Duty Cycle:	0.1 sec/1 sec		
Response Time (Hot Pulse)			
Rise Time(ms):	60 @ nominal duty cycle & 22 bar		
Decay Time (ms):	150 @ nominal duty cycle & 22 bar		
Total Delivered Impulse (N-s):	OFEQ	GB*2	Galileo
	100,000	120,000*	60,000
Total Number of Pulses	OFEQ	GB*2	Galileo
	200,000	305,000*	58,000
Leakage			
Internal Leakage (Scc/s GHe):	$1x10^{-4}$ @ 3.5 and 24 bar		
External Leakage (Scc/s GHe):	$1 x10^{-6}$ @ 36 bar		
Temperature	Operating: +5°C to 90°C Non Operating: -10°C to 95°C		
Flow Control:	FCV – dual-coil, dual seat, N.C. solenoid valve		
FCV Operating Voltage (VDC):	23 to 36		
FCV Power (Watt):	9.2 @ 28 VDC		
Heater – Dual Element			
Heater Operating Voltage (VDC):	23 to 36		
Heater Resistance (ohms):	257 for each element		
Nozzle Expansion Ratio:	130		
Total Life (Storage and Flight):	15 years		
Inlet Filtration	15 micron absolute		
Inlet Interface:	MS 33656-4 or S.S-304L 0.25" tube		
Weight (gr):	≤ 310 (1000 mm lead wire length)		
Heritage:	Qualified for OFEQ, Galileo, Venus, Sentinel1. Under qualification for GlobalStar 2, O3B		

Additional comments:

[Reference 1][Jan 2019][General info]
The 1N hydrazine thruster generates the required thrust for maneuvering the satellite by means of a hot gas jet created by hydrazine decomposition and expansion through the exit nozzle. The thruster was designed and qualified for the OFEQ program. The RAFAEL 1N thruster was chosen for the following programs: Globalstar-2, O3B constellation (by TAS-F). It was also chosen for ESA programs: Galileo IOV (by EADS-ST) and Sentinel (by TAS-I). The thruster is commanded by a solenoid-operated, dual-coil, dual-seat normally-closed Flow Control Valve (FCV). Closed position is maintained by springs for both seats. The FCV is equipped with an integral filter, 15 micron absolute, placed at the valve inlet. The thruster is equipped with an electrical catalyst bed heater (CBH), with two resistance coils, providing the initial thermal condition required for long duration and repeatable operation. The pre-heating time is needed for reliable start of the thruster. The recommended pre-heating temperature is 180°C. The elapsed time to reach this temperature depends on the thruster's initial temperature. A typical time for pre-heating from +25°C is about 20 minutes.

References:

[1] http://www.rafael.co.il/5719-2612-EN/Marketing.aspx
[2] https://www.flightglobal.com/news/articles/globalstar-2-satellite-system-to-carry-rafael-fuel-t-212707/
[3] Flyer distributed at Small Sat Conference 2023.

	8	NO
Comm. avail.	TRL	Aerospace-tested

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5N Hydrazine thruster

Propulsion Technology	Hydrazine Monopropellant
Manufacturer/Country	Rafael (Israel)
TRL	8
Size (including PPU)	Small (<310 g)
Design satellite size	
Isp (s)	220s @ 22 bar feed pressure [1] 210s @ 5.5 bar feed pressure [1]
Thrust type/magnitude	1.8 to 6.1 N (continuous) [1] 74,000 N*s (impulse, total) [1]
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	<10W at 28VDC
Flight heritage (if any)	Extensive. OFEQ, EROS, TECSAR
Commercially available	YES
Last updated	*01/2019*

Parameter	Characteristics
Propellant:	Hydrazine (N_2H_4)
Feed Pressure (bar abs):	24 to 5.5 (nominal), tested down to 4.5
Thrust, Steady State (N):	6.1 @ 22 bar to 1.8 @ 5.5 bar
SSF Specific Impulse (sec):	>220 @ 22 bar
	>210 @ 5.5 bar
Minimum Impulse Bit (N-s):	<0.25 @ 5.5 bar & 0.1 sec / 1 sec <0.012 @ 5.5 bar & 0.06 sec / 1000 sec
Nominal Duty Cycle:	0.1 sec / 1 sec
Response Time (Hot Pulse)	
Rise Time(ms):	< 65 @ nominal duty cycle & 22 bar
Decay Time (ms):	<100 @ nominal duty cycle & 22 bar
Total Delivered Impulse (N-s):	74,000
Total Number of Pulses	42,000
Leakage	
Internal Leakage (Scc/s GHe):	$<1\times10^{-4}$ @ 3.5 and 24 bar
External Leakage (Scc/s GHe)	$<2.6\times10^{-4}$ @ 36 bar
Temperature	
Operating Temperature:	+4°C to 90°C
Non Operating Temperature:	-20°C to 90°C
Flow Control:	FCV - single-coil, dual-seat, N.C. solenoid valve
FCV Operating Voltage (VDC):	23 to 36
FCV Power (Watt) @ 28 VDC	< 10
Heaters - 3 Heaters	
Heater Operating Voltage (VDC):	15 to 36
Heater Resistance (ohms):	257 for each element
Nozzle Expansion Ratio:	50
Total Life (Storage and Flight):	15 years
Inlet Filtration	15 micron absolute
Inlet Interface:	MS 33656
Weight (gr):	≤ 310 (2000 mm lead wires length)
Heritage:	OFEQ , EROS and TECSAR programs

Additional comments:
This thruster has extensive flight history.

References:
[1] http://www.rafael.co.il/5719-2612-EN/Marketing.aspx
[2] Hasan, D., Jaeger, M., Oren, A., Adler, S., Miller, N., & Zemer, E., "Application of satellite hydrazine propulsion system in-orbit monitoring model," Proceedings of the 4th International Spacecraft Propulsion Conference (ESA SP-555). 2-9 June, 2004

	8	NO
Comm. avail.	TRL	Aerospace-tested

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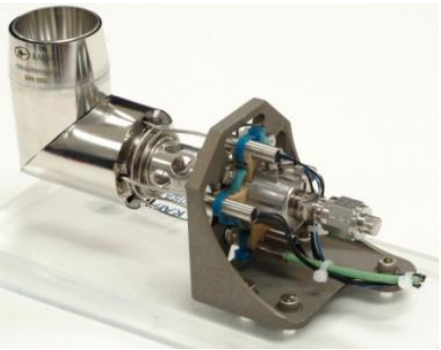
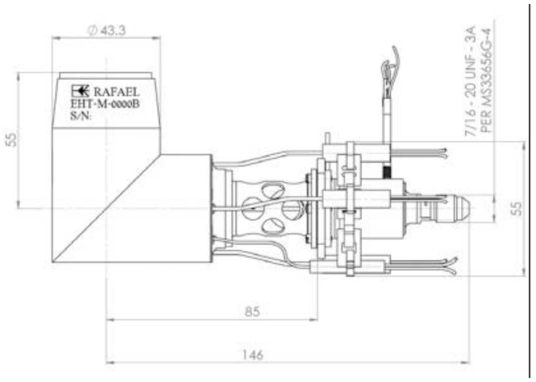
25N Hydrazine Thruster

Propulsion Technology	Hydrazine Monopropellant
Manufacturer/Country	Rafael (Israel)
TRL	8
Size (including PPU)	82.5mmx82.5mmx162.8mm (~1.5U)
Design satellite size	250 kg
Isp (s)	205-220 s
Thrust type/magnitude	9.5-28 N
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	15
Flight heritage (if any)	OFEQ and EROS
Commercially available	YES
Last updated	08/2020

Parameter	Characteristics
Propellant	Hydrazine (N_2H_4)
Feed Pressure (bar abs.)	22 to 5.5
Thrust, Steady State (N)	28 to 9.5
SSF Specific Impulse (sec)	> 220 @ 22 bar
	> 205 @ 5.5 bar
Minimum Impulse Bit (N-s)	0.3
Nominal Duty Cycle	0.24 sec / 1 sec
Response Time (Hot Pulse)	
Rise Time (ms)	65 @ nominal duty cycle & 22 bar
Decay Time (ms)	200 @ nominal duty cycle & 22 bar
Total Delivered Impulse (N-s)	100,000 (<5%Isp degradation)
Total Number of Pulses:	12,000
Leakage	
Internal Leakage (Scc/s GHe):	$<1.0\times10^{-4}$ @ 3.5 & 24
External Leakage (Scc/s GHe):	$<1.0\times10^{-6}$ @ 24
Temperature	
Operating Temperature	+4°C to 90°C
Non Operating Temperature	-10°C to 90°C
Flow Control	FCV - single-coil, dual-seat, NC solenoid valve
FCV Operating Voltage (Vdc)	23 to 36
FCV Power (W)	15 @ 28 Vdc
Heaters – 4× Single Heaters	
Heater Operating Voltage (Vdc)	24 to 32
Heater Resistance (ohms)	260 per each heater
Nozzle Expansion Ratio	60
Total Life (Storage & Flight)	15 years
Inlet Filtration	15 micron absolute
Inlet Interface	MS 33656-4 or welded tube (1/4" or 3/8")
Weight (gr.)	≤ 530 (1000 mm lead wires length)
Heritage	OFEQ and EROS programs





Additional comments:

References:

[1] https://www.rafael.co.il/wp-content/uploads/2019/03/RAFAEL_SPACE_PROPULSION_2019-CATALOGUE.pdf

	8	NO
Comm. avail.	TRL	Aerospace-tested

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SPT-50 Hall-type thruster (and advanced version, SPT-50M) [1 of 2]

Propulsion Technology	Hall thruster
Manufacturer/Country	RCC Kurchatov Institute/Fakel (Russia)/Airbux Defence and Space (France)
TRL	SPT-50 TRL=8, SPT-50M TRL=6
Size (including PPU)	Thruster 1.5 kg Entire propulsion system dry weight ~20kg [3]
Design satellite size	Large (>50 kg)
Isp (s)	~900 s
Thrust type/magnitude	14 mN at 220W
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	200W, nominal. 300W on Canopus-V [3]
Flight heritage (if any)	None known for SPT-50M Previous design SPT-50 has flown on Canopus-V/Kanopus-V and Canopus-V-IK/Kanopus-V-IK spacecrafts (2012), and many other missions (Meteor[1977,1974,1981], Astrofizika[1978]) [4]
Commercially available	Unknown
Last updated	*01/2021*

Table 3 Comparative characteristics of SPT-50 и SPT-50M

	SPT-50	SPT-50M
Discharge Voltage, V	180	
Discharge Current, A	1.2	
Discharge Power, W	220	
Thrust, mN	14.0	14.8
Specific Impulse, s	860	930
Mass, kg	1.23	1.32
Operation life, h	≥2500	~ 5000

Additional comments:

[Reference 1-2][Jan 2019][Thruster info]
At present, EDB Fakel, in co-engineering with Airbus Defence and Space Toulouse, is engaged in the development of advanced low-power Hall thrusters. The flight-proven SPT-50 thruster was chosen as a prototype. To guarantee the requested operational lifetime, innovative magnetic field topology and discharge chamber material have been implemented. In addition, a new cathode has been developed to operate at reduced discharge currents and mass flow rates. To support the definition of the advanced SPT-50 thruster (called SPT-50M), several engineering models have been manufactured and tested for performance, mechanical and thermal vacuum capabilities. In addition, to estimate the thruster performance during extended operation, a comparative analysis of the operating and lifetime characteristics of the advanced SPT-50M thruster and prototype thruster has been performed. The SPT-50 thruster is a part of a propulsion system on Canopus-V and Canopus-V-IK spacecrafts, and the cathode is qualified for 3000 start cycles. This cathode is designed to work with a discharge current from 1.25 A to 2.00 A. The mass flow rate in the cathode is less than 0.15 mg/s.
SPT-50 is qualified for a Russian customer. The qualification tests for the SPT-50 included: Acceptance testing, Total firing time accumulating –20 hours and 50 cycles, Mechanical test (transporting, random vibration and shock), Thermocycles, Parametrical tests, and Life test: 1200 hours and 3000 cycles. The SPT-50M required improvements to specific impulse, mechanical design, lifetime, and number of cathode on/off cycles.
Through these various design improvements, the performance of the thruster was improved to those listed on the table above. The thruster was tested to 1000 hrs. The estimate lifetime is 5000 hrs (based on calculations from a similar thruster).

References:

[1] Saevets, P., Semenenko, D., Albertoni, R., Scremin, G., "Development of a long-life low-power Hall thruster," IEPC-2017-38.
[2] Guerrini, G., Michaut, C., Dudeck, M., Bacal, M., "Parameter analysis of three small ion thrusters (SPT-20, SPT-50, A3)," Proceedings of the 2nd European Spacecraft Propulsion Conference, 1997.
[3] Gorbunov, A., Khodnenko, V., Khromov, A., Murashko, V., Koryakin, A., Zhosan, V., and Grikhin, G., "Vernier Propulsion System for Small Earth Remote Sensing Satellite "Canopus-V"," 32nd IEPC, Wiesbaden, Germany, 2011.
[4] https://en.wikipedia.org/wiki/List_of_spacecraft_with_electric_propulsion

NO	8	NO
Comm. avail.	TRL	Aerospace-tested

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SPT-50 Hall-type thruster (and advanced version, SPT-50M) [2 of 2]

Additional comments:

[Reference 1-2][June 2020]Kanopus-V Mission and thruster info]
Kanopus-V (also spelling of Canopus-V N1) is an Earth observation minisatellite mission of the Russian Space Agency, Roskosmos and ROSHYDROMET/Planeta. The overall objective is to monitor Earth's surface, the atmosphere, ionosphere, and magnetosphere to detect and study the probability of strong earthquake occurrence.

“Canopus-V” comprises two “Canopus-V” satellites located in one plane with phase difference of 180° and on 510km altitude orbit. The “Canopus-V” SC includes a Vernier Propulsion System (VPS) based on SPT-50 Stationary Plasma Thruster.
The VPS based on Stationary Plasma Thrusters SPT-501,2,3 developed by OKB “Fakel” (Kaliningrad, Russia) was chosen for “Canopus-V” SC taking into account the achieved characteristics and grade of experience in natural conditions. The VPS of “Canopus-V” SC contains the following units:
- Two Thrusters SPT-50, one of which is a backup, providing a corrective pulse thrust
- Two Xenon Flow Controller XFC-50 to supply xenon to main and redundant thrusters SPT-50
- respectively
- Flow Control Unit – FCU (the same Xenon Feed Unit) containing the main and backup branches to
- conduct xenon to XFC-50
- Xenon Storage System (unit) XSS providing storage and supply of stock-pile into FCU
- Power Processing Unit PPU-CV designed for power supply and control of VPS units.
- Two SPT-50 thrusters, two gas control units, xenon feed unit, interunit pipes with receiver are structurally
- united in SC Orbit Correction Unit.

[Reference 3][June 2020][Kanopus-V-IK Mission and thruster info]
Kanopus-V-IK is a small Russian (Roscosmos) remote sensing satellite for Earth-observation purposes. Designed to be operational for up to five years, the spacecraft has an infrared capability for a primary purpose of detecting sources of fire as small as5 m x 5 m on a 2,000 km swath of land. The satellite could also monitor other natural and man-made disasters, such as floods and chemical spillage. It could also be used to support agriculture and land usage, monitor shorelines and water conditions and search for natural resources (IK =Infra-Krasny, means "infrared" in Russian).

References:
[1] Gorbunov, A., Khodnenko, V., Khromov, A., Murashko, V., Koryakin, A., Zhosan, V., and Grikhin, G., “Vernier Propulsion System for Small Earth Remote Sensing Satellite “Canopus-V”,” 32nd IEPC, Wiesbaden, Germany, 2011.
[2] https://directory.eoportal.org/web/eoportal/satellite-missions/k/kanopus-v-1
[3] https://directory.eoportal.org/web/eoportal/satellite-missions/k/kanopus-v-ik-1

NO	8	NO
Comm. avail.	TRL	Aerospace-tested

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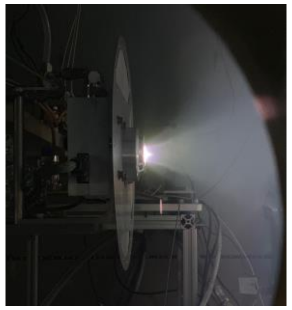
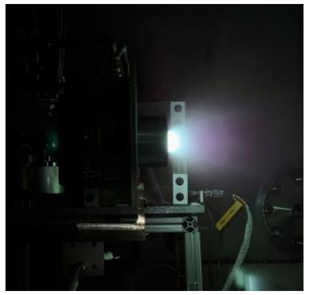
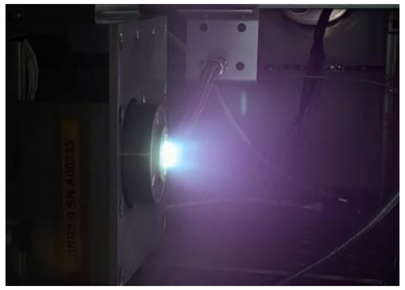
MAXWELL [1 of 3]
Phase Four

Propulsion Technology	RF plasma thruster
Manufacturer/Country	Phase Four (USA)
TRL	5-6
Size (including PPU)	7.5”x7.5”x5.3”, wet mass 8.4 kg
Design satellite size	3U and larger (SmallSats)
Isp (s)	374 to 1121s (747s at 330 W)
Thrust type/magnitude	2.6 to 7.9 mN (160 to 500 W) for 100 kg, 5.2 mN at 330 W Sample operating points: 950s and 18 mN at 550W, 110s and 13.6 mN thrust at 550W, 1440s and 8.8 mN at 550W [12]
Delta-V (m/s)	~152 m/s at 330 W for 100 kg wet SmallSat (calculated, using Phase4 GUI with 2.1kg propellant and Isp = 747s)
Propellant	Xenon (~2.1kg)
Power consumption (W)	160 to 500W (330 W avg)
Flight heritage (if any)	Transporter-1 (SpaceX rideshare) (launched Jan 24, 2021) – 2 units [8] Transporter-2 (launched Jun 2021) – 1 unit [11] SpaceX Starlink 26 (launched May 2021) – 1 unit [11] Transporter-3 (launched Jan 2022) – 2 units [11] Was projected for ROSE-1 (December 2018) but removed from launch schedule. [7] Projected delivery to Capella Space in 2019 [6] As of April 2022, total of 10 Maxwell systems delivered, and 6 are operating nominally on-orbit, with ~630 days accumulated operations.[11]
Commercially available	YES, ~$200,000 each (with volume discounts) [10]
Last updated	*12/2023*



Maxwell firing on water propellant, above, and operating in vacuum chambers (two images below) [11]





Additional comments:

[References 1-4][Mar 2019][General info]

The Phase Four RFT is an electrodeless RF propulsion engine that scales from the mass, volume and power budget of Cube Satellites up to larger satellite applications. Figure 1 shows a diagram of the core components of The RFT and Figure 2 shows an image of The RFT-2 unit firing in the Phase Four laboratory. Propellant (nominally xenon gas) is injected into a “plasma liner” at a fixed mass flow rate, which is wrapped in an RF antenna with a proprietary geometry. The liner-antenna assembly is housed inside a series of permanent magnets that generate a fixed magnetic field inside the liner and out of the liner’s exit orifice. A high frequency radio signal is applied to the antenna and the “near field” radiation under the antenna inside the liner ignites the gas into a plasma, and subsequently heats the plasma propellant. The hot xenon plasma then expands rapidly in all directions inside the liner. Similar to how a chemical rocket engine nozzle directs the hot propellant, the magnetic field inside the liner and in the near-region of the liner exit is designed to direct the hot plasma out of the exit orifice, generating thrust. The baseline RFT system includes a thruster, power processing unit, propellant storage and management unit, and engine controller. It uses radio frequency waves to efficiently ionize and heat xenon plasma. Magnetic fields then direct the plasma out of the engine nozzle, producing thrust. The P4 Radio Frequency Thruster (RFT) is a new system designed for small satellites while being scalable to large satellite and even launch vehicle applications. The RFT was inspired by technology developed at The University of Michigan and licensed exclusively to Phase Four for commercialization.

References:

[1] Siddiqui, M., “Updated Performance Measurements of the Phase Four RF Thruster,” 34th Space Symposium, 2018.
[2] Siddiqui, M., Cretel, C., Synowiec, J., Hsu, A., Young, J., Spektor, R., “First Performance Measurements of the Phase Four RF Thruster,” IEPC-2017-431.
[3] http://phasefour.io/wp-content/uploads/2017/06/SPEC.pdf
[4] https://www.prnewswire.com/news-releases/phase-four-signs-contract-with-nasa-to-vet-its-propulsion-system-for-upcoming-small-satellite-missions-300654094.html
[5] https://spacenews.com/phase-four-wins-orders-for-smallsat-electric-thrusters/
[6] Open panel discussion at SmallSat Symposium 2019, James Behmer (P4, Director of Sales)
[7] https://space.skyrocket.de/doc_sdat/rose-1.htm
[8] https://spacenews.com/phase-four-launches-first-plasma-propulsion-systems/
[9] Public forum, Oct 2021, Panel presentation by Beau Jarvis, Phase Four
[10] https://www.phasefour.io/maxwell/
[11] Email correspondence with Umair Jan 2021, public information
[12] Flyer distributed at Small Sat Conference, Aug 2023.

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MAXWELL [2 of 3]
Phase Four

Additional comments:

[References 5, 6, 8][Mar 2019][Thruster sales and missions]
Phase Four announced Jan. 31 that it sold 6 of its Maxwell electric propulsion systems to Capella Space, a company developing a constellation of radar imaging satellites, with an option for an additional, undisclosed number of thrusters. Capella Space is well-respected for its Synthetic Aperture Radar (SAR) technology that is designed to detect sub-meter changes on the Earth's surface and tapped Maxwell as the company's preferred propulsion solution for the firm's phased deployment of a constellation of 36 smallsats.
The company separately announced a deal with Tyvak Nano-Satellite Systems, a smallsat manufacturer, for "multiple" Maxwell thrusters. Maxwell is the first electric thruster system offered by Phase Four, which has been developing systems that use radiofrequency technologies, rather than electrodes, for generating plasma. The company argues that approach is less expensive and easier to manufacture that alternative thrusters. While the company announced last year smaller deals for thrusters with NASA and Earth imaging company Astro Digital, Phase Four considers these deals to be the first major order for their thrusters. The company is currently able to produce up to 10 Maxwell thrusters a month, and expects to double that production rate by the end of the year using its existing facilities.
James Behmer commented that they have sold 10 thrusters so far (as of Jan 2019), with Maxwell to be delivered at the end of 2019.

[Reference 7][Feb2019][ROSE-1 mission]
"ROSE 1 is a 6U CubeSat experimental spacecraft designed to provide an orbital test-bed for the Phase Four Radio Frequency Thruster (RFT), the first plasma propulsion system to fly on a nanosatellite. This research program is intended to demonstrate that the Phase Four RFT can safely launch, operate and perform experimental orbital course corrections in space. For the ROSE-1 mission, the spacecraft will fly in a LEO near-circular orbit with altitude of approximately 575 km and with inclination of approximately 98°. The satellite was to be launched on Spaceflight Industry's SSO-A multi-satellite launch on a Falcon-9 v1.2 (Block 5) rocket, but was removed from this launch."

[Reference 9][Mar 2019][Customers]
March 2019: "Phase Four, producers of electric radio frequency (RF) thrusters for in-space propulsion, created a new agreement with Japan-based Sunrise. Sunrise specializes in aerospace technology, including satellite hardware and launch. As part of a three-year agreement, Sunrise will be bringing Maxwell, Phase Four's turnkey electric propulsion solution for small satellites (20-200kg) and other spacecraft, to market in Japan."

[Reference 10][Aug 2019][Update]
Phase Four: [POCs Umair Siddiqui, Beau Jarvis]
Phase Four continues to strengthen their marketing presence. They brought a demo unit that was approximately 2U. Plumbing and tank made of titanium. They have also tested water propellant, which generated lots of interested questions from the audience. This would require a propellant-feed system re-design. Development time to COTS for water is unknown. They are still interested in EMI testing at Aerospace.
They have completed export control, FCC license, range safety, and shipping considerations.

[Reference 11]Mar 2021][Flight info]
Electric propulsion company Phase Four flew its first plasma thrusters on two spacecraft that were part of a SpaceX dedicated rideshare launch Jan. 24. Phase Four said its Maxwell plasma propulsion systems were on two of the 143 spacecraft launched on the Transporter-1 mission. The company declined to name the satellites at the request of its customer, which is flying an operational mission but is also testing other new designs on those spacecraft.

References:

[1] Siddiqui, M., "Updated Performance Measurements of the Phase Four RF Thruster," 34th Space Symposium, 2018.
[2] Siddiqui, M., Cretel, C., Synowiec, J., Hsu, A., Young, J., Spektor, R., "First Performance Measurements of the Phase Four RF Thruster," IEPC-2017-431.
[3] http://phasefour.io/wp-content/uploads/2017/06/SPEC.pdf
[4] https://www.prnewswire.com/news-releases/phase-four-signs-contract-with-nasa-to-vet-its-propulsion-system-for-upcoming-small-satellite-missions-300654094.html
[5] https://spacenews.com/phase-four-wins-orders-for-smallsat-electric-thrusters/
[6] Open panel discussion at SmallSat Symposium 2019, James Behmer (P4, Director of Sales)
[7] https://space.skyrocket.de/doc_sdat/rose-1.htm
[8] http://satnews.com/story.php?number=1950028036
[9] https://www.satellitetoday.com/innovation/2019/03/22/phase-four-and-sunrise-bring-electric-propulsion-to-japan/undefined
[10] SmallSat presentation, public release.
[11] https://spacenews.com/phase-four-launches-first-plasma-propulsion-systems/

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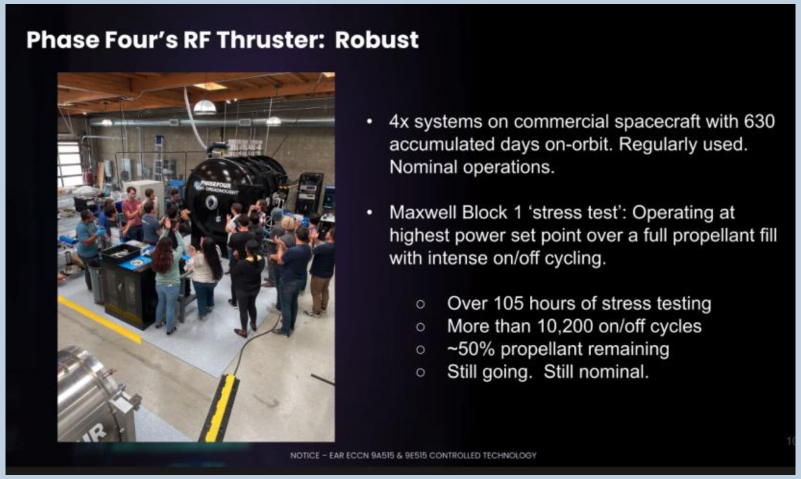
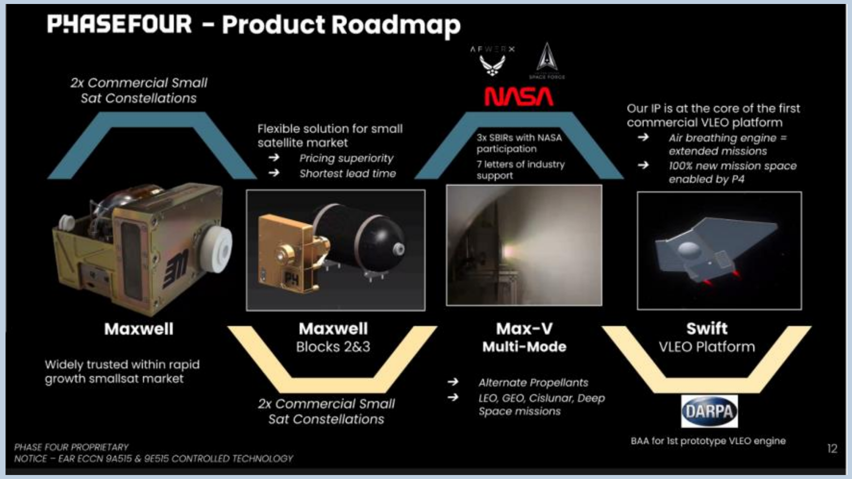
MAXWELL [3 of 3]
Phase Four

Additional comments:

[Reference 1][Oct 2021][Company and thruster information]
Public forum/panel presented by Beau Jarvis





References:
[1] Public forum, Oct 2021, Panel presentation by Beau Jarvis, Phase Four

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High Performance Green Propellant – 1N (HPGP-1N) Series [1 of 6]
ECAPS/Bradford Engineering/Orbital ATK

Propulsion Technology	ADN monopropellant, (hydrazine substitute)
Manufacturer/Country	ECAPS(Ecological Advanced Propulsion Systems)/Bradford Engineering (SWEDEN) and Orbital ATK/Northrop Grumman (US)
TRL	7-8 for 1 N model
Size (including PPU)	Various models, from 0.5U to large
Design satellite size	Various models, from 1U to large (SkySats are roughly 100 kg each)
Isp (s)	231s [7]
Thrust type/magnitude	1N model: 0.25 to 1 N (thrust range), 70 mN*s (impulse, minimum) SkySat-3: 21 kN*s (impulse, total) [1]
Delta-V (m/s)	~60 m/s to PRISMA (~200 kg) s/c, ~180 m/s to SkySat (~120 kg) s/c.
Propellant	LMP-103S (ADN mixture)
Power consumption (W)	8-10W
Flight heritage (if any)	As of December 2020, there are 12 systems and 46 thruster in orbit [7] PRISMA/Mango/Tango (2010), SkySat-3,4,5,6,7 (2016), SkySat 8-13 (2017), SkySat 14-15 (2018). Launched on Astroscale ELSA-d (~175kg) (March 2021), ArgoMoon aboard Artemis-1 (100 mN thruster) (2021), Blue Canyon Tetra-3 (2021), and Altair [6]
Commercially available	YES
Last updated	*08/2022*

Thruster Type	HPGP
Propellant	LMP-103S
Thrust Class	1 N
Primary Operational Mode	RCS + Δ v
Inlet Pressure Range	4.5 - 22 Bar
Thrust Range	.25 - 1 N
Nozzle Expansion Ratio	100:1
Steady State ISP (vacuum) Typical	2000 - 2270 Ns/Kg (204 - 231 s)
Density Impulse (vacuum)	2480 - 2815 Ns/L
Minimum Impulse Bit	≤ 70 mNs
Overall Length	178 MM
Mass	0.38 KG
FCV Type	Solenoid
- No of Seats	Dual Seat

- Pull-in Voltage	28 ± 4 VDC
- Holding Voltage	10 ± 1 VCD
- Coil Resistance (each coil)	190 Ω
Nominal Reactor Pre-heating Voltage	28 VDC
Regulated Reactor Ore-heating Power	8 - 10 W
Target Life - Qual. Level	
Pulses	60,000
Propellant Throughput	24kg
Longest Continues Firing	45 minutes
Accumulated Firing Time	25 hours
Firing Sequences	1500
Demonstrated Life	
Pulses	60,000
Propellant Throughput	24 kg
Longest Continues Firing Time	1.5 hours
Accumulated Firing Time	25 hours
Firing Sequences	1500
Maturation Level	TRL 9

SkySat-3 HPGP flight system. Multiple 1N systems installed.

Additional comments:
On following pages…

References:
[1] Dinardi, A., Anflo, K., Friedhodd, P., “On-Orbit Commissioning of High-Performance Green Propulsion (HPGP) in the SkySat Constellation,” 31st Annual AIAA Conference on Small Satellites, SSC17-X-04.
[2] Friedhoff, P., Anflo, K., Persson, M., Thormahlen, P., “Growing Constellation of ADN based high performance green propulsion (HPGP) systems,” AIAA JPC, 2018.
[3] Krejci, D., Lozano, P., “Space Propulsion Technology for Small Spacecraft,” Proceedings of the IEEE, 2018.
[4] Friedhoff, P., Hawkins, A., Carrico, J., Dyer, J., “On-Orbit Operation and Performance of ADN based HPGP systems,” AIAA JPC, 2017.
[5] http://ecaps.space/assets/pdf/Bradford_ECAPS_Folder_2017.pdf, http://ecaps.space/products-100mn.php, https://www.orbitalatk.com/defense-systems/missile-products/HPGP/Docs/HPGP%20Fact%20Sheet%20APPROVED%20OSR%2015-S-2043%20072115.pdf
[6] ECAPS public newsletter June 2020
[7] https://www.ecaps.space/products-1n.php

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High Performance Green Propellant – 1N (HPGP-1N) [2 of 6]
ECAPS/Bradford Engineering/Orbital ATK

Additional comments:

[References 1-5] [October 2018][General information about the missions]
Manufacturer reports PRISMA successfully demonstrated 8% higher performance using HPGP than hydrazine on orbit.
ECAPS was selected to provide 19 complete 1N HPGP systems for Planet's constellation of SkySat Earth observation satellites. Five SkySat satellites with HPGP systems have been operational in orbit since 2016, and 6 additional SkySat satellites with HPGP systems launched in 2017. The 1N system is space qualified with 46 thrusters currently in-orbit. Eleven Earth imaging satellites with ECAPS High Performance Green Propulsion (HPGP) systems are being flown by Planet (previously Skybox Imaging and Terra Bella). SkySat- 3 was launched in June 2016 from the Satish Dhawan Space Centre on Antrix's PSLV, SkySat-4 through SkySat-7 were launched in September 2016 from the Guiana Space Centre on Arianespace's Vega, and SkySat-8 through 13 were launched in October 2017 from Vandenberg Air Force Base on Orbital ATK's Minotaur-C. Each spacecraft's HPGP system has been successfully commissioned and is operating nominally in orbit. Combined the HPGP systems have accumulated 12.8 years on-orbit, executed 118 maneuvers, and imparted 110 m/s of V. ECAPS is currently expanding its portfolio of thrusters to include 5N, 22N, and 220N thrusters. HPGP and HPGP thrusters are available through Orbital ATK in the US.

References:
[1] Dinardi, A., Anflo, K., Friedhodd, P., "On-Orbit Commissioning of High-Performance Green Propulsion (HPGP) in the SkySat Constellation," 31st Annual AIAA Conference on Small Satellites, SSC17-X-04.
[2] Friedhoff, P., Anflo, K., Persson, M., Thormahlen, P., "Growing Constellation of ADN based high performance green propulsion (HPGP) systems," AIAA JPC, 2018.
[3] Krejci, D., Lozano, P., "Space Propulsion Technology for Small Spacecraft," Proceedings of the IEEE, 2018.
[4] Friedhoff, P., Hawkins, A., Carrico, J., Dyer, J., "On-Orbit Operation and Performance of ADN based HPGP systems," AIAA JPC, 2017.
[5] http://ecaps.space/assets/pdf/Bradford_ECAPS_Folder_2017.pdf, http://ecaps.space/products-100mn.php, https://www.orbitalatk.com/defense-systems/missile-products/HPGP/Docs/HPGP%20Fact%20Sheet%20APPROVED%20OSR%2015-S-2043%20072115.pdf

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High Performance Green Propellant – 1N (HPGP-1N) Series [3 of 6]
ECAPS/Bradford Engineering/Orbital ATK

Additional comments:

[Reference 1][Jan 2019][More information on PRISMA/Mango/Tango mission]

"PRISMA is a Swedish-led technology mission to demonstrate formation flying and rendezvous technologies (in-orbit servicing), designed and developed by SSC (Swedish Space Corporation). The mission concept employs the small-satellite philosophy to demonstrate the functionality of a wide range of newly developed formation flying, proximity ranging and propulsion techniques with future use in a wide range of missions. The project is funded by the Swedish National Space Board (SNSB) with SSC as the prime contractor. Further international project participants/contributors are: DLR (German Aerospace Center), the Technical University of Denmark (DTU), and CNES, the French Space Agency. The main goals of PRISMA are to perform GNC (Guidance, Navigation and Control) demonstrations and sensor technology experiments for a family of future missions where rendezvous and formation flying are a necessary prerequisite. The mission consists of two spacecraft, one advanced and highly maneuverable one, called MAIN (Mango), and a smaller S/C without a maneuvering capability, called TARGET (Tango). The latter one simply follows the trajectory into which it is injected by the launch system. The MAIN spacecraft has full translational capability, and will perform a series of maneuvers around the TARGET, on both close and long range approach, using the different sensors provided. Both S/C will be delivered into the same orbit. In most cases, the MAIN will fly along-track with respect to the TARGET, such that the MAIN can "look" at the TARGET." As of 2013, all the PRISMA HPGP propulsion tests were deemed successful.

[Reference 2][Feb 2019][More information on SkySat configuration and on-orbit commissioning]

<u>SkySat configuration:</u>

For SkySat-3, "The propulsion system design consists primarily of 4X 1N HPGP thrusters, three propellant tanks, two service valves, a latch valve, a pressure transducer, and a system filter. All of the fluid control components selected had flight heritage from previous missions. The three propellant tanks, which are connected in series and each of which has a Propellant Management Device (PMD), hold a combined total of 10.5 kg of LMP-103S with sufficient ullage for the Helium pressurrant. The system operates in blowdown from a Beginning of Life (BOL) pressure of about 18.5 bar (absolute) at 21C and is capable of delivering approximately 21 kN*s of total impulse."

<u>Propellant:</u>

"The SkySat HPGP propulsion system utilizes the first "green" storable monopropellant qualified for space flight, which is the ADN-based LMP-103S. LMP-103S propellant is a blend of Ammonium DiNitrimide (ADN), water, methanol, and ammonia. The most harmful chemicals in LMP-103S are methanol and ammonia. Unlike hydrazine the LMP-103S blend has low toxicity, is non-carcinogenic, and environmentally benign. Satellite propellant loading therefore does not require the use of SCAPE suits. LMP-103S has undergone extensive ground testing with respect to performance, sensitivity, thermal characterization, compatibility, radiation sensitivity and storability. The propellant has been stored for more than 11 years (and ongoing) in a ground propulsion system end-to-end test, without an indication of degradation or pressure build-up. Despite its high energy content, LMP-103S is classified as an insensitive substance (NOL 1.3) and further classified for transportation as a UN 1.4S (when stored in its designated transport container), which allows for shipment as air cargo on commercial passenger aircraft."

<u>Thrusters before delivery:</u>

"Each SkySat propulsion system includes 4X 1N HPGP thrusters. In HPGP thrusters, the propellant is thermally and catalytically decomposed and ignited by a pre-heated reactor. Nominal pre-heating is regulated between 340 to 360C. For thermal control, the thruster is equipped with redundant heaters and thermocouples. The design and function of the thrusters developed for ADN-based propellant blends have several similarities with monopropellant hydrazine thrusters. The combustion temperature of LMP-103S (1600C) is however significantly higher than for a hydrazine thruster. The Thrust Chamber Assembly (TCA) is therefore made of iridium/rhenium and other high-temperature resistant materials. Prior to hot-fire testing, all thrusters are subjected to thermal vacuum (TVAC) testing, random vibration testing, and radiographic (X-ray) inspection. ECAPS then performs acceptance hot-fire testing of each 1N HPGP thruster at three different inlet pressures prior to integration into the SkySat propulsion systems."

<u>On-orbit commissioning:</u>

"Following separation from the launch vehicle upper stage, the same propulsion system commissioning activities were performed on each SkySat. Depending on ground station contact scheduling, the process took approximately 8 hours per satellite. First, the thruster catalyst bed heaters were activated and allowed to operate within their pre-heating temperature setpoints of 330 to 370C for 1 hour in order to thoroughly drive off any residual moisture and ensure complete and uniform heating of the entire reactor assembly. Then the 2 bar (absolute) Helium downstream of the isolation latch valve was vented by opening all four thruster FCVs for two minutes, leaving the manifold in vacuum. After the FCVs were closed again, the isolation valve was commanded open to fill the manifold with liquid propellant down to the upstream FCV seat. Finally, a manual firing sequence of 50 pulses with 100 ms on-time at 1% duty cycle was used to prime the FCVs with liquid, expel any Helium gas that may have been trapped in the propellant feed lines (due to the tanks not being vacuum loaded) and to begin smooth and repeatable combustion. Experience has shown that it takes approximately 5 pulse for propellant to reach each thruster's reactor and for combustion heating to be observed on the reactor thermocouples. The entire system priming operation requires approximately 7.5 grams of propellant. With the system primed and successful combustion demonstrated, the last step of propulsion system commissioning is to perform a 20 second closed-loop burn with the firing commands issued by the satellite's ACS controller."

<u>Anomalies on flight:</u>

Overall all of the SkySat missions to date were considered successes. However, "in December 2016, SkySat-7 experienced an aborted propulsive maneuver due to a fault indicating that the satellite had insufficient torque to maintain the burn attitude." "A collaborative investigation was performed by Planet and ECAPS to determine the cause of the non-fire and develop mitigation options. The investigation team determined that the most likely cause of the thruster non-fire was a leaking downstream FCV seat that caused ADN precipitation (due to long term exposure of the inter-seat propellant volume to vacuum) and resulted in the downstream valve or feed tube becoming clogged. The issue was ultimately resolved with a new flight software command which allowed for an increase to the FCV pull-in (opening) voltage application and duration."

References:

[1] https://directory.eoportal.org/web/eoportal/satellite-missions/p/prisma-prototype

[2] Dinardi, A., Anflo, K., Friedhoff, P., "On-Orbit Commissioning of High-Performance Green Propulsion (HPGP) in the SkySat Constellation," 31st Annual AIAA Conference on Small Satellites, SSC17-X-04.

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High Performance Green Propellant – 1N (HPGP-1N) Series [4 of 6]
ECAPS/Bradford Engineering/Orbital ATK

Additional comments:

[Reference 1][Jun 2020][Thruster manufacturing update]
ECAPs has a number of thrusters in the pipeline, to be delivered to various customers in 2020 and 2021.
•Preparatory activities for Moog's first SL-OMV mission out of the United Kingdom with a scheduled delivery of 6 units in Q3, 2020. For more information about this mission, see Small Launch Orbital Manoeuvring Vehicle will Enable UK Launched Small Satellite Missions.
•Procurement and manufacturing begun on 100 thrusters for Boeing.
•Eight 1N HPGP High Throughput systems for the first Astranis micro-GEO mission. Targeting delivery by Q3 and ready for launch Q1, 2021 this program will feature an innovative combined HPGP / EP system.
•Twelve thrusters delivered to VACCO in Q4 2019 and the latest four have been delivered in March 2020 for use on Millennium Space Systems ALTAIR spacecraft.
•Four thrusters delivered to NanoAvionics in early May 2020.
•A double-capacity SkySat-like system is being engineered and built at Bradford Space in the Netherlands for York Space Systems, US, with a scheduled delivery in Q2, 2021

[Reference 2][Aug 2020][Thruster info for 5N model]
The 5N HPGP thruster is currently undergoing a test fire campaign with the NASA Goddard Space Flight Center, characterizing the performance of the thruster. The 5N HPGP is being examined for potential use for an interplanetary mission, where it will provide a key maneuver and orbit-insertion capability.

References:
[1] ECAPS public newsletter Jun 2020
[2] https://www.ecaps.space/products-5n.php

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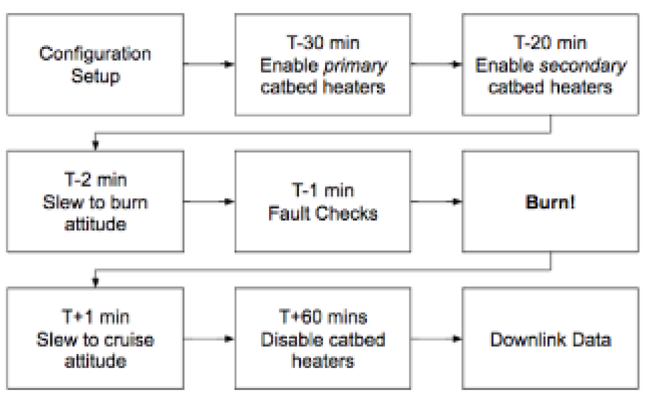
High Performance Green Propellant – 1N (HPGP-1N) Series [5 of 6]
ECAPS/Bradford Engineering/Orbital ATK

Additional comments:

[Reference 1][Feb 2019][On-orbit burning sequence, provided by TerraBella/Planet (open literature)]

On-Orbit Maneuvers



43 burns to-date
- 5 minute burn on SkySat-3!
- Collision avoidance burn on SkySat-4

Spacecraft	Maneuvers	Impulse To-Date
SkySat-3	14	2370 N-s
SkySat-4	4	70 N-s *
SkySat-5	5	150 N-s
SkySat-6	6	334 N-s
SkySat-7	14	317 N-s

* Note: SkySat-4 is being used as the 'reference' for maintaining constellation phasing (and has thus required fewer maneuvers than all of the other satellites)

Terra Bella
planet.

On-Orbit Maneuvers (cont'd)

Maneuver Calibration

Maneuver	SkySat-3	SkySat-4	SkySat-5	SkySat-6	SkySat-7
OMM 01 (Priming)	-	-	-	-	-
OMM 02	N/A	-1.1%	-3.5%	-2.4%	+1.6%
OMM 03	+4.5%	+3.4%	+3.1%	+2.8%	Abort
OMM 04	-4.4%	-3.3%	+3.9%	+5.4%	Test
OMM 05	Abort		-0.7%	+3.2%	Test
OMM 06	Test			+1.9%	Test
OMM 07	Test				Test
OMM 08	-2.7%				Test
OMM 09	-3.3%				Test
OMM 10	Abort				Test
OMM 11	Test				Test
OMM 12	-0.1%				Test
OMM 13	-0.2%				+7.6%
OMM 14	-1.8%				+6.9%

Anomaly Resolution

SkySat-7 Thruster B
- Dec 2016: Automatic abort ~ 4.5s into burn
  - Insufficient torque to maintain attitude
  - Probable thruster non-fire
- Collaborative investigation by Planet and ECAPS
  - 9 on-orbit test maneuvers
  - Numerous ground tests
- Determination of most likely cause
  - Leaking down-stream FCV seat
  - ADN precipitate resulted in clogged valve or feed tube

Resolved!
- **Successfully recovered in Feb 2017**
  - New flight software command to increase FCV pull-in voltage application and duration
- Help mitigate recurrence with 1 hour post-heat
- 4 burns completed since recovery
- Thruster performance is unaffected after the non-fire
- **S/C released to normal operations**

Terra Bella
planet.
bradford ecaps

References:

[1] Dinardi, A., Anflo, K., Friedhoff, P., "On-Orbit Commissioning of High-Performance Green Propulsion (HPGP) in the SkySat Constellation," 31st Annual AIAA Conference on Small Satellites, SSC17-X-04 (presentation charts from conference).

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High Performance Green Propellant – 1N (HPGP-1N) [6 of 6]
ECAPS/Bradford Engineering/Orbital ATK

Additional comments:

[Reference 1][April 2022][Additional mission info and thruster anomalies]
COLORADO SPRINGS — Astroscale plans to resume an attempt to capture a satellite acting as a piece of debris in low Earth orbit despite losing half the servicer's eight thrusters. Most of the other issues that forced Astroscale to pause its End-of-Life Services by Astroscale-demonstration (ELSA-d) mission Jan. 26 have been mitigated or resolved, the Tokyo-based startup said in an April 6 news release. However, the company has been unable to fix ongoing technical issues affecting four "non-functional" 1-newton High Performance Green Propulsion (1N HPGP) thrusters. All eight thrusters were provided by Swedish propulsion specialist ECAPS, which is owned by U.S.-based Bradford Space. Bradford Space CEO Ian Fichtenbaum said his company is aware of the thruster issues and is providing support "to the best of our abilities."

Fichtenbaum said: "These issues do not relate to and are not a result of the design or build of the thrusters and we have full confidence in our products."

References:
[1] https://spacenews.com/astroscale-to-restart-debris-removal-demo-with-half-the-thrusters/

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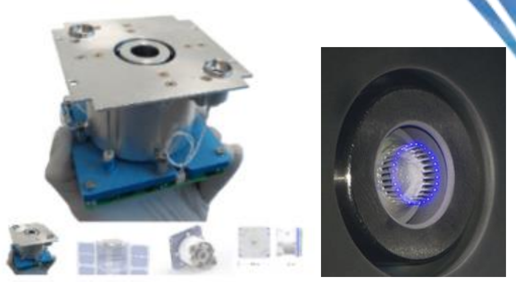
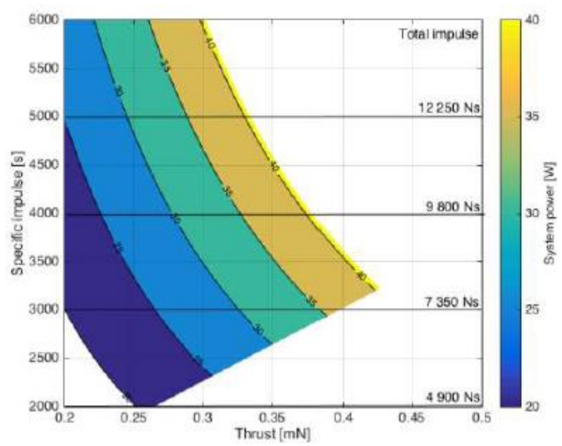
Nano (previously named IFM NanoThruster) [1 of 9]
Enpulsion

Propulsion Technology	Field Emission Electric Propulsion (FEEP)
Manufacturer/Country	FOTEC/ENPULSION (AUSTRIA), ENPULSION Inc. (US)
TRL	6-7
Size (including PPU)	0.6U to 1U, 670g (dry), 900g (wet) [1]
Design satellite size	1U and larger
Isp (s)	2000 to 6000 s [1], (4000s confirmed on-orbit) [6], 5000s demonstrated on orbit [7]
Thrust type/magnitude	350 uN (continuous, nominal, at 35W power), 200 uN (continuous, nominal, at 20W power) 250 uN confirmed on-orbit [6], 10uN to 0.5 mN (dynamic, nominal), 5000 N*s (impulse, total) [1]
Delta-V (m/s)	2000 m/s for 3 kg spacecraft, 525 m/s for 15 kg spacecraft
Propellant	Indium
Power consumption (W)	40W (operational, including neutralizer) [1], 3 to 5W (standby) [5]. 12V or 28V input power. Can be throttled.
Flight heritage (if any)	YES. 136 systems in space on 61 different spacecraft [11] Successful testing in orbit, performing confirmed orbit changes (customer un-named, launched 2018) [6, 7]. Successful testing in orbit, Planet (2018) [8] Successful commission and on-orbit data reported for ICEYE-X2 (launched Dec 2018) Scoped for OHB Italia's IRIDE Constellation [12]
Commercially available	YES. Several models are now available for immediate delivery. "Base model" is ~$50K [1] Now available as a stock item on the SmallSat Catalog from Orbital Transports [10]
Last updated	*03/2023*



Indium on tungsten needles (FEEP)



Depending on available power, the user can choose from any operational point - Data shown corresponds to 12 V configuration

Additional comments on following charts…

References on next chart:

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IFM NanoThruster [2 of 9]
Enpulsion

References:

[1] https://www.enpulsion.com/
[2] https://www.cubesatshop.com/wp-content/uploads/2017/04/ENP-IFM-Nano-Thruster-Product-Overview.pdf
[3] https://forum.nasaspaceflight.com/index.php?topic=45723.0
[4] https://spacenews.com/austrian-startup-ramping-to-mass-produce-tricky-electric-propulsion-thrusters/
[5] Open panel at SmallSat Symposium (2019), David Krecji, Enpulsion CTO
[6] https://www.enpulsion.com/news/17-FEEP-First-Successful-In-Orbit-Demonstration-of-a-FEEP-Thruster.html
[7] Krecji, D., Schonherr, T., Reissner, A., "Direct thrust measurements and In-orbit demonstration of the IFM Nano Thruster," Interplanetary Small Symposium (San Luis Obispo), 2019. Public charts.
[8] Krejci, D., Reissner, A., Seifert, B., Jelem, D., Horbe, T., Plesescu, F., Friedhoff, P., Lai, S., "Demonstration of the IFM Nano FEEP Thruster in Low Earth Orbit," 4S Symposium, 2018.
[9] https://www.enpulsion.com/wp-content/uploads/ENP2019-086.B-IFM-Nano-Thruster-COTS-Product-Overview-1.pdf
[10] https://smallsatnews.com/2021/05/18/smallsat-thruster-modules-from-enpulsion-now-in-orbital-transports-smallsat-catalog/
[11] Krejci, D., Reissner, A., "The first 100 FEEP propulsion systems in space: A statistical view and lessons learnt of 4 years of ENPULSION," IEPC-2022-199.
[12] https://www.enpulsion.com/news/ohb-italia-selected-enpulsion-as-propulsion-partner-for-the-iride-constellation/

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IFM NanoThruster [3 of 9]
Enpulsion

Additional comments:

[References 1-7][Jan 2019][General information]
For 15 years, FOTEC has followed a technology push from ESA developing a FEEP propulsion technology for a very niche market of scientific satellites in formation flight. ENPULSION was founded in 2016 as a FOTEC spin-out to scale the production of this thruster to several hundred units per year. The IFM Nano Thruster is a mature technology, developed under ESA contracts for 15 years. In this time more than 100 emitters have been tested and an ongoing lifetime test has demonstrated more than 18,000 h of firing without degradation of the emitter performance. The technology is scalable, and multiple IFM units can be clustered for a variety of mission needs. Field emission is an effect which is closely tied to the presence of strong electric fields. In practice, this means that the fundamental structure on which field emission takes place is shaped like a needle, due to the field-enhancing effect at the tip. An important application of this effect is the so-called 'Liquid Metal Ion Source' (LMIS), because it uses the process of field emission to ionize a thin film of liquid metal covering a needle which has been biased to a few kV with respect to a counter electrode. The thusly created ions are then accelerated by the strong electric fields and can be used for ion implantation in semiconductor industry or micromachining in a focused ion beam (FIB). This principle of generating positive ions and accelerating them by the very same field can also be used to generate thrust. When a liquid metal ion source is used in this fashion, it is termed 'field emission electric propulsion' (FEEP). Due to the accuracy with which it is possible to regulate the voltage between the needle and the extraction electrode, the ensuing thrust can be controlled with unmatched accuracy. The main advantage of using FEEP thrusters lies in their capability to produce thrust from the sub-µN level to several tens of µN per emission site. In this environment, the proprietary porous tungsten crown emitter has been developed, which employs 28 needles for field emission. Apart from the multiple emission sites, the most important new feature is the porous tungsten matrix which enables internal flow of the liquid metal to a very sharp tip. Neutralization is achieved by the use of two cold-redundant electron sources acting as neutralizers. Such an electron source consists of a thermionic cathode type, which is heated up to 1,800 K and biased to -200 V.

References:

[1] https://www.enpulsion.com/
[2] https://www.cubesatshop.com/wp-content/uploads/2017/04/ENP-IFM-Nano-Thruster-Product-Overview.pdf
[3] https://forum.nasaspaceflight.com/index.php?topic=45723.0
[4] https://spacenews.com/austrian-startup-ramping-to-mass-produce-tricky-electric-propulsion-thrusters/
[5] Open panel at SmallSat Symposium (2019), David Krecji, Enpulsion CTO
[6] https://www.enpulsion.com/news/17-FEEP-First-Successful-In-Orbit-Demonstration-of-a-FEEP-Thruster.html
[7] Krecji, D., Schonherr, T., Reissner, A., "Direct thrust measurements and In-orbit demonstration of the IFM Nano Thruster," Interplanetary Small Symposium (San Luis Obispo), 2019. Public charts.

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IFM NanoThruster [4 of 9]
Enpulsion

Additional comments:

[Reference 1] [June 2018] [Company and general thruster info]
“ENPULSION, the only commercial manufacturer worldwide of the indium-based FEEP (Field-Emission Electric Propulsion) thruster, is announcing the successful demonstration of an in-orbit CubeSat equipped with their proprietary IFM Nano product. This accomplishment occurred after our product was integrated in a 3U Platform that launched in January 2018. This marks a huge step for innovation and technology by using the first ever FEEP thruster in space. “This is a historic moment not only for our company, but for the whole space industry. We strongly believe that the FEEP technology is bringing a number of capabilities to the table that might very well disrupt our industry.” says Dr. Alexander Reissner, Founder and CEO of ENPULSION. “Immediately after the spin-out from FOTEC, where this technology was developed for more than 15 years, we have seen an overwhelming demand for our product, even before we demonstrated the technology in space and are pleased that we are now able to fulfill the expectations of our customers.”

During the commissioning phase, all subsections of the thruster have performed nominally and a fully neutralized 2mA ion beam has been emitted generating a thrust of ~250µN at an ISP of ~4000s. As part of the commissioning, a 15-minute constant thrust burn was performed resulting in a delta v of 4.1 cm/s which has been independently verified by measuring the orbital parameters of the spacecraft.”

[Reference 2] [Feb 2019] [Company status]
David Krecji discussed Enpulsion’s status. They now have customers in 3 different continents, with several important deliveries in 2018. They just delivered a GEO smallSat, and the first SmallSat travelling to an Asteroid. In 2018 they also delivered their first multiple NanoSat constellation, and delivered to ICEYE constellations. They opened batch production in June 2018, and have delivered 40 thrusters which are currently in integration at customer facilities. They have now 6 thrusters flying in space, with on-orbit data available by end of 2019 (projected). They have focused most of their efforts towards scaling up production. Currently they are producing approximately 2-3 thrusters per week with projections for 2019 of up to 10 per week with batch processes. They are working towards a 2-week lead time from order placed to delivery. One important advantage over the ionic liquid systems (MIT/Accion) is that each of these thrusters is pre-fired and characterized before delivery/flight.

Thruster operation:
FEEP thruster requires ~1 hr of pre-heating to melt the Indium, and then it takes 3-5W to maintain the liquid state (hot-standby mode).
In regards to contamination, David thinks that the peripheral part of the plume with have more neutrals and will therefore deposit metals on anything that might be impinging. In the core of the plume, the ions would erode away any surfaces (which would be bad) but would not deposit neutrals (good).

[Reference 4][Feb 2019][Company news and manufacturing]
Sypniewski (Enpulsion’s senior business development engineer) said the company plans to produce 100 to 200 thrusters per year, and has 150 pre-orders from customers in Europe and the United States. Among those customers is Iceye, a Finnish synthetic aperture radar startup that is flying a cluster of Enpulsion FEEP thrusters next year. Sypniewski said Fotec continues to support Enpulsion with a team of more than 40 full-time engineers. Enpulsion consists of 15 full time employees today, he said, and will open its US office with two full-time employees. “The plan is to expand quickly as demands are high,” he said. Sypniewski said Enpulsion is producing FEEP thrusters in Austria, but is open to manufacturing in the US if demand there warrants further expansion.

[Reference 3][July 2019][Thruster maturation]
Enpulsion’s website states,”The IFM Nano Thruster is a mature technology, developed under ESA contracts for 15 years. In this time more than 100 emitter have been tested and an ongoing lifetime test has demonstrated more than 17,000 hrs of firing without degradation of the emitter performance.”

[Reference 5][Aug 2019][Thrusters in space]
In December 2018, the first satellite with the IFM Nano Thruster was launched. As of March 2020, there are 28+ IFM Nano thrusters in space.

References:
[1] https://www.enpulsion.com/news/17-FEEP-First-Successful-In-Orbit-Demonstration-of-a-FEEP-Thruster.html
[2] Open panel at SmallSat Symposium (2019), David Krecji, Enpulsion CTO
[3] https://www.enpulsion.com/order/ifm-nano-thruster/
[4] https://spacenews.com/austrian-startup-ramping-to-mass-produce-tricky-electric-propulsion-thrusters/
[5]] https://www.enpulsion.com/wp-content/uploads/ENP2019-086.B-IFM-Nano-Thruster-COTS-Product-Overview-1.pdf

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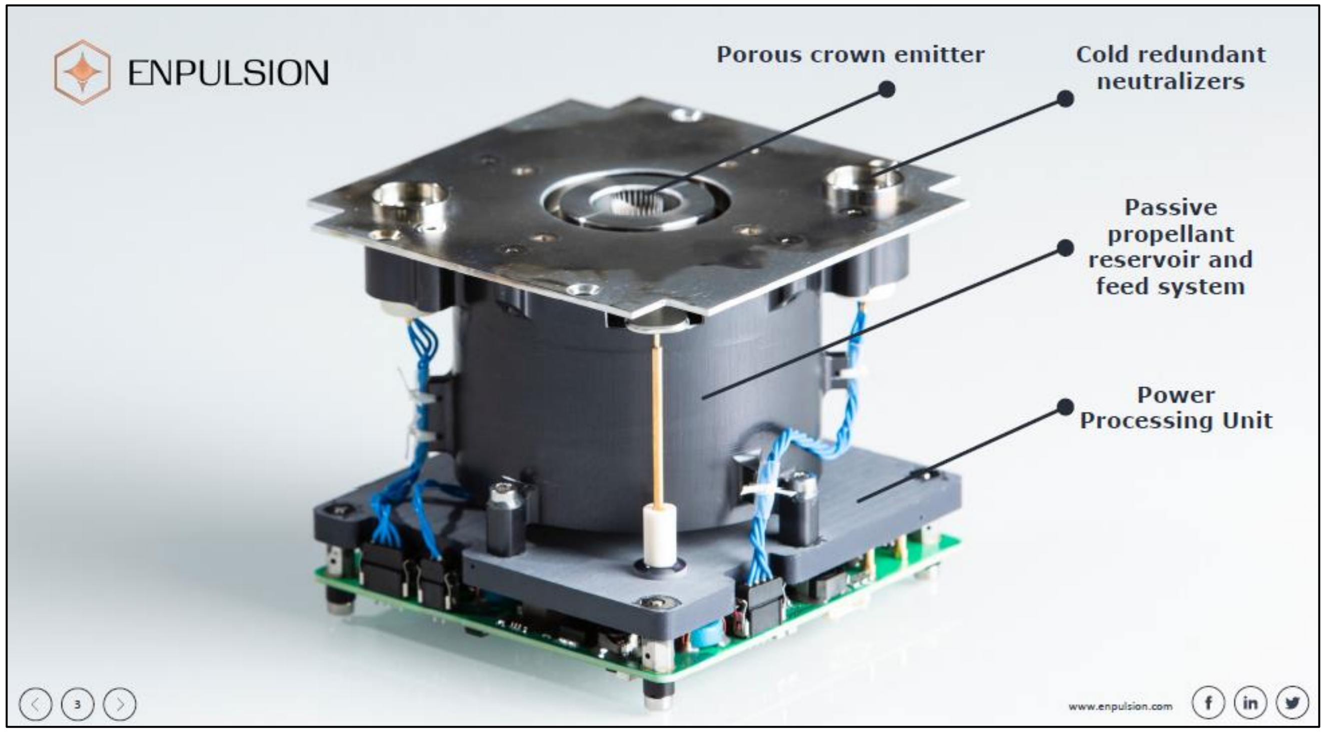
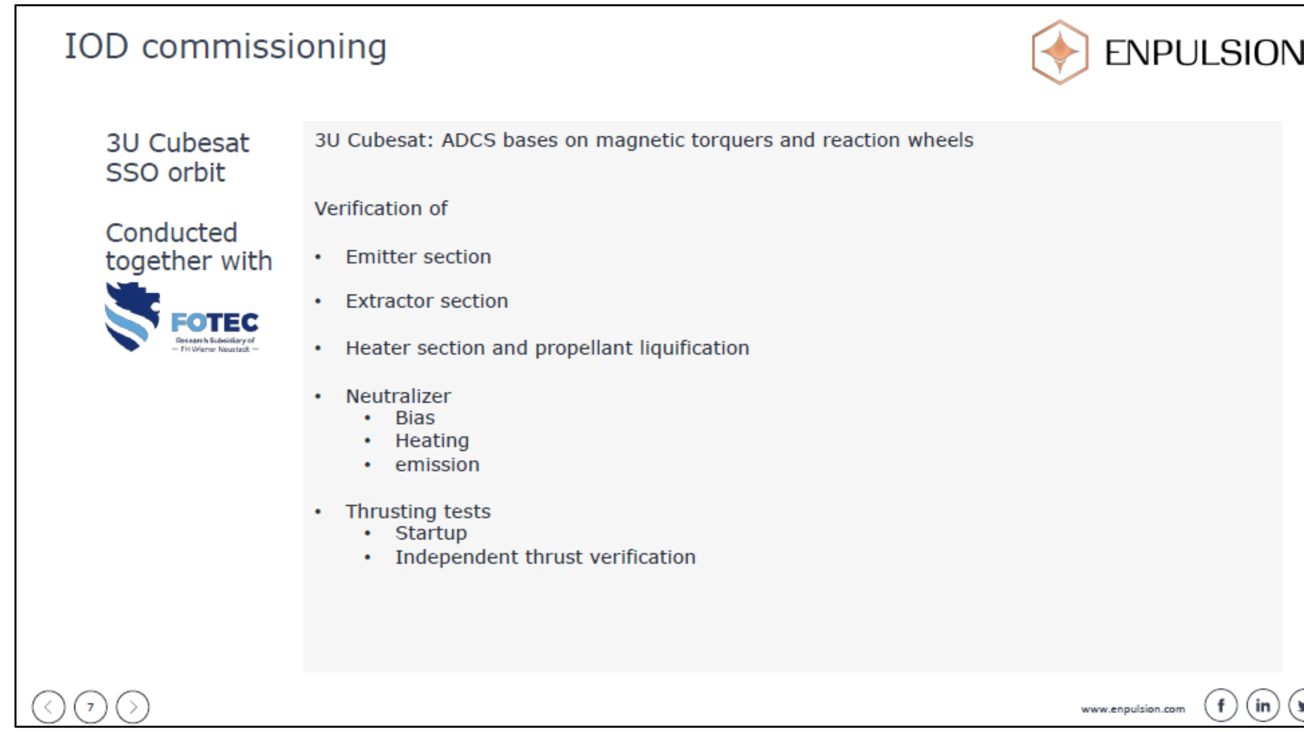
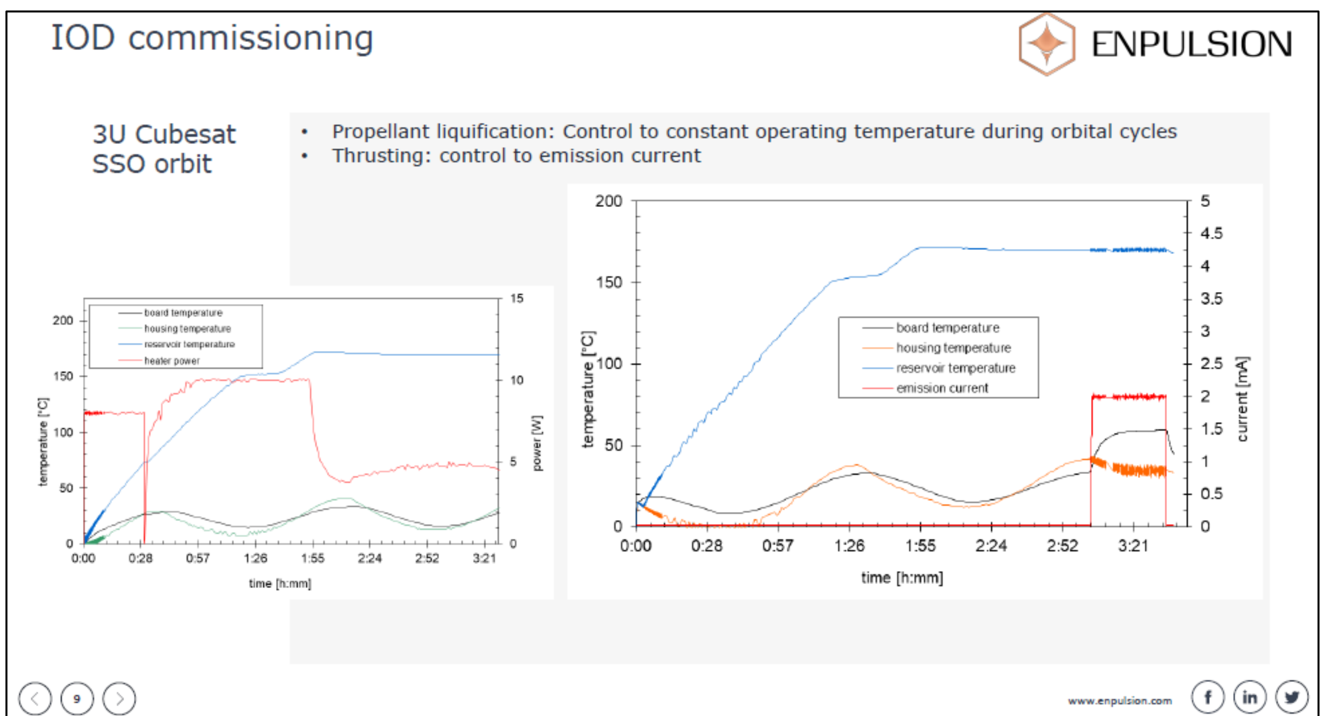
IFM NanoThruster [5 of 9]
Enpulsion

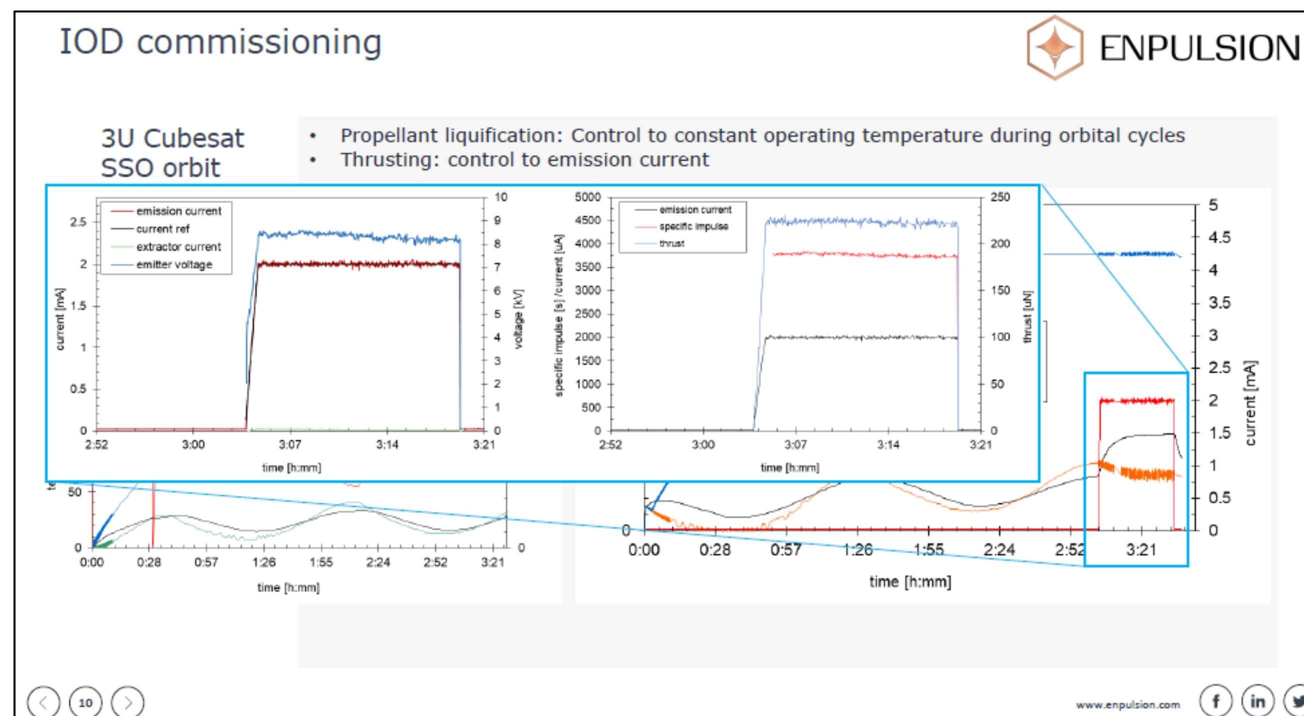
Additional comments:

[Reference 1][Aug 2019][On-orbit demonstration data]









References:

[1] Krecji, D., Schonherr, T., Reissner, A., “Direct thrust measurements and In-orbit demonstration of the IFM Nano Thruster,” Interplanetary Small Symposium (San Luis Obispo), 2019. Public-released charts.

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IFM NanoThruster [6 of 9]
Enpulsion

Additional comments:

[Reference 1][Aug 2019][On-orbit demonstration data]

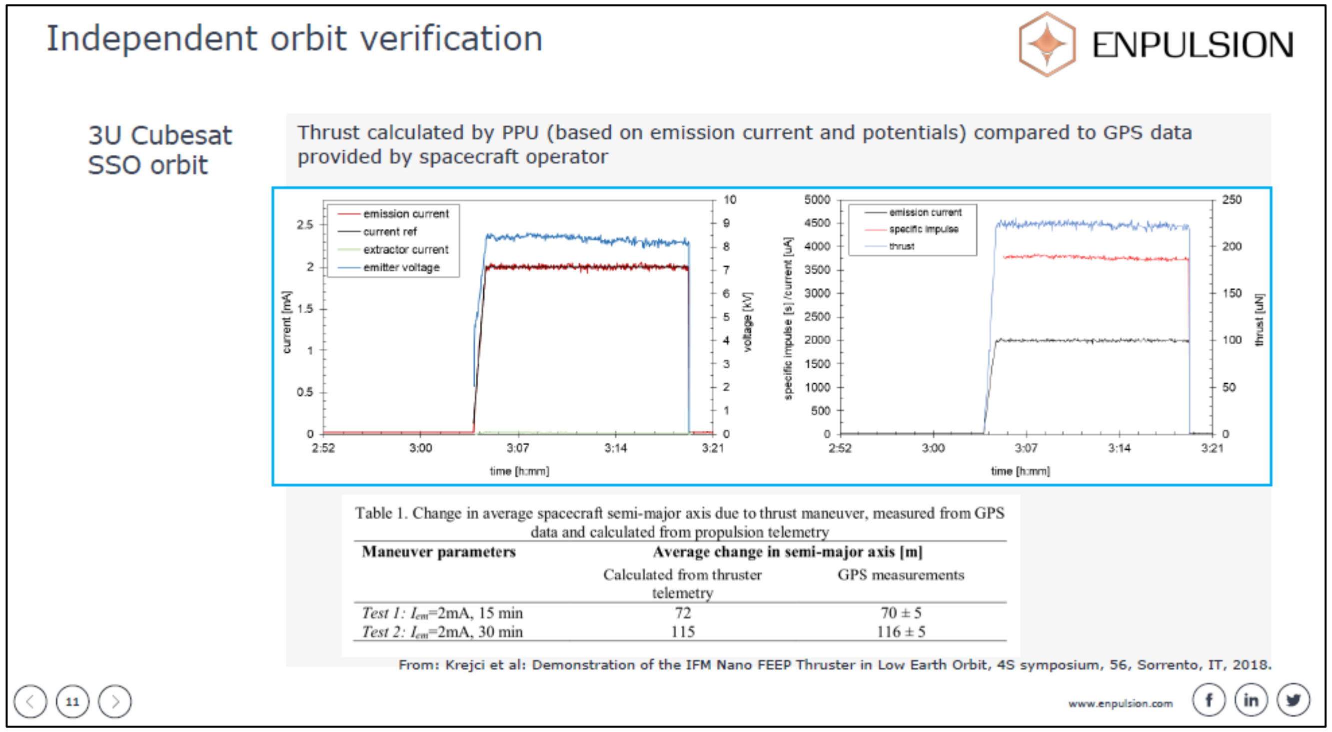
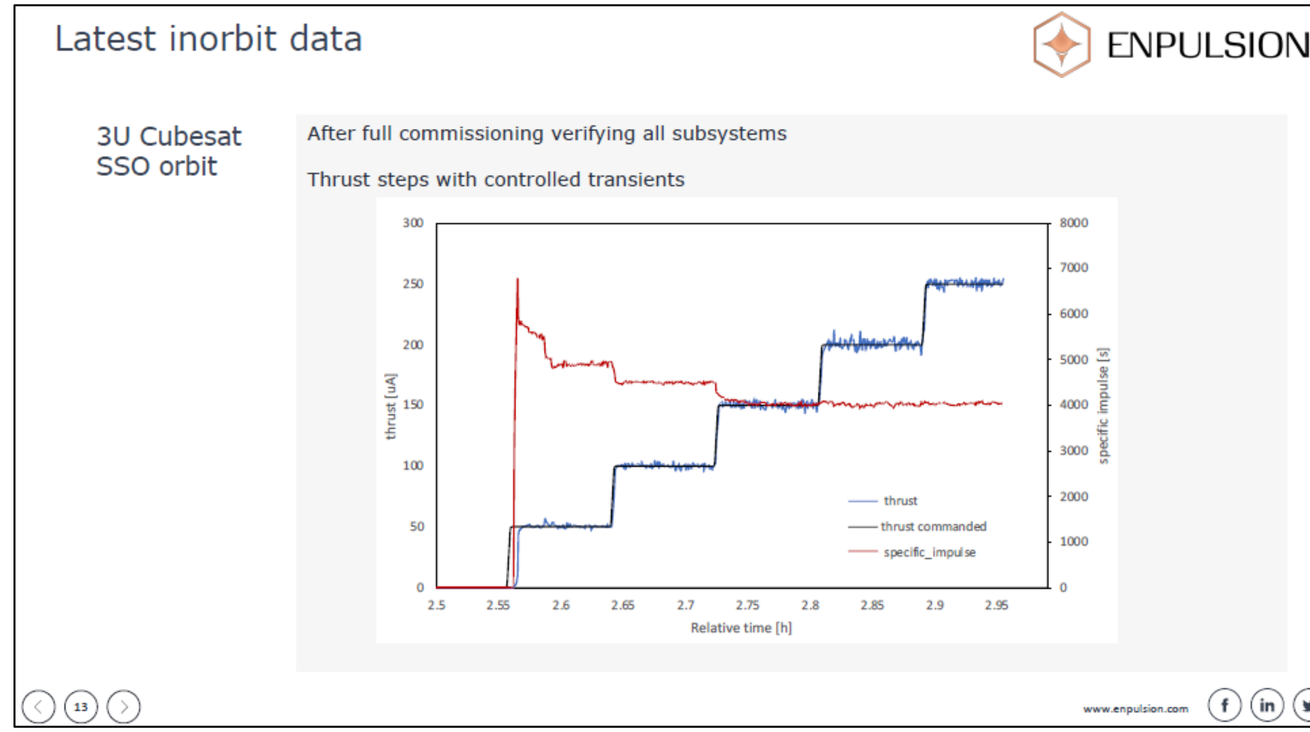
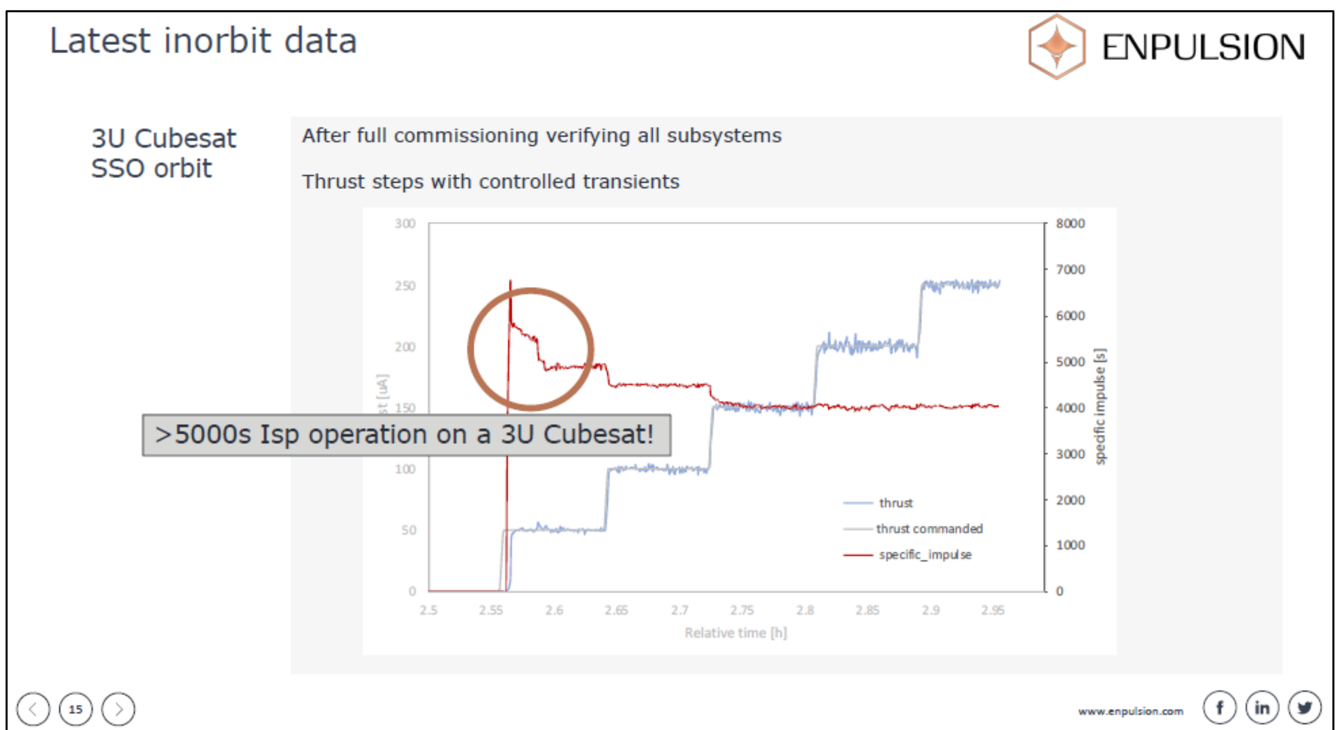
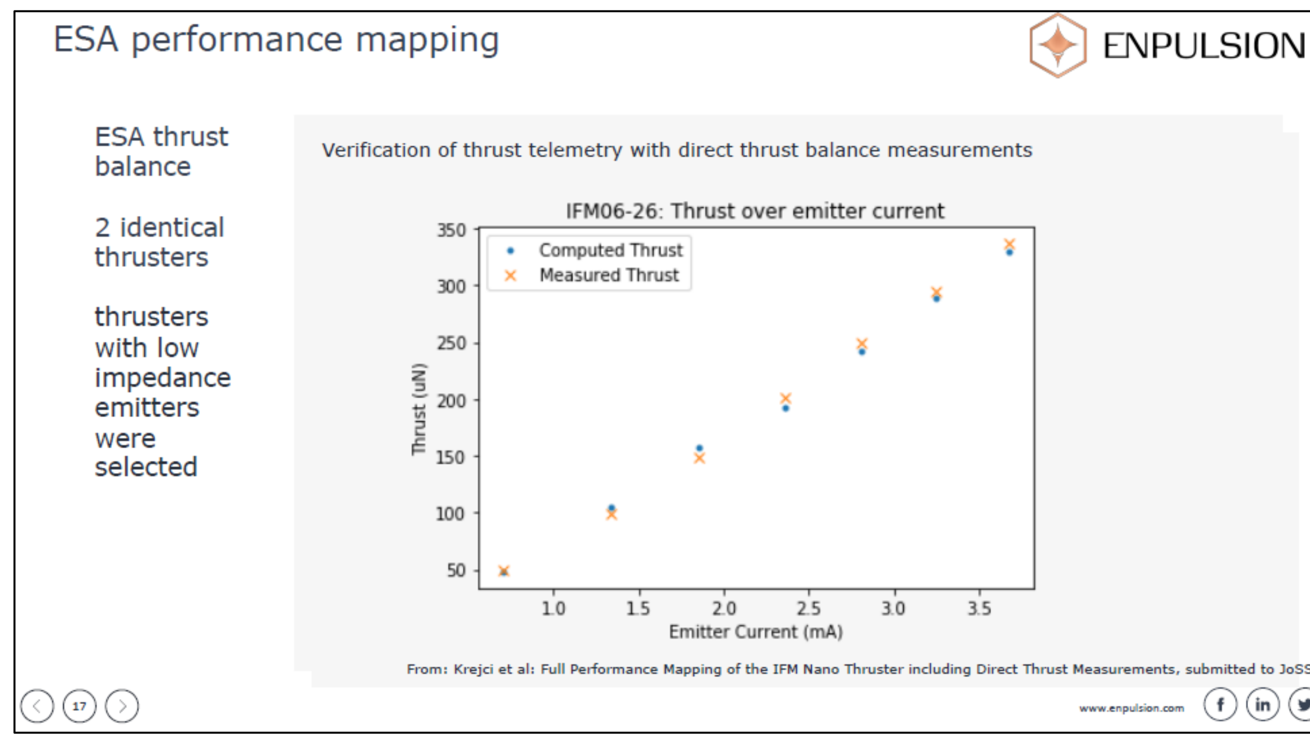


Table 1. Change in average spacecraft semi-major axis due to thrust maneuver, measured from GPS data and calculated from propulsion telemetry

Maneuver parameters	Average change in semi-major axis [m]	
	Calculated from thruster telemetry	GPS measurements
Test 1: I_{em}=2mA, 15 min	72	70 ± 5
Test 2: I_{em}=2mA, 30 min	115	116 ± 5







References:
[1] Krecji, D., Schonherr, T., Reissner, A., "Direct thrust measurements and In-orbit demonstration of the IFM Nano Thruster," Interplanetary Small Symposium (San Luis Obispo), 2019. Public-released charts.

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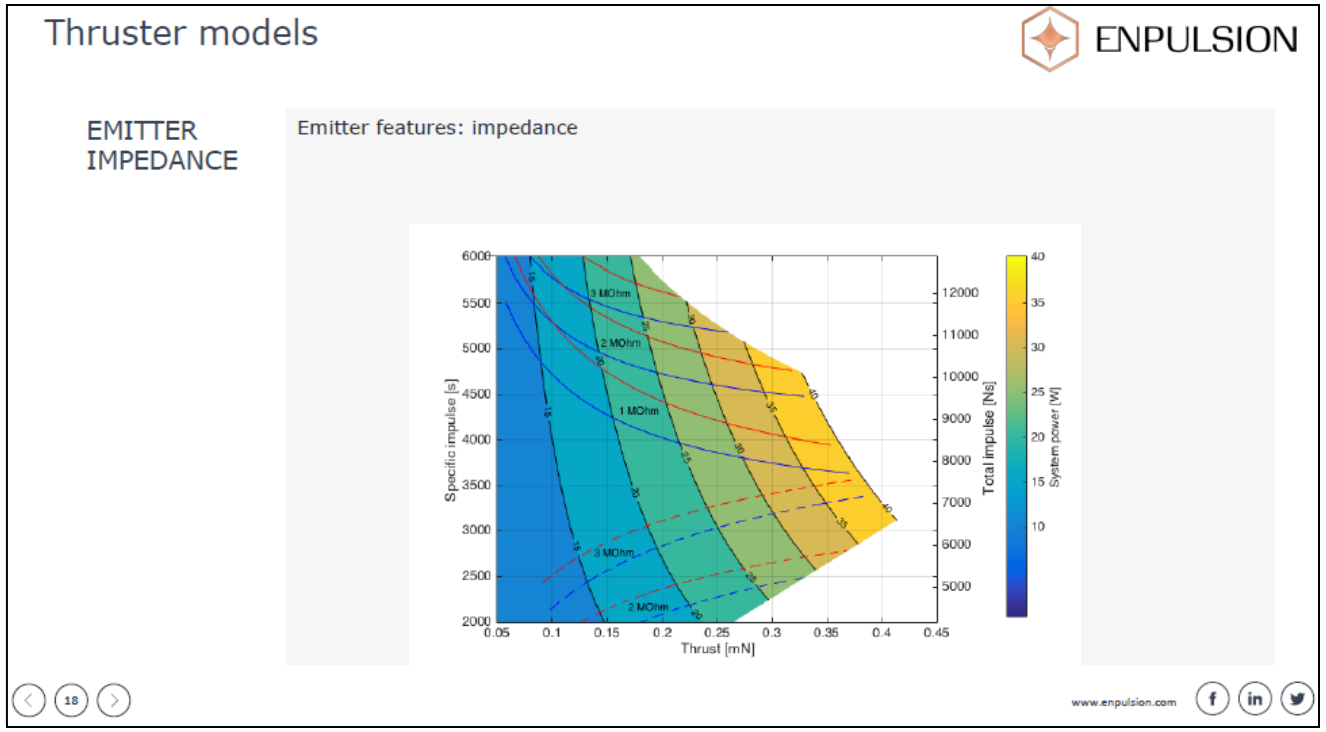
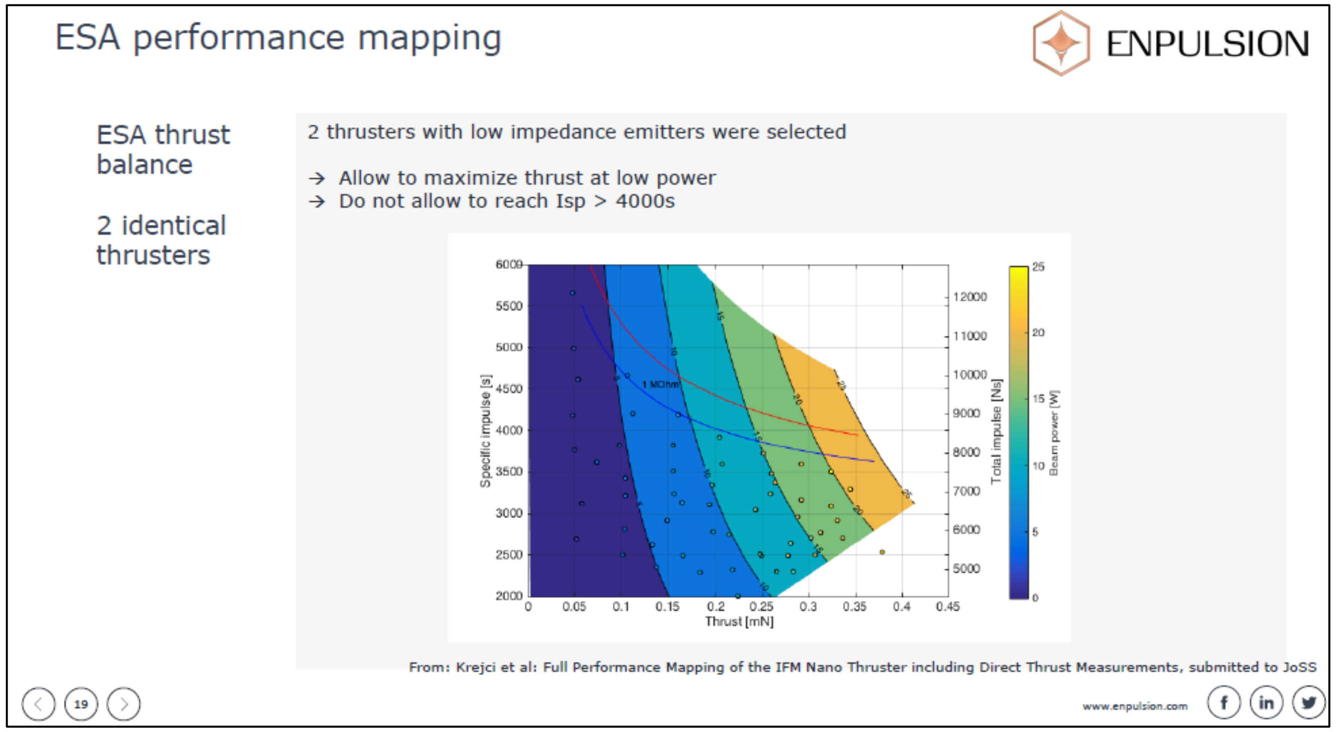
IFM NanoThruster [7 of 9]
Enpulsion

Additional comments:

[Reference 1][Aug 2019][On-orbit demonstration data]





References:
[1] Krecji, D., Schonherr, T., Reissner, A., “Direct thrust measurements and In-orbit demonstration of the IFM Nano Thruster,” Interplanetary Small Symposium (San Luis Obispo), 2019. Public-released charts.

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IFM NanoThruster [8 of 9]
Enpulsion

Additional comments:

[Ref 1][Oct 2019][On-orbit data from IFM Nano thrusters]

In total, over 85 IFM Nano Thrusters were delivered since 2018, with 25 currently in orbit onboard 7 spacecraft.

On-orbit results from an un-named customer (3U commercial CubeSat, launched in 2018 into an 500 km sun-synchronous orbit (SSO)) verified performance via GPS measurements to within the uncertainty of the GPS measurements.

In addition, on-orbit results from the ICEYE X2 spacecraft, which carried 4 IFM Nano thrusters, launched in Dec 2018 into a 570 km x 587 km orbit showed good agreement for thruster performance, and demonstrated various modes of operation. The on-orbit data presented verifies the thermal stability, maximum thrust operation as well as advanced thrust controllability of the commissioned thrusters

[Reference 2][June 2020][On-orbit data from Planet]
The IFM Nano Thruster, a Cubesat sized liquid metal FEEP thruster has been tested on board of a 3U Cubesat. After an extensive commissioning phase, in which the functionality of all subsections of the thruster was verified, first thrust maneuvers have been performed. After initial short firing tests, a first constant thrust maneuver with 15 minutes duration has been performed, with the spacecraft ADCS maintaining thrust vector alignment. Comparison of GPS data before and after the thrust maneuver verified an average semi-major axis change of the spacecraft by 70 ± 5m. This change in orbital altitude corresponds very well with the expected 72m height change that was expected based on onboard telemetry provided by the thruster. This test was followed by several thrust maneuvers including a 30-minute thrusting phase, showing again good accordance between orbit change calculated from thruster telemetry and GPS measurements amounting to approximately 115m change in average orbit altitude. Throughout all ion emission phases, the spacecraft charge build-up was prevented using the thruster’s neutralizer.

References:
[1] Krejci, D., Reissner, A., Schonherr, T., Seifert, B., Saleem, Z., Alejos, R., “Recent flight data from IFM Nano thrusters in a low earth orbit,” IEPC-2019-A724.
[2] Krejci, D., Reissner, A., Seifert, B., Jelem, D., Horbe, T., Plesescu, F., Friedhoff, P., Lai, S., “Demonstration of the IFM Nano FEEP Thruster in Low Earth Orbit,” 4S Symposium, 2018.

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IFM NanoThruster [9 of 9]
Enpulsion

Additional comments:

[Reference 1][Aug 2022][Thruster testing]
We presented selected flight telemetry from propulsion systems on 4 spacecraft, including two significant propulsive orbit maneuvers, and discuss different applications, including an example of precise orbit keeping during the operational phase of two spacecrafts. We discuss data availability regarding a large number of ENPULSION NANO propulsion systems and based on this present high level statistical ENPULSION NANO data including the data availability regarding total firing and hot standby durations, and report an accumulated firing duration of >650 hours on orbit for an ENPULSION NANO in space. We discuss a variety of lessons learnt based on on-orbit operation, integration, and customer side ground test campaigns, which have been incorporated in the next generation ENPUSLION R3 propulsion products.
Lessons learnt include:
- Propellant solidification cycling and propulsion system resets
- Volatile contamination during storage, AIT, and launch
- OBC commanding forbidden states
- Value of flexibility to change on-orbit command software
- Beam interaction with metallic structures (baffle or facility)
- Space environment interaction effects
- Propellant accumulation on extractor

[Reference 2][March 2023][News]
OHB Italia selected ENPULSION as propulsion partner for the IRIDE constellation

Wr. Neustadt, Austria, Jan 23rd, 2023 – OHB Italia selected ENPULSION as their propulsion partner for the IRIDE constellation. In December 2022 OHB Italia and ENPULSION signed a contract for the delivery of 12 NANO thrusters, using ENPULSION's unique Field Emission Electric Propulsion (FEEP) technology.
Under the supervision of ESA and ASI (Agenzia Spaziale Italiana) and in the frame of PNRR (Piano Nazionale Ripresa e Resilienza) the IRIDE constellation will be implemented in Italy and completed by 2026. ESA (European Space Agency) and OHB Italia have signed the contract for the development of an initial batch of 12 satellites to be delivered by November 2024, with a negotiated option for a further batch of 12 satellites to be delivered by November 2025. The industrial consortium led by OHB Italia also includes Telespazio, Optec, and Aresys as partners.
The IRIDE constellation will be composed of satellites of different types and sizes combining SAR, optical, panchromatic, hyperspectral, and infrared sensors. A unique and innovative constellation designed to observe from space what is happening on Earth.

References:
[1] Krejci, D., Reissner, A., "The first 100 FEEP propulsion systems in space: A statistical view and lessons learnt of 4 years of ENPULSION," IEPC-2022-199.
[2] https://www.enpulsion.com/news/ohb-italia-selected-enpulsion-as-propulsion-partner-for-the-iride-constellation/

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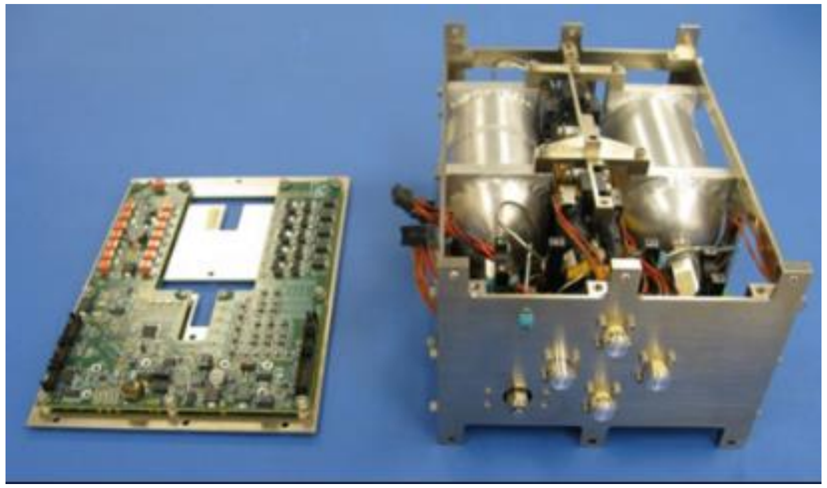
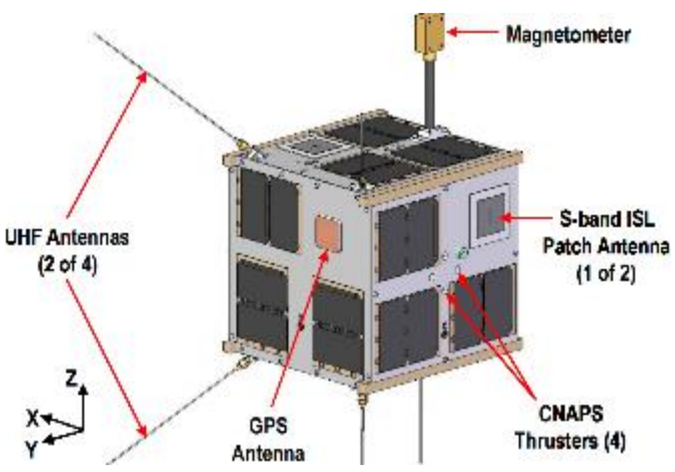
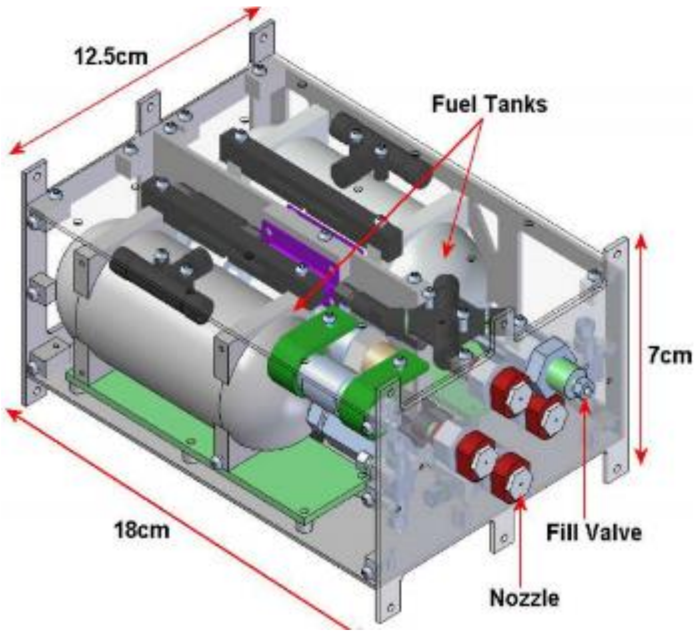
NANOsatellite Propulsion System (NANOPS) / Canadian Advanced Nanosatellite Propulsion System (CNAPS) – University of Toronto SFL

Propulsion Technology	Cold gas propulsion N2O monopropellant
Manufacturer/Country	University of Toronto Space Flight Laboratory (SFL) (CANADA)
TRL	7, Successful mission operations
Size (including PPU)	~2U
Design satellite size	3 to 9
Isp (s)	45 (new efforts targeting 100-200s)
Thrust type/magnitude	45mN thrust average, 200 mN peak, minimum impulse bit 0.0005N*s
Delta-V (m/s)	>35 m/s (up to 100 m/s)
Propellant	Liquefied SF6, upgraded to N2O
Power consumption (W)	4W
Flight heritage (if any)	Flown on 3U CANX2 CubeSat in 2008. Follow-on mission aboard CANX4 and X5 in June 2014 (15 kg each)
Commercially available	Unknown
Last updated	*06/2020*



CNAPS used by CANX-4 and CANX-5





Additional comments:
[Reference 1-3][Jan 2019][General info]
Thruster can operate in both continuous and impulse modes, and material costs were very low (<$20K). “Formation Flying” was achieved with CANX4 and X5. More information on mission and accomplishments is available through the websites in the references. They have claimed to be the only micro-propulsion systems known to have been developed in Canada for actual micro-missions to date. They have ongoing collaborations with COM DEV, MDA, Magellan Aerospace. The thruster was funded by the Canadian Space Agency.

References:
[1] Mauthe, S., Pranajaya, F., Zee, R., “The Design and Test of a Compact Propulsion System for CanX Nanosatellite Formation Flying,” AIAA-SSC05-VI-5.
[2] https://www.utias-sfl.net/?page_id=1274
[3] http://utias-sfl.net/?p=2154
[4] Bonin, G., Noth, N., Armitage, S., Newman, J., Risi, B., Zee, R., “CanX-4 and CanX-5 Precision Formation Flight: mission Accomplished!,” 29th Annual AIAA/USU Small Satellite Conference, 2015.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

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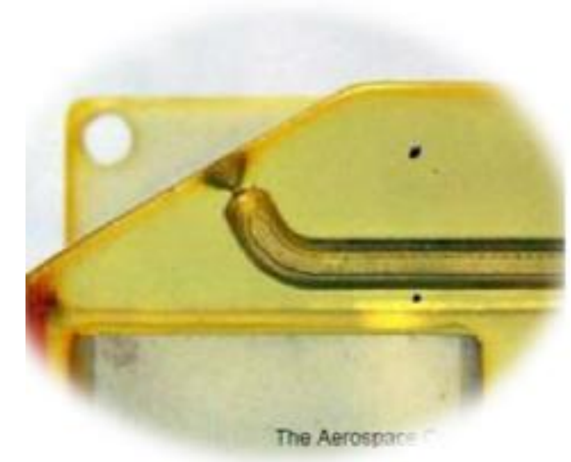
Micro Electro-Mechanical Systems-based PicoSat Inspector (MEPSI)
The Aerospace Corporation

Propulsion Technology	Cold gas
Manufacturer/Country	The Aerospace Corporation (US)
TRL	8+ System proven through successful mission operations.
Size (including PPU)	~0.25U
Design satellite size	~1U
Isp (s)	30-40s
Thrust type/magnitude	2.6 mN*s (impulse) 100 mN (continuous)
Delta-V (m/s)	20 m/s (design, using HFC propellant) 0.4 m/s (flight, using Xenon)
Propellant	HFC-236fa, Xenon
Power consumption (W)	
Flight heritage (if any)	Flown on STS-113 and STS-116. Flight used 100 psia Xenon to comply with NASA requirements
Commercially available	No
Last updated	*01/2019*



Cold gas propulsion unit

Additional comments:

[Reference 1-5][Jan 2019][General info]

The propulsion unit is a 3-D (Additively Manufactured) printed propulsion unit, using refrigerant or xenon as a propellant. Unit produced data on orbit, demonstrating rotation rate when the propulsion unit fired. The reported thrust numbers are as demonstrated on orbit.

References:

[1] Hinkley, D., “A Novel Cold Gas Propulsion System for Nanosatellites and Picosatellites,” AIAA, 22nd Annual Conference on Small Satellites, SSC08-VII-7.
[2] https://pdfs.semanticscholar.org/ec6a/2a6fff20911326549f03dc959e5e5741fdd9.pdf
[3] Hinkley, D., Hardy, H., “Picosatellites and Nanosatellites at The Aerospace Corporation,” In-space Non-destructive Inspection Technology Workshop, 2012.
[4] https://www.nasa.gov/pdf/626635main_inspace-4-3-hinkley.pdf
[5] http://space.skyrocket.de/doc_sdat/mepsi.htm

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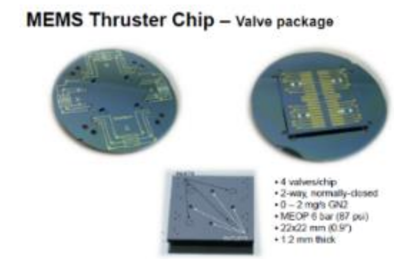
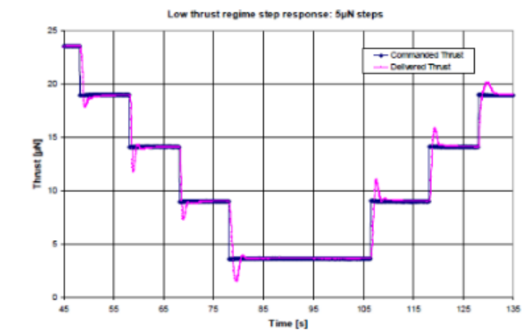
NanoProp 3U Propulsion (MEMs cold/warm gas thruster modules) [1 of 2]
NanoSpace / GOMSPACE

Propulsion Technology	Warm gas thruster
Manufacturer/Country	NanoSpace AB (SWEDEN) – now GOMSPACE (DENMARK)
TRL	7-8
Size (including PPU)	~0.5U (several models are available)
Design satellite size	~3U and ~6U models
Isp (s)	50 to 100 s
Thrust type/magnitude	0.01 to 1 mN/thruster. Each unit has 8 thrusters, 40 N*s (impulse, total) Thruster module offers 6 degrees of freedom. [10]
Delta-V (m/s)	10-20 m/s
Propellant	Warm gas (Nitrogen) or other (recently Butane)
Power consumption (W)	2W per thruster head (8W/unit)
Flight heritage (if any)	PRISMA (2010), TW-1 (2015, 3U model, aka STU-2), GOMX-4B (2018, 6U model) ESTCube-2 (was 2018, now 2021 projected) [8] CANYVAL-C (launched March 2021) [9]
Commercially available	YES
Last updated	*12/2023*





GomX-4B's cold-gas thruster system takes up two half-cubesat units at one side of the nanosatellite, with two spherical titanium tanks filled with liquid butane. It has four 1 mN thrusters, typically to be fired in pairs while keeping one set in reserve.
Photo is courtesy of Nanospace.

The thruster chip contains valves and heaters and runs on nitrogen (although other gases may be substituted)

Additional comments:

[References 1-7][Feb 2019][General info]
NanoSpace was sold to GOMSPACE in 2016. The thruster module contains a silicon wafer stack with four complete rocket engines with integrated flow control valves, filters, and heaters. Each wafer houses 4 thruster heads. Extremely small heaters are located inside the thrust chamber to improve the specific impulse and hence make efficient use of the propellant. Laboratory results are promising and show thrust measurements. Feed pressures are about 60 psia.
The technology was first flown on PRISMA. TW-1 reported successful thruster firing, and thrusters are currently aboard GOMX-4B, launched Feb 2018. The BOMX-4B is carrying a warm butane, 6U version of the thruster module. The components of the thruster system include a propellant tank, the MEMs thruster module, a pressure regular, a MEMs isolation valve, two pressure transducers, a fill/vent valve, and a MEMs pressure relief valve.

References:

[1] Ransten, P., Johansson, H., Bendixen, M., et al. "MEMs Micropropulsion Components for Small Spacecraft," AIAA-SSC11-X-2
[2] Palmer, K., et al, "In-Orbit Demonstration of a MEMS-based Micropropulsion System for CubeSats,"
[3] https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3467&context=smallsat (presentation slides)
[4] Wu, S., Chen, W., Chao, C., "The STU-2 CubeSat Mission and In-Orbit Test Results," Small Satellite Conference, SSC16-III-09
[5] http://rymdstyrelsen.se/Global/Forskare/Innovativa%20satellitprojekts%20I%C3%A5g%20kostnad/NanoSpace_pres_SNSB_hearing_nov_2011_v2.pdf
[6] http://space.skyrocket.de/doc_sdat/prisma.htm
[7] https://gomspace.com/Shop/subsystems/propulsion/nanoprop-3u-propulsion.aspx
[8] https://www.nanosats.eu/sat/estcube-2
[9] Kim, G., Park, S., Lee, T., Kang, D., Kim, N., Jeon, S., Lee, E., Song, Y., "Development of formation flying cubesats and operation systems for the CANYVAL-C Mission: launch and lessons learned," Small Satellite Conference 2021, SSC21-WKII-01.
[10] Teerikoski, S., Tegedor, J., Bartle, J., Lawrence, J., Robin, F., "Optimization of propulsion systems with real-time precise orbit determination technology to enable proximity operations and advanced mission capabilities," Small satellite conference SSC23-X-07.

7	NO
Comm. avail.	TRL	Aerospace-tested

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NanoProp 3U Propulsion (MEMs cold/warm gas thruster modules) [2 of 2]
NanoSpace / GOMSPACE

Additional comments:

[Reference 1][Feb 2019][News]
"ESA is making use of the standardized 10 cm. cubesats for testing new technologies in space. GomX-4B was ESA's first six-unit cubesat, double the size of its predecessor GomX-3, built for ESA by GomSpace in Aalborg, Denmark, who is also the builder of GomX-4A for the Danish Ministry of Defence. The cubesat pair was launched in February of 2018 from Jiuquan, China. GomX-4B used its butane cold gas propulsion system to maneuver away from its twin, flying up to 4,500 km. away in a fixed geometry — a limit set by Earth's curvature and representative of planned smallsat constellation spacing — to test inter-satellite radio links allowing the rapid transfer of data from Earth between satellites and back to Earth again. Supplied by the Swedish branch of GomSpace, the propulsion system allows the cubesat to adjust its orbital speed in a controlled manner by a total of 10 m/s

[Reference 2][Nov 2019][Company news]
GomSpace's subsidiary in Sweden and ESA have signed a contract to develop a miniaturized electric propulsion system suitable for small spacecrafts going on interplanetary missions. The contract will be carried out under ESA's General Support Technology Program during the next 18 months and the value is 700,000 euros. The work will be led by GomSpace Sweden and executed with ASP Equipment and IMS Space Consultancy. In this project, the goal is to develop an electric propulsion system that can take a 20 to 40 kg. class spacecraft from the edge of the Earth's gravitational field to an asteroid. The project will expand GomSpace's propulsion capabilities to span both cold-gas technology for station-keeping, collision avoidance and maneuvering as well as electric propulsion technology for orbit changes, e.g., for safely disposing of spacecraft after the end of a mission.

[Reference 3-4][June 2020][Flight information]
ESTCube-2 will serve as a prototype for ESTCube-3, an Estonian mission to orbit the moon that will blast off in the early 2020s. In addition, the European Space Agency is now officially considering a joint Estonian-Finnish proposal to send a swarm of satellites based on the same Estonian design to rendez-vous with hundreds of asteroids.
The main objective for ESTCube-2 is to test a "plasma brake". This is a new method of deorbiting satellites, which could help mitigate the problem of space debris. A tether is charged in the ionosphere and the braking force then enables the satellite to drop out of orbit up to ten times faster than current methods.
ESTCube-2 is slated for launch in 2021.

[Reference 5][October 2021][Flight information]
It sounds like the CANYVAL-C mission flew a version of the GOMSPACE cold-gas thruster, although the exact model is not called out.

References:
[1] http://satnews.com/story.php?number=1595137208
[2] http://www.satnews.com/story.php?number=1093166159
[3] https://estonianworld.com/technology/estonias-mission-moon-revolutionise-space-travel/
[4] https://www.nanosats.eu/sat/estcube-2
[5] Kim, G., Park, S., Lee, T., Kang, D., Kim, N., Jeon, S., Lee, E., Song, Y., "Development of formation flying cubesats and operation systems for the CANYVAL-C Mission: launch and lessons learned," Small Satellite Conference 2021, SSC21-WKII-01.
[6] Teerikoski, S., Tegedor, J., Bartle, J., Lawrence, J., Robin, F., "Optimization of propulsion systems with real-time precise orbit determination technology to enable proximity operations and advanced mission capabilities," Small satellite conference SSC23-X-07.

	7	NO
Comm. avail.	TRL	Aerospace-tested

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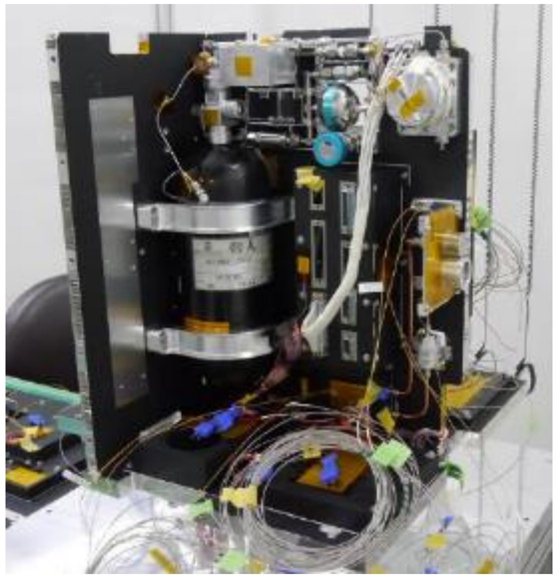
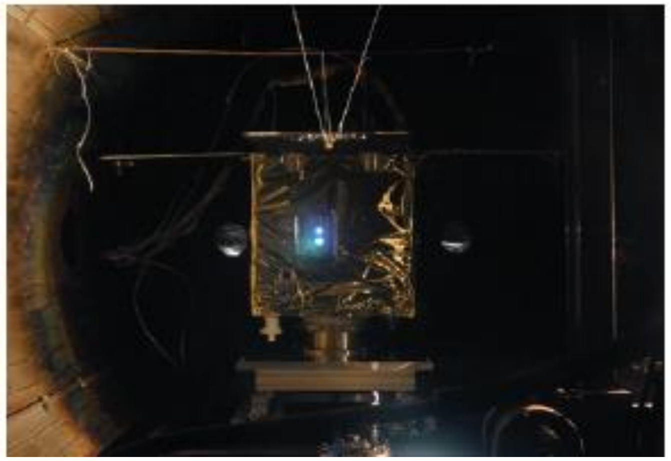
I-COUPS (Ion thruster and COld-gas thruster Unified Propulsion System)
University of Tokyo

Propulsion Technology	Ion + cold gas
Manufacturer/Country	University of Tokyo
TRL	7
Size (including PPU)	10kg (~3U)
Design satellite size	50kg and larger
Isp (s)	1000s
Thrust type/magnitude	300 to 350 uN
Delta-V (m/s)	100 m/s for ~70kg S/C
Propellant	Xenon
Power consumption (W)	35 to 38 W
Flight heritage (if any)	PROCYON (2015)
Commercially available	No
Last updated	*01/2021*



I-COUPS, ready for PROCYON

Firing of the ion thruster on the PROCYON flight model



Additional comments:

[Reference 1][Jan 2019][General info]

The University of Tokyo has successfully developed and operated miniature propulsion systems using ion thrusters on two small satellites: HODOYOSHI-4 and PROCYON. HODOYOSHI-4 is a 65 kg LEO satellite that was launched in June 2014 by a Dnepr rocket. It is equipped with a miniature ion propulsion system, named MIPS, and the first ion thruster operation was successfully conducted on December 28th that year. PROCYON is a 67 kg space probe that was inserted into an orbit around the Sun in December 2014 by a H-IIA rocket. PROCYON is equipped with a micropropulsion system, named I-COUPS, which unifies eight cold-gas thruster heads for RCS and an ion thruster for high Δv maneuver. The cold gas thrusters are operated since December 6th and the ion thruster has accomplished 223 hours operation since December 28th. MIPS (Miniature Ion Propulsion System) was developed by the University of Tokyo together with Next Generation Space Technology Research Association (NESTRA) in Japan, which developed HODOYOSHI-4. The satellite’s primary mission was to demonstrate innovative small satellite technologies, and MIPS was one of the selected technologies. Development of the MIPS started from its EM in September 2011 to its final FM in March 2014. The FM has a total mass of 8.1 kg (dry mass: 7.1 kg), a volume of 34×26×16 cm3, a power consumption of 39 W, and produces a thrust of 300 μN with a specific impulse of 1200 s. I-COUPS (Ion thruster and COld-gas thruster Unified Propulsion System) was developed by the University of Tokyo as a propulsion system for the small space probe PROCYON. PROCYON was launched as a small secondary payload by an H-IIA launch vehicle along with the main payload HAYABUSA-2 and it will be the first small space probe to explore deep space in the class of less than 100 kg. Components and structure of ICOUPS were based on MIPS and development of I-COUPS was finished within one year. Total mass of ICOUPS FM is 9.5 kg including 2.5 kg xenon propellant. The ion thruster produces a thrust of 350 μN and a specific impulse of 1000 s at 38 W of power consumption, and the cold-gas thruster yields a thrust of 22 mN and a specific impulse of 24 s at 8 W of power.

[Reference 2][Jan 2019][Mission info]

Recently, the Japanese Proximate Object Close flyby with Optical Navigation (PROCYON) mission has shown successful operation of a propulsion system in space. The Ion thruster and Cold-gas thruster Unified Propulsion System (I-COUPS) was designed at the University of Tokyo and is an integrated system composed of two sets of ion and cold gas thrusters. Both technologies share the same gas feed system that provides xenon to be used as propellant. This combines high thrust and large ΔV capabilities. Cold gas thrusters are used for reaction wheel de-saturation and small correction burns, while ion engines are kept for deep space maneuvers. In total, the mass of the propulsion system is less than 10 kg, including propellant. The ion engines in the I-COUPS unit are an evolution of the Miniature Ion Propulsion System (MIPS), which was previously launched on-board the Hodoyoshi-3/4 mission (October 2014). This spacecraft was placed on a Sun Synchronous Orbit and had 65 kg of mass. The MIPS had a wet mass of 8.1 kg with 1 kg of propellant mass. Ion thruster operation was proven by providing continuous acceleration.

References:

[1] Takegahara, H., Kuninaka, H., Funaki, I., et al., “Overview of electric propulsion research activities in Japan,” IEPC, 2015.
[2] Koizumi, H., Inagaka, T., Kasagi, Y., et al., “Unified propulsion system to explore near-Earth asteroids by a 50 kg spacecraft,” AIAA-SSC14-VI-6.

7 | NO

Comm. avail. | TRL | Aerospace-tested

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Aerotech 24MM E28T-7
Apogee Components

Propulsion Technology	Solid rocket motors
Manufacturer/Country	Aerotech (Apogee Components) & The Aerospace Corporation (US)
TRL	7-8
Size (including PPU)	<1 U (depends on bus)
Design satellite size	~2U
Isp (s)	220s (calculated from manufacturer's spec)
Thrust type/magnitude	40 N*s (impulse, total) 50 N (max thrust)
Delta-V (m/s)	
Propellant	Ammonium Perchlorate
Power consumption (W)	
Flight heritage (if any)	Pico-Satellite Solar Cell Testbed 2 (PSSC-2), 2011
Commercially available	YES
Last updated	*01/2019*

E28-T SRMs from AeroTech

Various propellant formulations offered by Apogee Components

- **Model**: 52807
- **Qty per pack**: 3 motors
- **Size**: 24 mm Reload
- **Casing (Not Included)**: AeroTech 24/40 Case (PN: 60001)
- **Delay**: 7 sec
- **Burn Time**: 1.2 sec
- **Total Impulse**: 40.0 Newton-seconds
- **Motor Length**: 70 mm
- **Max Thrust**: 50.5 Newtons
- **Total Mass**: 55.0 g
- **Propellant Mass**: 18.4 g
- **Manufactured by**: AeroTech

Photo of PSSCT-2 as it is released inside the Atlantic Space Shuttle bay

Additional comments:

[Reference 1-3][Jan 2019][General info]
Vehicle was flown on the final shuttle mission STS-135. 4X E28T boosters were flown on PSSCT-2 to demonstrate orbit-raising capability. In order to increase altitude, the motors had to be fired along the trajectory of the satellite, and in order to meet NASA safety guidelines, the rocket firing command had to be sent manually while in contact with the ground station. The first solid motor was fired on 11/4/2011, but alignment of the thrust vector through the satellite cg was off and caused the spacecraft to rotate. But positive thrust was observed and rotation quantified. Over the next few weeks, the remaining 3 solid motors were commanded to fire, but none of them ignited. It is unknown whether the failure was due to the prolonged exposure of the solid propellant to vacuum, or whether the initial firing had an adverse effect on the remaining motors.
Burn time of the motors is 1.2 seconds, with a delay of 7 seconds. Aerotech makes various other sizes and types of solid rocket motors, but no others have been space qualified, to our knowledge.

References:
[1] https://directory.eoportal.org/web/eoportal/satellite-missions/p/pssct-2
[2] http://www.apogeerockets.com/Rocket_Motors/AeroTech_Motors/24mm_Propellant_Kits/Aerotech_24mm_Propellant_Kit_E28T-7
[3] http://en.wikipedia.org/wiki/PSSC-2

Comm. avail.	TRL	Aerospace-tested
	7	NO

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Steam Propulsion – Aerocube 7 (OCSD Mission) and Aerocube 10
The Aerospace Corporation [1 of 2]

Propulsion Technology	Water/steam
Manufacturer/Country	The Aerospace Corporation (USA)
TRL	7
Size (including PPU)	~1U
Design satellite size	1.5U, 3U, 6U
Isp (s)	~90s (nominally 70s)
Thrust type/magnitude	3 to 5 mN
Delta-V (m/s)	3 to 10 m/s
Propellant	Water
Power consumption (W)	Requires 2.9W/mN to support continuous thrust, Nominally 5W
Flight heritage (if any)	NASA OCSD/Aerocube 7 (AC7), launched 2017 Updated model flown on Aerocube 10A (JimSat) and 10B(DougSat), launched 2019
Commercially available	NO
Last updated	*10/2019*

Aerospace's AC7 additively manufactured steam propulsion unit.

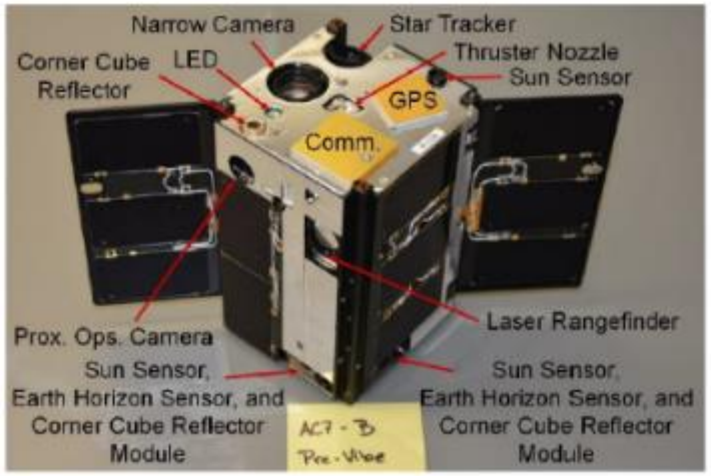

Figure 1: AeroCube-OCSD-B with deployed solar panels.

Additional comments:

[Reference 1-6][Jan 2019][General information]

OCSD (Optical Communications and Sensor Demonstration), formerly known as IOCPS (Integrated Optical Communications and Proximity Sensors for Cubesats), is a cubesat mission by The Aerospace Corporation of El Segundo to demonstrate a laser communication system for sending large amounts of information from a satellite to Earth and also demonstrate low-cost radar and optical sensors for helping small spacecraft maneuver near each other. OCSD A was launched as a pathfinder in mid-2015 with AeroCube 5C to demonstrate all the subsystems required for the primary OCSD mission, and will be used to evaluate the performance of the attitude-control system. In orbit, it suffered an attitude control problem that is preventing its laser communications payload from being tested. OCSD B and OCSD C, featuring a simplified version of the laser flown on OCSD-A, as well as a new thruster system that uses steam for propulsion, was launched in 2017. The propulsion requirements call for ~3 m/s of delta-v to bring two CubeSats to within 1 km of each other and to perform 30 sets of proximity operations. The propulsion system is oversized to 10 m/s to account for inevitable missteps in orbit control and to allow for multiple tests of collision avoidance maneuvers. This propulsion system, like the one Aerospace flew on MEPSI in 2006, is fabricated out of plastic using additive manufacturing. It uses water as a propellant, and ejected water vapor (steam) into space. The propellant tank and feed lines are voids in a single block of plastic. MEPSI had a plastic converging/diverging nozzle integrated into the structure, but for this project, the team used an aluminum nozzle with a 700-µm diameter machined throat. The thruster was tested by mounting the module on a sensitive electronic balance with the nozzle pointing up. The whole system, except for the electronic balance display, was put in a vacuum chamber with feedthrough carrying the scale data output lines, the RS232 thruster control lines, and the power plus ground lines for both the thruster and the scale. The satellites were commanded to fire thrusters early in 2018 and were successful; however, impulse bits generated by the thruster have not scaled reliably with valve "on" time and we are still trying to understand the mechanisms at work. However, we believe these are the first CubeSats to perform proximity operations. Proximity operations were enabled by an on-board GPA receiver and a 3-axis attitude control system with better than 0.05 degree pointing accuracy, originally developed the express purpose of aiming a laser downlink in each CubeSat.

References:

[1] Rowen, D., Janson, S., Coffman, C., et al., "The NASA Optical Communications and Sensor Demonstration Program: Proximity Operations," SSC18-I-05, SmallSat Conference, 2018.
[2] Janson, S., Welle, R., Rose, T., Rowen, D., et al., "The NASA Optical Communication and Sensor Demonstration Program: Initial Flight Results," Small Satellites Conference, SSC16-III-03
[3] Welle, R., Utter, A., Rose, T., Fuller, J., Gates, K., Oakes, B., Janson, S., "A CubeSat-Based Optical Communication Network for Low Earth Orbit," Small Satellites Conference, SSC17-XI-01
[4] http://space.skyrocket.de/doc_sdat/aerocube-7-ocsd.htm
[5] https://directory.eoportal.org/web/eoportal/satellite-missions/a/aerocube-ocsd
[6] https://space.skyrocket.de/doc_sdat/aerocube-10.htm

NO	7	
Comm. avail.	TRL	Aerospace-tested

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Steam Propulsion – Aerocube 7 (OCSD Mission) and Aerocube 10
The Aerospace Corporation [2 of 2]

Additional comments:

[Reference 2][Oct 2019]AC7 performance, success]
On June 21, 2019, NASA demonstrated the first coordinated maneuver between two CubeSats in low-Earth orbit as part of NASA's Optical Communications and Sensor Demonstration mission. The twin spacecraft, each approximately the size of a tissue box, were orbiting Earth about 5.5 miles apart when they established a radio frequency communications cross-link to "talk" with each other. One spacecraft issued a command to the second to activate its thruster and close the gap between the two. The fuel tanks on both spacecraft are filled with water. During this propulsive maneuver, the water was converted to steam by the thrusters to propel the spacecraft.

[Reference 1][Oct 2019][AC10 design and performance]
As of October, 2019, AC10 is about to begin operation. We should have on-orbit data shortly (within a few weeks).
David Hinkley gave a summary of the design of the AC10 thruster, limited to information available in the public domain, focusing on design improvements of AC10 over AC7, since design information on AC7 is readily available publicly. Overall, AC10's design is very similar to AC7 with some engineering design improvements.

One important lesson learned from AC7 is that the nozzle produced an ice-ball while firing, which could only be alleviated by waiting for the ice to sublimate/evaporate. So the AC10 heater was moved to the nozzle to fix this issue. This is the only heater on the whole system and ensures that the nozzle is the hottest part of the assembly. The unit is run at 40C nominally, but could go up to 60C if needed. The temperature for AC10 is measured in only one location – outside of the aluminum tank.
Valve redundancy was another difference between AC7 and AC10. AC7 had redundancy but AC10 did not.

AC7 experienced propellant overload problems due to oversight in water propellant loading volume and expansion upon freezing within the sponge reservoir. Therefore, the propellant was not filled to 100% for AC10, to fix this issue. Similarl to AC7, AC10 utilized a sponge that carried the water propellant. The sponge physically touches the walls of the chamber so that when heat is applied to the chamber, the sponge also heats. When the thruster propellant load is completely consumed, there is still enough moisture in the sponge that it retains contact with the walls (the propellant is not designed to be 100% evacuated).

The nozzle for both systems is a simple conical 60 degree in and out design, with a 0.030" diameter throat, 0.020" throat length. The design of the nozzle was not optimized, as flow rates/densities are low.

One last improvement from AC7 is the upgrade from a plastic to an all-metal (aluminum) tank. The tank has a gold plating for corrosion-resistance. This offers minimal leak risks and is better for heating, is a cleaner package, and therefore has higher reliability.

[Reference 3][Oct 2021][AC10 performance on orbit]
In the summer of 2020, the pair of AeroCube-10 1.5U CubeSats completed a series of mutual proximity operations as close as 22 meters separation and captured several sets of satellite-to-satellite resolved imagery, inspecting all faces of a vehicle in each pass with a resolution less than 8 mm.

References:
[1] Conversations with David Hinkley
[2] https://www.nasa.gov/image-feature/ames/cubesats-dance-one-water-powered-nasa-spacecraft-commands-another-in-orbit
[3] Gangestad, J., Venturini, C., Hinkley, D., Kinum, G., "A Sat-to-Sat Inspection demonstration with the AeroCube-10 1.5U CubeSats," Small Satellite Conference, SSC21-I-11, 2021.

NO	7	
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

STAR-3 (STAR-3A) Series Solid Rocket Motors
Northrop Grumman

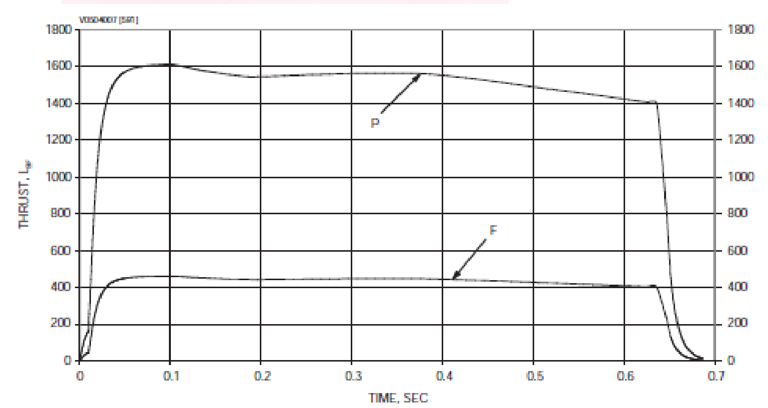
Propulsion Technology	Solid rocket motor
Manufacturer/Country	Orbital ATK (now Northrop Grumman) (USA)
TRL	7
Size (including PPU)	12” (30.5 cm) L x 3” (7.6 cm) DIA (~3U)
Design satellite size	3U and larger
Isp (s)	266s
Thrust type/magnitude	1900 N (thrust, average) 2050 N (thrust, max) 1250 N*s (impulse, total)
Delta-V (m/s)	230 m/s for 10 kg spacecraft (calc)
Propellant	TP-H-3498, case material titanium
Power consumption (W)	n/a
Flight heritage (if any)	MER Spirit Lander (2003),
Commercially available	YES
Last updated	*07/2019*

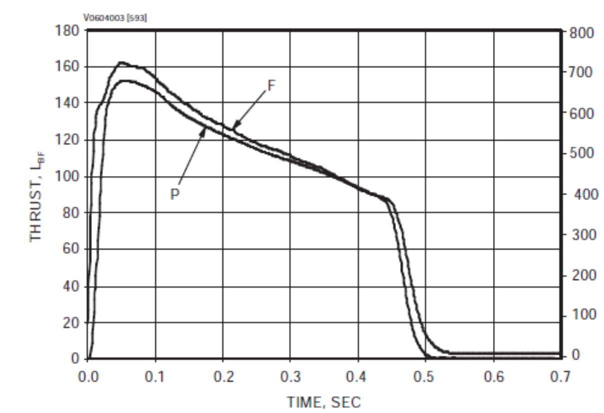
STAR Motor Performance and Experience Summary

STAR Designation	Model Number	Nominal Diameter		Total Impulse, lb_f-sec	Effective Specific Impulse, lb_f-sec/lb_m	Propellant Weight		Propellant Mass Fraction	Tests	Flights
		in.	cm			lb_m	kg			
3	TE-M-1082-1	3.18	8.08	281.4	266.0	1.06	0.48	0.42	26	3
3A	TE-M-1089	3.18	8.08	64.4	241.2	0.27	0.12	0.14	2	3
4G	TE-M-1061	4.45	11.30	595	269.4	2.16	0.98	0.65	2	0
5*	TE-M-500	5.05	12.83	895	189.0	3.8	1.72	0.87	4	11
5A	TE-M-863-1	5.13	13.02	1,289	250.8	5.05	2.27	0.49	6	3
5C/5CB	TE-M-344-15 TE-M-344-16	4.77 4.77	12.11 12.11	1,252 1,249	268 262.0	4.55 4.62	2.06 2.10	0.47 0.47	245 20	686 160
5D	TE-M-989-2	4.88	12.39	3,950	256.0	15.22	6.90	0.68	13	3
5F	TE-M-1198	4.85	12.32	2,216	262.9	8.42	3.82	0.37	9	194
6	TE-M-541-3	6.2	15.75	3,077	287.0	10.7	4.85	0.80	47	238
6A*	TE-M-542-3	6.2	15.75	2,063	285.3	7.2	3.27	0.72		
6B	TE-M-790-1	7.32	18.59	3,686	269.0	13.45	6.10	0.60	8	18


Star 3 motor


Star 3A motor





Additional comments:

[Reference 1] [Jan 2019][General info]
According to NGC website: The STAR 3 motor was developed and qualified in 2003 as the transverse impulse rocket system (TIRS) for the Mars Exploration Rover (MER) program for the Jet Propulsion Laboratory (JPL) in Pasadena, CA. Three TIRS motors were carried on each of the MER landers. One of the TIRS motors was fired in January 2004 to provide the impulse necessary to reduce lateral velocity of the MER Spirit lander prior to landing on the Martian surface. The motor also has applicability for spin/despin and separation systems.
NGC reports the production status as flight-proven, as of Sept 2018.

References:
[1] https://www.northropgrumman.com/Capabilities/PropulsionSystems/Documents/NGIS_MotorCatalog.pdf

Comm. avail.	7 TRL	NO Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

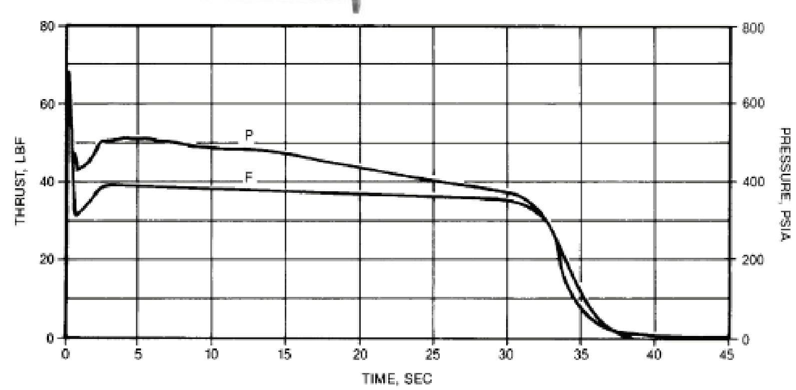
STAR-5 (STAR-5A/STAR-5F) Series Solid Rocket Motors
Northrop Grumman

Propulsion Technology	Solid rocket motor
Manufacturer/Country	Orbital ATK (now Northrop Grumman) (USA)
TRL	7
Size (including PPU)	8.8” (22.4 cm) L x 5.13” (13 cm) DIA (~2.5U)
Design satellite size	3U and larger
Isp (s)	250s
Thrust type/magnitude	170 N (thrust, average) 170 N (thrust, max) 5700 N*s (impulse, total)
Delta-V (m/s)	700 m/s for 10 kg spacecraft (calc)
Propellant	TP-H-3399, aluminum case
Power consumption (W)	n/a
Flight heritage (if any)	STAR-5A => 3 flights STAR-5F => Many
Commercially available	YES
Last updated	*07/2019*

STAR Motor Performance and Experience Summary

STAR Designation	Model Number	Nominal Diameter in.	Nominal Diameter cm	Total Impulse, lb_f-sec	Effective Specific Impulse, lb_f-sec/lb_m	Propellant Weight lb_m	Propellant Weight kg	Propellant Mass Fraction	Tests	Flights
3	TE-M-1082-1	3.18	8.08	281.4	266.0	1.06	0.48	0.42	26	3
3A	TE-M-1089	3.18	8.08	64.4	241.2	0.27	0.12	0.14	2	3
4G	TE-M-1061	4.45	11.30	595	269.4	2.16	0.98	0.65	2	0
5*	TE-M-500	5.05	12.83	895	189.0	3.8	1.72	0.87	4	11
5A	TE-M-863-1	5.13	13.02	1,289	250.8	5.05	2.27	0.49	6	3
5C/5CB	TE-M-344-15 TE-M-344-16	4.77 4.77	12.11 12.11	1,252 1,249	268 262.0	4.55 4.62	2.06 2.10	0.47 0.47	245 20	686 160
5D	TE-M-989-2	4.88	12.39	3,950	256.0	15.22	6.90	0.68	13	3
5F	TE-M-1198	4.85	12.32	2,216	262.9	8.42	3.82	0.37	9	194
6	TE-M-541-3	6.2	15.75	3,077	287.0	10.7	4.85	0.80	47	238
6A*	TE-M-542-3	6.2	15.75	2,063	285.3	7.2	3.27	0.72		
6B	TE-M-790-1	7.32	18.59	3,686	269.0	13.45	6.10	0.60	8	18

Star 5A motor



Additional comments:

[Reference 1][Jan 2019][General info]
According to NGC website: The STAR 5A rocket motor was qualified in 1988 to provide a minimum acceleration and extended burn delta-v impulse. With a low-average thrust and a unique off-center nozzle design, the motor can be utilized in many nonstandard geometric configurations for small payload placement or spin-up applications. The STAR 5A first flew in 1989 from the Space Shuttle.
NGC reports the production status as “flight proven” as of Sept 2018.

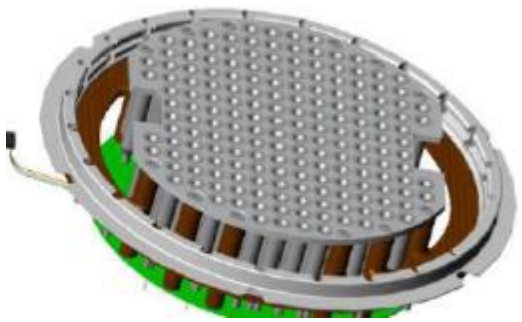
References:
[1] https://www.northropgrumman.com/Capabilities/PropulsionSystems/Documents/NGIS_MotorCatalog.pdf

7 | NO
Comm. avail. | TRL | Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Modular Architecture Propulsion System (MAPS)
Pacific Scientific Energetic Materials Co.

Propulsion Technology	Solid Rocket Motor array
Manufacturer/Country	Pacific Scientific (PacSci) EMC (USA)
TRL	7
Size (including PPU)	<1U, customizable
Design satellite size	1U and larger. Demonstrated on 3U PacSciSat
Isp (s)	>210s
Thrust type/magnitude	Depends on number of SRMs in array, customizable. 165N over 60 ms using 4.8g propellant [5]
Delta-V (m/s)	Customizable
Propellant	SRM (contact manufacturer for info)
Power consumption (W)	<1W for 48 thruster array
Flight heritage (if any)	PacSciSat (2017)
Commercially available	YES
Last updated	*01/2021*



SRM array

PACSCISAT [Tyvak]

Additional comments:

[Reference 1-4][May 2019][General info]

From Nelson (2018): "The MAPS system is configured with arrays of hermetically sealed, single shot, solid rocket motors (thrusters) commanded by a low power SEA bus. The SEA bus is a tactical missile flight proven, very low volume and power, multiple inhibit, space radiation tolerant, ASIC based control and firing system. SEA enables firing of hundreds of motors with microsecond repeatability and sub-millisecond sequencing. SEA may also be used to control other vehicle functions. SEA interfaces easily with the satellite control system via RS-422 or other parallel or serial interface options."

Also from Nelson (2018): "MAPS utilizes a patented, flight proven, very low volume and power, multiple inhibit, space radiation tolerant, ASIC based control and firing system known as Smart Energetics Architecture (SEA™). SEA enables firing of hundreds of motors with microsecond repeatability and sub-millisecond sequencing. SEA may also be used to control other vehicle functions. SEA is based on the ISO 22896, Safe-by-Wire standard developed by PacSci (Special Devices Inc.) in late 1998 and Philips Semiconductors. PacSci acquired all rights from Philips including intellectual property, ASIC wafer fabrication masks and all associated Safe-by-Wire hardware. Additionally, PacSci has designed and manufactured many sizes of attitude control systems (ACS) rocket motors and conducted thousands of tests and is flight validated to TRL-9 in the tactical missile and space market. These motors are used in active protection systems, missiles, and space vehicles. Motor impulse levels ranging from 0.0005 N-s to 1500 N-s have been manufactured, tested and flown. MAPS and SEA also have a robust SEA patent portfolio. To achieve space flight heritage, PacSci designed, fabricated and orbited a CubeSat demonstrator called PACSCISAT. PACSCISAT launched June 23, 2017 on PSLV-C38 and included SEA control electronics four MAPS solid rocket motors and four independent initiation devices. The mission was a success with the following results:

- 24 SEA functional commands w/zero errors
- 840 SEA status commands and 60,480 responses w/zero errors
- Four pyrotechnic initiator firings
- Two 20 N-s and two 4 N-s MAPS motor firings with exact and predicted PACSCISAT ΔV delivery"

The manufacturer claims 10+ years life. PACSCISAT, also known under the manufacturer's designation Tyvak 53b, is a technology demonstrator built by Tyvak Nano-Satellite Systems, Inc. for Pacific Scientific Energetic Materials Company (PacSci EMC) to provide spaceflight heritage to several of PacSci EMC's satellite products. PacSci EMC self-funded PACSCISAT to establish flight heritage, or flight-proven history, for these products.

References:

[1] Nelson, S., Current, P., "Modular architecture propulsion system (MAPS)," AIAA JPC, 2018.
[2] https://psemc.com/products/satellite-propulsion-system/#1520706709297-1c1a0650-aad1
[3] https://space.skyrocket.de/doc_sdat/pacscisat.htm
[4] Propulsion System Comprising Plurality of Individually Selectable Solid Fuel Motors, US Patent No 9790895 B2, 2017.
[5] Calculated values from [1]

	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

RIT 10 EVO (Radiofrequency Ion Thruster)
Ariane Group

Propulsion Technology	RF Ion Thruster
Manufacturer/Country	Ariane Group (Airbus/Safran) (FRANCE/GERMANY)
TRL	7-8
Size (including PPU)	~1.5U (186 mm diameter, 134 mm depth)
Design satellite size	6U or larger (due to power requirement)
Isp (s)	>1900 s
Thrust type/magnitude	5 mN (continuous, nominal) (up to 25 mN with increased power) >1,000,000 N*s (total impulse)
Delta-V (m/s)	>1500 m/s (calculated using 10 kg wet spacecraft, with 500g Xenon)
Propellant	Xenon
Power consumption (W)	145W at 5 mN thrust
Flight heritage (if any)	Based on RIT-10, which flew on EURECA (1992) and ARTEMIS (2001).
Commercially available	YES
Last updated	*01/2021*

RIT THRUSTER FAMILY PERFORMANCE DATA

	RIT µX	RIT 10 EVO	RIT 2X
THRUST & POWER			
Nominal Thrust nom. Power	50 - 500 µN < 50 W	5 mN | 15 mN | 25 mN 145 W | 435 W | 760 W	70–88 mN | 151–171 mN | 198–215 mN 2000–2500 W | 4000–4500 W | 4800–5300 W
FUNCTIONAL PERFORMANCE			
extended / on request Isp max. demonstrated Divergance angle*	10-100 µN, 300 - 3000 µN 300 - 3000s > 3500s < 17°	> 1900s | > 3000s | > 3200s > 3400s < 15°	3400–3500s | 3300–3500s | 2450–2750s < 25°
LIFETIME			
Total Impulse Max Operational cycles Total Lifetime	> 10kNs up to 200kNs > 10000 > 20000 h	> 1.1 MNs > 10000 > 20000 h	> 10 MNs > 10000 > 20000 h
TECHNOLOGY			
Ionisation Acceleration Gridsystem Propellant	RF-Principle Electrostatic 2 Grids Xenon	RF-Principle Electrostatic 2 Grids Xenon	RF-Principle Electrostatic 2 Grids Xenon
DESIGN			
mass Dimensions Diameter Height	440 g 78 mm 76 mm	1.8 kg 186 mm 134 mm	< 10 kg < 330 mm < 220 mm
ENVIRONMENT			
Random	20-60Hz: +9db/oct 60-400Hz: 0.5g^2/Hz 400-2000Hz: -6dB/oct Overall: 18.4gRMS	20-50Hz: +6dB/oct 50-1200Hz: 0.32g^2/Hz 1200-2000Hz: -6dB/oct Overall: 22.9gRMS	20Hz: 0.004g^2/Hz 100-250Hz: 0.1g^2/Hz 400-800Hz: 0.4g^2/Hz 2000Hz: 0.006g^2/Hz Overall: 8.1gRMS
Sine	5-20Hz: 11mm (0-peak) 20-100Hz: 20g	Z-Axis: 5-18Hz: 11mm 18-35Hz: 15g 35-60Hz: 12g 60-100Hz: 6g X-Y-Axis: 5-16.5Hz: 11mm 16.5-35Hz: 12g 35-60Hz: 8g 60-100Hz: 4g	5-20Hz: +- 10mm 20-100Hz: 35g
Shock	500Hz: 100g 1000Hz: 1500g 10000Hz: 1500g	100Hz: 10g 3000Hz: 2000g 10000Hz: 2000g	100Hz: 10g 4500Hz: 10000g 10000Hz: 10000g
Operating Temperature	-40°C to +160°C	-75°C to + 140°C	-50°C to +190°C
Non-Operating Temperature range	-60°C to +160°C	-85°C to +140°C	-60°C to +190°C

* Half angle 95%

Photo of the RIT 10 EVO

Additional comments:
[References 1-4][Jan 2019][General info]

The radio frequency Ion thruster uses a high-frequency electromagnetic field to ionize xenon gas atoms to form a plasma containing free 'light' electrons and 'heavy' positive ions. The heavy positive ions are then accelerated by an electrostatic field before being ejected to cause thrust. After the ions have been ejected from the thruster, electrons are added from a neutralizer. The plasma is thereby neutralized, which prevents the satellite from becoming charged.

Ariane Group makes a family of RF thrusters, and RIT 10 EVO is the second smallest in the family (the RIT uX is the smallest). The RIT 10 EVO has medium thrust has 10 years of flight heritage. The divergence angle of the plume is roughly 15 degrees, and lifetime has been tested to more than 10,000 operational cycles and >20,000 hrs. It has also been qualification tested (vibration, thermal cycling) extensively. Its design derives from that of the RIT-10, which has flown. The thrusters are basically identical, except for the grid system. In the RIT-10 EVO, a contemporary grid design is implemented.

The RIT-10 engine was the first western European ion thruster in space. It had its maiden flight onboard the retrievable platform EURECA (European Retrievable Carrier): EURECA was brought to space with the US space shuttle ATLANTIS and back to Earth onboard the ENDEVOUR. Most probably RIT-10 is the only ion engine that could be inspected after operation in space. The measured acceleration of EURECA confirmed the thrust prediction and was an important step in validating its proof of concept and design.

ARTEMIS was ESA's first GEO data relay communication satellite with the objective to demonstrate new communication technologies, principally for data relay and mobile services. The technology demonstrations included an optical intersatellite link, first European operational use of an electric ion propulsion system, and a transponder for the support of EGNOS (European Geostationary Navigation Overlay Service) for signal enhancement of the GPS/GLONASS navigation satellite constellations.

References:

[1] Leither, H., Altmann, D., Porst, J., Lauer, D., “Six Decades of Thrust – The Ariane Group Radiofrequency Ion Thrusters and Systems Family,” IEPC-2017-027
[2] Leither, H., Killinger R., Bassner, H., Muller, J., Kukies, R., “Development of the Radio Frequency Ion Thruster RIT XT- A Status Report,” IEPC-01-104
[3] http://www.space-propulsion.com/brochures/electric-propulsion/electric-propulsion-thrusters.pdf
[4] https://directory.eoportal.org/web/eoportal/satellite-missions/e/eureca

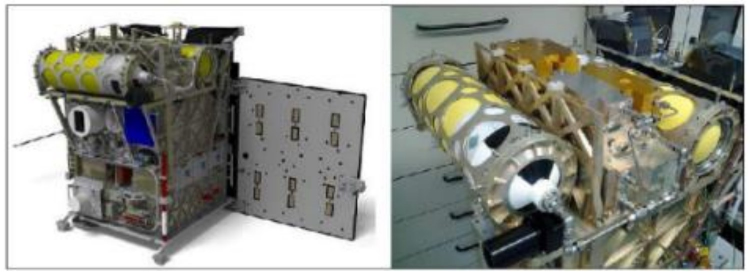
	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

MICROJET/MICROJET2000/AQUAJET [1 of 2]
Aerospace Innovation

Propulsion Technology	Warm gas/cold gas
Manufacturer/Country	Aerospace Innovation (GERMANY)
TRL	7-8. Flown and spacecraft reported success, but no on-orbit data reported in public literature.
Size (including PPU)	0.3U (TET-1), ~20U (BIROS)
Design satellite size	~100kg
Isp (s)	~60s (estimated from similar technologies)
Thrust type/magnitude	67 mN/thruster (resistojet mode), 118 mN/thruster (cold gas mode)
Delta-V (m/s)	
Propellant	Water/antifreeze (TET-1), Nitrogen –max 310 bar (BIROS)
Power consumption (W)	36W (resistojet mode), 12W (cold gas mode). 18-24V
Flight heritage (if any)	MICROJET launched on DLR TET-1 Satellite (2012) and BIROS (2016).
Commercially available	YES
Last updated	*08/2022*

Microjet for TET-1



Microjet 2000 implementation on the BIROS satellite

Additional comments:

[References 1-6] [Jan 2019][General info]
Very limited information on performance of module on-orbit or on the ground from websites. TET-1 (Technologieerprobungsträger 1) is the core element of DLR's On-Orbit Verification Program (OOV). The main aim of this program is to test new space technologies in a space environment over a period of one year. BIROS carried 2 thruster units, each capable of generating 0.1N thrust. TET-1 and BIROS are part of the DLR’s “FireBird” Constellation. Microjet, developed by AIG (Aerospace Innovation GmbH) of Berlin, is a modularly designed propulsion system for nanosatellites and microsatellites based on the gas resistojet concept. It consists of a PST (Pressure Tank Unit) with nitrogen which is filled or drained, respectively, through an FDU (Fill and Drain), an FCU (Flow Control Unit) responsible for the control of correct propellant mass flow, as well as one or more THUs (Thruster Units). Each of these THUs contains a pulse valve and a nozzle for the actual thrust generation. Additionally, according to the definition of the resistojet-concept, an electrical resistance-heating element might be applied for higher performance demands. The entire propulsion system is controlled by the PCU (Propulsion Control Unit). The propulsion system is assumed successful. Various websites report mission success in terms of autonomous rendezvous (one of the goals of BIROS), ““In the AVANTI experiment, we demonstrated for the first time that merely one passive camera is sufficient to enable the autonomous approach of one satellite toward a non-cooperative object,” says Gabriella Gaias from Space Operations and Astronaut Training at DLR. The image data was used to identify the target satellite and monitor its position. This then enabled the calculation and execution of the thrust maneuver needed to complete the approach. All of the steps were fully autonomous and took place on board BIROS. During the experiment, BIROS approached its target cube satellite – which has an edge length of just 10 centimeters – to within 50 meters.

References:

[1] Wemuth, M., Gaias, G., “Operational Concept of a Picosatellite Release from a LEO Satellite,” 25th International Symposium on Space Flight Dynamics (ISSFD), 2015.
[2] http://www.aerospace-innovation.com/innovation_activities.html
[3] http://space.skyrocket.de/doc_sdat/tet-1.htm
[4] https://directory.eoportal.org/web/eoportal/satellite-missions/b/biros
[5] http://www.parabolicarc.com/2016/12/20/biros-demonstrates-autonomous-rendezvous-space-image-data/
[6] https://best-of-space.de/portfolio-type/aerospace-innovation-gmbh-2/?lang=en

Comm. avail.	7	NO
	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

MICROJET/MICROJET2000/AQUAJET [2 of 2]
Aerospace Innovation

Additional comments:

[Reference 1] [Jan 2021][Company info]
Aerospace Innovation GmbH was founded in March 2007 in order to provide complete system solutions and products in the field of aerospace. It was launched as a complementary evolution of AI: Aerospace Institute, which was founded in May 2000 within the frame of the Technology Transfer Program at Berlin University of Technology (TU Berlin). Aerospace Innovation GmbH and AI: Aerospace Institute are precursors for new and innovative technologies, providers of environmentally friendly and cost-efficient rocket propulsion systems for terrestrial and orbital operation as well as centers of competence for strategic and technological aerospace-related questions. Due to a long-standing experience in research and education along with extensive and detailed experimental work, both companies are characterized by a unique technical know-how in the area of rocket propulsion and space system development. Being close to the Institute of Aeronautics and Astronautics (ILR) at TU Berlin, AI: Aerospace Innovation GmbH as well as AI: Aerospace Institute supports a closer integration of research and industry.

[Reference 2][Aug 2022][Thruster info and follow-on efforts]
Components of the MICROJET were used for the IonJet (see IonJet), such as the flow subsystem.

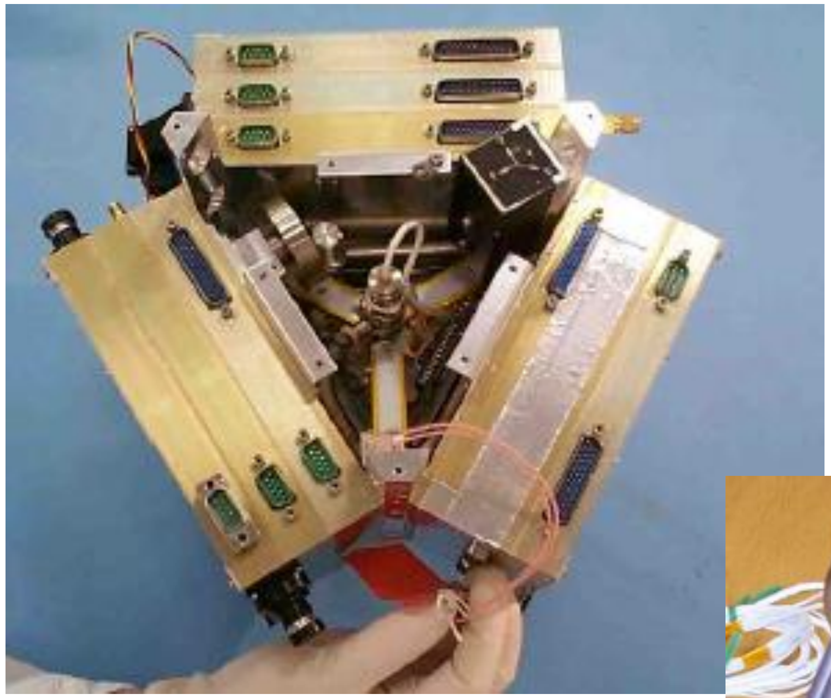
References:
[1] http://www.aerospace-innovation.com/innovation_profile.html
[2] Scholze, F., Pietag, F., Bundesmann, C., Woyciechowski, R., Spemann, D., Kreil, M., kron, M., Adirim, H., “IonJet: Development of a cost-efficient gridded ion thruster propulsion system for smallsats,” IEPC-2022-246

Comm. avail.	TRL	Aerospace-tested
	7	NO

DISTRO A: Approved for public release. OTR-2024-00338

SNAP-1 Butane Propulsion
Surrey Satellite Technologies (SSTL)

Propulsion Technology	Warm/cold gas
Manufacturer/Country	Surrey Satellite Technologies (SSTL) (USA)
TRL	7-8
Size (including PPU)	<1U (size of a pencil)
Design satellite size	1U, 3U
Isp (s)	~45 s
Thrust type/magnitude	100 mN
Delta-V (m/s)	~2 m/s for 6 kg spacecraft
Propellant	Butane
Power consumption (W)	~15W
Flight heritage (if any)	SNAP-1 (2000)
Commercially available	YES
Last updated	*01/2021*



SNAP-1 vehicle, with butane propulsion system

Additional comments:

[Reference 1-2][Jan 2019][Thruster and mission info]
A low-cost butane propulsion system has been successfully flown on Surrey's SNAP-1 spacecraft – the first nanosatellite to successfully demonstrate an orbit-control propulsion system. Due to its simplicity, we were able to design, build and test the propulsion system in 7 months, as necessary given SNAP-1's rapid development schedule. Once in orbit, the propulsion system was used to raise the orbit of SNAP-1 by 2.6 km and then ~0.4 km in absolute terms, giving ~3 km in total. However, once the effects of atmospheric drag have been taken into account, this translates to an equivalent of almost 4 km change in height. The overall mission specific impulse achieved (43 s) was significantly lower than the theoretical figure (70 s). This has been shown to be due to liquid-phase propellant being expelled at the start, which resulted in a much-reduced efficiency. Even so, a total mission ΔV of ~2 m/s was achieved with just 32.6 g of butane propellant.
Surrey has various other butane propulsion systems for larger spacecraft, based on the SNAP-1 design.

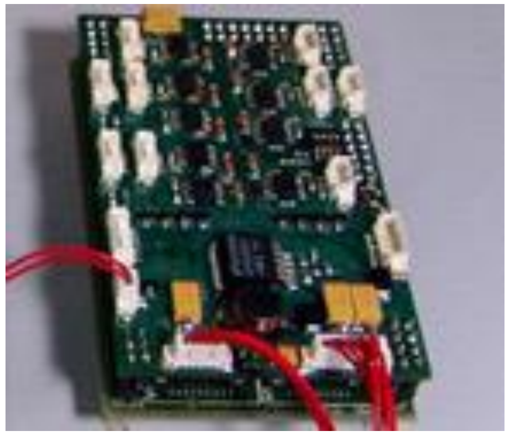
References:
[1] Gibbon, D., Underwood, C., "Low Cost Butane Propulsion Systems for Small Spacecraft," 15th AIAA/USU Conference on Small Satellites, SSC01-X1-1.
[2] Gibbon, D., Underwood, C., Sweeting, M., Amri, R., "Cost effective propulsion systems for small satellites using butane propellant," Acta Astronautica, Vol 51, 2002.

🛒	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

NanoSat MiPS
MICROSPACE

Propulsion Technology	Warm/Cold gas
Manufacturer/Country	MICROSPACE/MICRO-SPACE/MICRO SPACE (ITALY/SINGAPORE)
TRL	7
Size (including PPU)	Various models (1 or 2 axis 1/3U or 1U systems)
Design satellite size	1 U and larger
Isp (s)	50 to 100s
Thrust type/magnitude	100 uN to 10 mN. Thrust control 1% resolution
Delta-V (m/s)	3 m/s for a 3U CubeSat
Propellant	Argon (or other inert gas)
Power consumption (W)	2W (operational)
Flight heritage (if any)	POPSAT-HIP1 (2014)
Commercially available	YES, price listed on CubeSatShop as 80,000 to 130,000 Euros [3]
Last updated	*01/2021*



MicroSpace MEMS-based Micropropulsion System

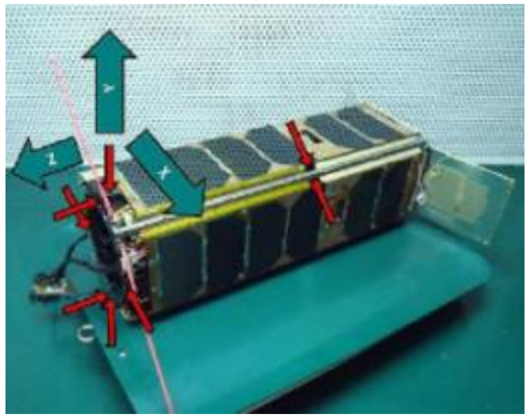


Photo of POPSAT with thrust vectors

Additional comments:

[Reference 1-3][Jan 2019][General info]

Cold gas propulsion system complete with electronic controls and PPU. Eight micronozzles are placed on the corners and edges of the satellite to control 3 rotational axes. POPSAT-HIP1 was launched from Russia in 2014, and papers at the 2015 Small Satellite conference report nominal behavior and success. These units appear to be able to be bought off the shelf. Pointing resolution is advertised as 0.1 arcsec.

Other propulsion systems may be available. *The website mentions other technologies, describing them as "Modular, Fully integrated, Cold gas to Arcjet" and:*

- 0.1, 1, 5 & 10 mN Nominal Thrust
- 50s to 500s Specific Impulse
- 10pNs Minimum Impulse Bit
- 0.5W to 10W Power Consumption
- 1/3U Minimum Volume
- 5m/s to 500m/s delta-v
- MEMS Technology
- 100% Customizable

But the website does not provide information on additional specific models available.

References:

[1] Manzoni, G., Brama, Y ., "CubeSat Micropropulsion Characterization in Low Earth Orbit," 29th Annual AIAA/USU Conference on Small Satellites, SSC15-IV-5.
[2] http://www.micro-space.org/index.html
[3] https://www.cubesatshop.com/product/nanosatellite-micropropulsion-system/

	7	NO
Comm. avail.	TRL	Aerospace-tested

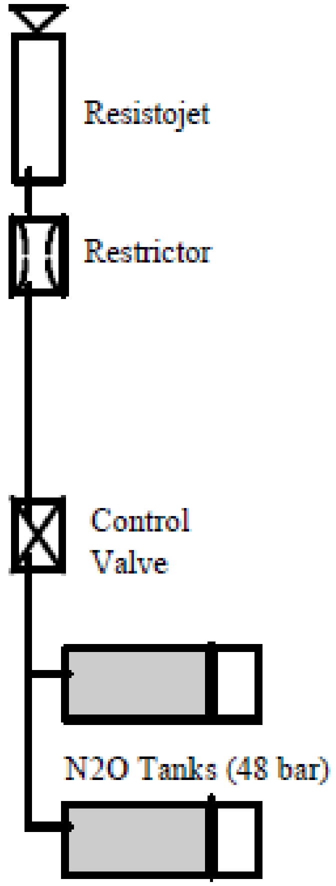
DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

Resistojet electric propulsion system

Propulsion Technology	Resistojet
Manufacturer/Country	Surrey Space Center (UK)
TRL	7
Size (including PPU)	Not reported, but estimated ~1U from images
Design satellite size	UoSat-12 was ~100 kg
Isp (s)	127s
Thrust type/magnitude	125 mN at 100W power
Delta-V (m/s)	9.7 m/s for Uo-Sat
Propellant	N2O + heaters
Power consumption (W)	100W
Flight heritage (if any)	UoSat-12 (1999)
Commercially available	No
Last updated	*01/2021*

Flight resistojets from Surrey



Additional comments:

[Reference 1][Jan 2019][General info]
UoSat-12 incorporated two separate propulsion systems, a compressed nitrogen cold gas system and a nitrous oxide resistojet system. The combined ΔV afforded to the UoSat-12 mission is 26.8 m/s (16.4 m/s from the N2 cold gas, 10.4 m/s from the N2O resistojet). The UoSat-12 reported qualification of the resistojet and cold gas propulsion system.

• The N2 cold gas system is used for attitude control and velocity change whereas, the resistojet is a technology demonstrator primarily used for velocity change. After initial checkout and experimentation, the N2 cold gas propulsion system is being configured to operate in an experimental autonomous mode via software developed by the Microcosm corporation.

• EPS (Electric Propulsion System). EPS is an experimental resistojet electric propulsion system developed at SSC (Surrey Space Center). Water on nitrous oxide is super-heated over a resistive heater element, the resulting hot gas is expelled through a nozzle to produce low-level thrust at moderate specific impulse. The thruster provides a thrust of 93 mN, using 90 W of input power. A total ΔV of 10.4 m/s is provided by a 2-liter tank of self-pressurized nitrous oxide.

[Reference 2] [Jan 2019][Thruster development history]
The resistojet technology program was started at Surrey in 1995. Initially, the resistojet research focused on finding the right combination of power, working fluid, and heat transfer medium to produce a cost effective thruster for small spacecraft applications. As the resistojet research progressed, the design converged on two systems, both utilising the same heating element and silicon carbide heat transfer bed but having different working fluids: water and nitrous oxide (N2O). By the time the resistojet research was completed, both thrusters were manifested on two separate space missions. The water and N2O resistojet designs each consume 100 watts of electrical power providing an Isp of 127s (N2O) and 152s (H2O). The N2O is stored at its vapor pressure, 48 bar.

[Reference 3][Jan 2019][On orbit data]
The most recent achievement in UoSAT-12 checkout sequence is the commissioning of the cold-gas propulsion system and execution of a planned orbit change. This experiment met the following objectives: verification of thruster commands, verification of accumulator closed-loop control system, calibration of thrusts, verification of attitude control system in presence of thrusting, and execution of 120-second in-track propulsive maneuver. The 120-second maneuver was designed to change the semi-major axis of UoSAT-12 by about 200 metres and to move the satellite closer to the frozen orbit conditions required for the Microcosm Orbit Control Kit experiments scheduled to commence this summer. GPS measurements from the UoSAT- 12 SGR confirmed the success of this maneuver.

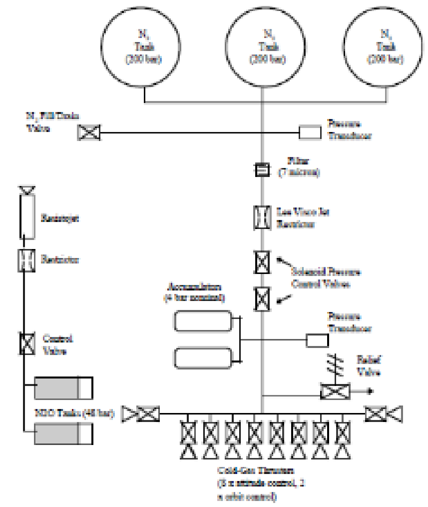
References:
[1] https://directory.eoportal.org/web/eoportal/satellite-missions/u/uosat-12
[2] Haag, G., Sweeting, M., Richardson, G., "Low cost propulsion development for small satellites at the Surrey Space Centre," SSC99-XII-2
[3] Ward, J., Sweeting, M., "First in-orbit results from the UoSAT-12 Minisatellite," SSC99-I-2.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

UoSat-12 cold gas

Propulsion Technology	Cold gas
Manufacturer/Country	Surrey Space Center (UK)
TRL	7
Size (including PPU)	Not reported, but estimated a few U from images.
Design satellite size	UoSat-12 was ~100 kg
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	16.4 m/s for Uo-Sat
Propellant	Nitrogen
Power consumption (W)	3W
Flight heritage (if any)	UoSat-12 (1999)
Commercially available	No
Last updated	*01/2021*



Additional comments:

[Reference 1][Jan 2019][Flight information]

UoSat-12 incorporated two separate propulsion systems, a compressed nitrogen cold gas system and a nitrous oxide resistojet system. The combined ΔV afforded to the UoSat-12 mission is 26.8 m/s (16.4 m/s from the N2 cold gas, 10.4 m/s from the N2O resistojet). The UoSat-12 reported qualification of the resistojet and cold gas propulsion system.

• The N2 cold gas system is used for attitude control and velocity change whereas, the resistojet is a technology demonstrator primarily used for velocity change. After initial checkout and experimentation, the N2 cold gas propulsion system is being configured to operate in an experimental autonomous mode via software developed by the Microcosm corporation. The N2 system is pressurized to 4 bar.

• EPS (Electric Propulsion System). EPS is an experimental resistojet electric propulsion system developed at SSC (Surrey Space Center). Water on nitrous oxide is super-heated over a resistive heater element, the resulting hot gas is expelled through a nozzle to produce low-level thrust at moderate specific impulse. The thruster provides a thrust of 93 mN, using 90 W of input power. A total ΔV of 10.4 m/s is provided by a 2-liter tank of self-pressurized nitrous oxide.

[Reference 2][Jan 2019][Flight information]

The Uosat-12 cold gas design is composed largely of off-the-shelf components assembled into a seemingly ordinary cold gas propulsion system. One significant departure from an ordinary system design is the inclusion of a bang-bang (BB) pressure regulation system. Space qualified pressure regulators have historically been high cost items; The BB regulator replaces the conventional regulator with two valves, two pressure transducers and two small accumulators. The BB system effectively steps down the stored N2 pressure to the operating pressure of the cold gas thrusters. The BB system does require more volume and mass than its costly regulator alternative, but for this mission (as well as others currently under consideration) it provides a viable trade to save a significant amount of mission funds.

References:

[1] https://directory.eoportal.org/web/eoportal/satellite-missions/u/uosat-12
[2] Haag, G., Sweeting, M., Richardson, G., “Low cost propulsion development for small satellites at the Surrey Space Centre,” SSC99-XII-2

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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MIPS (Miniature Ion Propulsion System)

Propulsion Technology	Ion thruster
Manufacturer/Country	Univ. of Tokyo/Next Generation Space Tech. Research Assoc. (NESTRA) (Japan)
TRL	7
Size (including PPU)	34x26x16 cm^3, 8.1 kg (wet mass), 7.1 kg (dry mass)
Design satellite size	50kg or larger (Hodoyoshi was 65 kg)
Isp (s)	800 to 1200s
Thrust type/magnitude	200 to 300 uN (continuous, nominal)
Delta-V (m/s)	140 m/s for 50 kg s/c
Propellant	Xenon
Power consumption (W)	39W
Flight heritage (if any)	HODOYOSHI-4 (2014)
Commercially available	No
Last updated	*01/2021*

Flight model of the MIPS

Additional comments:

[Reference 1-2][Jan 2019][Mission info]
The University of Tokyo has successfully developed and operated miniature propulsion systems using ion thrusters on two small satellites: HODOYOSHI-4 and PROCYON. HODOYOSHI-4 is a 65 kg LEO satellite that was launched in June 2014 by a Dnepr rocket. It is equipped with a miniature ion propulsion system, named MIPS, and the first ion thruster operation was successfully conducted on December 28th that year. PROCYON is a 67 kg space probe that was inserted into an orbit around the Sun in December 2014 by a H-IIA rocket. PROCYON is equipped with a micropropulsion system, named I-COUPS, which unifies eight cold-gas thruster heads for RCS and an ion thruster for high Δv maneuver. The cold gas thrusters are operated since December 6th and the ion thruster has accomplished 223 hours operation since December 28th.
MIPS (Miniature Ion Propulsion System) was developed by the University of Tokyo together with Next Generation Space Technology Research Association (NESTRA) in Japan, which developed HODOYOSHI-4. The satellite's primary mission was to demonstrate innovative small satellite technologies, and MIPS was one of the selected technologies. Development of the MIPS started from its EM in September 2011 to its final FM (Flight Model) in March 2014. The FM has a total mass of 8.1 kg (dry mass: 7.1 kg), a volume of 34×26×16 cm3, a power consumption of 39 W, and produces a thrust of 300 μN with a specific impulse of 1200 s.

[Reference 3][Jan 2019][Thruster info]
MIPS was developed using an ECR (Electron Cyclotron Resonance) plasma of a 4.2 GHz microwave system. The ECR plasma provides advantages of longer lifetimes and a simpler structure for ion thrusters. These features are suitable for the down-scaling of ion thrusters. However, the down-scaling of plasma inherently leads to high ion production cost. This problem was solved by a new antenna design for a small-sized cavity, and a small plasma source with low ion-production-cost was developed for microwaves as low as 1.0 W. This technique enabled a miniature ion source and a miniature electron source, neutralizer, driven by a 1.0 W microwave power source, respectively, resulting in a miniature and low-power ion thruster. The MIPS consists of four units: an ITU (Ion Thruster Unit), a PPU (Power Processing Unit), a GMU (Gas Management Unit), and a MCU (MIPS Control Unit). All of the units are installed on a double-deck frame , and MIPS is handled as a modularized component to a satellite.

[Reference 4][Jan 2021][Updates]
We are currently working on a microwave-driven small ion thruster that will be installed on a small 50-kg satellite. The plasma source has a 1-cm diameter and an extracted/accelerated ion beam provides 200-400 micro-N thrust and 1000-1500 s specific impulse. We have already developed two flight systems using these small ion thrusters for a small satellite, HODOYOHI-4, and a small space probe, PROCYON, that were launched in 2014.

References:

[1] Takegahara, H., Kuninaka, H., Funaki, I., et al., "Overview of electric propulsion research activities in Japan," IEPC-2015-01/ISTS-2015-b-01.
[2] Koizumi, H., Komurasaki, K., Arakawa, Y., "Development of the miniature ion propulsion systems for 50 kg small spacecraft," 48th AIAA JPC, 2012.
[3] https://directory.eoportal.org/web/eoportal/satellite-missions/h/hodoyoshi-3-4
[4] https://www.k.u-tokyo.ac.jp/pros-e/person/hiroyuki_koizumi/hiroyuki_koizumi.htm

Comm. avail.	TRL	Aerospace-tested
NO	7	NO

DISTRO A: Approved for public release. OTR-2024-00338

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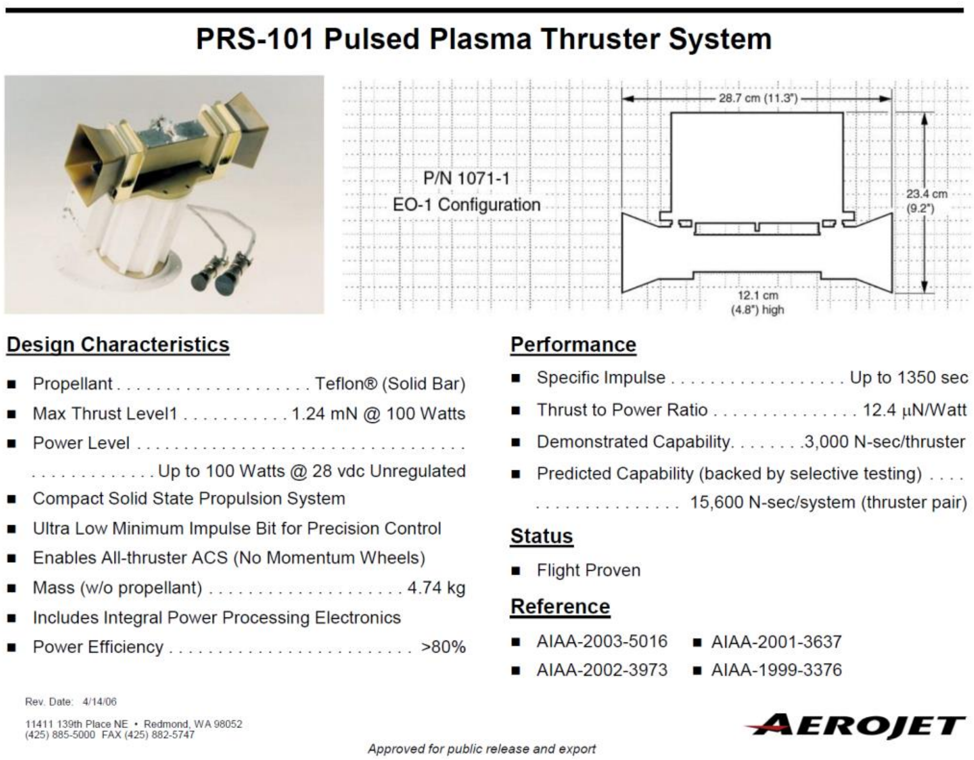
PRS-101 (Plasma Rocket System-101), Pulsed Plasma Thruster for EO-1

Propulsion Technology	Pulsed Plasma
Manufacturer/Country	Primex/General Dynamics (now Aerojet) (USA)
TRL	7
Size (including PPU)	5 kg each
Design satellite size	Large (50-100 kg)
Isp (s)	Up to 1350s [5], 650 to 1400s [3]
Thrust type/magnitude	1.24 mN @ 100W [5] 90 to 1000 uN*s (impulse bit, range), 460 N*s (impulse, total) [3]
Delta-V (m/s)	
Propellant	Solid teflon
Power consumption (W)	12 to 70 W (variable), at 28V [3], up to 100W [5]
Flight heritage (if any)	EO-1 (2000)
Commercially available	YES
Last updated	*01/2021*



PRS-101 Pulsed Plasma Thruster System

P/N 1071-1
EO-1 Configuration

28.7 cm (11.3")
23.4 cm (9.2")
12.1 cm (4.8") high

Design Characteristics

- Propellant . . . . Teflon® (Solid Bar)
- Max Thrust Level1 . . . . 1.24 mN @ 100 Watts
- Power Level . . . . Up to 100 Watts @ 28 vdc Unregulated
- Compact Solid State Propulsion System
- Ultra Low Minimum Impulse Bit for Precision Control
- Enables All-thruster ACS (No Momentum Wheels)
- Mass (w/o propellant) . . . . 4.74 kg
- Includes Integral Power Processing Electronics
- Power Efficiency . . . . >80%

Performance

- Specific Impulse . . . . Up to 1350 sec
- Thrust to Power Ratio . . . . 12.4 µN/Watt
- Demonstrated Capability. . . . . . . .3,000 N-sec/thruster
- Predicted Capability (backed by selective testing) . . . . 15,600 N-sec/system (thruster pair)

Status

- Flight Proven

Reference

- AIAA-2003-5016
- AIAA-2001-3637
- AIAA-2002-3973
- AIAA-1999-3376

Rev. Date: 4/14/06

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[5]

Additional comments:

[Reference 1][Jan 2019][Mission info]
Information on the EO-1 mission. EO-1 is a large (>100 kg) satellite that utilized mainly hydrazine thrusters but carried PPTs as a secondary system for demonstration. The PPTs it carried consumed roughly 100W, weighed 5 kg, and produced 460 N*s total impulse. Specific impulse was approximately 650-1400s (estimated). A series of fine pitch pointing maneuvers were performed after the end of the primary imaging mission. Flight operations of the EO-1 PPT began on January 4, 2002. As of June 15, 2002, a total of 26.9 hours of operation and almost 97,000 pulses have been logged, including several image acquisitions and continuous control of the pitch attitude of the spacecraft for over 9 hours for 5.5 orbits. This was the first flight demonstration of PPT throttling. Spacecraft pitch attitude was controlled to well within the 30 arcsec requirement during image acquisition and was generally within 10 arcsec. In addition, sensitive tests with images of the dark Earth have detected no evidence of electromagnetic interference from the discharge or light pollution from the plume even though the ALI instrument was known to have very sensitive electronic components.
[Reference 2][Jan 2019][Thruster development]
A Pulsed Plasma Thruster (PPT) has been developed for use in a technology demonstration flight experiment on the Earth Observing I (EO-1) New Millennium Program mission. The thruster replaces the spacecraft pitch axis momentum wheel for control and momentum management during an experiment of a minimum three-day duration. The EO-1 PPT configuration is a combination of new technology and design heritage from similar systems flown in the 1970's and 1980's. Acceptance testing of the protoflight unit has validated readiness for flight, and integration with the spacecraft, including initial combined testing, has been completed. The thruster provides a range of capability from 90 uN-sec impulse bit at 650 sec specific impulse for 12 W input power, through 860 uN-sec impulse bit at 1400 sec specific impulse for 70 W input power. Development of this thruster reinitiates technology research and development and reestablishes an industry base for production of flight hardware.
[Reference 3][Jan 2019][Thruster info]
The PPT uses solid Teflon propellant and is capable of delivering high specific impulse (650-1400 sec), very fine impulse bits (90-1000µN-s) at low average power (12 to 70W). The PPT consists of a coiled spring to feed the Teflon propellant, an igniter plug to initiate a small trigger discharge and an energy storage capacitor and electrodes. Plasma is created by the ablation of the Teflon propellant from discharge of the storage capacitor across the electrodes. The plasma is accelerated by Lorenz force in the induced magnetic field to generate thrust.
[Reference 4][Jan 2019][Thruster info] The overall efficiency of the unit is just short of 10%, with a PPU efficiency of over 80%. Stored energy is 9 to 50 J, and is throttleable.

References:

[1] https://directory.eoportal.org/web/eoportal/satellite-missions/e/eo-1
[2] Benson, S., Arrington, L., Hoskins, W., Meckel, N., "Development of a PPT for the EO-1 spacecraft," AIAA-99-2276.
[3] https://eo1.gsfc.nasa.gov/new/Technology/PPT.htm
[4] https://earth.esa.int/web/eoportal/satellite-missions/e/eo-1
[5] https://www.rocket.com/sites/default/files/documents/Capabilities/PDFs/Electric%20Propulsion%20Data%20Sheets.pdf

Comm. avail.	TRL	Aerospace-tested
	7	NO

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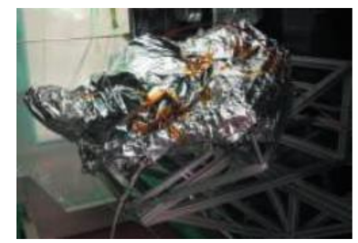
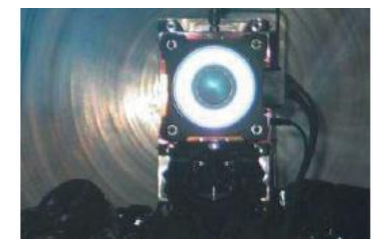
HET-300 (IHET-300), R-400EPS
Israeli Hall Effect Thruster [1 of 2]

Propulsion Technology	Hall thruster
Manufacturer/Country	Rafael (Israel)
TRL	7
Size (including PPU)	~2U (PPU size unknown)
Design satellite size	Larger due to power requirements. VENUS was 270 kg.
Isp (s)	>1210 s [1], >1300 s [2]
Thrust type/magnitude	14.3 mN at 300W [1], 135 kNs (impulse, total) [1]
Delta-V (m/s)	
Propellant	Xenon (16 kg aboard VENUS)
Power consumption (W)	250 to 600 W [1]
Flight heritage (if any)	VENUS/VENµS (2017)
Commercially available	YES
Last updated	*01/2021*

Figure 1. HET-300 flight model

[1]





HET-300 during test [1]

Photo of thruster on-board the VENUS satellite [2]

Property	Value
Thrust @ 300W (EOL)	> 14.3 mN
Specific Impulse @ 300W (EOL)	> 1210 sec
Power Operation Range	250W to 600W
Operating Life	> 1100 hours
Number of Operation Cycles	> 2000
Total Impulse	> 135 kNs

[2]

Additional comments:

[Reference 1-2][Jan 2019][Thruster info]
VENUS includes a full on-board electric propulsion system, denoted R-400EPS, based on two low power Hall effect thrusters. The Hall thrusters, denoted IHET-300, operate in the 300-600 W power range according to mission requirements.
HET-300's mass is about 1.5 kg and its dimensions are 170x120x90 mm. Recent laboratory tests results of thrust and Isp of the qualification model at EOL are given in the reference. The PMA is composed of a high-pressure tank storing 16 kg of Xenon and a set of valves, pressure reducers and manifolds to transport the gas. An extensive qualification campaign was carried out to qualify all EPS equipment for the VENUS mission environment conditions. The thrusters were tested to a full life test of 2000 hours, which is twice (a factor of 2.0) as long as needed for Venus mission. Life test was performed at various power levels and at various firing durations, but mainly on the representative mission figures of about 425 W and less than a hour operation (representing the sunlight period of a LEO revolution). The lifetime test was carried along with the qualification cathode, in an identical as possible setup to satellite one. Many tests were performed towards qualification for the environment conditions, including random vibrations, sine vibrations, shock, thermal vacuum, and static acceleration.

References:
[1] Herscovitz, J., Zuckerman, Z., Lev, D., "Electric propulsion development at Rafael," IEPC-2015-30/ISTS-2015-b-30.
[2] Lev, D., Zimmerman, R., Shoor, B., Appel, L., Ben-Ephraim, M., Herscovitz, J., Epstein, O., "Electric propulsion activities at Rafael in 2019," IEPC-2019-600.

	7	NO
Comm. avail.	TRL	Aerospace-tested

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HET-300 (IHET-300), R-400EPS
Israeli Hall Effect Thruster [2 of 2]

Additional comments:

[Reference 1-4][Jan 2019][Mission info]
VENµS is the first cooperative Earth observation program between Israel (ISA) and France (CNES). The mini-satellite mission is being developed jointly by ISA (Israel Space Agency) and CNES, under a memorandum of understanding between the two space agencies, signed in April 2005. In this setup, ISA and CNES are sharing responsibilities for the VENµS program. ISA is responsible for the spacecraft bus, satellite integration, engineering data, and the satellite control center including mission operations. CNES is responsible for the science mission center, including the science data processing center and programming center. CNES is also providing the superspectral camera and is in charge of the launcher interface. The satellite carries two missions, a Scientific mission and a Technological mission. There are two main objectives for the Technological mission: Hall Effect Thruster verification and validation in space. The verification is achieved by operating the thrusters in the space environment. Its performances will be tested and qualified. Validation will be demonstrated for some mission enhancement operations. The VENµS spacecraft of ISA/CNES, along with OptSat-3000 of the Italian Ministry of Defense, was launched on August 02, 2017 on a Vega vehicle (VV10) from the Guiana Space Center in Kourou. As of Jan 2019, VENµS is still completing its technological mission. The Technological mission is the demonstration of the advantages of using plasma engine thrusters vs hydrazine ones for station keeping, LEO to LEO transfer, and drag compensation at low altitude. This electric propulsion system will bring the satellite down to 410 km – once the 2.5 years are over (in 2020) - and will maintain this altitude during one year (autonomous close loop navigation).

[Reference 5][Jun 2020]VENUS flight info]
VENUS has performed several experiments in 2018 and 2019, demonstrating performance of the thrusters between 300W and 500W.

[Reference 6][Jan 2021][Thruster status]
As of June 2019, the electric propulsion system was activated 147 times. Thus far, the propulsion system has been successful and proven to operate properly at a variety of system power levels of 250-600W.

References:

[1] https://directory.eoportal.org/web/eoportal/satellite-missions/v-w-x-y-z/venus
[2] http://www.rafael.co.il/5719-2612-EN/Marketing.aspx
[3] Herscovitz, J., and Karnieli, A., "VENuS Program: Broad and New Horizons for Super-Spectral Imaging and Electric Propulsion Missions for a Small Satellite," 22nd AIAA/USU Conference on Small Satellites, Logan, Utah, 2008.
[4] Herscovitz, J., Appel, L., Barnett, D., Baron, D., Davidson, A., Gontmacher, P., Kedem, M., Lev, D., Merenstein, A., Rbinovich, L., Reiner, D., Salama, O., Amit-Shapira, Y., Shechter, Y., Shoor, B., Warshavsky, A., and Zhuravel, N., "VENuS – A Novel Technological Mission Using Electric Propulsion," 35th IEPC, Atlanta, Georgia, 2017.
[5] Herscovitz, J., Lev, D., Shoor, B., Katz-Franco, D., Berkman, S., Baron, D, and Adler, S., "VENuS – Updates on Technological Mission using the Israeli Hall Effect Thruster (IHET)," 36th IEPC, Vienna, Austria, 2019.
[6] Lev, D., Zimmerman, R., Shoor, B., Appel, L., Ben-Ephraim, M., Herscovitz, J., Epstein, O., "Electric propulsion activities at Rafael in 2019," IEPC-2019-600.

	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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Drag Sail

Propulsion Technology	Passive de-orbit
Manufacturer/Country	University of Toronto, Institute for Aerospace Studies (UTIAS)-Space Flight Laboratory (SFL) (CANADA)
TRL	7
Size (including PPU)	<1U
Design satellite size	3U
Isp (s)	n/a
Thrust type/magnitude	Propellant-less
Delta-V (m/s)	n/a
Propellant	n/a
Power consumption (W)	
Flight heritage (if any)	CANX-7 (2016)
Commercially available	NO
Last updated	03/2019

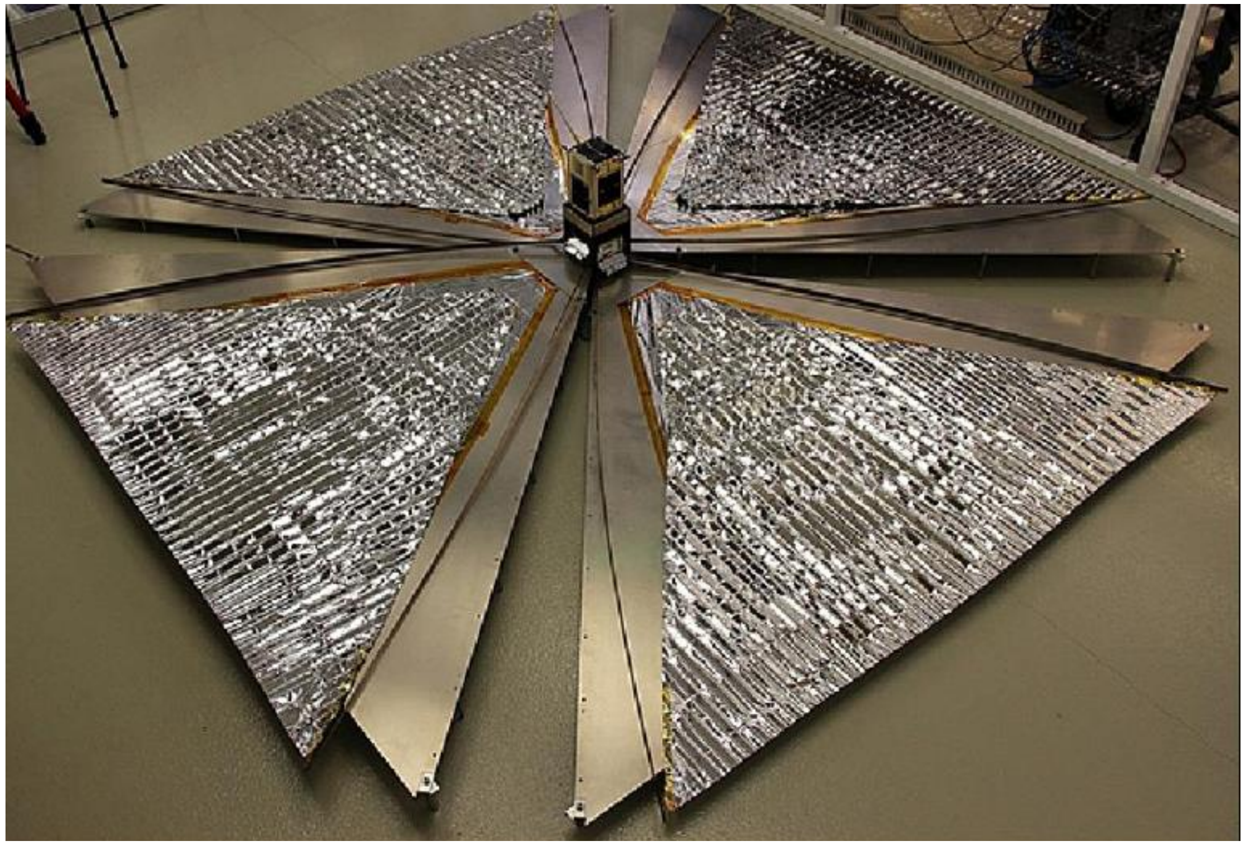


Photo of CanX-7 with drag sails deployed

Additional comments:

[Reference 1, 2][March 2019][Mission information]
CanX-7 (Canadian Advanced Nanospace eXperiments 7) is a demonstration mission involving a 3U-CubeSat nanosatellite that will incorporate a lightweight, compact, deployable drag sail under development at SFL. The mission is funded by Defence R&D Canada (Ottawa), NSERC and COM DEV Ltd. The mission will demonstrate the drag sail's customizability, modularity, stowability and effectiveness at achieving the deorbiting requirements of the IADC. The results will then be used to create a low cost, modular, and customizable deorbiting device for nanosatellites and microsatellites in low Earth orbit, thus alleviating the programmatic and technical risk to space missions when using satellites of this class.
CanX-7 as a secondary payload was launched on Sept. 26, 2016 on the PSLV-C35 vehicle of ISRO from SDSC (Satish Dhawan Space Center) on the east coast of India. The primary payload on the flight was SCATSat-1 of ISRO. The sail was successfully deployed on 3 May 2017.

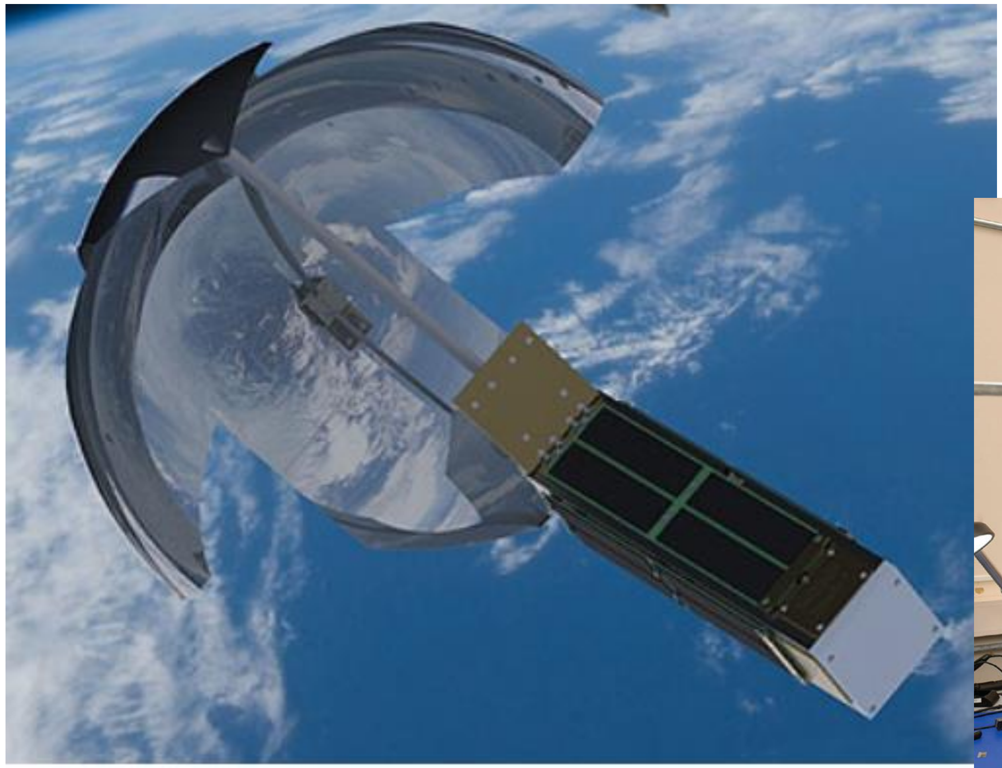
References:
[1] https://space.skyrocket.de/doc_sdat/canx-7.htm
[2] https://directory.eoportal.org/web/eoportal/satellite-missions/c-missions/canx-7

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

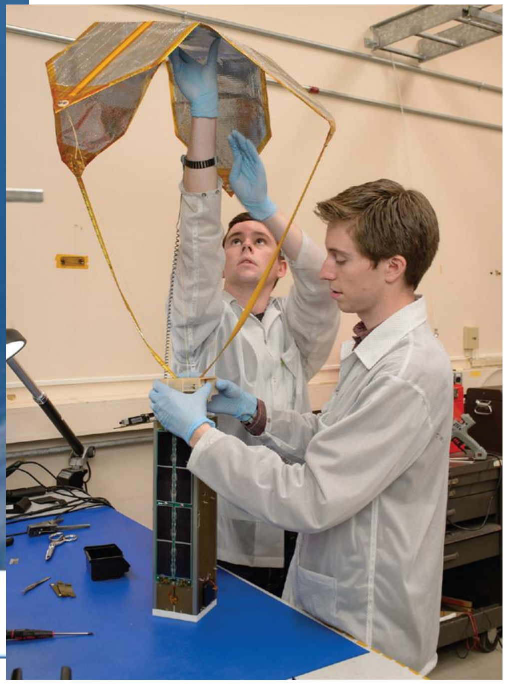
DISTRO A: Approved for public release. OTR-2024-00338

Exo-Brake [1 of 2]

Propulsion Technology	Passive de-orbit
Manufacturer/Country	NASA (USA)
TRL	7
Size (including PPU)	<1U
Design satellite size	3U, 6U
Isp (s)	n/a
Thrust type/magnitude	Propellant-less
Delta-V (m/s)	n/a
Propellant	n/a
Power consumption (W)	
Flight heritage (if any)	TechEdSat-5 (2016), 6, 8 (2019)
Commercially available	NO
Last updated	03/2019



TechEdSat 5 *[NASA]*



Additional comments:

[Reference 1][Mar 2019][Device information]
Recent CubeSats have used NASA's Exo-Brake Parachute for mission deorbiting. An Exo-Brake increases the spacecraft's drag once the tension-based, flexible braking device that resembles a cross-parachute is deployed from the rear. The Exo-Brake development is funded by the Entry Systems Modeling project within the NASA Space Technology Mission Directorate's Game Changing Development program.

[Reference 2][Mar 2019][TechEdSat-5 mission]
TechEdSat 5 (Technical and Educational Satellite 5) is a 3.5U CubeSat. It was built as a conjoined project between San Jose State University (SJSU) and the University of Idaho as a collaborative engineering project, with oversight from the NASA Ames Research Center.The TechEdSat-5 satelliteis based on the TechEdSat-4 design, but using an enlarged 3.5U CubeSat bus. It will introduce a modulating exo-brake capable of changing its surface area allowing the satellite to more precisely enter the atmosphere. TechEdSat 5 has following science and mission objectives: Establish improved uncertainty analysis for eventual controlled flight through the Thermosphere (perform detailed comparison to the TES-3 and TES-4 with respect to key Thermosphere variable uncertainty). Improve prediction of re-entry location. Provide the base technology for sample return technology from orbital platforms. Provide the eventual testing of independent TDRV-based planetary missions Provide engineering data for an On-Orbit Tracking Device that could improve the prediction of jettisoned material from the ISS. The satellite was launched on board of HTV 6 on an H-2B-304 rocket to be delivered to the International Space Station, from where it will be deployed at a later date.

References:
[1] https://sst-soa.arc.nasa.gov/12-passive-deorbit-systems
[2] https://space.skyrocket.de/doc_sdat/techedsat-5.htm

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

Exo-Brake [2 of 2]

Additional comments:

[Reference 1][Mar 2019][TechEdSat-6 mission]
TechEdSat 6 (Technical and Educational Satellite 6) is a 3.5U CubeSat. It was built as a conjoined project between San Jose State University (SJSU) and the University of Idaho as a collaborative engineering project, with oversight from the NASA Ames Research Center. It is a technology demonstration mission to demonstrate an Exo-Brake system to provide a targeted nanosatellite de-orbit using fully propellant-less techniques.
The basic 3.5 U design for The Development of On-Demand Sample Return Capability-Small Payload Quick Return (TechEdSat-6) differs from the TechEdSat-5 design in that a basic aluminum (T-6060) extrusion is used, but the length is adjusted to the accepted 400 mm length compatible with the NanoRacks CubeSat Deployer (NRCSD). The approximate mass is 3.60 kg. On the TechEdSat-6 front end, the direction of flight is indicated by the Teflon cap labeled ‘front end’, protects the GPS/Iridium dual-patch antennas just like in the previous TES-5 and 4 designs. This improves Global Positioning System (GPS)/Iridium reception/locking. The second Iridium (Iridium-B, associated with the level 2 functionality) remains on one of the side-mounted locations and is used during the terminal re-entry phase. The internal design and structure remains essentially the same as TechEdSat-5 and -4. After removal of the Remove Before Flight (RBF) screw, TechEdSat-6 is loaded into the NRCSD. At that point, three Auxiliary Lateral Inhibit (ALI) switches provide the two-fault tolerant design to inhibit inadvertent power from initiating the system. Structural fasteners use at least two inhibits—at least two of three: torque specification, locking nut, or Loctite-243. The software is also similar to the previous TechEdSat-5 design. The PWR Level 1 software has similar but more robust function such as second initiator pulses should the Exo-Brake actuators not deploy the first time. This uses the Arduino Pro-Mini (processor: Atmel Mega328P) board which controls the Iridium-A, actuators, and ultimately the upper level function. The upper level, or ‘Nominal’ mode, software is almost identical to TechEdSat-5, and runs in the Intel/Edison environment. This controls the GPS and Iridium-B functionality. As before, the pc-boards are conformal-coated and the harnesses/wires staked with the same approved materials. All testing, interface control document (ICD) and safety verification are conducted via the same procedures, and captured in the integrated TechEdSat-6 Test/Verification Document (T6P6-06-XT001) Environmental_Master Test Report. It was selected in 2017 by NASA to be launched as part of the ELaNa program.

[Reference 2][Mar 2019][TechEdSat-8 mission]
TechEdSat 8 (Technical and Educational Satellite 8) is a 1×6U CubeSat. It was built as a conjoined project between San Jose State University (SJSU) and the University of Idaho as a collaborative engineering project, with oversight from the NASA Ames Research Center. It is a technology demonstration mission that will further develop and demonstrate the Exo-Brake system through full recovery of a payload. It will feature a semi-autonomous control system to target the entry face point, as well as capabilities to measure a unique ablation device on the forebody.
It was selected in 2017 by NASA to be launched as part of the ELaNa program. The satellite was launched to the ISS in late 2018 and was deployed on 31 January 2019 from the ISS.

References:
[1] https://space.skyrocket.de/doc_sdat/techedsat-6.htm
[2] https://space.skyrocket.de/doc_sdat/techedsat-8.htm

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

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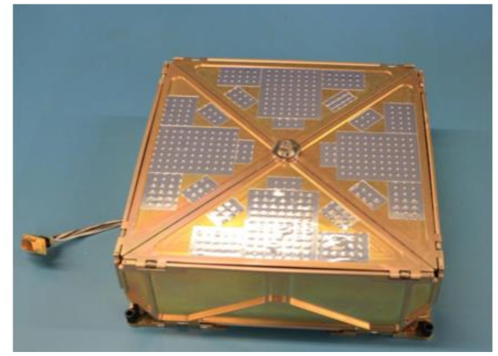
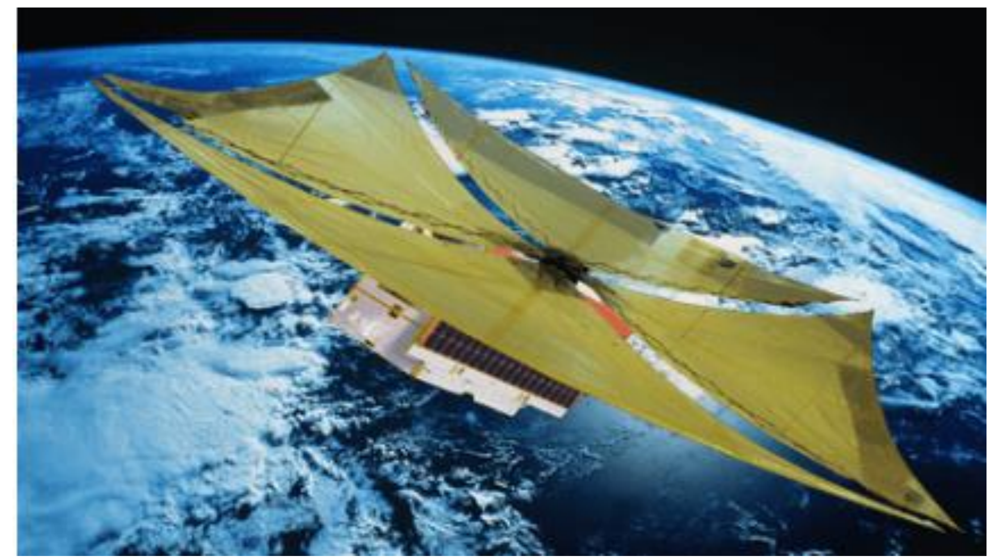
Drag-Net

Propulsion Technology	Passive de-orbit
Manufacturer/Country	MMA Design (USA)
TRL	7
Size (including PPU)	2.8 kg
Design satellite size	100 to 200 kg
Isp (s)	n/a
Thrust type/magnitude	Propellant-less
Delta-V (m/s)	n/a
Propellant	n/a
Power consumption (W)	
Flight heritage (if any)	ORS-3 Minotaur
Commercially available	Yes
Last updated	03/2019





Additional comments:

[Reference 1, 2][Mar 2019][Device design]
MMA's dragNET™ De-orbit System meets DoD and NASA requirements for de-orbiting space assets in low earth orbit (LEO) and has successfully de-orbited the ORS-3 Minotaur I Upper Stage within a 2-year time frame. It features four compactly-stowed, thin membranes that release using a single heater-powered actuator. The deployment is powered via the release of stored spring energy acting through articulating booms and, once tensioned, the membranes form a high-drag, aerodynamic shape to passively de-orbit the space asset thereby obviating the need for additional space-propulsion resources. Release occurs after approximately two minutes of power at -45 degrees Celsius, and 15 seconds of power at 75 degrees Celsius. Power is turned off to the release unit via an integrated limit switch or timed event. After release, the damped deployment takes approximately three seconds in ambient conditions, which then deploys a 14m^2 membrane using the pantographs that structure the membrane tension. The dragNET™ De-orbit System has a mass of only 2.8 kg and can de-orbit a 180-kg spacecraft from an altitude of 850 km in less than 10 years.

References:
[1] https://mmadesignllc.com/product/dragnet-de-orbit-system/
[2] http://launchstories.org/stories/WhatGoesUpMustComeDown

7
NO
Comm. avail. TRL Aerospace-tested

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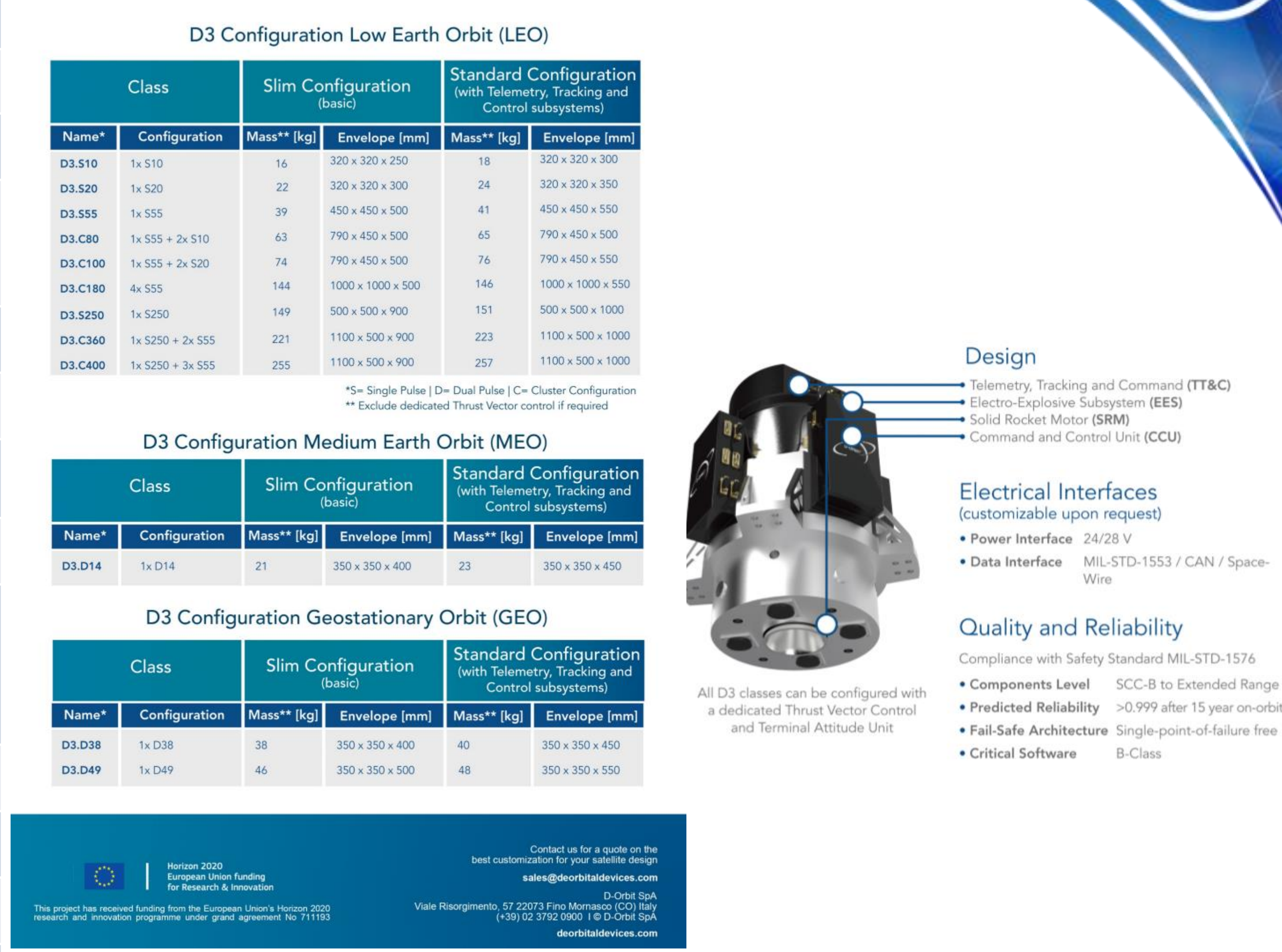
D-Orbit Decommissioning Device (D3) [1 of 2]

Propulsion Technology	Propulsive de-orbit/Solid rocket
Manufacturer/Country	D-Orbit (ITALY)
TRL	7
Size (including PPU)	>16 kg (several models available) [1,2] Smallest model is 300mmx300mmx250mm [1,2] D-Sat flew a ~1U unit
Design satellite size	50 to 100 kg (or larger)
Isp (s)	
Thrust type/magnitude	750 N*s [3]
Delta-V (m/s)	70 m/s on a 3U [3]
Propellant	Solid propellant (specifics not provided by manufacturer on website) [1,2] Non-metallized propellant based on AP + HTPB [3]
Power consumption (W)	n/a
Flight heritage (if any)	D-Sat (2017)
Commercially available	YES
Last updated	07/2023



D3 Configuration Low Earth Orbit (LEO)

Class		Slim Configuration (basic)		Standard Configuration (with Telemetry, Tracking and Control subsystems)	
Name*	Configuration	Mass** [kg]	Envelope [mm]	Mass** [kg]	Envelope [mm]
D3.S10	1x S10	16	320 x 320 x 250	18	320 x 320 x 300
D3.S20	1x S20	22	320 x 320 x 300	24	320 x 320 x 350
D3.S55	1x S55	39	450 x 450 x 500	41	450 x 450 x 550
D3.C80	1x S55 + 2x S10	63	790 x 450 x 500	65	790 x 450 x 500
D3.C100	1x S55 + 2x S20	74	790 x 450 x 500	76	790 x 450 x 550
D3.C180	4x S55	144	1000 x 1000 x 500	146	1000 x 1000 x 550
D3.S250	1x S250	149	500 x 500 x 900	151	500 x 500 x 1000
D3.C360	1x S250 + 2x S55	221	1100 x 500 x 900	223	1100 x 500 x 1000
D3.C400	1x S250 + 3x S55	255	1100 x 500 x 900	257	1100 x 500 x 1000

*S= Single Pulse | D= Dual Pulse | C= Cluster Configuration
** Exclude dedicated Thrust Vector control if required

D3 Configuration Medium Earth Orbit (MEO)

Class		Slim Configuration (basic)		Standard Configuration (with Telemetry, Tracking and Control subsystems)	
Name*	Configuration	Mass** [kg]	Envelope [mm]	Mass** [kg]	Envelope [mm]
D3.D14	1x D14	21	350 x 350 x 400	23	350 x 350 x 450

D3 Configuration Geostationary Orbit (GEO)

Class		Slim Configuration (basic)		Standard Configuration (with Telemetry, Tracking and Control subsystems)	
Name*	Configuration	Mass** [kg]	Envelope [mm]	Mass** [kg]	Envelope [mm]
D3.D38	1x D38	38	350 x 350 x 400	40	350 x 350 x 450
D3.D49	1x D49	46	350 x 350 x 500	48	350 x 350 x 550

Design
- Telemetry, Tracking and Command **(TT&C)**
- Electro-Explosive Subsystem **(EES)**
- Solid Rocket Motor **(SRM)**
- Command and Control Unit **(CCU)**

All D3 classes can be configured with a dedicated Thrust Vector Control and Terminal Attitude Unit

Electrical Interfaces
(customizable upon request)
- **Power Interface** 24/28 V
- **Data Interface** MIL-STD-1553 / CAN / Space-Wire

Quality and Reliability

Compliance with Safety Standard MIL-STD-1576
- **Components Level** SCC-B to Extended Range
- **Predicted Reliability** >0.999 after 15 year on-orbit
- **Fail-Safe Architecture** Single-point-of-failure free
- **Critical Software** B-Class

Horizon 2020
European Union funding
for Research & Innovation

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grand agreement No 711193

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deorbitaldevices.com

Additional comments:

[Reference 2][Mar 2019][D-Sat mission]

D-Sat is a 3U CubeSat designed, built, and operated by D-Orbit. The CubeSat was launched on June 23rd, 2017 into a 500 km sun-synchronous orbit, with the goal to validate D-Orbit Decommissioning Device (D3) in space.
June 2017 - The mission was successfully launched from Satish Dhawan Space Centre in India atop a PSLV rocket.
Sep 2017 - D-Sat successfully completed of the orbital segment of the mission; it completed an eleven-week flight plan, during which D-Sat performed multiple iterations of SatAlert and DeCas experiments.
Oct 2017 - D-Sat has concluded its mission, proving that D-Orbit Decommissioning Device (D3) is a flight-ready technology that can be integrated into the next-generation satellites. All subsystems, onboard sensors, and actuators have been working perfectly throughout the mission, and all three experiments — DeCAS, Atmosphere Analyzer, and SatAlert — produced remarkable scientific contributions. In D-Sat's design for redundancy, critical software, manufacturing, flawless orbital performance, and flight-worthiness of D3, we have achieved most of our mission's key objectives: the goal of a direct and controlled decommissioning, however, was not achieved. During the final phase of the mission, D-Sat successfully fire-tested the onboard D-Orbit Decommissioning Device (D3). The satellite moved into an elliptical orbit with a different inclination, compliant with orbital debris regulations. All objectives related to motor ignition and operation process were achieved, and the change in orbital parameters confirmed that the motor produced the expected thrust. Our team was able to re-acquire the signal of the satellite after the maneuver, and collect further data for analysis. According to a preliminary analysis, the cause for the missed reentry of the satellite is related to the interface between the D3 and the small satellite: the alignment of the motor with the spacecraft's center of gravity resulted to be outside the designed tolerance. While we had put in place strategies to mitigate this outcome, we knew we had little margin to play with considering that the D3 installed onboard was designed for satellites one order of magnitude bigger.
As in any space mission we had to make a tradeoff that included a calculated risk, i.e. by not installing a thrust vector control for the solid propellant motor because it would have been not suitable for the volume available in such a small satellite. The same D3 installed into a bigger satellite would allow a sufficiently reasonable misalignment tolerance between the motor and the spacecraft's center of gravity. The adoption of a thrust vector control will also remove the tolerance issue. We are proud of the work of our team, which is currently collecting further data.

References:

[1] https://www.deorbitaldevices.com/products/
[2] https://www.dsat.space/
[3] Fanfani, A., "D-Sat Mission: An in-orbit demonstration of satellite controlled re-entry," Clean Space Industrial Days, ESA-ESTEC, October 2017. Chart deck.

7 | NO
Comm. avail. | TRL | Aerospace-tested

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D-Orbit Decommissioning Device (D3) [2 of 2]

Additional comments:

[Ref 1][Oct 2019][Thruster details]
The D-Sat satellite uses an Electro Explosive Device (EED) to ignite the rocket motor in a safe a controlled way. Main features of the rocket motor:
- Designed according to MIL-STD-1576 standard
- Mechanical barrier with a double lock architecture
- Four electronic barriers to avoid inadvertent EED ignition
- Hermetically sealed metallic box against EMI, humidity, explosive atmosphere and external fire
- Safing plug connector and additional mechanical provision for a safe ground handling
- Operating temperature range between -34 and 71C
- CubeSat form factor

It delivers about 750 N*s total impulse to the satellite, and uses about 300 grams of non-metallized composite propellant base on ammonium perchlorate (AP) and binder (HTPB). The unit does NOT have thrust-vector control and instead relies on spin stabilization.

On-orbit data from D-Sat's flight demonstrated a total deltaV of 70 m/s delivered, versus the ideal calculated 180 m/s. Reasons for the off-nominal performance include:
- Mounting misalignments of SRM within satellite structure (tolerances were <1.5 mm)
- Possible combustion instabilities, which may deviate the thrust vector during the fire

Possible mitigations include:
- Thrust misalignments could be assessed both during SRM verification and during D-SAT qualification campaign via dedicated firing test on thrust vectoring bench.

[Ref 1, 2][Oct 2019][Launches]
Future flights:
Projected on ION CubeSat Carrier (developed by D-Orbit), to be launched 2020.

References:
[1] Fanfani, A., "D-Sat Mission: An in-orbit demonstration of satellite controlled re-entry," Clean Space Industrial Days, ESA-ESTEC, October 2017. Chart deck.
[2] https://space.skyrocket.de/doc_sdat/ion-cubesat-carrier.htm

	7	NO
Comm. avail.	TRL	Aerospace-tested

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Icarus-1 Drag Sail

Propulsion Technology	Drag Sail
Manufacturer/Country	Cranfield University
TRL	7
Size (including PPU)	
Design satellite size	~100 kg (TDS-1 was 157 kg) [2]
Isp (s)	n/a
Thrust type/magnitude	n/a
Delta-V (m/s)	
Propellant	None
Power consumption (W)	
Flight heritage (if any)	TechDemoSat-1 (TDS-1), launched 2014
Commercially available	NO
Last updated	06/2019

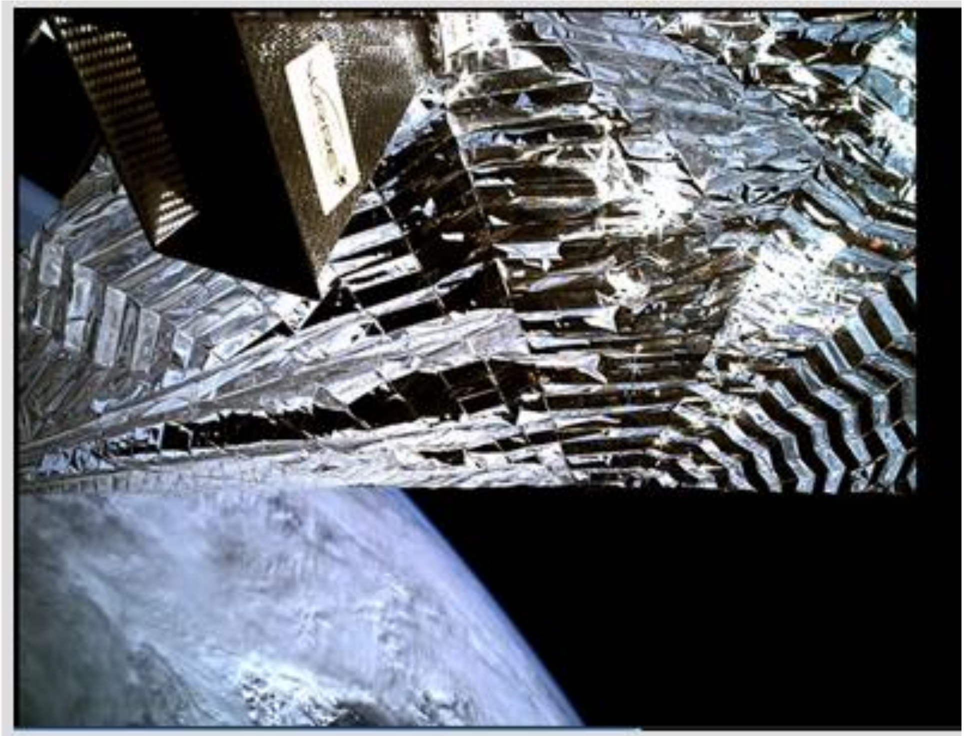

Image acquired by the inspection camera on board TechDemoSat-1 showing the Icarus-1 sail deployed with a view of Earth beyond. The equipment top left is the satellite's Antenna Pointing Mechanism.

Photo is courtesy of SSTL

Additional comments:

[References 1, 2][Sail and mission general info]
DOS, developed at Cranfield University, is intended to demonstrate a novel means for de-orbiting a satellite at the end of its mission lifetime through deploying a sail to increase the aerodynamic drag. The de-orbit sail is the product of several years of Cranfield University's work on sustainable approaches to space exploration. SSTL's TechDemoSat-1 gave the Cranfield team the unique opportunity to take-on the challenge of evolving their ideas from designs on paper, to flight-ready hardware. Maintaining a low mass is always a challenge with space projects; the TechDemoSat-1 de-orbit sail, Icarus-1 is made from a material called Kapton, which is just 25 µm thick.
The Icarus-1 drag sail consists of a thin aluminium frame fitted around one of the external panels of the spacecraft in which four trapezoidal Kapton sails and booms are stowed and restrained by a cord. Deployment is achieved by activating cord-cutter actuators, allowing the stored energy in the spring hinges to unfold the booms and the sail.
The sail will be deployed when TechDemoSat-1 issues a command at the end of its mission.

This was completed successfully in 2018.

References:
[1] https://2019.smallsatshow.com/2019/05/31/sstl-image-reveals-de-orbit-drag-sail-on-board-techdemosat-1-successfully-deployed/
[2] https://directory.eoportal.org/web/eoportal/satellite-missions/t/techdemosat-1

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

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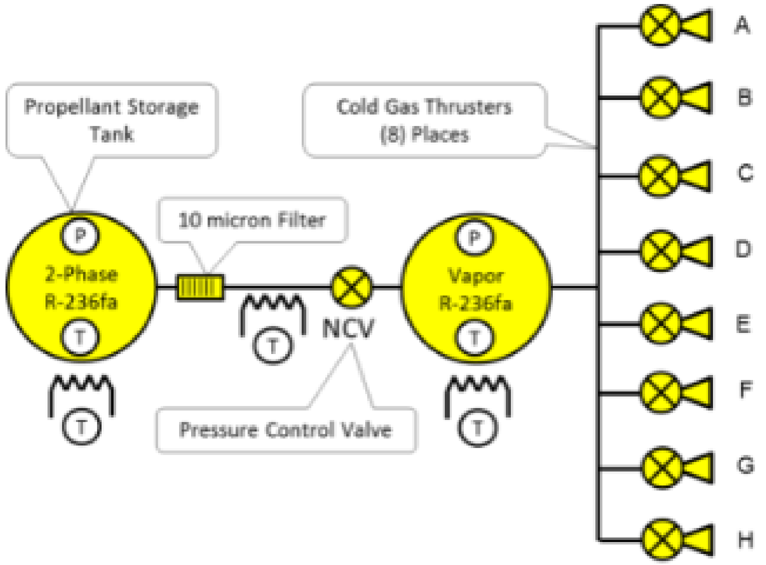
MarCO Micro CubeSat Propulsion System [1 of 2]
VACCO

Propulsion Technology	Cold gas
Manufacturer/Country	VACCO (USA)
TRL	6-7
Size (including PPU)	1.5U (estimated), mass 3.5kg [5]
Design satellite size	6U
Isp (s)	40 s (estimated from similar technologies)
Thrust type/magnitude	200 mN (total) = 4 axial and 4 RCS 25 mN thrusters 755 N*s (impulse, total), 0.5 mN*s (impulse, minimum)
Delta-V (m/s)	40 m/s
Propellant	R236fa refrigerant
Power consumption (W)	0.5W (standby)
Flight heritage (if any)	MarCO (“Mars Cube One”), 2018.
Commercially available	YES
Last updated	*06/2020*



Additional comments:

[References 1-4][Thruster information and MarCO mission][Jan 2019]
The MarCO MiPS is an all-welded aluminum system-in-a-tank design with propellant storage, feed system, thrusters, and a controller based on VACCO’s patented Chemically Etched Micro Systems (ChEMS)™ technology. This unit is designed to control a 6U CubeSat and can be easily application-engineer for other CubeSat configurations. Valve response time reported <20 msec.
The JPL Mars Cube One (MarCO) was the first interplanetary CubeSat and was propelled by VACCO’s smart, self-contained Micro Propulsion System (MiPS).
Mars Cube One was the first spacecraft built to the CubeSat form to operate beyond Earth orbit for a deep space mission. The primary mission of MarCO was to test new miniaturized communication and navigation technologies. MarCO was a Mars flyby mission consisting of two nanospacecraft, of the 6U CubeSat format, that was launched on 5 May 2018 alongside NASA's *InSight* Mars lander mission. The MarCO spacecraft were launched as a pair for redundancy, and flew at either side of InSight. The mission was for all three spacecraft to journey to Mars, and for the two CubeSats to provide real-time communications link to Earth for *InSight* during its entry, descent, and landing when *InSight* will be out of sight from the Earth. (Note the CubeSats did not descend to Mars with Insight, they only provided communication while Insight descended while continuing their fly-by). They successfully completed their primary mission. Having completed their primary mission, the small spacecraft continued in their elliptical orbits around the Sun. Engineers expected them to keep working for a couple weeks after they pass Mars orbit, depending on how long their propellant and electronics lasted. The two Mars Cube One spacecraft were identical and officially called MarCO-A and MarCO-B and were launched together for redundancy; they were nicknamed by JPL engineers as WALL-E and EVE in reference to the main characters in the animated film WALL-E. The MarCo mission cost was $18.5 million USD.
A few notes on the propulsion system performance are as follows: A slight leak was detected from a thruster on MarCO-B following a blow-down maneuver for thruster characterization early in the mission. After characterizing the leak, and altering onboard behaviors to account for it, the team adopted a slightly different strategy for the second spacecraft. First, in anticipation that the leak might not end, or could change in the future, the spacecraft performed regular plenum chamber blowdowns at specified attitudes to keep the spacecraft pushing towards Mars. This reduced the need for extensive thruster firing. The team continued to characterize the leaky thruster, as well as slightly tweak the flyby location, as the spacecraft headed towards Mars. As of December 2018, Vacco has claimed a successful mission for both MarCO missions. They succeeded in providing real-time communication relay while the InSight lander was in the entry, descent, and landing phases despite the MarCO-B leaks. No updated information on the leaky thruster has been released.
[Reference 5][Jun 2020][Mission info]
The MarCO spacecraft performed five trajectory correction maneuvers during the mission to Mars. The propulsion systems each contained 4X thrusters for altitude control and another 4X for trajectory corrections maneuvers.

References:
[1] http://www.cubesat-propulsion.com/jpl-marco-micro-propulsion-system/
[2] https://www.jpl.nasa.gov/news/press_kits/insight/appendix/mars-cube-one/
[3] https://en.wikipedia.org/wiki/Mars_Cube_One
[4] Klesh, A., Clement, B., Colley, C., Essmiller, J., Forgette, D., Krajewski, J., Marinan, A., Martin-Mur, T., et al., “MarCO: Early Operations of the First CubeSats to Mars,” SSC18-WKIX-04,, 2018.
[5] NASA 2020 SOA for Small Satellites (POC Gabriel Benavides). https://www.nasa.gov/smallsat-institute/sst-soa-2020/in-space-propulsion

Comm. avail.	7 TRL	NO Aerospace-tested

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MarCO Micro CubeSat Propulsion System [2 of 2]
VACCO

Additional comments:

[References 1][MarCO mission][Mar 2019]
FREMONT, Calif. — The twin cubesats that played a key role in NASA's most recent Mars lander mission have been out of contact with the Earth for more than a month, suggesting their trailblazing mission has come to an end. In a Feb. 5 statement, NASA's Jet Propulsion Laboratory said that it not heard from either of the Mars Cube One, or MarCO, cubesats since the beginning of the year. One, nicknamed WALL-E, last contacted Earth Dec. 29, while the other, Eve, has been silent since Jan. 4. The MarCO spacecraft were 6U cubesats launched in May 2018 as secondary payloads on the Atlas 5 that sent the InSight mission to Mars. As InSight landed on Mars, the MarCO cubesats flew by the planet, serving as communications relays to allow controllers to get real-time telemetry from InSight as it landed.
The spacecraft carried out that prime mission as intended, receiving UHF signals from InSight as it landed and rebroadcasting it back to Earth at X-band frequencies. "MarCO was there to relay information back from InSight in real time, and we did that extraordinarily well," said Andy Klesh, MarCO chief engineer, at a press conference at JPL immediately after the successful InSight landing Nov. 26. In its statement, JPL said that there were several possible explanations for why the two spacecraft were no longer in contact with the Earth, including problems with sensors used to keep the spacecraft pointed at the sun or problems with their attitude control systems. JPL hasn't ruled out restoring contact with the MarCO cubesats, which are still receding from the sun in their heliocentric orbits but will start to move closer again this summer. JPL said the project will at that point try to restore contact with the cubesats, but acknowledges that "it's anyone's guess" if the spacecraft will still be functional then.

[Reference 2][Aug 2019][Conclusion of the MarCO mission]
More details and a thorough summary of the mission.

References:
[1] https://spacenews.com/mars-cubesats-fall-silent/
[2] Klesh, A., Baker, J., Krajewski, J., "MarCO: Flight review and lessons learned," SSC19-III-04.

	7	NO
Comm. avail.	TRL	Aerospace-tested

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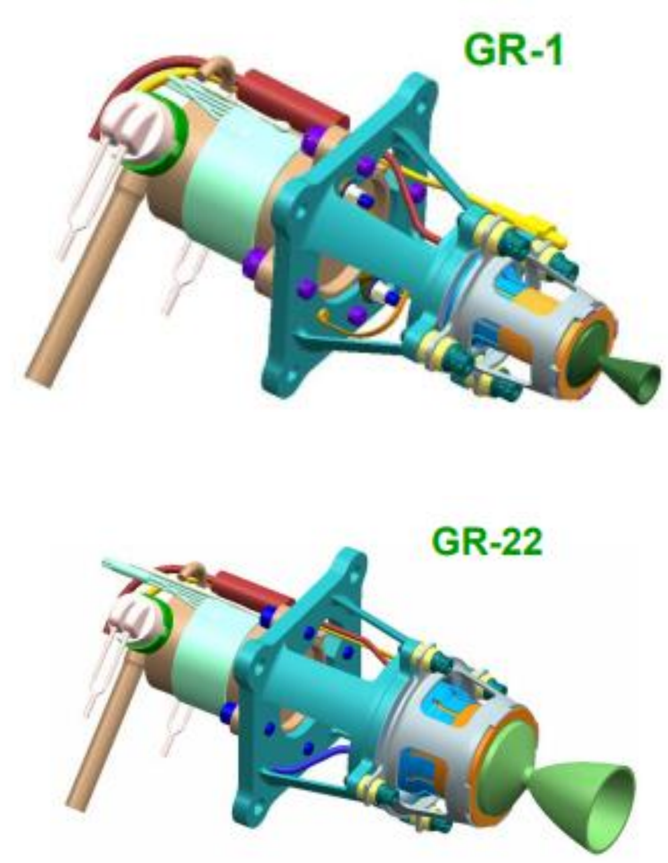
GR-1 (1N), GR-22 (22N) Green Monopropellant (aka MPS-230)
Aerojet Rocketdyne/Ball Aerospace [1 of 3]

Propulsion Technology	Green Monopropellant
Manufacturer/Country	Aerojet Rocketdyne/Ball Aerospace (USA)
TRL	7
Size (including PPU)	0.33kg
Design satellite size	1U and larger
Isp (s)	235s (1N), 250 (22N)
Thrust type/magnitude	1N thruster: 0.4 to 1.1 N (continuous), 23,000 N*s (total impulse), 8 mN*s (impulse bit, min) 22N thruster: 8 to 25 N (continuous), 74,000 N*s (total impulse), 116 mN*s (impulse bit, min)
Delta-V (m/s)	
Propellant	AF-M315E
Power consumption (W)	1N thruster: 12W (valve) + 10W (preheat power) 22N thruster: 28W (valve) + 30W (preheat power)
Flight heritage (if any)	Flown on GPIM (aka STP-2, ~200 kg, launched June 2019)
Commercially available	YES
Last updated	*08/2020*



Aerojet Green Monopropellant thrusters

Additional comments:

[References 1-4][Jan 2019][Thruster and missions, general info]

Under development as a self-contained module to allow independent assembly at Aerojet Rocketdyne for subsequent integration into the bus, the GPIM demonstration payload, illustrated in Figure 3 and shown in schematic in Figure 2, will deliver 50% more impulse than a comparably-packaged hydrazine system. Designed to attach to the Ball Aerospace BCP-100 bus via its standard payload interface plate (PIP), the GPIM demonstration payload comprises a simple, single-string, blow-down AF-M315E advanced green monopropellant propulsion system employing four 1N attitude-control thrusters and a single 22N primary divert thruster. The propellant feed manifold's principal components, consisting of a standard diaphragm propellant tank, latch valve, and service valves, represent all flight-proven (TRL 9 with hydrazine propellant) designs selected specifically for the long-term compatibility of their materials of construction with AF-M315E.

A major effort of the GPIM program is to mature and qualify all AF-M315E propulsion system components for this mission, and for infusion on future space missions. An extensive materials compatibility test campaign is currently underway to confirm that all materials in system components that are wetted with the AF-M315E propellant are fully compatible, or material replacement of known incompatibles. The thruster valve requires the most extensive modifications to ensure it is AF-M315E compatible. All wetted surfaces for the thruster valve, service valve, latch valve and propellant filter will be manufactured from materials which are fully compatible with this propellant. The service valves being updated requires minor changes to all the sealing subcomponents. The latch valve is being evaluated to determine if any modifications to its materials is required. The system filter is the only system component that does not require any changes since its propellant wetted surfaces are already compatible.

Through the Green Propellant Infusion Mission (GPIM), NASA is developing a green alternative to conventional chemical propulsion systems for next-generation launch vehicles and spacecraft. Led for NASA's Space Technology Mission Directorate by Ball Aerospace & Technologies Corp., the project seeks to improve overall propellant efficiency while reducing the handling concerns associated with the highly toxic fuel hydrazine. The space technology infusion mission also strives to optimize performance in new hardware, system and power solutions while ensuring the best value for investment and the safest space missions possible. The Green Propellant Infusion Mission is scheduled to launch in 2018.

References:

[1] Masse, R., Spores, R., Allen, M., et al., "Enabling High Performance Green Propulsion for SmallSats," 29th Small Satellite Conference, SSC15-XI-6.
[2] Spores, R., Masse, R., Kimbrel, S., McLean, C., "GPIM AF-M315E Propulsion System," 49th AIAA Joint Propulsion Conference, AIAA 2013-3849.
[3] https://www.nasa.gov/mission_pages/tdm/green/index.html
[4] https://en.wikipedia.org/wiki/Green_Propellant_Infusion_Mission

Comm. avail.	TRL	Aerospace-tested
(cart icon)	7	NO

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GR-1 (1N), GR-22 (22N) Green Monopropellant (aka MPS-230) Aerojet Rocketdyne/Ball Aerospace [2 of 3]

Additional comments:

[Reference 1][June 2019][GPIM mission]

• May 21, 2019: Ball Aerospace, a partner in the new NASA Green Propellant Infusion Mission (GPIM) announced their Ball Aerospace-built small spacecraft arrived in Florida today to prepare for a June 2019 launch on board a SpaceX Falcon Heavy rocket. GPIM is NASA's first opportunity to demonstrate a new "green" propellant and propulsion system in orbit – an alternative to conventional chemical propulsion systems.
- GPIM is a sustainable and efficient approach to spaceflight, and the new propellant will demonstrate the practical capabilities of a Hydroxyl Ammonium Nitrate fuel and oxidizer blend, called AF-M315E. This innovative, low toxicity, "green" propellant was developed by the Air Force Research Laboratory. GPIM is part of NASA's Technology Demonstration Missions program within the Space Technology Mission Directorate.
- Dr. Makenzie Lystrup, vice president and general manager, Civil Space, Ball Aerospace stated that GPIM was a truly collaborative effort, working with their partners, NASA, Aerojet Rocketdyne, Air Force Research Laboratory, U.S. Air Force and SpaceX. They are proud to be part of this historic mission to test a new 'green' propellant on board Ball's flight-proven small satellite, helping to provide science at any scale.
- Ball Aerospace is responsible for system engineering; flight thruster performance verification; ground and flight data review; spacecraft bus; assembly, integration and test; and launch and flight support. The GPIM bus uses the smallest of the Ball Configurable Platform (BCP) satellites, which is about the size of a mini refrigerator, and was built in just 46 days. The BCP provides standard payload interfaces and streamlined procedures, allowing rapid and affordable access to space with flight-proven performance.

• March 31, 2016: GPIM recently took another major step toward demonstrating the capabilities of a new propellant that is safer to handle on the ground and more efficient for thrusters in space. The GPIM spacecraft has passed a major flight readiness milestone marking the successful completion of functional and environmental testing of its systems and software, and is on track for launch in early 2017.

• Oct. 5, 2015: The propulsion subsystem for NASA's Green Propellant Infusion Mission has been integrated onto the spacecraft, moving the mission another major step toward scheduled launch in 2016.

• August 19, 2015: NASA's Green Propellant Infusion Mission to develop a high-performance, low-toxicity fuel and propulsion system for spacecraft has passed a major milestone. A green propellant propulsion subsystem, built by Aerojet Rocketdyne in Redmond, Washington, has been delivered to the mission's prime contractor, BATC (Ball Aerospace & Technologies Corp.) in Boulder, Colorado.
- The green propellant propulsion subsystem consists of a propellant tank and five 1 N thrusters that will use the new fuel. Because AF-M315E burns hotter than hydrazine, it required new metals to withstand the temperatures in the thrusters aboard the propulsion system.

[Reference 2][Aug 2019][GPIM mission status]

Ball Aerospace has officially commissioned NASA's Green Propellant Infusion Mission (GPIM) and begun on-orbit testing of a non-toxic, high-performance propellant. GPIM launched on June 25, 2019 at 2:30 a.m. EDT on board a SpaceX Falcon Heavy rocket.
Over the next thirteen months, Ball Aerospace and its partners will test the thruster capabilities by verifying the propulsion subsystem, propellant performance, thruster performance and spacecraft attitude control performance. The primary mission of testing the thrusters and fuel will be complete within three months followed by testing of the secondary science payloads.

[Reference 3][June 2020][Flight information]

An AF-M315E (ASCENT) based propulsion system has flown as a technology demonstration on the NASA Green Propellant Infusion Mission (GPIM), launched July 2019. This small spacecraft was designed to test the performance of this propulsion technology in space by using five 1-N class thrusters for small attitude control maneuvers. Aerojet completed a hot-fire test of the GR-1 version in 2014 and further tests in 2015. An updated variant of the GR-1 to improve manufacturability is in-development. Initial plans to incorporate the GR-22 thruster (22-N class) on the GPIM mission were deferred in mid-2015 in order to allow for more development and testing of the GR-22. As a result, the GPIM mission only carried five (5) GR-1 units when launched.

References:
[1] https://directory.eoportal.org/web/eoportal/satellite-missions/g/gpim
[2] https://2019.smallsatshow.com/2019/07/09/ball-aerospace-sees-green-in-the-sky-successful-small-sat-on-orbit-testing-of-green-fuel/
[3] NASA 2020 SOA for Small Satellites (POC Gabriel Benavides). https://www.nasa.gov/smallsat-institute/sst-soa-2020/in-space-propulsion

Comm. avail.	7	NO
	TRL	Aerospace-tested

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GR-1 (1N), GR-22 (22N) Green Monopropellant (aka MPS-230) Aerojet Rocketdyne/Ball Aerospace [3 of 3]

Additional comments:

[Reference 1][Aug 2020][GPIM mission on-orbit data]

There is now on-orbit data from the GPIM mission. This was reported at the SmallSat 2020 virtual conference.

GPIM program was awarded in 2012. The GPIM flight system is comprised of the ESPA class BALL BCP-100 spacecraft bus and the Green Propellant Propulsion System (GPPS), designed and built by Aerojet Rocketdyne which uses green propellant AF-M315E. Flight system was completed in 2015, and put into storage until Spring 2019, due to Falcon Heavy development schedule.
Mission objectives included qualifying the propulsion system through a system of demonstrations and tests, totally ~11,000 total thruster pulses:
-Characterization of thruster efficiency over the life of the system across a range of tank pressures to understand thruster performance. Do this by determining thruster impulse bit at the end and beginning of life and after each delta-v campaign. This consisted of 60-s long firings, followed by 30 pulses of 200 ms each, commanded on each of the 4 ACS thrusters, spaced 10 seconds apart. The change in spacecraft attitude determines thruster impulse bit, i.e. performance.
-Perform series of 4 perigee lowering campaigns. Performed 3 burns, each ~6 minutes long. Once thrusters reached steady state operation, excellent pointing performance was maintained during delta-v maneuvers.
-Demonstrations of thruster-based attitude control modes. Holding attitude on thrusters and managing reaction wheel momentum, then dumping total system momentum via thruster detumble.
-At end of mission, burn remaining propellant to lower perigee under 180 km altitude, and expect spacecraft to re-enter within 2 weeks.

Progress to date:
As of July, 2020, a total of 7 impulse-bit measurements have been performed on orbit, with 2 more planned. Perigee lowering campaigns have been completed to reach 400 and 300 km altitudes. Final orbit lowering burns will target a perigee of ~180 km, and are projected to occur in mid-August, 2020.

References:

[1] Marotta, V., “On-orbit performance of the BCP-100 green propellant infusion mission (GPIM),” Small Sat Conference 2020, virtual talk. Paper SSC20-II-03.

Comm. avail.	TRL	Aerospace-tested
	7	NO

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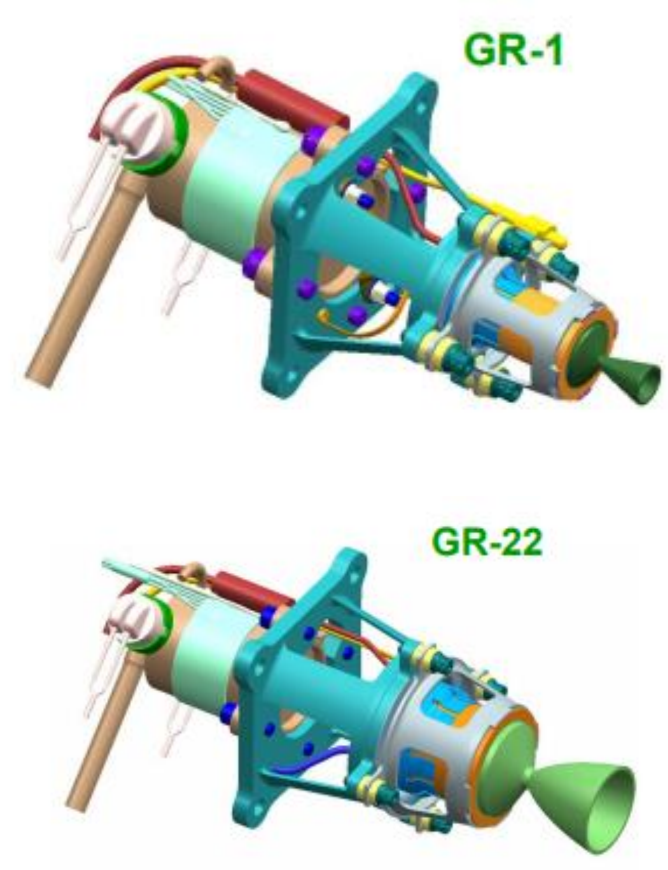
DISTRO A: Approved for public release. OTR-2024-00338

GR-1 (1N), GR-22 (22N) Green Monopropellant (aka MPS-230) Aerojet Rocketdyne/Ball Aerospace [1 of 3]

Propulsion Technology	Green Monopropellant
Manufacturer/Country	Aerojet Rocketdyne/Ball Aerospace (USA)
TRL	7
Size (including PPU)	0.33kg
Design satellite size	1U and larger
Isp (s)	235s (1N), 250 (22N)
Thrust type/magnitude	1N thruster: 0.4 to 1.1 N (continuous), 23,000 N*s (total impulse), 8 mN*s (impulse bit, min) 22N thruster: 8 to 25 N (continuous), 74,000 N*s (total impulse), 116 mN*s (impulse bit, min)
Delta-V (m/s)	
Propellant	AF-M315E
Power consumption (W)	1N thruster: 12W (valve) + 10W (preheat power) 22N thruster: 28W (valve) + 30W (preheat power)
Flight heritage (if any)	Flown on GPIM (aka STP-2, ~200 kg, launched June 2019)
Commercially available	YES
Last updated	*08/2020*



Aerojet Green Monopropellant thrusters

Additional comments:

[References 1-4][Jan 2019][Thruster and missions, general info]

Under development as a self-contained module to allow independent assembly at Aerojet Rocketdyne for subsequent integration into the bus, the GPIM demonstration payload, illustrated in Figure 3 and shown in schematic in Figure 2, will deliver 50% more impulse than a comparably-packaged hydrazine system. Designed to attach to the Ball Aerospace BCP-100 bus via its standard payload interface plate (PIP), the GPIM demonstration payload comprises a simple, single-string, blow-down AF-M315E advanced green monopropellant propulsion system employing four 1N attitude-control thrusters and a single 22N primary divert thruster. The propellant feed manifold's principal components, consisting of a standard diaphragm propellant tank, latch valve, and service valves, represent all flight-proven (TRL 9 with hydrazine propellant) designs selected specifically for the long-term compatibility of their materials of construction with AF-M315E.

A major effort of the GPIM program is to mature and qualify all AF-M315E propulsion system components for this mission, and for infusion on future space missions. An extensive materials compatibility test campaign is currently underway to confirm that all materials in system components that are wetted with the AF-M315E propellant are fully compatible, or material replacement of known incompatibles. The thruster valve requires the most extensive modifications to ensure it is AF-M315E compatible. All wetted surfaces for the thruster valve, service valve, latch valve and propellant filter will be manufactured from materials which are fully compatible with this propellant. The service valves being updated requires minor changes to all the sealing subcomponents. The latch valve is being evaluated to determine if any modifications to its materials is required. The system filter is the only system component that does not require any changes since its propellant wetted surfaces are already compatible.

Through the Green Propellant Infusion Mission (GPIM), NASA is developing a green alternative to conventional chemical propulsion systems for next-generation launch vehicles and spacecraft. Led for NASA's Space Technology Mission Directorate by Ball Aerospace & Technologies Corp., the project seeks to improve overall propellant efficiency while reducing the handling concerns associated with the highly toxic fuel hydrazine. The space technology infusion mission also strives to optimize performance in new hardware, system and power solutions while ensuring the best value for investment and the safest space missions possible. The Green Propellant Infusion Mission is scheduled to launch in 2018.

References:

[1] Masse, R., Spores, R., Allen, M., et al., "Enabling High Performance Green Propulsion for SmallSats," 29th Small Satellite Conference, SSC15-XI-6.
[2] Spores, R., Masse, R., Kimbrel, S., McLean, C., "GPIM AF-M315E Propulsion System," 49th AIAA Joint Propulsion Conference, AIAA 2013-3849.
[3] https://www.nasa.gov/mission_pages/tdm/green/index.html
[4] https://en.wikipedia.org/wiki/Green_Propellant_Infusion_Mission

	7	NO
Comm. avail.	TRL	Aerospace-tested

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GR-1 (1N), GR-22 (22N) Green Monopropellant (aka MPS-230)
Aerojet Rocketdyne/Ball Aerospace [2 of 3]

Additional comments:

[Reference 1][June 2019][GPIM mission]
• May 21, 2019: Ball Aerospace, a partner in the new NASA Green Propellant Infusion Mission (GPIM) announced their Ball Aerospace-built small spacecraft arrived in Florida today to prepare for a June 2019 launch on board a SpaceX Falcon Heavy rocket. GPIM is NASA's first opportunity to demonstrate a new "green" propellant and propulsion system in orbit – an alternative to conventional chemical propulsion systems.
- GPIM is a sustainable and efficient approach to spaceflight, and the new propellant will demonstrate the practical capabilities of a Hydroxyl Ammonium Nitrate fuel and oxidizer blend, called AF-M315E. This innovative, low toxicity, "green" propellant was developed by the Air Force Research Laboratory. GPIM is part of NASA's Technology Demonstration Missions program within the Space Technology Mission Directorate.
- Dr. Makenzie Lystrup, vice president and general manager, Civil Space, Ball Aerospace stated that GPIM was a truly collaborative effort, working with their partners, NASA, Aerojet Rocketdyne, Air Force Research Laboratory, U.S. Air Force and SpaceX. They are proud to be part of this historic mission to test a new 'green' propellant on board Ball's flight-proven small satellite, helping to provide science at any scale.
- Ball Aerospace is responsible for system engineering; flight thruster performance verification; ground and flight data review; spacecraft bus; assembly, integration and test; and launch and flight support. The GPIM bus uses the smallest of the Ball Configurable Platform (BCP) satellites, which is about the size of a mini refrigerator, and was built in just 46 days. The BCP provides standard payload interfaces and streamlined procedures, allowing rapid and affordable access to space with flight-proven performance.
• March 31, 2016: GPIM recently took another major step toward demonstrating the capabilities of a new propellant that is safer to handle on the ground and more efficient for thrusters in space. The GPIM spacecraft has passed a major flight readiness milestone marking the successful completion of functional and environmental testing of its systems and software, and is on track for launch in early 2017.
• Oct. 5, 2015: The propulsion subsystem for NASA's Green Propellant Infusion Mission has been integrated onto the spacecraft, moving the mission another major step toward scheduled launch in 2016.
• August 19, 2015: NASA's Green Propellant Infusion Mission to develop a high-performance, low-toxicity fuel and propulsion system for spacecraft has passed a major milestone. A green propellant propulsion subsystem, built by Aerojet Rocketdyne in Redmond, Washington, has been delivered to the mission's prime contractor, BATC (Ball Aerospace & Technologies Corp.) in Boulder, Colorado.
- The green propellant propulsion subsystem consists of a propellant tank and five 1 N thrusters that will use the new fuel. Because AF-M315E burns hotter than hydrazine, it required new metals to withstand the temperatures in the thrusters aboard the propulsion system.

[Reference 2][Aug 2019][GPIM mission status]
Ball Aerospace has officially commissioned NASA's Green Propellant Infusion Mission (GPIM) and begun on-orbit testing of a non-toxic, high-performance propellant. GPIM launched on June 25, 2019 at 2:30 a.m. EDT on board a SpaceX Falcon Heavy rocket.
Over the next thirteen months, Ball Aerospace and its partners will test the thruster capabilities by verifying the propulsion subsystem, propellant performance, thruster performance and spacecraft attitude control performance. The primary mission of testing the thrusters and fuel will be complete within three months followed by testing of the secondary science payloads.

References:
[1] https://directory.eoportal.org/web/eoportal/satellite-missions/g/gpim
[2] https://2019.smallsatshow.com/2019/07/09/ball-aerospace-sees-green-in-the-sky-successful-small-sat-on-orbit-testing-of-green-fuel/

🛒	7	NO
Comm. avail.	TRL	Aerospace-tested

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GR-1 (1N), GR-22 (22N) Green Monopropellant (aka MPS-230) Aerojet Rocketdyne/Ball Aerospace [3 of 3]

Additional comments:

[Reference 1][Aug 2020][GPIM mission on-orbit data]

There is now on-orbit data from the GPIM mission. This was reported at the SmallSat 2020 virtual conference.

GPIM program was awarded in 2012. The GPIM flight system is comprised of the ESPA class BALL BCP-100 spacecraft bus and the Green Propellant Propulsion System (GPPS), designed and built by Aerojet Rocketdyne which uses green propellant AF-M315E. Flight system was completed in 2015, and put into storage until Spring 2019, due to Falcon Heavy development schedule.
Mission objectives included qualifying the propulsion system through a system of demonstrations and tests, totally ~11,000 total thruster pulses:
-Characterization of thruster efficiency over the life of the system across a range of tank pressures to understand thruster performance. Do this by determining thruster impulse bit at the end and beginning of life and after each delta-v campaign. This consisted of 60-s long firings, followed by 30 pulses of 200 ms each, commanded on each of the 4 ACS thrusters, spaced 10 seconds apart. The change in spacecraft attitude determines thruster impulse bit, i.e. performance.
-Perform series of 4 perigee lowering campaigns. Performed 3 burns, each ~6 minutes long. Once thrusters reached steady state operation, excellent pointing performance was maintained during delta-v maneuvers.
-Demonstrations of thruster-based attitude control modes. Holding attitude on thrusters and managing reaction wheel momentum, then dumping total system momentum via thruster detumble.
-At end of mission, burn remaining propellant to lower perigee under 180 km altitude, and expect spacecraft to re-enter within 2 weeks.

Progress to date:
As of July, 2020, a total of 7 impulse-bit measurements have been performed on orbit, with 2 more planned. Perigee lowering campaigns have been completed to reach 400 and 300 km altitudes. Final orbit lowering burns will target a perigee of ~180 km, and are projected to occur in mid-August, 2020.

References:

[1] Marotta, V., “On-orbit performance of the BCP-100 green propellant infusion mission (GPIM),” Small Sat Conference 2020, virtual talk. Paper SSC20-II-03.

Comm. avail.	TRL	Aerospace-tested
(cart icon)	7	NO

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NanoFEEP (GO-2) [1 of 2]

Propulsion Technology	FEEP
Manufacturer/Country	TU Dresden (Germany), now commercialized by Morpheus Space
TRL	7* (thruster has not yet launched, though core technology, NanoFEEP, has been demonstrated)
Size (including PPU)	Dry mass 160g, wet mass 170g, Total system size = 90x25x43 mm. 4 NanoFEEP systems (8 thrusters in total) can be integrated into 1U [3]
Design satellite size	1U or larger
Isp (s)	1000 to 6000s [1,2], 3000 to 8500s [3]
Thrust type/magnitude	4X thrusters, 8 to 22 uN per thruster [2] Dynamic thrust range 1 to 20 uN, maximum 40 uN, total impulse max 3400 N*s [3]
Delta-V (m/s)	
Propellant	Gallium metal
Power consumption (W)	700 mW (at 2 uN thrust) per thruster [1], 150 to 500 mW [2] 0.2 to 3W [3]
Flight heritage (if any)	UWE-4 (launched Dec 2018) demonstrated core technology, however the thruster package as it is marketed has not yet launched to our knowledge
Commercially available	YES
Last updated	*12/2023*


GO-2 [3]

Additional comments:
[Reference 1] [Jan 2019][UWE-4 mission and thruster info]
The technical objective of the UWE-4 mission is the in-orbit demonstration and characterization of an electric propulsion system for 1U CubeSats. For this, the project cooperated with TU Dresden who developed the NanoFEEP propulsion system. The system consists of the thruster heads and two dedicated power processing units. The thrust is generated through ionization and subsequent acceleration of small amounts of Gallium fuel. The fuel is stored in the thruster heads (0.25 g each) and is heated to a temperature of about 50C at which the Gallium in liquid and flows due to capillary forces along the porous needle to its tip. An electric voltage of up to 12 kV between the needle and the extractor cathode ejects the ions from the thruster by electrostatic force. The required voltage is generated from the unregulated battery voltage on one of the two PPUs which can provide up to 250 uA of current. Each PPU can interface and power two thruster heads and one neutralizer individually. A single thruster can generate continuously a thrust level of up to 8 uN with peaks of 20 uN and requires approximately 700 mW at 2 uN thrust.

References:
[1] Bangert, P., Kramer, A., Schilling, K., “UWE-4: Integration State of the First Electrically Propelled 1U CubeSat,” SSC17-WK-47.
[2] Bock, D., Tajmar, M., “Highly miniaturized FEEP propulsion system (NanoFEEP) for attitude and orbit control of CubeSats,” Acts Astronautica, Vol 144, 2018.
[3] http://www.morpheus-space.com/documents/M-Space%20Products.pdf

7* NO
Comm. avail. TRL Aerospace-tested

NanoFEEP [2 of 2]

Additional comments:

[Reference 1] [Jan 2019][Thruster characterization]
With the measured mass efficiency, the specific impulse was calculated as a function of thrust. For determining the generated thrust, our analytical thrust model was used which shows very good agreement with recently performed thrust measurements with the force probe of Kiel University. It was shown that the specific impulse decreases exponential with higher thrust levels starting approximately at 6000 s, but never drops below 1000 s over the whole thrust range. The total efficiency (considering mass efficiency and beam divergence) of the NanoFEEP thrusters depends on the emitted current and lies between 40% at higher thrusts (8 μN) and 90% at low thrust (2 μN). The lifetime (calculated by using results of performed mass efficiency measurements) of one NanoFEEP thruster of around 1800 h for continuous operation at low thrust (1–2 μN) and around 400 h for higher thrusts (8 μN) is only limited by the reservoir size and consequently by the amount of propellant stored in one thruster. However, the size of the reservoir can be easily increased to extend the thruster's lifetime. The here presented design of the NanoFEEP thrusters results in a highly miniaturized and compact thruster module which has a diameter of only 13mm (including housing) and a length of 21 mm. The total weight of one thruster head is less than 6 g.

[Reference 2, 3][March 2019][Morpheus Space]
Morpheus Space is a small company which is a spin-off from TU Dresden. “After 7 years of tireless development at the tu dresden, the spin-off, Morpheus Space has successfully ignited the world's smallest ion beam thruster on the "UWE-4" nano-satellite. Four of the thumb-sized thrusters are located on UWE-4, the 1 kg nano-satellite of the University of Wurzburg. This enabled the Germany-based company to operate the first electric thruster in this satellite size in space. The primary objective of the satellite mission is to test the propulsion system in orbit in order to obtain space qualification, the final and most important milestone.”
“The company team includes Daniel Bock (CEO), István Lőrincz (CBO), Christian Schunk (CTO), Christian Boy (Head of Production), Philipp Laufer (Head of R&D) and Prof. Martin Tajmar (Advisor).”

[Reference 4 and 5][March 2019][Mission status, UWE-4]
“February 27, 2019: After 7 years of tireless development at the TU Dresden, the spin-off, Morpheus Space has successfully ignited the world's smallest ion beam thruster on the UWE-4 CubeSat mission. Four of the thumb-sized thrusters are located on UWE-4, the 1 kg CubeSat of the University of Würzburg.”
No on-orbit data is available yet as of March 2019.

[Reference 6][August 2019][Mission status, on-orbit data for UWE-4]
The thruster system was turned on in Feb 2019. Each thruster head contains 0.25 g Gallium as propellant and can create a thrust of up to 20 μN and thus a torque of up to 0.8 μNm. Measured thrust (from the measured rotation rate of the spacecraft) was 6 uN. Theoretical thrust was estimated at ~5 uN.

References:
[1] Bock, D., Tajmar, M., “Highly miniaturized FEEP propulsion system (NanoFEEP) for attitude and orbit control of CubeSats,” Acts Astronautica, Vol 144, 2018.
[2] http://www.spacedaily.com/reports/SusMorpheus_Space_qualifies_the_worlds_smallest_satellite_propulsion_system_in_orbit_999.html
[3] http://www.esa.int/Our_Activities/Space_Engineering_Technology/TTP2/MORPHEUS_Cutting-edge_spacecraft_propulsion/(print)
[4] https://directory.eoportal.org/web/eoportal/satellite-missions/u/uwe-4
[5] http://satnews.com/story.php?number=262938185
[6] Kramer, A., Bangert, P., Schilling, K., “Hybrid attitude control on-board UWE-4 using magnetorquers and the electric propulsion system NanoFEEP,” SSC19-WK1-02

Comm. avail.	TRL	Aerospace-tested
	7*	NO

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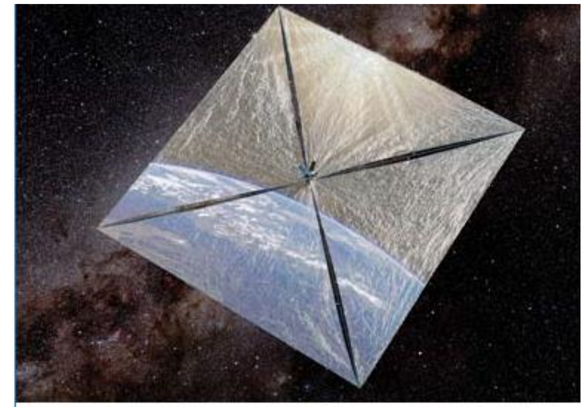
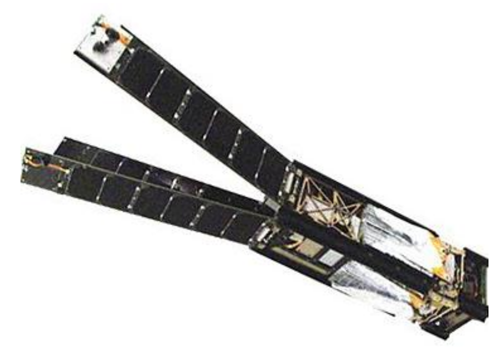
Solar Sail (Planetary Society) [1 of 2]

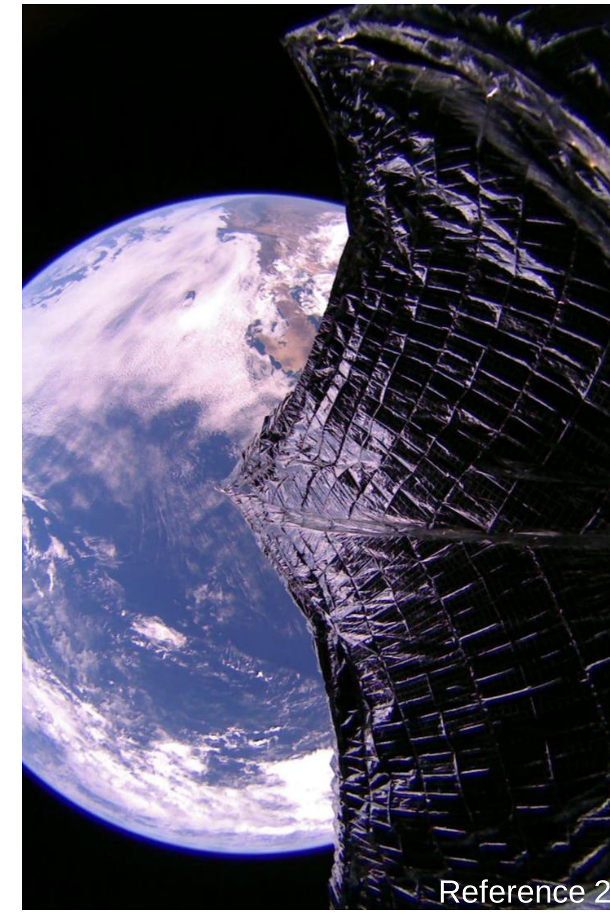
Propulsion Technology	Solar Sail - propellantless
Manufacturer/Country	Planetary Society (USA)
TRL	7
Size (including PPU)	3U
Design satellite size	3U
Isp (s)	N/A
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	None
Power consumption (W)	
Flight heritage (if any)	Light Sail 1 (2015 launch), Light Sail 2 (June 2019)
Commercially available	No
Last updated	08/2020





LightSail (before deployment) [The Planetary Society]

Reference 1



Reference 2

Additional comments:
[Reference 1, 3][June 2020][General mission info]
LightSail, developed by The Planetary Society, will demonstrate that sunlight alone can propel a spacecraft in Earth orbit. It is a follow up mission to the failed Cosmos 1 project.
Taking advantage of the technological advances in micro- and nano-spacecraft over the past five years, The Planetary Society will build LightSail based on a 3 Unit Cubesat spacecraft. One unit will form the central electronics and control module, and two additional units will house the solar sail module. Cameras, additional sensors, and a control system will be added to the basic Cubesat electronics bus.
LightSail will have four triangular sails, arranged in a diamond shape resembling a giant kite. Constructed of 32 square meters of mylar, LightSail will be placed in an orbit over 800 kilometers above Earth, high enough to escape the drag of Earth's uppermost atmosphere. At that altitude the spacecraft will be subject only to the force of gravity keeping it in orbit and the pressure of sunlight on its sails increasing the orbital energy. The mission will give a good, clean trial of sunlight as a means of propulsion.
LightSail 1 was launched in 2015 in a low earth orbit to verify the deployment of the sail, although in this orbit the atmospherical drag prevents solar sailing. LightSail 1 suffered a software problem after two days, causing the computer to freeze. As it did not respond to reboot commands, it was hoped, that a random radiation induced reboot might solve the problem. The reboot happened after a few days and communications was re-established. The sail was finally deployed on 7 June 2015. Due to the increased drag, the satellite reentered the atmosphere on 15 June 2015 after 25 days on orbit.
LightSail 2 was deployed from the Prox 1 microsatellite in a higher orbit to perform its own solar sailing mission. It deployed its sail on 23 July 2019. On 31 August, the Planetary Society declared the mission a success, as it had raised the apogee of its orbit by nearly two kilometers in four days after deployment, while lowering the apogee.
The Planetary Society announced not to plan a follow-on mission, but to share the technology with others.

References:
[1] https://space.skyrocket.de/doc_sdat/lightsail-1.htm
[2] http://www.planetary.org/blogs/jason-davis/lightsail-2-weeks-solar-sailing.html
[3] Mansell, J., Spencer, D., Plante, B., Fernandez, M., Gillespie, C., Bellardo, J., Diaz, A., Betts, B., Nye, B., "Orbit and attitude performance of the LightSail 2 solar sail spacecraft," AIAA-2020-2177

Comm. avail.	TRL	Aerospace-tested
NO	7	NO

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Solar Sail (Planetary Society) [2 of 2]

Additional comments:

[Reference 1][Aug 2020][General mission info]
Lightsail2 has been funded entirely through private donors, with contributions from more than 50,000 people around the world. Primary mission has been concluded and was successful, and is now in the extended mission phase. It is the first small satellite mission to demonstrate controlled solar sailing, and provides a critical step along the solar sailing technology roadmap, leading to future science and infrastructure applications. The solar sail has successfully slow the orbit decay from 34 m per day (uncontrolled, with no solar sail), to 20 m per day. This demonstrates that the solar sail has been successful on orbit. The Aerospace Corporation provided the on-board cameras for this mission.

References:
[1] Spencer, D., Betts, B., Bellardo, J., Plante, B., Diaz, A., Mansell, J., "The LightSail 2 controlled solar sailing demonstration mission," Small Sat Conference 2020, virtual talk. Paper SSC20-II-01.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

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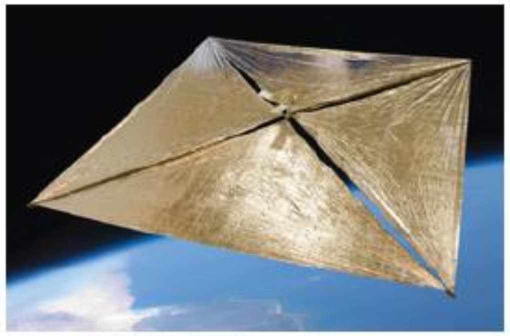
NanoSail-D (aka NanoSail-D2)

Propulsion Technology	Solar Sail (Propellant-less)
Manufacturer/Country	NASA (USA)
TRL	7
Size (including PPU)	1-3U
Design satellite size	
Isp (s)	n/a
Thrust type/magnitude	n/a
Delta-V (m/s)	
Propellant	None
Power consumption (W)	
Flight heritage (if any)	FASTSAT (2010)
Commercially available	NO
Last updated	06/2020

The FASTSAT spacecraft bus outfitted with six payloads. Credit: NASA

[1]



NanoSail-D deployed

[1]

Additional comments:

[Reference 1, 2][June 2020][Flight information]
Outfitted with six technology and atmospheric experiments, FASTSAT lifted off from Kodiak in late fall 2010. Approximately 20 minutes after launch, FASTSAT separated from the launch vehicle for orbital insertion. Thirty minutes later, FASTSAT automatically powered up to begin initial checkout operations, and the Marshall Center contacted the spacecraft and began on-orbit operations. For the first 11 days after launch, the spacecraft and the experiments went through an on-orbit commissioning phase. The next 180 days were focused on science operations. A checkout and performance analysis of each science instrument was performed. Then, one by one, each experiment was turned on to perform its science objectives. Upon completion of the science phase, additional characterization of the spacecraft was performed to test additional flight objectives. The experiments were performed in parallel to test the overall abilities of the spacecraft. This lasted approximately 120 days.
NanoSail-D was jointly designed and built by NASA's Marshall Space Flight Center and NASA's Ames Research Center. ManTech/NeXolve Corporation also provided key sail design support. The NanoSail-D experiment is managed by Marshall and jointly sponsored by the Army Space and Missile Defense Command, the Von Braun Center for Science and Innovation and Dynetics Inc. Ground operations support was provided by Santa Clara University, with radio beacon packets received from amateur operators around the world.

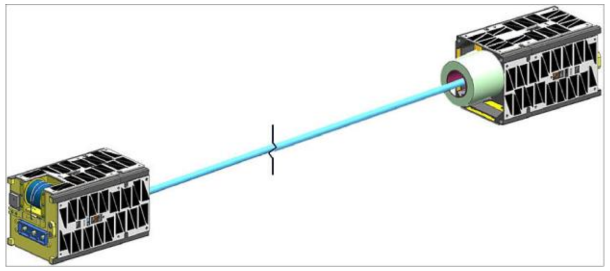
References:
[1] https://www.nasa.gov/centers/marshall/pdf/709025main_FASTSAT_Facts_11_2012.pdf
[2] Alhorn, D., Casas, J., Agasid, E., Adams, C., Laue, G., Kitts, C., O'Brien, S., "NanoSail-D: The small satellite that could!," SSC11-VI-1

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

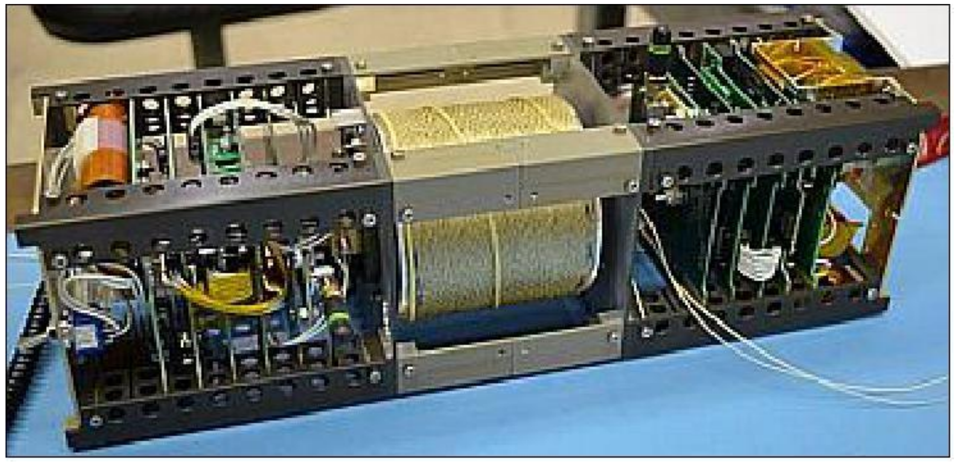
DISTRO A: Approved for public release. OTR-2024-00338

TEPCE electrodynamic tether

Propulsion Technology	Tether (propellant-less)
Manufacturer/Country	Naval Research Laboratory (NRL) (USA
TRL	7
Size (including PPU)	<1U
Design satellite size	TEPCE is 3U
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	None
Power consumption (W)	
Flight heritage (if any)	TEPCE, aboard STP-2 (2019)
Commercially available	NO
Last updated	06/2020



[1]



[1]

Additional comments:

[Reference 1][June 2020][Flight info]
TEPCE is a tethered spacecraft being built by U.S. NRL (Navel Research Laboratory), Washington D.C. to demonstrate electrodynamic propulsion in space. Electrodynamic propulsion holds the promise of limitless propulsion for maneuvering of spacecraft without using expendable fuel. The spacecraft, in its orbital configuration, will consist of two CubeSat end masses attached to the end of 1 km of electrically conducting tether.

Electrodynamic propulsion works on electromagnetic principles similar to an electric motor. The magnetic field in an electric motor attracts an electric current that flows through the windings of the armature causing the armature to spin. In space, the Earth has a naturally occurring magnetic field and for TEPCE, the tether wire serves the purpose of the armature. By inducing an electric current to flow along the tether, a mutual attraction between the Earth's magnetic field and the tether will occur. This electromagnetic attraction can propel TEPCE to higher altitudes or to change the orientation of its orbit. TEPCE is a 3U CubeSat demonstration of emission, collection, and electrodynamic propulsion. Two nearly identical endmasses with a stacer spring between them are used in TEPCE, which separate the endmass and start deployment of a 1 km long braided-tape conducting tether. TEPCE will use a passive braking to reduce speed and hence recoil at the end of electrodynamic current in either direction. The main purpose of this mission is to raise or lower the orbit by several kilometers per day, to change libration state, to change orbit plane, and to actively maneuver.
April 7, 2020: According to information of Jerome Pearson, President of Star Technology and Research, Inc. (Mount Pleasant, SC), TEPCE deployed on 17 November 2019 and re-entered on 1 February 2020. TEPCE actually did change its orbit slightly, but was limited by the power available (around 50 watts from solar cells on the body of the 3U CubeSat).

References:
[1] https://eoportal.org/web/eoportal/satellite-missions/content/-/article/tepce

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

I2T5 Iodine cold gas thruster [1 of 2]

Propulsion Technology	Cold gas
Manufacturer/Country	ThrustME (France)
TRL	7
Size (including PPU)	~0.5U, 0.9 kg (wet)
Design satellite size	3U and larger (Robusta is 3U)
Isp (s)	
Thrust type/magnitude	0.15 to 0.4 mN [1], 40-75 N*s total impulse [2]
Delta-V (m/s)	
Propellant	Iodine
Power consumption (W)	12W warm-up, 6W operating, 1W standby [7]
Flight heritage (if any)	Xiaoxian1-08 (Chinese 6U CubeSat) (launched Nov 2019) [2] Slated for ROBUSTA-3A (2021) [1] Slated for LEMUR 3U (Spire Global) Q4 2022 [6]
Commercially available	YES
Last updated	12/2023

THRUSTME

I2T5

COLD IODINE THRUSTER

FLIGHT PROVEN

The only solution with flight heritage for its category of thrust and size! ThrustMe's I2T5 is a non-pressurized cold gas propulsion system operating with solid iodine propellant. It is a stand-alone and fully integrated system that includes propellant storage, flow control, power processing unit (PPU), thermal management, and intelligent operation, all embedded into a 0.5U form factor. Its standardized architecture allows for short lead times and batch production to better serve constellation needs.

PRODUCT INFORMATION

FITTED FOR THE NEEDS OF ANY NANO-SATELLITE
- Longer lifetime
- Orbit adjustments
- End-of-life disposal
- Collision avoidance
- Proximity operations
- AOCS

INTELLIGENT AND USER-FRIENDLY
- Platform agnostic
- System shipped pre-filled
- Off-the-shelf solution with reduced lead times
- Engineering models available on demand
- AIT support and video instructions
- Batch production

PERFORMANCE & SPECIFICATIONS

Thrust	up to 0.35 mN
Total impulse	up to 75 Ns
Form factor	0.5 U
Total wet mass	0.9 kg
Power consumption	<1 W standby 5 W in steady state firing
Start-up time	10 min

ADVANCED SAFETY FEATURES
- Iodine storage in microgravity
- Storage tank with iodine resistant coatings
- Patented pipeless design
- Safety sealing for transport and storage
- Built-in-self test
- Passive during launch and in stand-by mode
- Embedded fail-safe modes
- Rad-hardened main controller

INTERFACE

Input Voltage	12 - 28 V
Bus interface	I^2C, CAN

The I2T5 allows for up to **46% cost savings** and **38% lifetime extension** for 3U cubesat constellations through much faster phasing while also providing collision avoidance capabilities.

ThrustMe
4bis Rue des Petits Ruisseaux
91370 Verrières-le-Buisson
France

contact@thrustme.fr
www.thrustme.fr

ThrustMe offers advanced mobility solutions for the growing space industry which is facing new challenges due to the rise of satellite constellations. As experts in in-space propulsion and satellite orbital manoeuvring strategies, we enable a future where space is used sustainably to create value both on Earth, and beyond. Founded in 2017, ThrustMe has a complete portfolio of game-changing turnkey propulsion products that have already been tested in space and delivered to clients worldwide. The company made history in 2019 and 2020 with the world's first in-orbit demonstration of iodine-fuelled electric propulsion systems: a technology that has the potential to revolutionize the entire industry.

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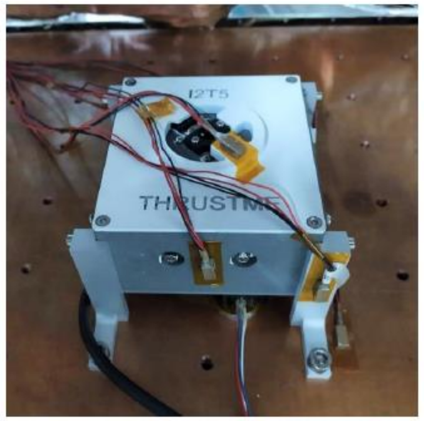
[7]



[1]

Flight unit on Xiaoxiang1-08 [2]

Additional comments:
[Reference 1-2][Aug 2020][Mission info and thruster testing]
The ROBUSTA-3A developed by the CSUM Spatial Centre with funding from the Van Alen Foundation (FVA), the French Aerospace Center (CNES) and Interreg Sudoe Program through the European Regional Development Fund (ERDF) will demonstrate a 3-axis stabilized platform of the CSUM and support the GEMMOC project by gathering water content data for improved weather pre-vision in south France. The mission analysis has shown that the mission is feasible under the given circumstances and that one of the drivers is the optimization of the satellite attitude with respect to the Sun during the thrust phase.
The I2T5 is a 0.5U cold gas thruster which operates with iodine as propellant. The core element of the system is the iodine reservoir, which contains iodine in solid state. It is self-pressurized, and the pressure of the system can be precisely controlled by regulating the vapor pressure of the gas in the reservoir. This is done through the thermal management system, which also maintains the necessary temperatures along the path of the gas to prevent deposition on any component, in order to prevent blockages or clogging. The gas is throttled and accelerated through the nozzle, which then discharges to vacuum, generating the thrust.
The first I2T5 prototype was launched on board the Xiaoxiang1-08, a 6U CubeSat satellite developed by Spacety Aerospace Co., in 2019, following an SSO, 500 km sun-synchronous orbit. On November 16, the sealing system was successfully sublimated on the thruster, performance the first series of short firings with a total power-on time of more than 4 hrs from Nov 16 to 19. The firing, slightly longer than 1 hr, was performed after successfully passing all service and check procedures. The firing duration is insufficient to measure yet the orbital change with only the TLEs of the satellite, and precise GPS tracking will be used for the following firings of the system (to be performed in the first quarter of 2020).

References:

[1] Martinez-Martinez, J., Raanfalskyi, D., Aanesland, A., Laurand, X., Martinez, S., Quinsac, G., "An off-axis iodine propulsion systems for the Robusta-3A mission," Small Sat Conference 2020, virtual talk. Paper SSC20-IX-03.
[2] Martinez Martinez, J., Ragalskyi, D., Zorzoli E., Aanesland, A., "Development, qualification, and first flight data of the iodine based cold gas thruster for CubeSats," IAA-AAS, Roma, 2020.
[3] http://thrustme.fr/
[4] Performance spec sheet: https://www.thrustme.fr/base/stock/ProductBannerFiles/1_20191014-thrustme-i2t5.pdf
[5] Pereira, R. M. "The I2T5: Enhancement of the Thermal Design of an Iodine Cold Gas Thruster" Thesis link
[6] https://smallsatnews.com/2022/09/02/seven-propulsion-systems-from-thrustme-delivered-to-spire-global-for-their-lemur-satellites/
[7] https://www.thrustme.fr/base/stock/ProductBannerFiles/1_thrustme-i2t5.pdf

7

NO

Comm. avail. TRL Aerospace-tested

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I2T5 Iodine cold gas thruster [2 of 2]

Additional comments:

[Reference 1][October 2020][Flight Qual Campaign]

The propellant tank is made of an aluminum alloy coated with a protective layer to prevent the corrosion due to iodine, and have inserts binding the propellant to avoid fracturing during operation (this is also detailed later). The tank is filled inside an inert atmosphere once before flight and delivered to the qualification facilities and later to the integrator without further manipulations of the propellant. The flow control subsystem is formed by the following elements: the static ON/OFF valve (optional), the thermally controlled nozzle, which provides the acceleration of the sublimated propellant, and a storage sealing system with a double barrier which prevents iodine vapor leaks through the exhaust during the ground manipulations, and therefore minimizing the risks of contamination of other equipment during the long time storage in harsh environments.
The qualification campaign of the I2T5 thruster has been performed during the summer of 2019 and included the following tests: random and sine vibration, shock, ambient thermal cycling and thermal vacuum cycling. Before the testing, an extensive modelling has been performed in order to identify highest risk points and develop a mitigation plan. The main levels of the qualifications were following: 2g at 5 Hz on Y and Z, 10g at 11.18 Hz on X (single frequency), 5 to 8 Hz at 4 mm on Y and Z, 8 to 100 Hz at 1g on Y and Z, 5 to 8 Hz at 4.5 mm on X (sweep), 5.9 G rms during 1min 30s 20 to 2000 Hz (random), 50 to 800 Hz: 30 to 1500 g and 800 to 5000 Hz: 1500 g, 3 impacts per direction and 3 oct/min (shock). The campaign has been passed successfully, which resulted in the assembly and integration of the flight model 4 into the 6U satellite Xiaoxiang1-08 at Spacety Aerospace Co. (China) facilities during September-October 2019.

[Reference 1][October 2020][In-Flight Operations]

The first I2T5 prototype was launched on board of the Xiaoxiang1-08, a 6U CubeSat satellite developed by Spacety Aerospace Co., on the 3rd of November 2019, following an SSO, 500 km sun-synchronous orbit. The purpose of the mission includes the demonstration of the laser communications technology payloads on board, as well as the first firing tests of an iodine thruster in space. The electronics were first tested on the 7th with successful connection and reading of the temperatures of the system. On the 16th of November, the sealing system was successfully sublimated on the thruster, performing the first series of short firings with a total power-on time of more than 4 hrs from the 16 to the 19th of November. The firing, slightly longer than 1 hr was performed after successfully passing all service and check procedures. The firing duration is insufficient to measure yet the orbital change with only the TLEs of the satellite, and precise GPS tracking will be used for the following firings of the system. These firings will be performed during the first quarter of 2020, after the rest of the payloads have conducted their experiments. The only inconvenience encountered up to now is a reduction of 6.5 degrees in the temperature of the thermal management system of the unit with respect to the desired value, which may reduce up to a 25% of the desired thrust.

[Reference 2, 3][Jan 2021][Thruster Overview]

ThrustMe is the first company to develop an iodine-based propulsion system for SmallSat applications. ThrustMe (which was part of the Laboratory of Plasma Physics at CNRS-Ecole Polytechnique at that time) decided to develop a propulsion system based on the RF gridded ion thruster operating on iodine technology. As a spin-off of this activity, another low-end propulsion system has been developed which is a cold gas thruster operating with solid iodine (I2T5). The original purpose was based on both the intention of providing a demonstration platform for an iodine propellant subsystem, and on the fact that there is a definite lack of non-pressurized low energy and low power propulsion systems for small CubeSats (such as 3U platforms) on the market. It should be mentioned that both the cold gas and the gridded ion propulsion systems developed at ThrustMe shared some parts of the development in common, ramping up the development process for both of them. They have developed a cold gas thruster (I2T5) and an RF ion thruster (NPT30-I2). The I2T5 is a self-pressurized, iodine-propelled cold gas thruster. Essentially, iodine propellant in a solid state residing inside the reservoir is sublimated using resistive heating. The iodine gas then pressurizes the reservoir and accelerates through the nozzle. On November 3, 2019, the I2T5 became the first ever iodine-based propulsion system to successfully reach space.

[Reference 5][Oct 2022][Mission information]

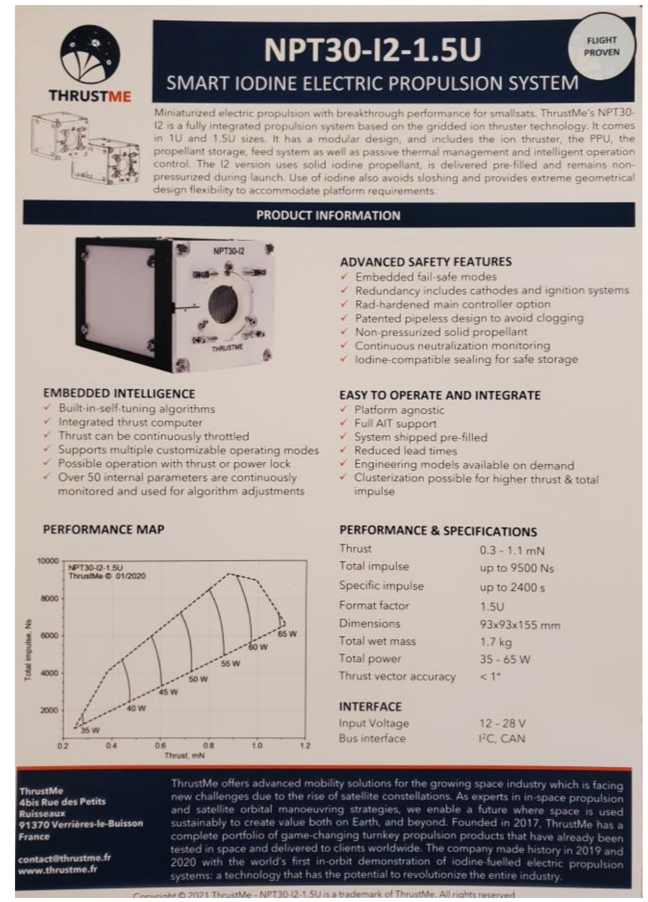
ThrustMe has delivered seven propulsion systems to Spire Global, Inc. for that company's LEMUR 3U satellites as it continues to build upon its fully deployed constellation of more than 100 satellites. Spire's LEMUR satellites will carry ThrustMe's I2T5 iodine cold gas system on the next launch that is scheduled for Q4 2022 onboard a SpaceX Falcon 9 rideshare mission. These propulsion systems will enable Spire to optimize its constellation performance and prepare for upcoming deorbiting regulations. For the first time, Spire will integrate and use propulsion on its LEMUR satellites.

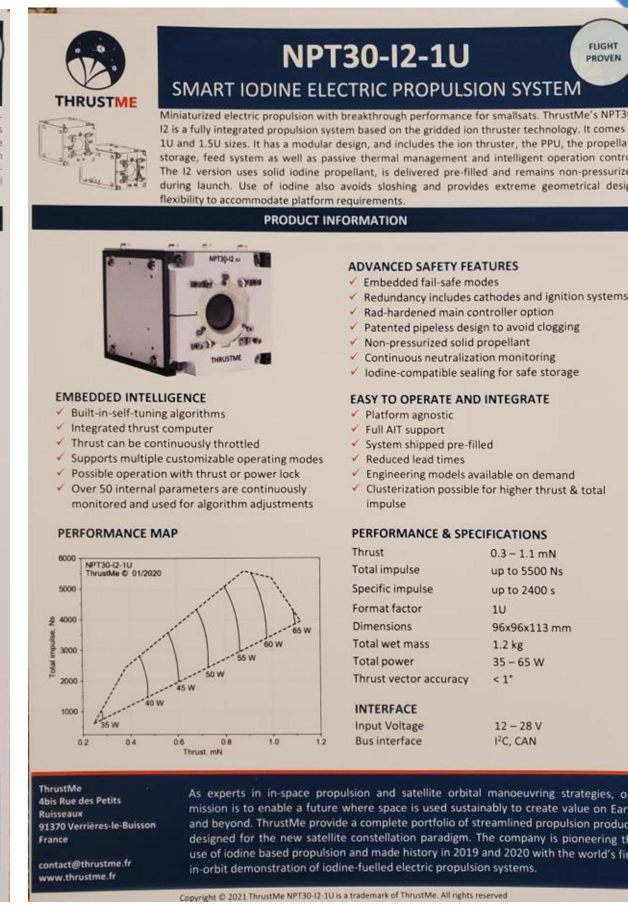
References:
[1] Information from panel talk at SmallSat Symposium 2019 (open discussion)
[2] Martinez Martinez, J., Ragalskyi, D., Zorzoli E., Aanesland, A., "Development, qualification, and first flight data of the iodine based cold gas thruster for CubeSats," IAA-AAS, Roma, 2020.
[3] http://thrustme.fr/
[4] https://spacenews.com/electric-propulsion-startup-thrustme-gets-2-8-million-from-european-commission/
[5] https://smallsatnews.com/2022/09/02/seven-propulsion-systems-from-thrustme-delivered-to-spire-global-for-their-lemur-satellites/

	7	NO
Comm. avail.	TRL	Aerospace-tested

Neptune (Iodine ion thruster)/NPT-30-I2 (aka NPT30) ThrustMe [1 of 5]

Propulsion Technology	RF Ion thruster
Manufacturer/Country	ThrustMe (FRANCE)
TRL	7 (Xenon version TRL7, Iodine version TRL7)
Size (including PPU)	Two different unit are available: 1U (9.6 x 9.6 x 11.3 cm), 1.2 kg [6], 1.5U (9.3 x 9.3 x 15.5 cm), 1.5 kg [6]
Design satellite size	3U and larger
Isp (s)	>1000 at max power [1-4], 700 to 1000s [5] 1U: up to 2400s (total impulse up to 5500 N-s), 1.5U: up to 2400s (total impulse up to 9500 N-s) [6]
Thrust type/magnitude	0.2 – 0.7 mN [1-4], 0.6 to 1 mN [5], 1U: 0.3 to 1.1 mN [6], 1.5U: 0.3 – 1.1 mN [6]
Delta-V (m/s)	
Propellant	Xenon or Iodine (with focus on iodine [5, 9])
Power consumption (W)	35 to 65W (both 1U and 1.5U units)
Flight heritage (if any)	Hisea-1 (launched Dec 2020) [10] BEIHANGKONGSHI-1 satellite (launched Nov 2020) [11] Projected launch 2019 (customer unknown) [3,4] Slated for GOMX-5 (2021) [6, 13] Xenon version slated for INSPIRESAT-4/ARCADE (2020) [8] Iodine version slated for NorSat-TD (to be launched early 2022) [12, 15]
Commercially available	YES
Last updated	*12/2023*





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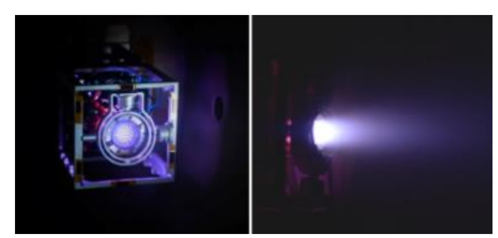
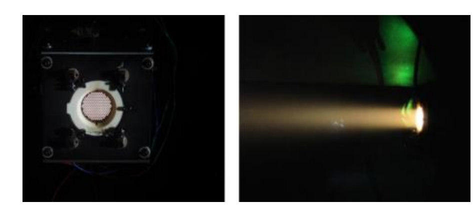


NPT30-I2 1U firing using xenon



NPT30-I2 1U firing using iodine [5]

NPT30-I2 1U flight unit [9]

Additional comments:
Notes and references on next chart…

Comm. avail. | 7 TRL | NO Aerospace-tested

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Neptune (Iodine ion thruster)/NPT-30-I2
ThrustMe [2 of 5]

Additional comments:

[References 1, 2][Jan 2019][General info]
ThrustMe, in partnership with the Laboratory of Plasma Physics and SATT Paris-Saclay is developing a complete propulsion system based on a patented ion thruster technology, called "Neptune". A miniaturized version with the thruster, power processing unit and solid propellant is fully imbedded into a one-unit Cubesat module (a 10 cm cube of 1 kg). The thruster has strong technology heritage from classical ion thrusters, but with significant innovation in the acceleration mechanisms using RF voltages applied to a set of grids, instead of the conventional DC voltage. This RF acceleration leads to a continuous ion beam neutralized by electrons exiting the thruster in short instants during the RF cycle. In this way, there is no need for an additional electron neutralizer, and thus the system is ideal for miniaturization as well as cost effective mass production. Solid iodine is integrated into the thruster body to simplify the propellant storage and flow control. The PPU based solely on radio-frequency modules operating in the MHz frequency range is also developed and can operate with powers from 20 to 60 W. This RF power is used for plasma generation, ion acceleration, neutralization and iodine flow control allowing the power system to be fully integrated into the 1U Cubesat module. The complete system is tested in various vacuum facilities where time-averaged and time-resolved electrostatic measurements of beam currents/fluxes and ion energies are compared with direct thrust measurements.In 2017, ThrustMe raised $1.9M from Kima Ventures and a collection of US and Europeans angle investors to begin developing their ion thruster. Two versions of the module are under development using Xe and I2, and the latter will have an internal propellant tank for simplified fluidics system. The Xe version of the propulsion module has been tested in a medium vacuum chamber available at LPP and also in a large chamber at ONERA (2017). The test campaign is not yet finished, however the preliminary results agrees well with the theoretical predictions.

References:
[1] Rafalskyi, D., Aanesland, A., "A Neutralizer-Free Gridded Ion Thruster Embedded into a 1U CubeSat Module," IEPC-2017-94
[2] http://thrustme.fr/
[3] Information from panel talk at SmallSat Symposium 2019 (open discussion)
[4] https://spacenews.com/electric-propulsion-startup-thrustme-gets-2-8-million-from-european-commission/
[5] Martinez, J., Rafalskyi, D., Aanesland, A., "Development and testing of the NPT30-I2 Iodine ion thruster," IEPC-2019-811.
[6] https://gomspace.com/news/payload-collaboration-initiated-for-the-gomx-.aspx
[7] https://spacenews.com/french-startup-thrustme-found-fast-route-to-orbit-through-chinas-spacety/
[8] Srivastava, S., Kandala, A., Gacal, G., "INSPIRESAT-4/ARCADE: A VLEO mission for atmospheric temperature measurements and ionospheric plasma characterization," SSC19-VIII-05.
[9] Performance spec sheet: https://www.thrustme.fr/base/stock/ProductBannerFiles/2_npt30-i2-1u-1-5u-datasheet.pdf
[10] https://smallsatnews.com/2021/01/03/iodine-electric-propulsion-to-become-a-critical-subsystem-for-sar-constellations/
[11] https://smallsatnews.com/2020/11/06/thrustmes-iodine-propulsion-system-launched-aboard-spacetys-smallsat/
[12] https://smallsatnews.com/2021/04/28/trial-integration-completed-by-norwegian-space-agency-of-thrustmes-propulsion-system-for-norsat-td/
[13] https://smallsatnews.com/2022/06/15/thrustme-wins-an-esa-gstp-contract-to-develop-qualify-an-electric-propulsion-system/
[14] Flyer from SmallSat Symposium, Feb 2023
[15] https://smallsatnews.com/2023/04/18/the-thrustme-npt30-i2-iodine-electric-propulsion-system-launched-on-board-the-norsat-td-satellite/

Comm. avail.	7	NO
	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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Neptune (Iodine ion thruster)/NPT-30-I2
ThrustMe [3 of 5]

Additional comments:

[Reference 1][Jan 2019][Company news]
In Aug 2018, ThrustMe received 2.4 million euros ($2.8 million) from the European Commission to commercialize an electric propulsion system for small satellites. ThrustMe received its European Commission funding Aug. 1 following a May selection through the EC's Horizon 2020 research and innovation investment program, ThrustMe founder and chief executive Ane Aanesland told SpaceNews. ThrustMe is commercializing technology from France's Ecole Polytechnique plasma physics laboratory and CNRS, the French National Center for Scientific Research. The 18-month-old company has raised 4.6 million euros to date, and in April moved into a newly built 300-square-meter headquarters in Paris. The company has 15 people on its payroll, according to Aanesland. Aanesland said ThrustMe anticipates shipping five thrusters for two customers next year, and scaling up by 2020 to be able to ship 50 to 70 thrusters a year.

[Reference 2][March 2019][Thruster development]
Ane Aanesland was present at the SmallSat Symposium and discussed her thruster. Some concerns with the iodine thruster include deposition/contamination on cold optics and corrosion on cold metals. For example, iodine will corrode copper. Deposition of iodine on cold surfaces can be expected for temperatures below -55C, so spacecraft components may require heating to prevent deposition. Also, working with iodine in the lab requires some special handling and pumping accommodations as it is slightly toxic, will coat laboratory surfaces, and can be corrosive towards some laboratory materials (mainly metals, as previously mentioned). However, one important advantage is that ThrustMe's thruster does not require a neutralizer, and iodine eliminates propellant sloshing concerns. In addition, iodine does not need to be pressurized, and so it requires a fraction of xenon's storage volume. ThrustMe is delivering their first unit in Spring 2019, and within a year, on-orbit data should be available.

[Reference 3][Oct 2019][Thruster development]
The development has been focused on various aspects such as iodine propellant storage and reliable flow control, corrosion risk mitigation, hardware optimization for achieving stable ignition and operation of a plasma discharge and acceleration stages. Iodine corrosion has been studied to be able to predict and estimate the degradation rates of the materials present on the thruster and potentially in a spacecraft, and all key materials have been identified. Flow control was achieved using the orifice-based configuration with a thermally managed propellant tank, where the system design was based on the analytical model presented here. Experimental verification of the flow control system demonstrated generation of the stable iodine flows well corelated with the temperature settings. The plasma ignition and beam acceleration tests have shown successful control of these processes; standard algorithms used for the NPT30 Xenon version required only slight adaptation to be fully compatible with the iodine propellant. Beam measurements in the high thrust / low Isp configuration have confirmed predicted performances of 0.6 – 1 mN thrust and 700 – 1000 s Isp. Future experiments will be focused on studies of a high specific impulse configuration with the Isp values above 1500 s, as well as preparations for the pre-flight endurance testing.

[Reference 4][Oct 2020][Company news]
ThrustMe has been contracted by ESA to demonstrate the world's first iodine electric propulsion in space. After significant support from the French state and the European Commission, ThrustMe announces their first contract with the European Space Agency (ESA) ARTES C&G program in support of the development of a breakthrough technology to solve emerging challenges in space associated with the rise of satellite constellations. ThrustMe has demonstrated groundbreaking achievements in developing electric propulsion systems with unmatched performance for the new space paradigm. "We have leveraged the technology of our existing cold gas system, the I2T5, which was launched last year, and which was the first ever iodine propulsion system tested in space. Our new iodine electric propulsion system, the NPT30, uses plasma generation and beam neutralization technologies that have been under development at ThrustMe since 2017, and have already reached a high-level of maturity through extensive testing and qualification campaigns" says Dmytro Rafalskyi, CTO of ThrustMe.

[Reference 5][Dec 2020][Flight information]
ThrustMe and Spacety have announce that the BEIHANGKONGSHI-1 satellite, carrying the world's first iodine electric propulsion system, was successfully launched into space on a CZ-6 Long March 6 rocket from Taiyuan in China on the November 6 at 04:20 a.m. (Paris time). The BEIHANGKONGSHI-1 satellite includes a ThrustMe NPT30-I2 electric propulsion system which uses iodine propellant. The demonstration of ThrustMe's NPT30-I2 on Spacety's BEIHANGKONGSHI-1 satellite will lead to a significant commercial collaboration between the two companies. The development of the NPT30-I2 flight model used on this demonstration mission was funded via the European Space Agency (ESA) ARTES C&G program. ThrustMe's prior research and development of iodine technology has been supported by the French state via SATT Paris-Saclay, BPIFrance I-LAB and the Centre National d'Études Spatiales (CNES) R&T program. BEIHANGKPNGSHI-1 is the first 12U satellite developed and launched by Spacety and is also the first space mission of the new Spacety satellite platform with advanced modules improved on designs with rich space heritage. The satellite platform is equipped with batteries of 400 Wh and a solar panel of nearly 100 W to support payloads with high power consumption and duty cycle.

References:
[1] https://spacenews.com/electric-propulsion-startup-thrustme-gets-2-8-million-from-european-commission/
[2] Information from panel talk at SmallSat Symposium 2019 (open discussion)
[3] Martinez, J., Rafalskyi, D., Aanesland, A., "Development and testing of the NPT30-I2 Iodine ion thruster," IEPC-2019-811.
[4] https://www.satellite-evolution.com/post/thrustme-contracted-by-esa-to-demonstrate-the-world-s-first-iodine-electric-propulsion-in-space
[5] https://smallsatnews.com/2020/11/06/thrustmes-iodine-propulsion-system-launched-aboard-spacetys-smallsat/

	7	NO
Comm. avail.	TRL	Aerospace-tested

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Neptune (Iodine ion thruster)/NPT-30-I2
ThrustMe [4 of 5]

Additional comments:

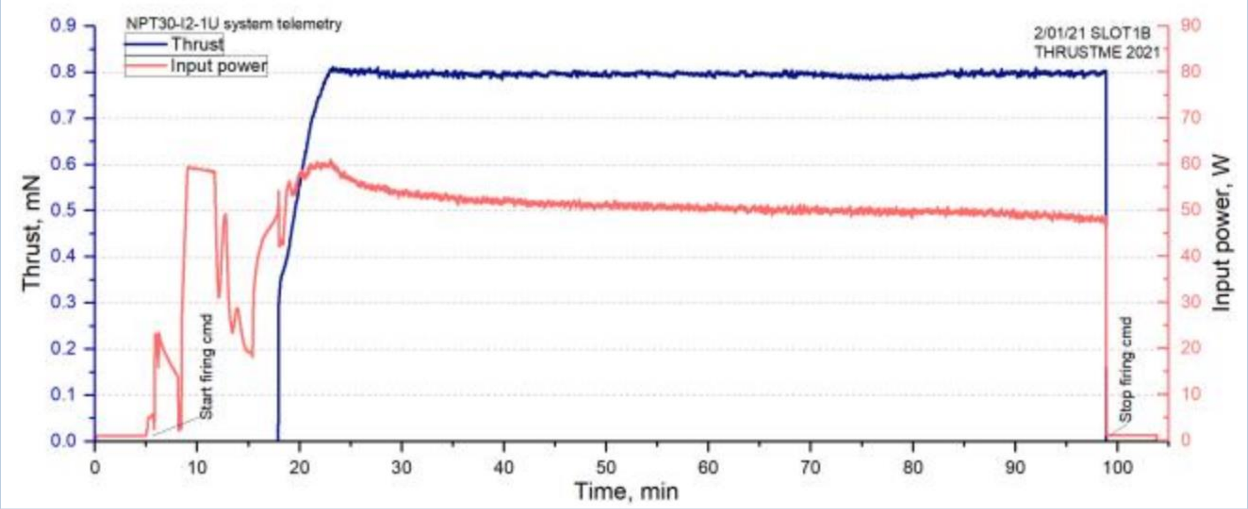
[Reference 1][Jan 2021][Flight information]
ThrustMe and Spacety have announced a new space launch, the 3rd in an ongoing series — this time, Spacety launched their Synthetic Aperture Radar (SAR) satellite, Hisea-1, which is the world's first, commercial, C-band, smallsat SAR with a phased array antenna. On board is ThrustMe's Iodine Electric Propulsion system to provide the satellite with crucial orbit maintenance, collision avoidance and de-orbiting at the end of its three years expected lifetime. The satellite was successfully launched into space on the inaugural flight of the Chinese medium-lift Long March 8 rocket, from Wenchang, China. Hisea-1 has a mass of 180 kg, and uses a phased-array antenna. It has three imaging modes with its finest resolution at 1m x 1m.

[Reference 2][Feb 2021][On-orbit data]
ThrustMe has announced that they have successfully tested the first iodine-fueled electric propulsion system in space aboard the Spacety Beihangkongshi-1 satellite. This world first, on-orbit demo has the potential to transform the space industry. On December 28, 2020, the first iodine electric propulsion system to be launched into space was successfully fired, with a second successful test on January 2, 2021. Both test burns were performed by ThrustMe's NPT30-I2-1U propulsion system onboard the Beihangkongshi -1 satellite from Spacety. The satellite was launched on November 6, 2020, and after several weeks of satellite commissioning, the propulsion system was operated during two, 90-minute burns that resulted in a total altitude change of 700 m. These tests represent the first in-space operation of the NPT30-I2-1U and the first demonstration of iodine as a viable propellant for electric propulsion systems: an important step in accelerating its commercial adoption.

[Reference 3, 4, 5][May 2021][Company news]
On December 28, 2020 ThrustMe performed the first on-orbit tests of an innovative iodine-fueled electric propulsion system, proving its ability to change a CubeSat's orbit. ThrustMe's NPT30-I2-1U, the first iodine electric propulsion system sent into space, is aboard the Beihangkongshi-1, a 12U CubeSat developed by Chinese commercial satellite maker Spacety. A Long March 6 rocket sent the satellite into orbit in November 6, 2020, tagging along with a batch of satellites for Argentina-based remote sensing firm Satellogic. The NPT30-I2 performed two 90-min burns in late December 2020 and early January 2021 resulting in a total orbit altitude change of 700 m.

ThrustMe is preparing to demo the NPT30-I2 in two upcoming missions: 1) a national space agency mission and 2) GOMspace GOMx-5 mission planned for Q2 2022.

From LinkedIn post, the in-flight telemetry is given below. NPT30-I2 seems to generate about 0.8 mN of thrust @ 50 W of input power for 70 mins.



References:
[1] https://smallsatnews.com/2021/01/03/iodine-electric-propulsion-to-become-a-critical-subsystem-for-sar-constellations/
[2] https://smallsatnews.com/2021/01/18/iodine-propulsion-proven-viable-for-smallsats-in-space-by-thrustme-spacety/
[3] https://spacenews.com/french-startup-demonstrates-iodine-propulsion-in-potential-boost-for-space-debris-mitigation-efforts/
[4] https://www.thrustme.fr/our-missions
[5] https://www.linkedin.com/posts/elena-zorzoli-rossi_thruster-propulsion-iodine-activity-6758292292009783297-SAvm

7
NO
Comm. avail. TRL Aerospace-tested

Neptune (Iodine ion thruster)/NPT-30-I2
ThrustMe [5 of 5]

Additional comments:

[Reference 1][May 2021][Upcoming flight]
The Norwegian Space Agency and ThrustMe have announced they have completed trial integration of ThrustMe's NPT30-I2 propulsion system into the NorSat- TD satellite. During the mission, which is on schedule for launch in early 2022, both parties will demonstrate, amongst other things, just-in-time, low-thrust satellite collision avoidance maneuvers—a critical capability for acting on space situational awareness data and ensuring a sustainable space environment.
The NorSat-TD is the Norwegian Space Agency's technology demonstrator mission that will lead the way to Norway's maritime surveillance constellation. Onboard are six essential payloads and innovative technologies to be tested during the mission. One critical goal for the NorSat-TD project is to build up experience in Norway for propulsive satellite operations and ensure space safety by supporting the development of space situational awareness and traffic management systems for Norway's upcoming future missions.

[Reference 2, 3][October 2021][On-orbit performance]
The propulsion system has been launched on the 6th of November 2020 onboard of a 12U platform with possibility to perform relatively long firings (up to 90 minutes) at high power for this class of platforms (50-60 W). After successful satellite commissioning, the first firing operations have been performed starting from December 2020. Multiple firings of 90 minutes each have been performed in different operational modes, having a thrust rage from 0.5 to 0.8 mN and steady power up to 55 W. The propulsion system telemetry downloaded after the firings showed correct
system operation with all major parameters staying within the specified margins.

[Reference 4][June 2023][Company news]
ThrustMe and Turion Space have announced the selection of the ThrustMe's iodine electric propulsion system for the DROID.002 spacecraft. Turion Space will integrate several ThrustMe NPT30-I2-1.5U thrusters to enable the maneuverability for orbit raising and end-of-life disposal to its space-debris observation and characterization mission. The DROID.002 mission serves as the initial asset of a small constellation designed to provide continuous debris monitoring and alert services, known as "resiliency" services. The mission also aims to generate a deeper understanding of space debris, assisting LEO operators and other debris mitigation companies. To ensure the success of the mission, it will rely on ThrustMe's NPT30-I2-1.5U thrusters as a key component. This contract confirms ThrustMe's electric propulsion systems market fit in a worldwide competitive environment and extend the company footprint in the U.S. and adds up to the undisclosed international and U.S. contracts won by ThrustMe. With seven systems already in space. and more than 80 orders, the ThrustMe production line is up with a capacity of 365 propulsion systems per year to be reached by Q1 2024.

[Reference 5][Dec 2023][Company news]
ThrustMe is scaling up production, aiming for one unit per day before the end of 2024.

References:
[1] https://smallsatnews.com/2021/04/28/trial-integration-completed-by-norwegian-space-agency-of-thrustmes-propulsion-system-for-norsat-td/
[2] Rafalskyi, D., Martinez, J., Habl, L., Aanesland, A., "Development and in-flight testing of an iodine ion thruster," Small Satellite Conference 2021, SSC21-XI-04.
[3] Rafalskyl, D., Martinez, J., Habl, L., Rossl, E., Proynov, P., Bore, A., Baret, T., Poyet, A., Lafleur, T., Dudin, S., Aanesland, A.," Nature, Bol 500, November 2021.
[4] https://smallsatnews.com/2023/05/08/thrustme-selected-to-provide-turion-space-with-vital-propulsion-capacities/
[5] https://smallsatnews.com/2023/10/27/thrustme-surpasses-200-orders-doubles-propulsion-system-orders-in-four-months/

	7	NO
Comm. avail.	TRL	Aerospace-tested

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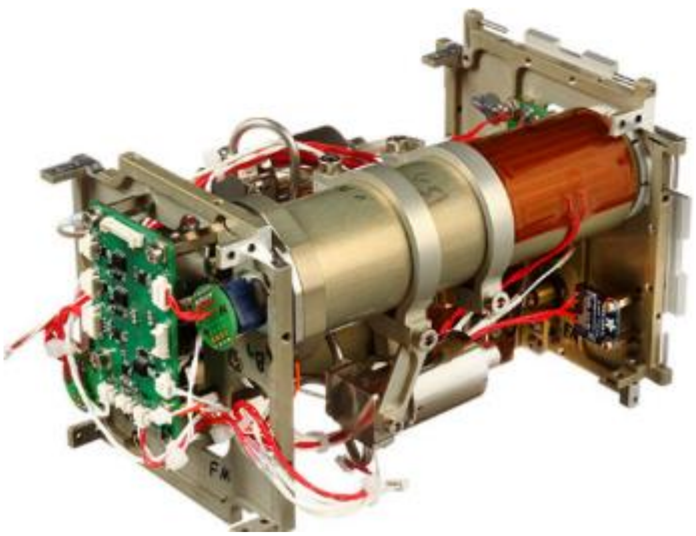
Enabling Propulsion System "EPSS" [1 of 2]
JSC NanoAvionika

Propulsion Technology	Green Monopropellant
Manufacturer/Country	NanoAvionics (LITHUANIA), also called "JSC NanoAvionika" Has US-based location as of 2021.
TRL	7
Size (including PPU)	1U
Design satellite size	3U and larger
Isp (s)	225s
Thrust type/magnitude	100 mN (nominal, continuous), 300 mN (peak, continuous) 0.002 N*s (impulse, minimum)
Delta-V (m/s)	10 cm/s for a 3U CubeSat (flight data), 200 m/s for a 3U CubeSat (design)
Propellant	ADN-based green propellant
Power consumption (W)	0.05W (idle), 5-7.5W (peak), 4.5W (operational)
Flight heritage (if any)	LituanicaSat-2/QB50 (2017) M6P (2019) [4]
Commercially available	Yes
Last updated	*01/2022*



Front and back of the monopropellant thruster

Additional comments:

[References 1-3][Jan 2019][General info]
On July 5, 2017, a successful in-orbit test of the first ever chemical propulsion system running on-board a CubeSat was performed. The Enabling Propulsion for Small Satellites (EPSS) system, designed and developed by NanoAvionics, provided the 3U CubeSat LituanicaSAT-2 with 10 cm/s of delta-v, making an evident change on its orbit parameters. The CubeSat was launched into polar sun-synchronous orbit on June 23, 2017. To test the EPSS, NanoAvionics ran a cold-start program, which is the most complicated in terms of the complexity of the satellite systems involved, followed by a train of pulses with a total duration of 2 seconds, reaching 0.3 g mass of the monopropellant to be used. The average thrust reached was 127 mN, followed by steady peaks of 300mN, demonstrating that the system works nominally as planned. Orbital change of approximately 200 meters has been observed, analyzing TLEs of the particular epoch when the experiments were performed.
LituanicaSAT-2 consists of three main modules: a science unit with the FIPEX (Flux-Φ-Probe Experiment) sensor for QB50, a functional unit with NanoAvionics Command and Service module plus power unit and an experimental unit with the "green" propulsion system. JSC NanoAvionika has been contracted by Vilnius University to build a satellite platform and a propulsion system for LituanicaSAT-2. The propulsion system is a state of art green monopropellant micro-thruster able to perform high impulse orbital maneuvering and drag compensation capabilities for a small scale satellite. The system is designed to provide 0.3 N maximum thrust and about 200 m/s of ΔV. It is powerful enough to perform impulsive Hohman orbital transfer, orbit shape corrections or even change of inclination for a 3 kg satellite. The fuel used is a LMP103S green monopropellant fuel blend developed by ECAPS (Sweden). The propulsion system is developed by design team from JSC NanoAvionika.

References:
[1] https://n-avionics.com/propulsion-systems/small-satellite-green-chemical-propulsion-system-epss/
[2] https://n-avionics.com/press-release/successful-orbit-test-first-ever-chemical-propulsion-system-running-board-cubesat-performed/
[3] http://space.skyrocket.de/doc_sdat/lituanicasat-2.htm
[4] https://space.skyrocket.de/doc_sdat/m6p.htm

Comm. avail.	7 TRL	NO Aerospace-tested

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DISTRO A: Approved for public release. OTR-2024-00338

Enabling Propulsion System "EPSS" [2 of 2]
JSC NanoAvionika

Additional comments:

[References 1-2][Jun 2020][Flight info]
M6P is a 6U-CubeSat project being developed by the Lithuanian NanoAvionics as a pathfinder mission for their M6P cubesat platform. It is a ride-share mission for two customers. During the mission NanoAvionics will be testing their 6U (called M6P – Multipurpose 6U Platform) platform based on a modular and highly integral design which extends payload volume. The M6P will be 4th Lithuanian built Cubesat and a lot of knowledge and experience will be used gathered from still active LituanicaSat-2 mission.
The M6P will be equipped with active stabilization: integrated magnetorquers and momentum wheels. There will also going to be installed in house build EPS, Flight computer with integrated ADCS, and COMMs. Satellite will also include 2 UHF transceivers (for redundancy purposes) that will work with deployable dual dipole turnstile type antennas.
The M6P platform also includes propulsion system capable to perform maneuvers such as orbital deployment, orbit maintenance, atmospheric drag compensation, precision flight in formations, orbit synchronization and atmospheric drag compensation resulting in extended satellite orbital lifetime. The propulsion unit also provides satellites with decommissioning utility at the end of mission, meeting the space debris mitigation requirements of ESA and NASA. So called "green" chemical propulsion system to reach TRL7 was previously launched with PSLV C-38 and successfully tested in orbit during LituanicaSat-2 mission.Propulsion experiment onboard M6P will bring propulsion system developed by NanoAvionics to TRL9.
To ensure the practical reliability of the platform, radiation-resistant components and design implementations have been incorporated to support critical systems such as the Flight Computer, Payload Controller, Electric Power System and Communication System. The platform is optimized to have a nominal 5 years operational lifetime in a Low-Earth Orbit (LEO) environment.
The M6P satellite carries ride-share payloads for two customers:

- SpaceWorks Orbital will be testing their IoT radio technology by demonstrating ground to space communications for their low-cost IoT architecture for their Blink Astro business line
- Lacuna Space will demonstrate the receiving of LoRaWAN signals from terrestrial IoT devices to relay the data through the company's cloud-based Lacuna Network

Additionally, the satellite will demonstrate NanoAvioncs' M6P nanosatellite technology.
The satellite was released into a lower than planned orbit due to a delayed deployment, reducing the orbital life time slightly

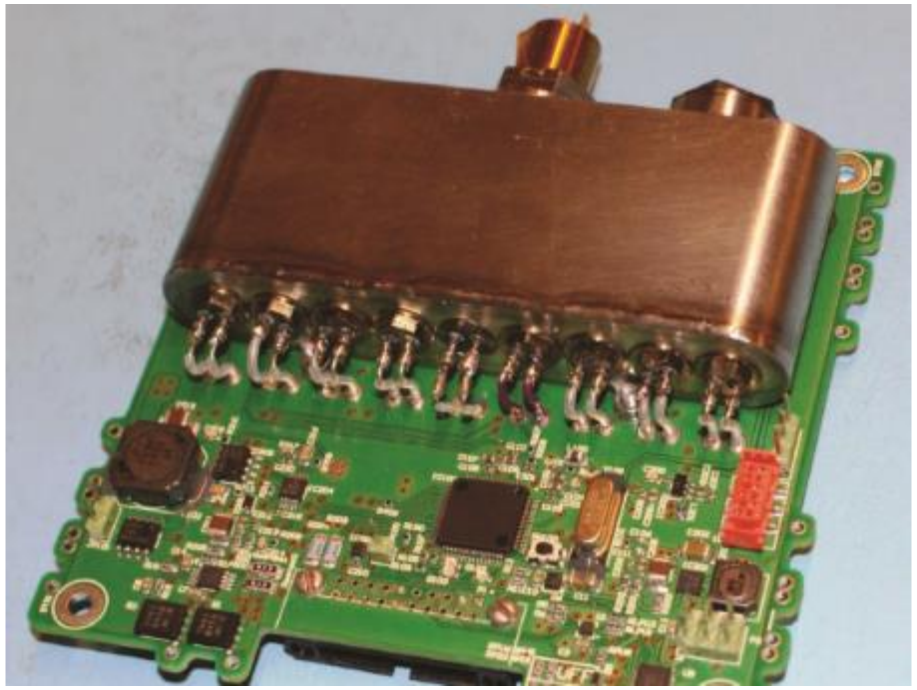
References:
[1] https://space.skyrocket.de/doc_sdat/m6p.htm
[2] https://nanoavionics.com/projects/lituanicasat-2-satellite-mission/
[3] http://mstl.atl.calpoly.edu/~workshop/archive/2016/Summer/Day%202/Session%207/5_VytenisBuzas(Alternate).pdf

	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

T³ μPS [1 of 2]
TU Delft/Delfi Space

Propulsion Technology	Cold/warm gas
Manufacturer/Country	TNO/TU Delft/University of Twente/SystematIC BV (NETHERLANDS) Delfi Space(commercialized)
TRL	7
Size (including PPU)	120g, 1/4U
Design satellite size	1U, 3U (Delfi was 3U, 3kg)
Isp (s)	>30s (~70s in warm gas mode)
Thrust type/magnitude	6 mN
Delta-V (m/s)	
Propellant	Nitrogen
Power consumption (W)	0.05W (idle), 0.37W (thrust), 13W (~10s, ignition)
Flight heritage (if any)	Delfi-n3Xt (2013)
Commercially available	YES
Last updated	*01/2021*



Cold gas propulsion board

Additional comments:

[Reference 1-3][Jan 2019][General and flight info]

Delfi-n3Xt is a Dutch nanosatellite which is operated by Delft University of Technology. It was launched on 21 November 2013 and was a three-unit CubeSat used to demonstrate propulsion and communications systems. In the Netherlands, TNO is active in the development of CubeSat propulsion systems based on a proprietary solid propellant cool gas generator technology. This research led to the development, in collaboration with TU Delft and the University of Twente, of the T3μPS micro-propulsion system. On orbit, TNO reported success of their propulsion unit:

“Two cold gas generators have been fired already and ten thrust events have been performed and recorded with detailed pressure and temperature measurements. According to TNO, this already has proven a successful demonstration of their system.”

The unit appears to be for sale via Delfi Space. Delfi Space is the small satellite program of Delft University of Technology for education, technology demonstration and to enhance capabilities of very small satellites. According to their website:

“TNO, in cooperation with the TU Delft, SystematIC BV and the University of Twente, developed a micropropulsion system based on cold gas generators called the T3μPS. The system is developed with relative orbit control of multiple spacecraft in mind, such as the DelFFi mission. Cold Gas Generators (CGGs) store nitrogen in a solidified form. When electro-thermal energy is added, the nitrogen releases in gaseous state and enters in a plenum which will buffer the pressurized gas. A valve and nozzle are used to release the gas into space to provide controlled thrust. The nozzle is produced with a novel femto-laser technique by the University of Twente. At TU Delft, a special test bench is created which can measure millinewton thrust levels while filtering out the micro vibrations of the building.

References:
[1] Cervone, et al, “Micro-Propulsion Research: Challenges towards future nano-satellite projects,” Article from Leonardo Times, March 2013
[2] https://www.tudelft.nl/en/2014/lr/delfi-n3xt-already-performed-a-major-part-of-its-mission/
[3] http://www.delfispace.nl/delfi-n3xt/micropropulsion-payload

Comm. avail.	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

T^3 μPS [2 of 2]
TU Delft/Delfi Space

Additional comments:

[Reference 1][Jan 2021][on-orbit data]
The maximum pressure reached can be approximated by examining the pressure vs. time curves of the gas release. The valve was opened delivering thrust on the 29th of November with duty cycles 75% and 50% and again on the 3rd of December, dropping the pressure to around 700 mbar before ignition of the second CGG. The opening of the valve and the subsequent lowering of the pressure inside the plenum indicate that gas is being expelled and thrust being delivered.
The second cool gas generator was successfully ignited and decomposed on the 6th of December 2013. Ignition required 10.3 W of power for 8 s and was again well within specification. The successful ignition was followed by a second thrust series, this time with 100% open valve to determine the complete thrust curve accurately. The valve was opened delivering thrust on the 9th of December 2013. On the 12th the third CGG was scheduled to be ignited, but no response was received. All remaining CGG′s were tried but no ignition was observed. This indicates that part of the ignition train (which is non-redundant) failed. The sensors and the valve are still operational and not impacted by the anomaly. The remaining gas was left in the plenum to further evaluate the leak tightness of the plenum. The temperature and time curves at the start of the leak tightness verification period and at the end were recorded.

References:
[1] Guo, J., Bouwmeester, J., Gill, E., “In-order results of Delfi-n3xt: lessons learned and move forward,” Acta Astronautica, Vol. 121, April-May 2016.
https://www.sciencedirect.com/science/article/pii/S0094576515004373

	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

SPT-70 (and advanced version, SPT-70M)

Propulsion Technology	Plasma Thruster
Manufacturer/Country	Fakel (Russia)
TRL	5-6
Size (including PPU)	1.5 kg, 198x146x98 mm
Design satellite size	Large (>50kg)
Isp (s)	1470 s at 700W [3]
Thrust type/magnitude	39 mN at 700W [3]
Delta-V (m/s)	
Propellant	Xenon, Krypton
Power consumption (W)	~600W to 1000W Nominal 700W [3]
Flight heritage (if any)	Yes, claimed. Mission unknown and unverified. [3]
Commercially available	Unknown
Last updated	03/2021

SPT-70

Propellant	Xe
Discharge voltage, V	300
Discharge current, A	2,23
Discharge power, W	670
Thrust, mN	39
Specific impulse, s	1470
Power-to-thrust ratio, W/mN	16,1
Lifetime, h Lifetime (cycles)	>3100 >3000
Mass, kg	1,5
Dimensions, mm	198×146×98
Development level	FM

SPT-70M

Propellant	Xe			Kr		
Discharge voltage, V	300			300		
Discharge current, A	2,00	2,67	3,33	2,00	2,67	3,33
Discharge power, W	600	800	1000	600	800	1000
Thrust, mN	36	48	59	28	37	47
Specific impulse, s	1430	1530	1600	1380	1490	1560
Power-to-thrust ratio, W/mN	15,2	16,7	16,9	21,4	21,6	21,3
Lifetime, h Lifetime (cycles)	>7000 >11000					
Mass, kg	2,6					
Dimensions, mm	200×128×94					
Development level	EM					

[1]

Additional comments:

[Reference 2][March 2021][Thruster flight info]
In the early 80s, EDB Fakel started its serial production of the thruster types SPT-50, SPT-60, and SPT-70. The first satellite equipped with SPT-70, Geizer 1, was launched in 1982; and in 1994, a new SPT-100 model was implemented aboard the communication satellite, Gals-1. Despite the press-release about successful testing of the EOL plasma thruster was published in the Space Investigations periodical in 1974, foreign designers still considered the SPT to be just an attractive theoretical development.

[Reference 3][March 2021][Thruster information]
Authors have claimed up to 3100 hours of demonstrated flight lifetime.

References:
[1] https://fakel-russia.com/en/productions
[2] https://web.archive.org/web/20170206085427/http:/www.fakel-russia.com/en/about/
[3] Kim V., “Stationary plasma thrusters in Russia: problems and perspectives,” Moscow Aviation Institute, 2012.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

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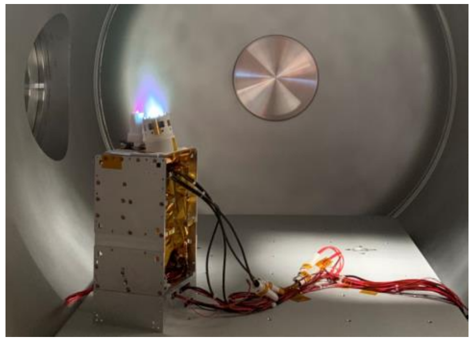
ExoMG-nano [1 of 5]
Exotrail

Propulsion Technology	Hall Effect Thruster
Manufacturer/Country	Exotrail (FRANCE)
TRL	7
Size (including PPU)	2U+ (nano L) and 1U+ (nano S)
Design satellite size	3U and larger, 10 to 30 kg typical M6P, ELO 3 and ELO4 are all 6U satellites. [3, 4, 5]
Isp (s)	800 s at 53W (tested range: 300s to 800s) [2]
Thrust type/magnitude	10 kN*s (total impulse) 1.5 mN (thrust, continuous, nominal) at 53 W (tested range 0.8 mN to 2.1 mN) [2]
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	40 to 50 W [2]. 53 W nominal (tested range 35 to 65 W)
Flight heritage (if any)	NanoAvionics R-2 M6P nanosatellite tech demo (launched Nov 2020) [3, 6] Slated for Eutelsat ELO3 and ELO 4 spacecrafts (2021) [4] Slated for Starfish Space's Otter Pup satellite (launched projected for summer 2023) – unclear exactly which hall thruster model [8]
Commercially available	YES
Last updated	*04/2023*



ExoMG™ – nano L during a coupling test [1]

ExoMG™ – nano thruster and cathode [2]

ExoMG™ – nano EP string relative scale [7]

Additional comments:

[Reference 1,2][Jan 2019][General info]

"Our team successfully proceeded to multiple ignitions of our Hall Effect Thruster (HET) at Plateforme d'Intégrations et Tests (OVSQ/CNRS) in December 2017. This is a major milestone for Exotrail, after 18 months of technical development. We have worked with the LAPLACE/GREPHE laboratory based in Toulouse – world expert in plasma physics applied to space propulsion – for the design of our thruster in order to optimize its performances. This thruster is the smallest Hall Effect Thruster ever designed and successfully ignited in the world.

The rest of the technical development is also going according to plan. Exotrail is aiming at developing a fully integrated thruster with all the necessary components (cathode, fluidics, electronics). We have successfully tested all the key sub-systems and are on our track to have a first version of our integrated system in mid-2018, only two years after the beginning of our development. This is the result of a great team work but also of the help of our partners – SATT Paris-Saclay, who has been funding our technical development since mid-2016, the Centre National de la Recherche Scientifique (CNRS), the Synchrotron Soleil and the Université Versailles Saint-Quentin en Yvelines. Exotrail is developing a range of electric propulsion systems for small satellites (10-100kg). Thanks to the use of Hall Effect technology, our thruster boasts a superior thrust-to-power ratio than competing systems. A high thrust means that you can access your operational orbit quicker than with other technologies (3 to 6 times quicker than FEEP, VAT or GIT electric thrusters) or double the power available for your main payload (vs. the same competing technologies). We provide the best balance between the high fuel efficiency brought by electric technologies and the highest thrust-to-power ratio. We will start official pre-orders in 2019, but you can contact us right now for more info."

References:

[1] https://exotrail.com/news/2018-01-15/32-we-successfully-ignited-the-smallest-het-ever-designed/
[2] https://exotrail.com/product/
[3] https://exotrail.com/news/2019-10-02/49-exotrail-delivers-its-first-hall-effect-propulsion-system-prototype-for-in-orbit-demonstration-mission/
[4] http://www.parabolicarc.com/2020/02/24/exotrail-secures-contract-with-aac-clyde-space-to-equip-spacecraft-for-eutelsats-elo-3-and-4/
[5] http://www.satnews.com/story.php?number=2134011401
[6] https://smallsatnews.com/2021/01/14/space-mobility-on-orbit-demo-success-by-exotrail/
[7] https://spacenews.com/wp-content/uploads/2021/01/rsz_exomg_with_prime_minister-879x485.jpg
[8] https://smallsatnews.com/2023/02/07/starfish-space-to-perform-leo-satellite-docking-using-electric-propulsion/

	7	NO
Comm. avail.	TRL	Aerospace-tested

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ExoMG-nano [2 of 5]
Exotrail

Additional comments:

[Reference 1][June 2020][Mission info – M6P]
Exotrail has delivered a Hall-Effect propulsion system demonstrator to NanoAvionics, a nano-satellite manufacturer and mission integrator based in Lithuania.
NanoAvionics and Exotrail partnered to integrate Exotrail's propulsion system into its M6P nanosatellite bus which is scheduled to be launched by the beginning of 2020 on a PSLV rocket. Exotrail along with its key supply chain partners has fully designed, built, integrated and qualified a Hall-Effect propulsion system demonstrator, in the space of only 10 months. This unprecedented high-speed roll-out of an electric propulsion solution has been made possible thanks to the amazing involvement of their investors, key partners and dedicated staff in Massy and Toulouse. Exotrail expects to release the first results from this demonstration mission during the first half of 2020. The software developed by Exotrail (ExoOPS™) for mission design and operation will serve as a key propulsion ground segment element for the mission. Future demonstration and customer missions are scheduled for 2020 and 2021 on 6U, 12U and microsatellites. Exotrail next objectives are to complete the life test qualification of its products in 2020 and ramp-up its production output to cope with current demand.

[Reference 2, 3][June 2020][Mission info – Eutelsat]
Exotrail will equip AAC Clyde Space, Europe's leaving nanosatellite solutions specialist, with cutting-edge propulsion solutions for their customer, the global satellite telecommunications leader Eutelsat, for its ELO 3 and ELO 4 spacecrafts.The French company will provide propulsion systems for the two 6U CubeSats which will be manufactured and delivered to orbit by AAC Clyde Space.
The Eutelsat mission is a precursor to a potential constellation called ELO (Eutelsat LEO for Objects). The contract is to be delivered before the end of the year, both satellites will be launched in 2021.

[Reference 4][June 2020][Ground testing]
The performance metrics and the plume characteristics of a miniaturized Hall thruster were investigated. The thruster head of the ExoMG-nano propulsion platform was experimentally characterized while operated with a PPU prototype. The thruster head consisted of a miniaturized Hall thruster and a thermionic cathode mounted on a metal baseplate. The tests were performed at ONERAs facility in Palaiseau and the diagnostic tools included a thrust balance, a one-grid Faraday probe, and a commercial ion energy analyzer. At about 53W of total input power and at a total xenon flow rate of 2:7 sccm (anode plus cathode), the thrust, total specific impulse and total efficiency were 2mN, 800 s and 15 %, respectively. At the same power, the mass utilization efficiency was about 67 %, the divergence efficiency was 70-75% and the half-angle where 90% of the plume ion current is found was 68-72 degrees.

[Reference 5][Aug 2020][Company info]
Currently Exotrail has 20 employees in Massy, France and 5 in Toulouse, France. They have raised more than 17 million euros to date. They have both public and non-public customers.

[Reference 6][Feb 2021][Mission info]
Exotrail reports the full success of the first-ever cubesat mission equipped with Hall-effect electric propulsion technology. Through an In-Orbit Demonstration mission launched to LEO on November 7, 2020, onboard a PSLV rocket, Exotrail nominally ignited its ExoMG™ Hall-effect electric propulsion system on the first attempt. ExoMG™ electric propulsion system is being operated with ExoOPS™, Exotrail's operation software, simultaneously validating not one but two products of the company. This mission opens up a new era for the space industry: ExoMG™ is the first ever Hall-effect thruster operating on a sub-100 kg spacecraft. This success is strengthened by the extremely short development timeframe, with less than a year from design to delivery.

References:
[1] https://exotrail.com/news/2019-10-02/49-exotrail-delivers-its-first-hall-effect-propulsion-system-prototype-for-in-orbit-demonstration-mission/
[2] http://www.parabolicarc.com/2020/02/24/exotrail-secures-contract-with-aac-clyde-space-to-equip-spacecraft-for-eutelsats-elo-3-and-4/
[3] http://www.satnews.com/story.php?number=2134011401
[4] Gurciullo, A., Jarrige, J., Lascombes, P., and Packan, D., “Experimental performance and plume characterization of a miniaturized 50W Hall thruster,” 36th IEPC, Vienna, Austria, 2019.
[5] Small Sat public virtual forum
[6] https://smallsatnews.com/2021/01/14/space-mobility-on-orbit-demo-success-by-exotrail/

🛒	7	NO
Comm. avail.	TRL	Aerospace-tested

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ExoMG-nano [3 of 5]
Exotrail

Additional comments:

[Reference 1 - 5][April 2021][Thruster]
Exotrail is a startup electric propulsion company based out of Palaiseau, France. In addition to fully-integrated EP strings which include the ExoMG HET, thermionic cathode, propellant management system (PMS) and on-board computer and power processing unit (PPU), Exotrail offers mission design software to its customers. Exotrail has developed two HET models: the ExoMGTM - nano (50 W HET) and the ExoMGTM - micro (100 W HET). The ExoMGTM - nano is fully designed by Exotrail while the ExoMGTM - micro is co-developed with ICARE (CNRS). On 11/7/2020, the Exotrail ExoMGTM - nano was launched as part of NanoAvionic's R-2 tech demonstration mission [4][5]. Following this, on January 12th, Exotrail announced the success of the first on-orbit demonstration of a miniaturized HET [4]. Exotrail reported nominal operations of their software ExoOPS and ignition on first attempt [4]. This achievement makes Exotrail the first ever HET operating <100W on a 6U Cubesat < 100 kg.

The ExoMGTM - nano comes in two configurations: 1) nano S and 2) nano L based on total Isp mission requirements [1].

The thruster has a diameter of 3.5 cm and uses an externally mounted LaB6 cathode [2]. Because of its miniaturization, thermal design is important for the ExoMG. The total input power required varies between 35 W to 70 W. The ExoMGTM - nano had its performance and plume properties fully characterized in [2]. The thrust ranges between 0.8 mN @ 35 W and 2.1 mN @ 60 W. The anode flow rates range between 2.5 – 3.1 sccm and total specific impulse ranges between 300 s @ 35 W and 750 s @ 60 W. Total efficiencies measured do not exceed 16%.

References:

[1] https://exotrail.com/product/
[2] http://electricrocket.org/2019/142.pdf
[3] https://spacenews.com/french-startup-exotrail-raises-13-million-for-propulsion-on-orbit-transport-systems/
[4] https://spacewatch.global/2021/01/exotrail-demonstrated-mini-thruster-for-small-satellites-in-space/
[5] https://www.nanosats.eu/sat/m6p-2

	7	NO
Comm. avail.	TRL	Aerospace-tested

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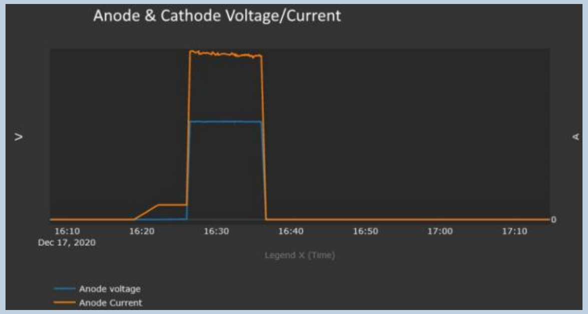
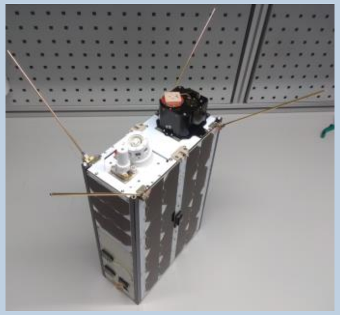
ExoMG-nano [4 of 5]
Exotrail

[Reference 1][April 2021][Company news]
The French new space start-up Exotrail used the 13th European Space Conference to announce the successful in-orbit demonstration of its innovative electric mini-propulsion system. "Exotrail reports full success of first-ever cubesat mission equipped with Hall-effect electric propulsion technology," the company said yesterday. "Through an In-Orbit Demonstration mission launched to Low Earth Orbit on 7th of November 2020 onboard a PSLV rocket, Exotrail nominally ignited its ExoMG Hall-effect electric propulsion system on the first attempt." Hall-effect thrusters are mainly used on large satellites due to their superior efficiency compared to other electric propulsion technologies, Exotrail says. "Legacy systems, however, are the size of a fridge and require kilowatts of power. Exotrail's nanosatellite thruster runs on 50 watts of power and is equivalent in volume to 2 liters of soda."
On top of "designing and packing world-leading innovations at the thruster level", Exotrail claims to have managed the integration of the propulsion system inside the 10 kilograms spacecraft. Small satellite constellations (ranging from 10 to 250 kilograms) "will now be able to quickly change their orbit once in space, giving new capabilities for satellite operators: more flexibility in their launch strategy, dramatic performance increases, collision avoidance and safe de-orbiting to prevent space pollution", Exotrail said.

[Reference 1][April 2021][Company News]
Exotrail posts 3rd party plots to indicate the on-orbit performance of the ExoMG™ - nano aboard the R-2 6U satellite. Additionally, Exotrail shared anode/cathode IV curves to confirm nominal HET op's in space.





ExoMG™ – nano L EP string on the R-2 NanoAvionics M6P CubeSate [1]

[Reference 5][April 2021][Company News]
Exotrail secures contract with AAC Clyde Space to equip their spacecrafts for Eutelsat's ELO3 and 4. Both satellites will be launched in 2021. From Eutelsat website [6], the ELO satellites weigh about 12 kg. Based on [7], the AAC Clyde Space contract will be for the 1U ExoMG™ - nano S models.

[Reference 8][October 2021][On-orbit performance]
On-orbit performance for ExoMG has now been published.
The R2 mission was a successful demonstration of the two main products of Exotrail: its propulsion unit ExoMG™ and its operations software ExoOPS™. This marks the first time a Hall thruster is flown on a <100kg satellite and the first time a permanent magnet Hall thruster is ignited in space. Performances of the thruster have been assessed. A thrust 20% higher than expected is achieved.

[Reference 5][April 2022][Company news]
The French Space Agency, CNES, has selected Exotrail to complete a research and technology study to optimize the operations of mega constellations. The study will focus on MEO and LEO, where thousands of satellites are soon expected to be operational and propelled by electric propulsion. The study will determine the best operational procedures to implement in mega constellation's flight dynamic system, including station keeping and collision avoidance – two critical operations.

References:

[1] https://exotrail.com/news/2021-01-12/100-exotrail-paves-the-way-for-new-space-mobility-with-first-of-its-kind-successful-in-orbit-demonstration-mission/
[2] https://spacewatch.global/2021/01/exotrail-demonstrated-mini-thruster-for-small-satellites-in-space/
[3] https://www.nanosats.eu/sat/m6p-2
[4] https://spacenews.com/india-back-in-action-with-launch-of-earth-observation-satellite-nine-rideshare-small-sats/
[5] https://www.spacenewsfeed.com/index.php/news/4360-exotrail-secures-contract-with-aac-clyde-space-to-equip-their-spacecrafts-for-eutelsat-s-elo-3-and-4
[6] https://www.eutelsat.com/en/satellites/leo-fleet.html
[7] https://spacenews.com/exotrail-demonstrates-miniature-hall-effect-thruster-in-orbit/
[8] Lascombes, P., Montes, M., Fiorentino, A., Gelu, T., Fillastre, M., Gurciullo, A., "Lessons learnt from operating the first Cubesat mission equipped with a Hall thruster," Small Satellite Conference, 2021, SSC21-X1-01.
[9] https://smallsatnews.com/2022/03/23/cnes-mega-constellation-optimization-study-contracted-to-exotrail/

Comm. avail.	TRL	Aerospace-tested
(cart)	7	NO

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ExoMG-nano [5 of 5]
Exotrail

[Reference 1][Aug 2022][Thruster testing]
The THD (thruster head) of the ExoMGTM - nano performed 1130 firing cycles and 188 hours of firing, with a total xenon flow rate in the range of [3.3, 4.5] sccm. The impact of the erosion of the magnetic circuit has changed the discharge properties during the lifetime test. Thus, a new THD for the ExoMGTM – nano has been designed. This new thruster has undergone a partial lifetime test by firing it with long firing. After 300 hours of operation, no impact on the discharge properties during the lifetime test has been observed.

References:
[1] Moriconi, B., Hallouin, T., Gurciullo, A., “Hall thruster ExoMG-micro, ExoMG-nano and low current cathode development at Exotrail: cyclic life testing results,” IEPC-2022-91

	7	NO
Comm. avail.	TRL	Aerospace-tested

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China: Medium power Hall thruster

Propulsion Technology	Hall thruster
Manufacturer/Country	China: SPMI (Shanghai Spaceflight Power Machinery Institute)
TRL	Unknown (estimated at 5-7)
Size (including PPU)	Thruster mass 1.5 kg (PPU unknown)
Design satellite size	unknown
Isp (s)	1600s
Thrust type/magnitude	40 mN
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	650W
Flight heritage (if any)	Unknown
Commercially available	No
Last updated	09/2021

Fig. 4 The picture of mid-power HET

Photo of Hall thruster [1]

Additional comments:

[Reference 1][September 2021][Thruster development]
Hall thruster was selected as a new thruster for the NSSD Chinese geostationary satellite due to its high impulse and high thrust. Research on hall thrusters started in 1996 and have been carried out at SPMI since.
A test facility was inaugurated at SPMI in 1996. It is a 1.2 meter diameter x 3.4 m long test facility, and has two 600 mm diffusion pumps to maintain a base pressure of approximately 10E-3 Pascals, designed for hall thrusters up to 1400W. The facility is currently being used for testing mid-power hall thrusters.
Additional facilities for hollow cathode testing have also been built (a 0.5 m diameter x 1.2 m long facility, with 2X 300 mm cryopumps to maintain vacuum levels below 10E-4 Pascals. A new facility is currently being built at SPMI, a 3m diameter x 9m long facility, for hall thruster plasma diagnostics and plume effects diagnostics.
The reference indicates that there is a thrust measurement system within their test facilities, with a thrust measurement uncertainty of about 10%.
The efficiency of this system is 50%.

References:
[1] Kang, X., Wang, Z., Wang, N., Li, A., Wu, G., Mao, G., Tang, H., Zhao, W., “An Overview of electric propulsion activities in China”, IEPC 2001.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

China: Ion thruster

Propulsion Technology	Ion thruster
Manufacturer/Country	China: Lanzhou Institute of Physics (LIP)
TRL	Unknown (estimated at 5-7)
Size (including PPU)	Unknown for current xenon system, previous mercury model specified as 28 kg [1]
Design satellite size	unknown
Isp (s)	2940s
Thrust type/magnitude	10 to 15 mN
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	400-450W
Flight heritage (if any)	Unknown
Commercially available	No
Last updated	09/2021

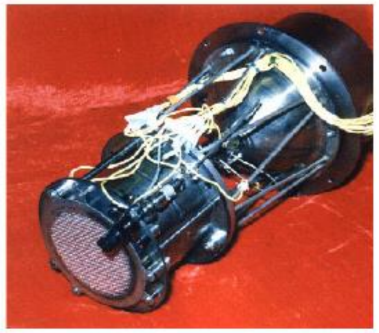

Fig. 7 The picture of Mercury ion thruster

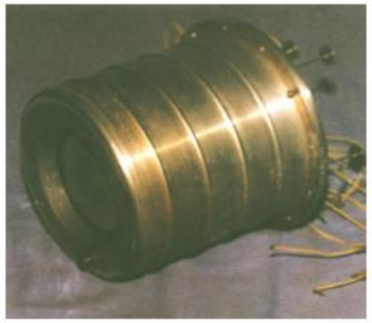

Fig.8 The picture of Xenon ion thruster

Photo of ion thruster [1]

Additional comments:

[Reference 1][September 2021][Thruster development]
Research and development of ion thrusters started as early as 1968 at CSSAR. From 1968 to 1973, two types of electron bombardment ion thrusters using mercury as propellant were development (one was 12 cm in diameter, the other was 6 cm in diameter). From 1974 to 1986, under the support of the Chinese Academy of Space Technology (CAST), LIP development an engineering model of 8 cm ion thruster using mercury. However, since 1988, LIP has turned to developing a xenon ion thruster. As a result, LIP has developed a 90 mm ion thruster with the specifications listed above.
In order to meet the needs of the new Chinese communication satellite, a 20 cm ion thruster is being developed at LIP.

References:
[1] Kang, X., Wang, Z., Wang, N., Li, A., Wu, G., Mao, G., Tang, H., Zhao, W., “An Overview of electric propulsion activities in China”, IEPC 2001.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

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China: Cold gas ammonia propulsion system (BX-1)

Propulsion Technology	Cold gas
Manufacturer/Country	China: Shanghai Engineering Centre for Microsatellites, Chinese Academy of Sciences
TRL	7 (mission was successful – images were taken and satellite was able to fly around SZ-7, so propulsion was assumed to work properly, but no on-orbit specifications were reported)
Size (including PPU)	A few U
Design satellite size	BX-1 was 40 kg (roughly 450mm x 430mm x 450mm)
Isp (s)	Not reported
Thrust type/magnitude	Not reported
Delta-V (m/s)	
Propellant	Ammonia
Power consumption (W)	Unknown
Flight heritage (if any)	BX-1 launched September 2008
Commercially available	NO
Last updated	09/2021

Additional comments:

[Reference 1][September 2021][Thruster and mission information]
BX-1 was the companion satellite for the Shenzhou VII (SZ-7) manned spaceship and carried out two in-orbit experiments for the Shenzhou VII mission: 1) capture images of SZ-7, and 2) execute companion flying experiment.

This propulsion system is a liquid ammonia cold-gas system. It is relatively simple, consisting of a simple dual tank system, heater system, and a set of fill/drain valves, a latch valve, and a few thermal sensors. The propellant is self-pressurized. BS-1 was launched in 2008 and the mission was deemed successful, suggesting that the propulsion system operated as expected.

References:
[1] Zhu, et al., "BX-1: the companion microsatellite in Shenzhou-7 Mission," SSC09-IV-4, 2009.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

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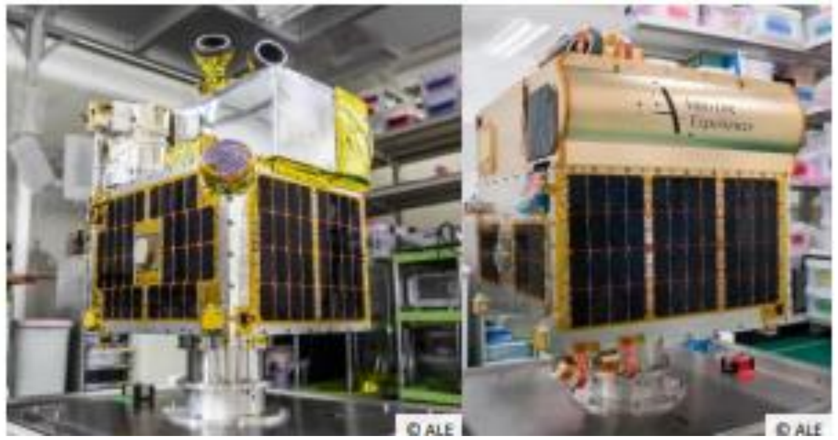
High Density Cold Gas Jet System (HDCGJ) for ALE-2

Propulsion Technology	Warm gas/cold gas
Manufacturer/Country	Patchedconics (JAPAN)
TRL	7
Size (including PPU)	7 kg (dry), 9 kg (wet) [1]
Design satellite size	ALE-2 is 76 kg [1]
Isp (s)	70s [1]
Thrust type/magnitude	3 mN per nozzle, total impulse 1400 N*s, maximum thrust when all four nozzles are firing is ~8-9 mN [1]
Delta-V (m/s)	
Propellant	R600a refrigerant [1]
Power consumption (W)	10 to 24W
Flight heritage (if any)	ALE-2, launched Dec 2019 [1]
Commercially available	NO
Last updated	10/2021



[1]

Additional comments:

[Reference 1][Oct 2021][General information]

The 76 kg satellite "ALE-2", which was jointly developed by Tohoku University and ALE Co., Ltd., has the world's first challenging mission to artificially generate shooting stars by ejecting small substances (meteor source) from the ejection device fixed on the satellite body. To avoid collision of the ejected meteor source with other flying objects, the mission must be performed in a sun-synchronous orbit at an altitude of less than 400 km, which is lower than that of the International Space Station.
ALE-2 was launched on December 6, 2019, and the in-orbit test of the RCS started four months later. Although the RCS was not able to achieve its initial orbit change capability due to an anomaly in the power supply system, various kinds of tests were conducted under conditions that allowed continuous thruster operation. It was confirmed that the orbit altitude was increased by 0.4 km per orbit.

The thrust is nominally 3 mN per unit, but the thrust can be increased to a maximum of 10 mN by controlling the tank pressure with heater control. To stabilize the thrust, a buffer tank is installed downstream of the main tank to store gas in a gas-liquid equilibrium state. Some heaters are driven to control the tank temperature and heat exchanger automatically.

References:
[1] Sato, Y., Fujita, S., Shibuya, Y., Kuwahara, T., Kamachi, K., “In-orbit demonstration of reaction control system for orbital altitude change of microsatellite ALE-2,” Small Satellite Conference 2021, SSC21-III-09.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

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NanoSat, CubeSat, and MicroSat Terminator Tape (NSTT), (CSTT), (MSTT) [1 of 2]
Tethers Unlimited

Propulsion Technology	Electrodynamic Tethers
Manufacturer/Country	Tethers Unlimited (USA)
TRL	7
Size (including PPU)	Various models
Design satellite size	CubeSats to 100 kg (ESPA-class)
Isp (s)	n/a
Thrust type/magnitude	De-orbit
Delta-V (m/s)	
Propellant	Propellantless
Power consumption (W)	Activation power: CubeSat: 200-300mA@3V for 1s NanoSat:1.6A @ 9VDC for 20s
Flight heritage (if any)	PROX-1 (STP-2) [launched 2019] [5] NPSAT-1 (STP-2) [launched 2020] [5] ALCHEMY/ALGURY "DRAGRACER" [launched Nov 2020] [4, 5, 6]
Commercially available	YES
Last updated	*12/2021*

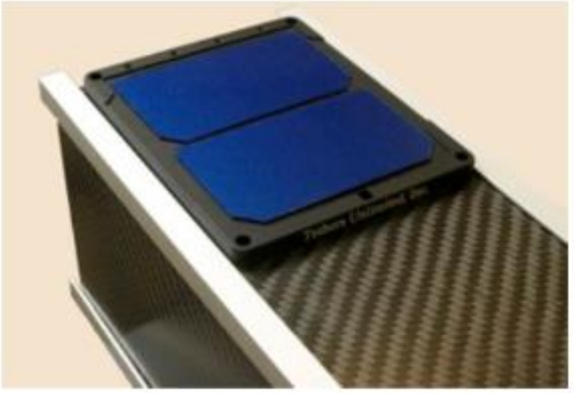

Fig. 2. CubeSat Terminator Tape mounted on a 3U CubeSat structure. Shown with mass simulator solar cell models.

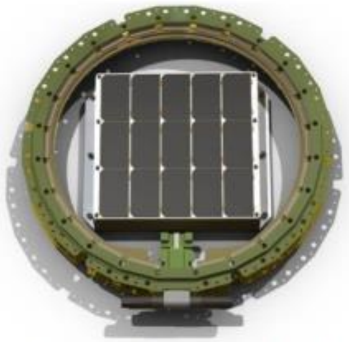

Fig. 3. The MicroSat Terminator Tape module is sized to fit within the Mark 2 Lightband used on the ESPA ring.

Additional comments:

[Reference 1-3][Jan 2019][General info]

The Terminator Tape deorbit module is intended for microsatellites operating at altitudes of less than 1000 km. The Terminator Tape is a 'pizza-box' shaped module that mounts to any face of a microsatellite. When the host spacecraft has completed its mission, the spacecraft will activate the module by sending it a pyro signal. The module will then deploy a 250 meter long conductive tape. Gravity gradient forces will then orient the tape along the local vertical direction. This tape will significantly increase the aerodynamic cross-section of the satellite, enhancing the drag it experiences due to neutral particles. In addition, the motion of this tape across the Earth's magnetic field will induce a voltage along the tape. This voltage will drive a current to flow up the tape, with electrons collected from the conducting ionospheric plasma at the top of the tape and ions collected at the bottom. This current will induce a 'passive electrodynamic' drag force on the tape. The enhanced aerodynamic drag and the passive electrodynamic drag force will lower the microsatellite's orbit, deorbiting it within 25 years. The Terminator Tape is a highly scalable technology. To date, TUI has developed two Terminator Tape modules. The CubeSat Terminator Tape (CSTT) is sized for CubeSats, shown in Figure 2, the NanoSat Terminator Tape is sized for large nanosats to small microsats (<100 kg), and the MicroSat Terminator Tape (MSTT) is sized for ESPA-class microsats (<200 kg), illustrated in Figure 3. Manufacturer states, "We have done extensive testing of deployment of the tethers as well as strength testing in the laboratory"

References:

[1] Hoyt, R., Forward, R., "The Terminator Tether: Autonomous Deorbit of LEO Spacecraft for Space Debris Mitigation," AIAA-00-0329, 2000.
[2] Pardini, C., "Potential Benefits and Risks of using Electrodynamics Tethers for End-of-life De-orbit of LEO Spacecraft," 21st IADC meeting, Bangalore, India, 2003.
[3] http://www.tethers.com/TT.html#TermTape
[4] https://smallsatnews.com/2020/12/08/smallsat-space-debris-remediation-technology-being-demod-by-millennium-space-systems-in-space/
[5] Stankey, H., Hoyt, R., "In-flight performance of the terminator tape end-of-life deorbit module," Small satellite conference 2021, SSC21-XI-03.
[6] https://smallsatnews.com/2021/08/26/deployable-tether-for-de-orbiting-satellites-demod-by-millennium-space-systems-using-tethers-unlimited-terminator-tape/

	7	NO
Comm. avail.	TRL	Aerospace-tested

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NanoSat, CubeSat, and MicroSat Terminator Tape (NSTT), (CSTT), (MSTT) [2 of 2] Tethers Unlimited

Additional comments:

[Reference 1][Jan 2021][Flight info]
In November, two Millennium Space Systems-built smallsats were successfully launched into LEO and the company's engineers, as well as the world's amateur satellite tracking community, are watching them as they race back to Earth. The DRAGRACER satellites were launched November 19 atop a Rocket Lab Electron launch vehicle in New Zealand. One satellite, called ALCHEMY, is equipped with a 70-meter, Tethers Unlimited Terminator Tape that was unfurled in LEO. The tether increases the surface area of the spacecraft and it is expected to sink and burn up as it falls from Earth's upper atmosphere in approximately 45 days. The other satellite, AUGURY, the control for the scientific experiment, is expected to follow a natural decay trajectory of between five and seven-and-a-half years. Millennium Space Systems engineers are monitoring the telemetry of both satellites as they return to Earth and comparing flight data with predictive de-orbit models. The amateur satellite tracking community can follow DRAGRACER's progress and provide data and images via a web portal. The DRAGRACER mission is a collaborative effort of Millennium Space Systems, a Boeing subsidiary; Tethers Unlimited; mission launch service provider TriSept; and Rocket Lab.

[Reference 2][Oct 2021][On-orbit data]
To date, three satellites have deployed Terminator Tapes, accumulating a total flight time of approximately thirty months. The first two deployments, on the NPSAT-1 and PROX-1 satellites, are starting multi-year deorbit profiles that will characterize Terminator Tape performance over a full solar cycle as they descend from altitudes above 700km.

NPSAT and PROX-1 were launched on June 25th, 2019 to a shared orbit at an average altitude of approximately 720km. The two NanoSat Terminator Tape (NSTT) units, each mounted on one of the satellites along with timer units programmed to activate the NSTT deployment a pre-determined time after separation of the satellite from the launch adapter. The timer unit on PROX-1 was programmed to deploy after 90 days. The second unit, on NPSAT-1, was programmed to activate after 18 months. Tracking data from USSPACECOM, obtained through the Space-Track web portal, indicate that both units activated as intended and the Terminator Tapes are accelerating the orbital decay of these two spacecraft.
On November 19th, 2020, as a part of the DRAGRACER experiment, twin satellites with identical size and mass were launched to 500km, one named "Alchemy" with an NSTT and one named "Augury" without, to serve as a control. Soon after launch, the Alchemy satellite deployed its NSTT and began deorbiting.
ALCHEMY and AUGURY showed a factor of 89 difference in decay rate between the two craft (for the first 90 days of flight) and a steady increase in this value as Alchemy falls further into the thicker atmosphere.

References:
[1] https://smallsatnews.com/2020/12/08/smallsat-space-debris-remediation-technology-being-demod-by-millennium-space-systems-in-space/
[2] Stankey, H., Hoyt, R., "In-flight performance of the terminator tape end-of-life deorbit module," Small satellite conference 2021, SSC21-XI-03.

	7	NO
Comm. avail.	TRL	Aerospace-tested

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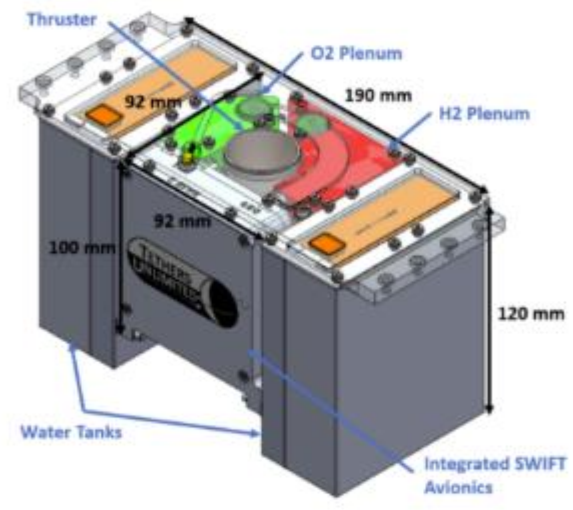
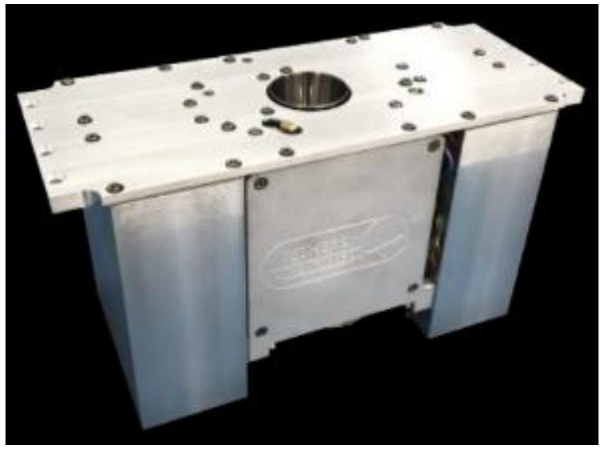
HYDROS-C [1 of 2]
Tethers Unlimited/Lee Corporation

Propulsion Technology	Electrolysis
Manufacturer/Country	Tethers Unlimited (USA)
TRL	7
Size (including PPU)	6U (190x130x92mm) 0.74 kg water, 1.87 kg dry mass, 2.61g wet mass However, [9] states the unit only takes up 2U
Design satellite size	up to 180 kg
Isp (s)	310s
Thrust type/magnitude	1.2N (average), 2.2N (max, continuous) 1.75 N*s (impulse, per event), 2150 N*s (impulse, total) 0.13 mN/W (thrust efficiency)
Delta-V (m/s)	200 m/s for 6U spacecraft
Propellant	Water
Power consumption (W)	5-25W
Flight heritage (if any)	Delivered to commercial customer (2017). Slated for NASA's Pathfinder Technology Demonstration PTD-1 (Thruster delivered in 2019, launched Jan 2021). [7, 8, 9]
Commercially available	YES
Last updated	*10/2021*



HYDROS-C

Two models of HYDROS



Additional comments:

[Reference 1-5][Aug 2019][Thruster info]
To enable small, low-cost spacecraft platforms such as CubeSat, nanosats, and microsats to perform missions requiring orbit agility and stationkeeping, TUI has developed the HYDROS Propulsion System. The HYDROS Propulsion System uses on-orbit electrolysis of water to generate hydrogen and oxygen propellant, which are fed to a simple bipropellant thruster. To enable this, we have developed a compact electrolysis cell designed to operate in microgravity. HYDROS enables you to launch your CubeSat with an inert, green propellant - water - and use solar power to provide high thrust and high specific impulse propulsion. The HYDROS system can provide 100 Ns per 100 ml of water, and is readily scalable to provide larger ΔV's. The HYDROS Propulsion System will initially be available in two standard configurations: a 2U HYDROS-C module intended for CubeSats and NanoSats, and a HYDROS-M module intended for 50-180 kg microsatellites. TUI can also develop customized tank configurations of these modules for your spacecraft for a reasonable NRE cost.

References:
[1] James, K., Bodnar, M., Freedman, M., Osborne, L., Grist, R., Hoyt, R., "HYDROS: High Performance Water-electrolysis Propulsion for CubeSats and MicroSats," AAS17-145, 2017.
[2] http://www.parabolicarc.com/2018/06/30/nasa-selects-tuis-hydrosc-thruster-ptd-cubesat-mission/
[3] http://www.tethers.com/HYDROS.html
[4] http://www.parabolicarc.com/2016/08/03/tethers-unlimited-signs-contracts-deliver-hydros-waterpropelled-thrusters/
[5] http://www.tethers.com/SpecSheets/Brochure_HYDROS.pdf
[6] NASA 2020 SOA for Small Satellites (POC Gabriel Benavides). https://www.nasa.gov/smallsat-institute/sst-soa-2020/in-space-propulsion
[7] https://space.skyrocket.de/doc_sdat/ptd-1.htm
[8] https://www.tethers.com/vivamus-quis-placerat-ligula-2/
[9] Porter, A., Freedman, M., Grist, R., Wesson, C., Hanson, M., "Flight qualification of a water electrolysis propulsion system," Small Satellite Conference 2021, SSC21-XI-06.

Comm. avail.	7 TRL	NO Aerospace-tested

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HYDROS-C [2 of 2]
Tethers Unlimited/Lee Corporation

Additional comments:

[Reference 1][June 2020][Flight info]
NASA Ames and Glenn Research Centers are working on the Pathfinder Technology Demonstration (PTD) project which consists of a series of 6U CubeSats that will be launched to test the performance of new subsystem technologies in orbit. Tethers Unlimited, Inc. is developing a water electrolysis propulsion system called HYDROS-C, which is less than 2.4U in volume and uses water as propellant. On-orbit, water is electrolyzed into oxygen and hydrogen and these propellants are combusted as in a traditional bi-propellant thruster. This thruster provides an average thrust of 1.2-N with 310 s Isp, and requires 10-15 minutes of recharge time for each 1.75-N*s thrust event. This system has been selected for NASA's first Pathfinder Demonstration CubeSat Mission planned for launch in late 2020. A variant of the HYDROS-C system is the HYDROS-M system, which is intended to be sized for micro-sats.

[Reference 2][Jan 2021][Mission status]
Bothell, WA, 2 July 2019 – Tethers Unlimited, Inc. (TUI) announced that it has successfully delivered its first HYDROS-C water-electrolysis thruster for integration with NASA's first Pathfinder Technology Demonstrator (PTD-1) CubeSat. The PTD-1 mission will demonstrate the HYDROS thruster's ability to provide both high thrust efficiency and excellent fuel economy. TUI's HYDROS-C was selected as the payload for the first PTD flight mission (PTD-1), which is conducted through NASA Ames Research Center at Moffett, California in collaboration with NASA Glenn Research Center in Cleveland, Ohio and is expected to launch in Q4 2019. The PTD project is part of NASA's Small Spacecraft Technology program under the Space Technology Mission Directorate. Tyvak Nano-Satellite Systems in Irvine, California, is integrating the PTD-1 CubeSat. The HYDROS technology was initially developed under a NASA Small Business Innovation Research (SBIR) contract and then matured under a NASA/STMD Tipping Point Partnership to prepare it for launch.
"We are very excited to deliver our first HYDROS-C Thruster to NASA," said Dr. Rob Hoyt, TUI's CEO. "Our team worked very hard to mature this product to the point where it is ready to support advanced small satellite missions, and the collaboration with NASA and Tyvak's engineering team was crucial to the delivery of this product. The PTD-1 mission will demonstrate HYDROS's ability to enable small satellites to perform missions requiring both orbit agility and orbit persistence. HYDROS is a key technology for several new in-space services we are developing, such as the LEO-Knight assembly and refueling robot and the HyperBus payload platform, so we are eager to demonstrate its capabilities on orbit."

[Reference 3][Oct 2021][Flight data]
With these differences in mind, the specific impulse of 223-241s from the mission demonstration is within the expected range when compared to the 269 s from ground testing under more favorable operating conditions. Future HYDROS testing is expected to be performed at higher plenum pressures in order to push the specific impulse above 300s. The HYDROS-C propulsion system is the first water electrolysis thruster to operate in space.

References:

[1] NASA 2020 SOA for Small Satellites (POC Gabriel Benavides). https://www.nasa.gov/smallsat-institute/sst-soa-2020/in-space-propulsion
[2] https://www.tethers.com/vivamus-quis-placerat-ligula-2/
[3] Porter, A., Freedman, M., Grist, R., Wesson, C., Hanson, M., "Flight qualification of a water electrolysis propulsion system," Small Satellite Conference 2021, SSC21-XI-06.

	7	NO
Comm. avail.	TRL	Aerospace-tested

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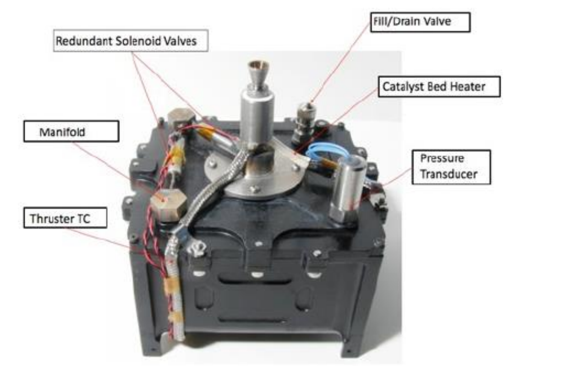
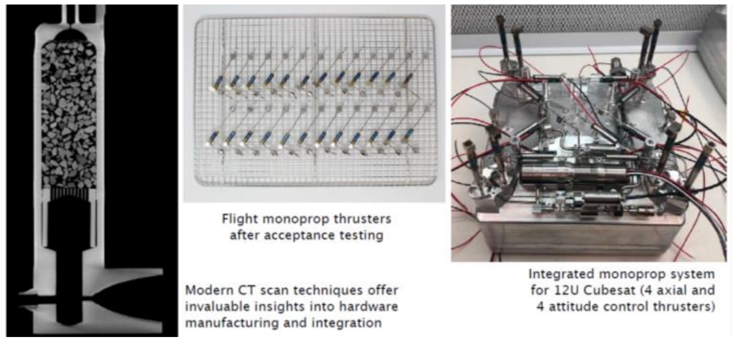
Hydrazine Monopropellant Micro Propulsion [1 of 4]

Propulsion Technology	Hydrazine monoprop
Manufacturer/Country	Stellar Exploration (USA)
TRL	3-4
Size (including PPU)	~1U
Design satellite size	3U or larger, Capstone is 12U [2]
Isp (s)	220s
Thrust type/magnitude	4X 1.5N thrusters 8X 0.25N thrusters for NASA Capstone [2]
Delta-V (m/s)	500 m/s (design, not measured) 200 m/s for a 25 kg spacecraft like Capstone[2]
Propellant	Hydrazine. Catalyst platinum/iridium
Power consumption (W)	n/a
Flight heritage (if any)	NASA Capstone launched June 2022 [2, 4, 6] Transporter-2 (hydrazine monoprop system, launched 06/30/2021) [3] EG3, performed to requirements [5] 7 dual-mode (monoprop + biprop) systems to be delivered to Millenium by end of 2023 [5]
Commercially available	YES
Last updated	*12/2023*



Integrated Hydrazine Micropropulsion

[3]



Additional comments:

[Reference 1][Jan 2019][General info]
The catalyst for this applications was a disc consisting of a platinum/iridium wire ring with platinum wire mesh laser welded to it. These discs were then stacked and held together with a stainless steel stud. The required mass flow was calculated to be 0.7 g/s to give the desired 220s Isp and thrust of 1.5N per thruster head. A nozzle expansion ratio of 15 was chosen since it gives the best overall performance (balance between the performance and volume of propellant carried). The status of this system is unknown as of January 2019.

References:
[1] Biddy, C., Svitek, T., “Monopropellant Micropropulsion System for CubeSats,” SmallSat Conference, SSC09-II-2, 2009.
[2] Gardner, T., Cheetham, B., Forsman, A., Meek, C., Kayser, E., Parker, J., Thompson, M., Latchu, T., Rogers, R., Bryant, B., Svitek, T., “CAPSTONE: A cubesat pathfinder for the lunar gateway ecosystem,” Small Satellite Conference 2021, SSC21-II-06.
[3] Publicly cleared information in email correspondence with T. Svitek (Jan 2022)
[4] Gardner, T., Cheetham, B., parker, J., Forsman, A., kayser, E., Thompson, M., Ott, C., DeMoudt, L., Bollinger, M., Kam, A., Thompson, K., Latchu, T., Rogers, R., Bryant, B., Svitek, T., “CAPSTONE: A summary of flight operations to date in the cislunar environment,” SSC22-IX-02.
[5] Email correspondence with Tomas Svitek [March 2023]
[6] Umansky, H., Clarke, K., Rogers, R., Hannon, A., Kelly, J., Latchu, T., Williams, A., Bryant, B., “CAPSTONE: Recovery and operations of a tumbling small satellite in deep space,” Small Satellite Conference, SSC23-WVII-06, 2023.

Comm. avail.	7 TRL	NO Aerospace-tested

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Hydrazine Monopropellant Micro Propulsion [2 of 4]

Additional comments:

[Reference 1][October 2021][Flight information]
The CAPSTONE spacecraft is a 12U CubeSat that has been designed and is being built by Tyvak Nano-satellite Systems based on their exiting, commercial 12U satellite bus. The spacecraft hosts a monopropellant hydrazine propulsion system, delivered by Stellar Exploration, Inc., providing over 200 m/s of total delta-V with eight 0.25-Newton thrusters. Four will be used for translational maneuvers and attitude control, and four will be used for attitude control and momentum desaturation.
The mission is scheduled to launch in October 2021, have an approximate three-month, low energy deep space transfer with several maneuvers leading up to the NRHO insertion and then perform its primary and enhanced mission over the next eighteen months.

References:
[1] Gardner, T., Cheetham, B., Forsman, A., Meek, C., Kayser, E., Parker, J., Thompson, M., Latchu, T., Rogers, R., Bryant, B., Svitek, T., “CAPSTONE: A cubesat pathfinder for the lunar gateway ecosystem,” Small Satellite Conference 2021, SSC21-II-06.

Comm. avail.	TRL	Aerospace-tested
	7	NO

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Hydrazine Monopropellant Micro Propulsion [3 of 4]

Additional comments:

[Reference 1][Jan 2021][Hardware development and flight information]

The monoprop system has sustained over 200seconds of stable firing, repeatable 25 msec pulses (starting cold), and >500 repeatable 200 msec on and off pulses.

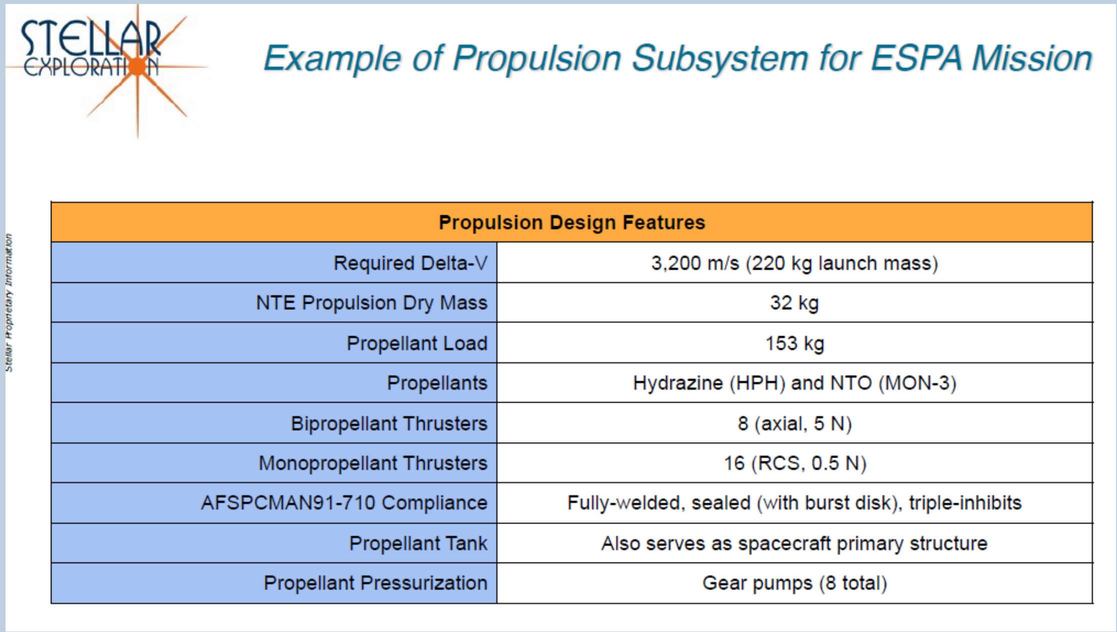
The first monoprop system that Stellar produced was launched on the Transporter-2, and demonstration 3 sequences of propulsion maneuvers: initial calibration burns, orbit raising (from 525 to 660 km, providing about 65 m/s of delta V, and an inclination change (~200 m/s of delta V). Additional maneuvers are planned in 2022.

It is now public knowledge that Stellar provided the propulsion system for the Capstone/EG3 12U system. It was a 2x2U footprint with “tuna cans”, consisting of 8 thrusters (each 0.25N, 200s Isp) for transitional and rotational control. They were all hydrazine monoprops with catalyst decomposition, variable propellant load (~3-6 kg), mission delta V from 200-550 m/s, with electric gear pump pressurization. Launch safety protocols were emphasized, and delivery within 1 year.

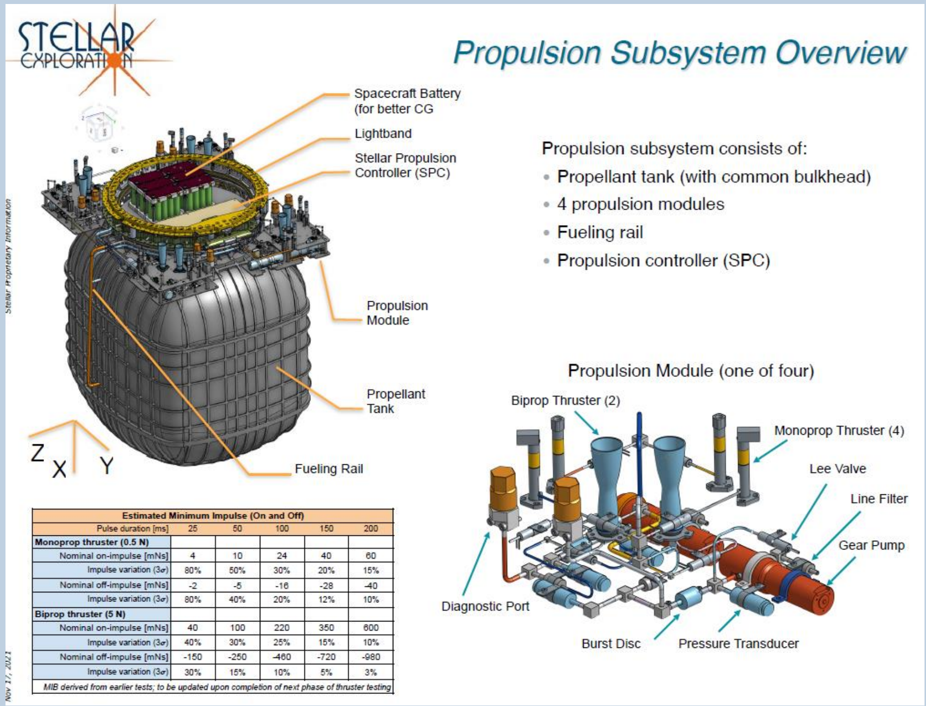
Pump operation has been demonstrated repeatedly in orbit.

Lessons learned from the Capstone/EG3 mission included: need to streamline PMD manufacturing and assembly, thruster mounting interface needs to be improved for better pointing accuracy, and the aluminum tank should be EB welded, instead of manual TIG welding.

Scaling up to a ESPA-sized propulsion system:
Stellar has designed an ESPA-sized propulsion system with the following specs:



Propulsion Design Features	
Required Delta-V	3,200 m/s (220 kg launch mass)
NTE Propulsion Dry Mass	32 kg
Propellant Load	153 kg
Propellants	Hydrazine (HPH) and NTO (MON-3)
Bipropellant Thrusters	8 (axial, 5 N)
Monopropellant Thrusters	16 (RCS, 0.5 N)
AFSPCMAN91-710 Compliance	Fully-welded, sealed (with burst disk), triple-inhibits
Propellant Tank	Also serves as spacecraft primary structure
Propellant Pressurization	Gear pumps (8 total)



Estimated Minimum Impulse (On and Off)					
Pulse duration [ms]	25	50	100	150	200
Monoprop thruster (0.5 N)					
Nominal on-impulse [mNs]	4	10	24	40	60
Impulse variation (3σ)	80%	50%	30%	20%	15%
Nominal off-impulse [mNs]	-2	-5	-16	-28	-40
Impulse variation (3σ)	80%	40%	20%	12%	10%
Biprop thruster (5 N)					
Nominal on-impulse [mNs]	40	100	220	350	600
Impulse variation (3σ)	40%	30%	25%	15%	10%
Nominal off-impulse [mNs]	-150	-250	-460	-720	-980
Impulse variation (3σ)	30%	15%	10%	5%	3%
MIB derived from earlier tests; to be updated upon completion of next phase of thruster testing					

References:
[1] Public information from email correspondence with T. Svitek (Jan 2022) (full report in email correspondence, Recent Flight Results Design Summary)

🛒	7	NO
Comm. avail.	TRL	Aerospace-tested

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Hydrazine Monopropellant Micro Propulsion [4 of 4]

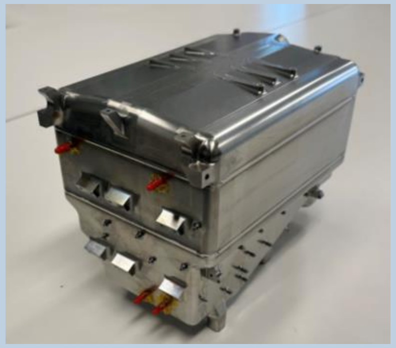
Additional comments:

[Reference 1][Nov 2022][Flight information]
NASA's tiny CAPSTONE probe has bounced back from a troubling glitch and is on track to reach the moon this month as planned, mission team members said. CAPSTONE, which is about the size of a microwave oven, entered a protective "safe mode" after experiencing an issue during an engine burn on Sept. 8 that caused the probe to start tumbling. Mission team members eventually identified the likely cause of the glitch as an issue with a valve in the probe's propulsion system. They worked hard to troubleshoot the problem over the ensuing weeks, finally getting CAPSTONE to stop spinning in early October.

[Reference 2][Nov 2022][Flight information]
Advanced Space LLC. has completed its fourth trajectory correction maneuver (TCM) for CAPSTONE — TCM-4 was the fourth of six planned maneuvers en route to the Moon, targeting the precise orbit for the CAPSTONE demonstration. This follows the restoration of the spacecraft's capabilities as it has recovered from the anomaly that occurred after TCM-3. CAPSTONE is just two weeks away as of this writing from arrival at the Moon.

[Reference 3][Dec 2022][Flight information]
CAPSTONE took a four-month journey from launch to orbit – overcoming challenges related to communications and propulsion along the way – and performed an initial orbit insertion maneuver on November 13. In the following days, the CAPSTONE mission operations team, led by Advanced Space of Westminster, Colorado, analyzed data from the spacecraft to confirm it was in the expected orbit and carried out two clean-up maneuvers to refine its track.

[Reference 4][March 2023][Flight information]
Capstone is now working quite well. An identical system was launched in 2021 on the EG3 mission, and has performed flawlessly at 265 m/s, but was not as high visibility as Capstone.
Stellar is scheduled to deliver 7 dual mode systems (axial biprop + monoprop RCS, about 2X size of Capstone). Tank shown at right.
Next steps include several ESPA-class systems as that seems to be the direction the market is moving.



[Reference 5,6][Dec 2023][Flight information]
On 09/08/2023, Capstone experienced a spin-up due to stuck "open" thruster". The burn abort tripped due to excessive spin rates, and spacecraft goes into safe mode. Vehicle settled at rotation of ~70 degree/sec, pointing ~77 degrees from the sun. Repeating ~5 min lock, ~50 min loss cycle as spacecraft charged enough to power on radio, then lost power. Propellant freezes (tank temp at -7C). Spacecraft team load sheds – able to run heaters enough to unfreeze the propellant after several weeks.
With propellant unfrozen, the prop system was tested, and spin rate increased to 105 deg/second. Narrowed down stuck thruster to #3 (axial) or #5 (rotational). Terran Orbital GNC team builds detumble controller that is robust to stuck-open thruster. Oct 7, detumble maneuver completed successfully and communication is regained with ground. Oct 11, pressurization test executed to conclusively determine thruster #3 was stuck.

References:

[1] https://www.space.com/nasa-capstone-overcomes-glitch-targets-moon-arrival
[2] https://smallsatnews.com/2022/11/01/advanced-space-offers-a-capstone-mission-update/
[3] https://smallsatnews.com/2022/11/21/a-new-path-for-nasas-future-artemis-moon-missions-is-forged-by-capstone/
[4] Email correspondence with Tomas Svitek [March 2023]
[5] Gardner, T., "Capstone: a summary of a highly successful mission in the cislunar environment," Conference proceedings Instellar Small Sat Conference, 2023.
[6] Umansky, H., Clarke, K., Rogers, R., Hannon, A., Kelly, J., Latchu, T., Williams, A., Bryant, B., "CAPSTONE: Recovery and operations of a tumbling small satellite in deep space," Small Satellite Conference, SSC23-WVII-06, 2023.

Comm. avail.	TRL	Aerospace-tested
🛒	7	NO

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PROITERES PPT

Propulsion Technology	PPT
Manufacturer/Country	Osaka Sangyo University (OIT) (JPN)
TRL	7 (for Proiteres system, 4-5 for subsequent evolutions that have not yet flown) [1]
Size (including PPU)	
Design satellite size	1U and larger
Isp (s)	~340s [1]
Thrust type/magnitude	2.47 mN*s impulse bit, thrust efficiency ~12-15%, total impulse 92 N*s [1]
Delta-V (m/s)	
Propellant	Teflon
Power consumption (W)	32J input energy
Flight heritage (if any)	PROITERES launched in 2012 with 1st version [1] Second PROITERES will launch 2023/2024 [1]
Commercially available	NO
Last updated	08/2022

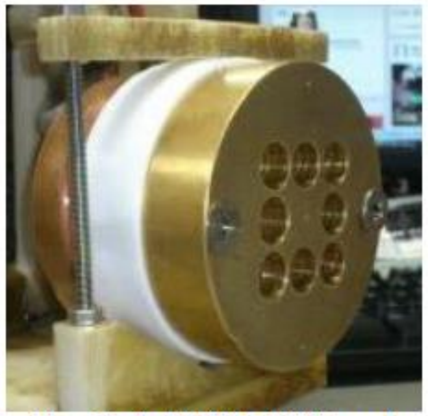

Fig. 26 1st MDR-PPT head.

[1]

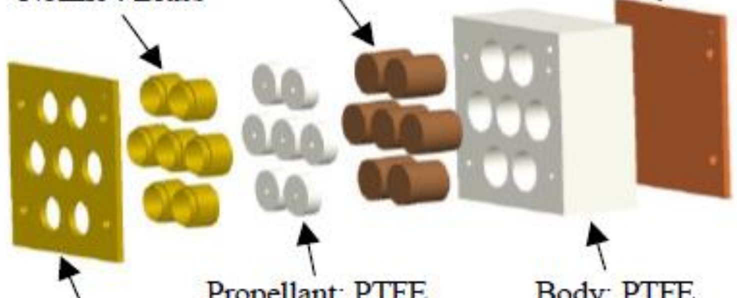

Fig. 29 Structure of 2nd MDR-PPT head.

Additional comments:
[Reference 1][Aug 2022][Thruster information]
In April 2020, nano-satellite/probe R&D project was started in Osaka Sangyo University (OSU) after PROITERES project was terminated at Osaka Institute of Technology (OIT). In PROITERES, a nano-satellite with electrothermal pulsed plasma thrusters (PPTs), the 1st PROITERES satellite, was successfully launched by the Indian PSLV C-21 launcher on September 9th, 2012. Currently, the 2nd PROITERES nano-satellite has been developed, and then the OSU-2 nano-satellite is being developed instead of the 2nd PROPITERES satellite. The main mission is to achieve long-distance powered flight of changing 50-100 km in altitude on near-earth orbit by high-power electrothermal PPTs. In this study, a high-power and long-operation PPT system with a multi-discharge room (MDR) of seven single discharge rooms, called the MDR-PPT, was developed. The single-discharge-room PPT head achieved a maximum impulse bit of 2.47 mNs and a total impulse of 92.0 Ns with a repetitive 110,000 shots at an input energy of 31.59 J. The total impulse means that a 50 kg nano-satellite with the MDR-PPT can be changed in altitude of approximately 25 km on LEO, although more improvement of thruster system is needed up to 50-100 km. The MDR-PPT system consists of MDR-PPT head, Power Processing Unit (PPU) and capacitors. Accordingly, the PPT-system test was successfully performed. Furthermore, a special onboard micro/nano PPT system was designed for orbital transfer and attitude control of 1-3U cubesates (OSU nano-satellite series). The 1J PPT system with 90 μNs/shot of measured impulse bit for 1U cubesates (specially OSU-1 cubesat) is successfully under test. Our OSU PPT systems can provide a total impulse of 5.0-105 Ns according to various main missions by changing the number of single PPT head and charging electric energy including structure. The OSU PPT systems are going to be marketed for micro/nano-satellites/probes all over the world.

References:
[1] Unegawa, T., Uedahira, M., Aoyagi, K., Shimada, T., Tahara, H., Ikeda, T., Takao, Y., Wakizoni, T., "Research and development of high-total-impulse electrothermal pulsed plasma thruster systems – from charging electric energy/power: 1J/1W for 1U (1kg) CubeSats to 50J/50W for 50 cm Cube (50 kg) Nano-Satellites," IEPC-2022-552.
[2] Aoyagi, K., Shimada, T., Uedahira, M., Unegawa, T., Itsuki, T., Tahara, H., Ikeda, T., Takao, Y., Wakizono, T., "Development of Osaka Sangyo University 1U Cubesat OSU-1 with 1J/1W Pulsed plasma thruster systems for powered flight, and development features of Nano-satellites and probes OSU-2,3 and 4, "IEPC-2022-553.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

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BHT-350

Propulsion Technology	Hall thruster
Manufacturer/Country	Busek (USA)
TRL	7
Size (including PPU)	1.7 kg (thruster mass) [1]
Design satellite size	Small sat (constellations)
Isp (s)	1244 s [1]
Thrust type/magnitude	17 mN
Delta-V (m/s)	
Propellant	Xenon, krypton, iodine
Power consumption (W)	200W to 600W, nominal discharge power 300W
Flight heritage (if any)	Initial units are flying, first on-orbit in December '22 and over 150 will be on-orbit for a range of customers in 2023. One named/public customer is Airbus OneWeb. [2]
Commercially available	Yes
Last updated	03/2023

BUSEK
Space Propulsion and Systems

BHT-350
Hall Effect Thruster
The perfect size for constellations.

Designed for high volume production.
Exceptional performance and lifetime.

Xe Kr I

Built with lessons learned from the BHT-200, the BHT-350 offers a solution that scales for new space applications. The BHT-350 was designed with modern manufacturing methods, and an innovative shell design coupled with precise magnetic lensing makes the BHT-350 the perfect low cost solution for constellations or small satellites.

We designed the BHT-350 for a new era of satellites. Sized for orbit operations and built specifically to minimize part count and assembly time, the BHT-350 perfectly fills the needs of new space for an economical propulsion solution without compromising on performance.

Table: Standard Specifications

Nominal Discharge Power:	300 W	**Thruster Mass:**	1.7 kg
Throttle Range:	200 W - 600 W	**Cathode Mass:**	0.2 kg
Nominal Thrust:	17 mN	**Demonstrated Impulse:**	212 kN-s
Nominal Specific Impulse:	1244 seconds	**Predicted Total Impulse:**	> 250 kN-s
Propellants:	Xenon, Krypton, Iodine		

Busek provides complete and fully integrated Hall Effect thruster systems that work with the BHT-350, including cathode, power processing unit, digital control unit, and propellant management systems.

11 Tech Circle, Natick MA 01760 | 508.655.5565 | info@busek.com 1
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[1]

Additional comments:

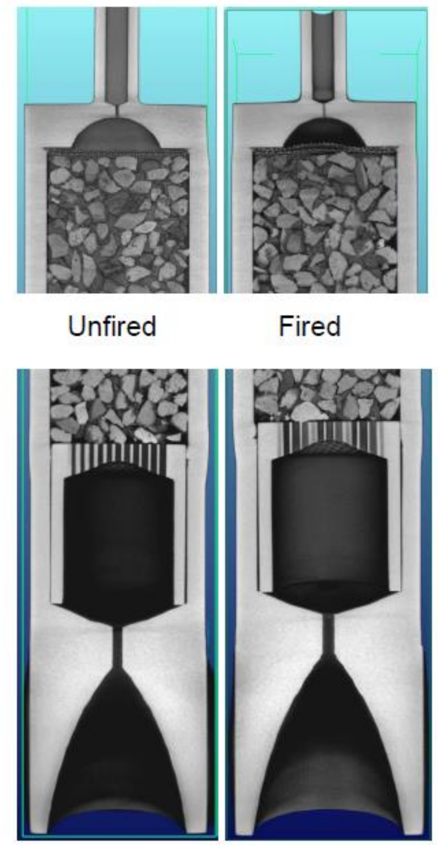
[Reference 1][March 2023][General information]
The BHT-350 has demonstrated over 4000 hours of operations in Busek's test facilities while maintaining class-leading thrust and specific impulse. With propellant choices including xenon, krypton, and iodine, the BHT-350 provides flexibility and high throughput for a huge class of missions. Busek provides the option of a complete and fully integrated Hall Effect thruster system with the BHT-350, including cathode, power processing unit, digital control unit, and propellant management systems.

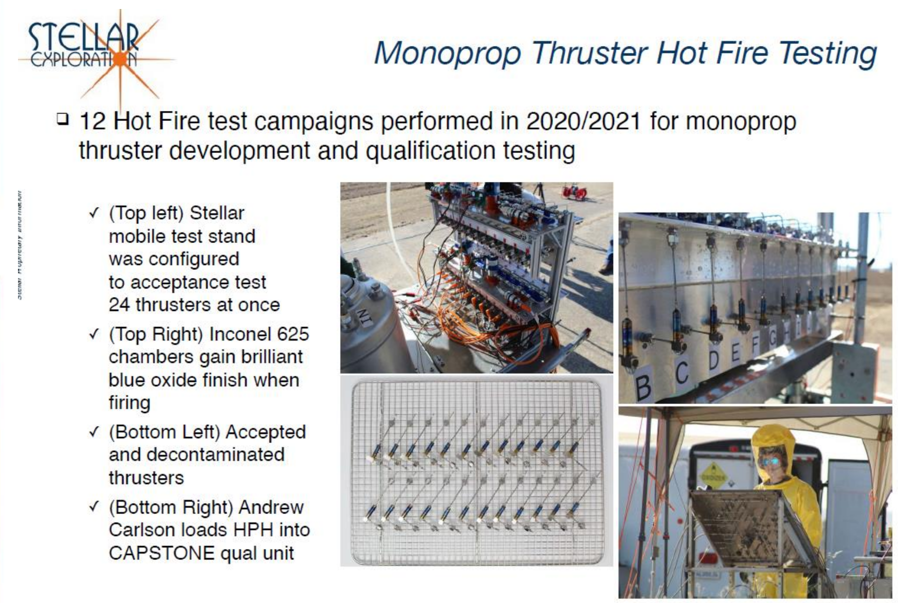
References:
[1] https://www.busek.com/bht350
[2] Email correspondence with P. Hruby [March 2023]

	7	NO
Comm. avail.	TRL	Aerospace-tested

Stellar SR-05M monoprop

Propulsion Technology	Hydrazine monopropellant
Manufacturer/Country	Stellar Explorations (USA)
TRL	6
Size (including PPU)	Small
Design satellite size	3U up to ESPA
Isp (s)	200 s
Thrust type/magnitude	0.5N
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	YES
Last updated	06/2022





[1]

Additional comments:

[Refence 1][Feb 2022][Testing information]
Stellar has conducted 12 hot fire campaigns in 2020/2021 for monoprop thruster development and qualification testing. More information available in the full report.

References:
[1] Public information from T. Svitek in email correspondence, Jan 2022, report “Recent flight results design summary”

Comm. avail.	6	NO
	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Astra Spacecraft Engine (ASE), previously Apollo Constellation Engine (ACE) [1 of 4]

Propulsion Technology	Hall effect thruster
Manufacturer/Country	Apollo Fusion (USA), now ASTRA (USA)
TRL	5-6
Size (including PPU)	~4U (7.6 kg dry mass including PPU on Kr) [1], 12 kg propellant [3]
Design satellite size	SmallSat (LEO constellations), 6U or larger (Astro Digital Ignis is 6U) [5]
Isp (s)	1040s 1400s (Xe), 1300s (Kr) [1, March 2021]
Thrust type/magnitude	16 mN (continuous) [1], 15 kN*s (total impulse) [1] 25 mN (Xe), 18 mN (Kr), 300 kN*s (total impulse) [1, March 2021]
Delta-V (m/s)	~~700 m/s for 250 kg wet satellite [3],~~ 500 m/s for 250 kg wet satellite [6]
Propellant	Xenon [1], Mercury [2], Krypton [4], “proprietary propellant” on Ignis [4]
Power consumption (W)	Designed for 300-500W. Optimized for 400W. [4]
Flight heritage (if any)	Flew on SHERPA-LTE1 (Launched June 2021) [7] Slated for AstroDigital Ignis (TBD, was 2019, now 2021) [5] Leostella satellites (delivery starting late 2022 and into 2023) [8]
Commercially available	YES
Last updated	*12/2022*

Apollo’s ACE Hall thruster


ASTRA

ASTRA SPACECRAFT ENGINE
KRYPTON/XENON PROPULSION SYSTEM

VERSION 04 | JUNE 2022

FIGURE 1. ASE OPERATION WITH XENON

The Astra Spacecraft Engine (ASE) 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:

- Compatible with xenon and krypton propellants
- Heaterless, center-mounted, instant-start cathode
- Novel magnetic lensing and magnetic circuit
- Advanced high temperature materials
- 95% efficient single board PPU

	KRYPTON	XENON
INPUT POWER	400 W	400 W
INPUT VOLTAGE (PRIMARY)	28 VDC unregulated	28 VDC unregulated
THRUST	~18 mN	~25 mN
SPECIFIC IMPULSE	~1,300 s	~1,400 s
TOTAL IMPULSE	300 kN-s	300 kN-s
DESIGNED & MANUFACTURED IN	USA	USA

TABLE 1. SYSTEM SPECIFICATION SUMMARY

ASTRA SPACECRAFT ENGINE | KRYPTON/XENON PROPULSION SYSTEM | 1

[6]

[9]

Additional comments:

[Reference 1][Jan 2019][Company and thruster info]

Apollo Fusion is a small company founded by Mike Cassidy and Ben Longmier. Mike was the CEO and co-founder of 4 startups and was previously a VP at Google where he led Project Loon, a high-altitude balloon telecommunications product. Ben Longmier is a former professor of Aerospace Engineering at the University of Michigan. Their thruster is available in a single unit or a 6-thruster configuration. The 6-thruster configuration is ideally suited for 3000W (large satellites).

References:
[1] http://apollofusion.com/index.html
[2] https://www.popularmechanics.com/space/rockets/a25242578/apollo-fusion-mercury/
[3] http://apollofusion.com/missions.html
[4] https://apollofusion.com/datasheets/ACE_Datasheet_Feb_27_2020.pdf
[5] https://space.skyrocket.de/doc_sdat/ignis.htm
[6] https://apollofusion.com/ace.html
[7] https://astra.com/news/apollo-fusion-thruster-spaceflight/
[8] https://smallsatnews.com/2022/04/13/astra-space-announces-electric-propulsion-system-contract-with-leostella/
[9] public data sheet, Nov 2022

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Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Astra Spacecraft Engine (ASE), previously Apollo Constellation Engine (ACE) [2 of 4]

Additional comments:

[Reference 3][Mar 2019][Thruster info]
A Silicon Valley startup wants to use mercury to launch satellites into orbit, potentially lacing the atmosphere with toxic substance. Industry insiders revealed that Apollo Fusion, a two-year-old company based in Mountain View, California, is designing propulsion systems that use mercury as spacecraft fuel. The company, which earlier this year has raised $10 million in venture funding, has already reportedly locked in one client and talking to two others.
Dangers Of Mercury: The use of mercury as spacecraft fuel is not a groundbreaking idea. In fact, NASA experimented with mercury back in the '60s during the Space Electric Propulsion Test (SERT) program. There are benefits to using mercury as spacecraft fuel. It is heavier than both xenon or krypton, two substances currently being used to power ion engines. A spacecraft using mercury, therefore, would be able to generate more thrust. However, there is a very serious reason why NASA immediately moved away from using mercury back in the '70s. Mercury is a powerful neurotoxin that can impair a person's cognitive functions. Apollo Fusion Responds To Toxic Mercury Propulsion Tech: The shocking report by Ben Elgin for Bloomberg Businessweek quoted anonymous industry insiders who refused to be named because they signed a non-disclosure agreement. They revealed that Apollo Fusion has pitched the technology, including the toxic element, to potential customers as recently as this summer. However, the startup has refused to name its clientele and neither confirmed nor denied the report. In a statement, chief executive officer and co-founder Michael Cassidy said that the company is still evaluating a number of other technologies. "We don't comment on our proprietary technology due to competitive risks, either on innovations that we've built or things that we're testing," he said through an e-mail to Bloomberg. "We are also committed to maintaining a low impact on the environment."

[Reference 1][June 2020][General info]
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

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

[Reference 2][June 2020][Launch info]
The Ignis spacecraft is a technology demonstration spacecraft built to the 6U CubeSat standard. It includes the Apollo Constellation Engine (ACE), a Hall thruster which ionizes and expels a high density proprietary propellant. The spacecraft will be launched aboard a LauncherOne rocket built by Virgin Orbit. The spacecraft bus is the Corvus-6 design. The common satellite bus uses reaction wheels, magnetic torque coils, star trackers, magnetometers, sun sensors, and gyroscopes to enable precision 3-axis pointing without the use of propellant. The anticipated lifetime of the spacecraft is <3 years in LEO.

References:
[1] https://apollofusion.com/datasheets/ACE_Datasheet_Feb_27_2020.pdf
[2] Astro Digital US, Inc., "Astro Digital Ignis Orbital Debris Assessment Report (ODAR) v1.0," FCC Public Database, 2019. https://apps.fcc.gov/els/GetAtt.html?id=228067
[3] https://www.popularmechanics.com/space/rockets/a25242578/apollo-fusion-mercury/

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Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Astra Spacecraft Engine (ASE), previously Apollo Constellation Engine (ACE) [3 of 4]

Additional comments:

[Reference 1 & 2][Mar 2021][Overview]
The Apollo Constellation Engine (ACE) is a Hall effect thruster propulsion system developed by Apollo Fusion, a US company based out of Mountain View, CA. ACE leverages the past 50 years of Hall thruster research in a clean sheet design with major innovations, including: 1) multi-propellant capability with Kr and Xe, and proprietary propellants, 2) heaterless, center-mounted, instant-start cathode, 3) propellant management system (PMS) with no moving parts, 4) novel magnetic lensing and circuit, 5) advanced high temperature materials, and 6) 95% efficient single power processing unit (PPU) board [1][2]. The ACE is an all-inclusive string (thruster + cathode + PPU + PMS). ACE PPU is radiation-tolerant (20 kRad TID) single circuit board designed for 400W and 500W operating points [3]. PPU input voltage is 22 – 38 VDC unregulated. ACE can be configured with multiple thrusters and PPUs to handle a wide range of mission requirements.

Various press releases have been made announcing the use of Apollo Fusion's ACE on York Space Systems, Spaceflight's Sherpa-LTE, and USAF intelligence satellite missions.

[Reference 3][Mar 2021][Company news]
On January 6, 2021 Apollo Fusion, announced it has been selected to provide the propulsion system for a LEO satellite constellation program placed by York Space Systems. York's order with Apollo will provide the electric propulsion system for a LEO constellation of 10+ satellites with an anticipated launch in 2022..

[Reference 4 & 5][Mar 2021][Company news]
On November 12, 2021 Apollo Fusion announced it was selected as the electric propulsion system for Spaceflight Inc.'s Sherpa-LTE. The Sherpa-LTE is a high specific impulse (Isp), xenon propellant, electric propulsion orbital transfer vehicle (OTV). It builds on Spaceflight's Sherpa-NG program by incorporating Apollo Constellation Engine (ACE) — a low thrust, high efficiency, radiation hardened Hall thruster propulsion system developed by Apollo Fusion, Inc. As ACE systems are able to generate more than 6 kilometers per second of delta-V, Sherpa-LTE now has the capability to deliver customers to GEO, Cislunar, or Earth-escape orbits. Sherpa-LTE provides a low-cost alternative to purchasing full direct-inject launch vehicles and will extend the ability of small launch vehicles that are currently under development to reach beyond low Earth orbit. The Sherpa-LTE is targeted to fly mid-2021.

[Reference 6][June 2021][Company news]
Astra has announced the company's planned acquisition of Apollo Fusion in a transaction valued up to $145 million.
Under the agreement, Astra is acquiring Apollo Fusion for a purchase price of $50 million: $30 million in stock and $20 million in cash. Additionally, there is potential for earn-outs of up to $95 million: $10 million in employee incentive stock, $10 million in cash for reaching technical milestones, and $75 million ($60 million in stock, $15 million in cash) for reaching revenue milestones. PJT Partners is acting as financial advisor to Astra in connection with this series of transactions.

References:
[1] https://apollofusion.com/datasheets/Apollo_ACE_Datasheet-Jan_2021.pdf
[2] https://apollofusion.com/ace.html
[3] https://www.prnewswire.com/news-releases/apollo-fusion-inc-selected-for-leo-constellation-program-by-york-space-systems-301214906.html
[4] https://www.prnewswire.com/news-releases/apollo-fusion-inc-to-propel-spaceflight-incs-orbital-sherpa-lte-301170586.html
[5] https://spacenews.com/spaceflight-announces-sherpa-tug-with-electric-propulsion/
[6] https://smallsatnews.com/2021/06/12/launch-company-astra-announces-an-apollo-fusion-amalgam/

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Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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Astra Spacecraft Engine (ASE), previously Apollo Constellation Engine (ACE) [4 of 4]

Additional comments:

[Reference 1][December 2021][Flight information]
Alameda, CA. August 24, 2021. Astra Space, Inc. ("Astra") (Nasdaq: ASTR), today announced the successful orbital ignition of its Apollo Fusion thruster on board the Spaceflight Sherpa-LTE1 orbital transfer vehicle (OTV). The Sherpa OTV launched June 30, 2021 from SpaceX's Transporter-2 mission from Cape Canaveral, Florida. After successfully deploying all rideshare payloads, Spaceflight commissioned the Apollo Fusion thruster, representing Astra's first attempt at firing the thruster in orbit.

"The telemetry from the on-orbit firing looked excellent and closely matched our ground test results," said Mike Cassidy, Vice President of Product Management at Astra. "We expect to deliver thrusters for additional satellites over the next quarter and these on-orbit test results provide further validation for several programs for which we are supplying propulsion systems."

"This represents the industry's first fully functional electric propulsion OTV," said Philip Bracken, VP of Engineering at Spaceflight.

References:
[1] https://astra.com/news/apollo-fusion-thruster-spaceflight/

DISTRO A: Approved for public release. OTR-2024-00338

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Comm. avail. TRL Aerospace-tested

Green Monopropellant Integrated Propulsion System (IPS)
Vacco/ECAPS

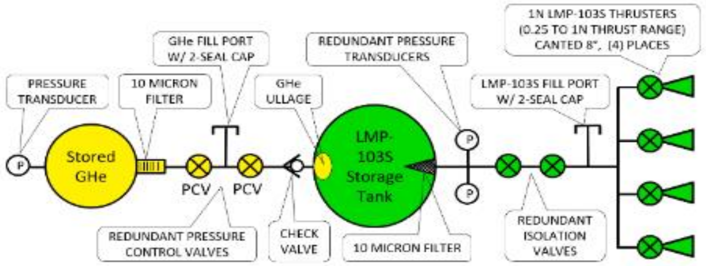
Propulsion Technology	Green Monoprop (LMP-103S)
Manufacturer/Country	VACCO/ECAPS (USA/SWE)
TRL	6
Size (including PPU)	Basketball (6 to 9U)
Design satellite size	27U and larger (ESPA class)
Isp (s)	230s at 1N steady thrust [1]
Thrust type/magnitude	4N total (4X 1N thrusters) 12,000 N*s total impulse [1]
Delta-V (m/s)	
Propellant	LMP-103S
Power consumption (W)	Up to 50W [1]
Flight heritage (if any)	None
Commercially available	YES
Last updated	10/2021

Self-Contained Bolt-on Propulsion Subsystem:
- (4) Flight-Proven 1N LMP-103S Thrusters.
- Thrusters Canted 8° for Provide Pitch, Yaw & Roll.
- 3.96N net Delta-V Thrust (Throttleable).
- Total Impulse: ≥12,000 N-sec.
- Minimum On/Off Pulse Width: 100ms.
- Robust, All-Welded Titanium Alloy Construction.
- Frictionless Micro Valves.

Built-In, Shielded Controller:
- 12V/25W (max) for Controller, Valves & Sensors.
- 28V/50W (max) for Valve Enable & Heater Power.
- RS422 Data Bus Command & Control Interface.
- PWM Electronic Pressure Regulators w/Cross-Strapped Drivers, Redundant Valves & Sensors.
- Redundant, Closed-Loop Catalyst Bed Heaters.

Range Safety Features:
- Non-Toxic LMP-130S Monopropellant.
- (3) Seals Against LMP or GHe Leakage.
- Benign GHe Pressurant.
- Safe and Arm Circuit.

Three Flight Systems in Production



	LMP-103S Propellant Mass (g)	Isp @ 1N Steady State Thrust (sec)	Total Impulse (N-Sec)	MiPS Dry Mass (Kg)
3.96N Net Axial Thrust	5490	230	12300	9.0

Over 12,000 N-Sec Total Impulse at 4N Thrust

Additional comments:

[Reference 1][Aug 2020][Thruster development info]
Vacco has application-engineered a green monopropellant Integrated Propulsion System (IPS) specifically designed for ESPA-class small satellites. The Integrated Propulsion System is a smart propulsion system with propellant storage, pressurant storage, feed system, controller, software, and four flight-proven 1N non-toxic thrusters in a compact bolt-on package. It is capable of imparting 12,000 N*s of total impulse to the host satellite.
The IPS features four, flight-proven, Bradford ECAPS 1N LMP-103S non-toxic monopropellant thrusters. They are mounted double-canted to provide both attitude control and delta-V.
Acceptance testing of the 12 flight thrusters was successfully completed by Bradford ECAPS at their facility.
Burst pressure testing of a non-flight unit including proof pressure, external leakage, pressure cycling, burst pressure, and rupture pressure is ongoing.
IPS system-level protoflight testing of each flight system will include examination of product, proof pressure, electrical functional testing, liquid pressure regulation and flow, random vibration, throughput verification, thermal vacuum testing, and valve leakage. After mounting the thrusters, electrical testing will occur followed by final examination of product.
Currently, the first IPS is at the entry point of protoflight testing.

[Reference 2][Oct 2021][Thruster development]
Proto-flight testing of 3 IPS systems has been completed.

References:
[1] Cardin, J., Schappell, T., Day, C., “Testing of a green monopropellant integrated propulsion system,“ Small Sat Conference 2020, virtual talk. Paper SSC20-IX-02.
[2] Cardin, J., Hsu, J., Sorothia, J., “Proto-flight testing of a green monopropellant integrated propulsion system,” Small Sat Conference 2021, SSC21-XI-08.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

PETRUS

Propulsion Technology	PPT
Manufacturer/Country	University of Stuttgart (DEU)
TRL	2-3
Size (including PPU)	~1U
Design satellite size	Small sat
Isp (s)	~850 s
Thrust type/magnitude	~100 uN (at 1 Hz rep rate)
Delta-V (m/s)	
Propellant	PTFE
Power consumption (W)	6W
Flight heritage (if any)	Launched on GreenCube (3U), July 2022. Awaiting on-orbit results.
Commercially available	No
Last updated	08/2022

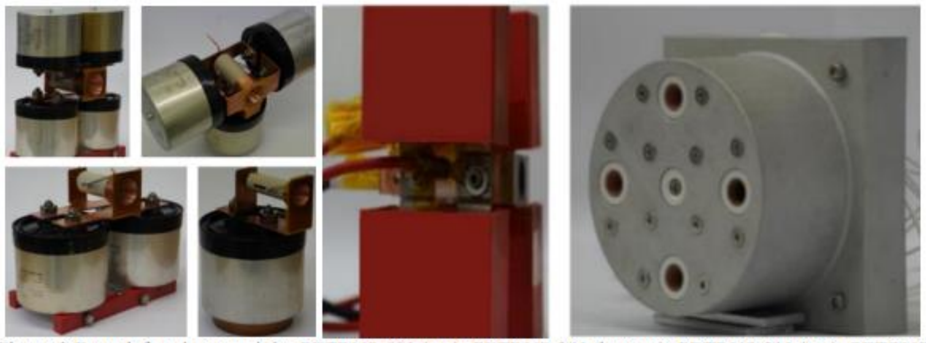
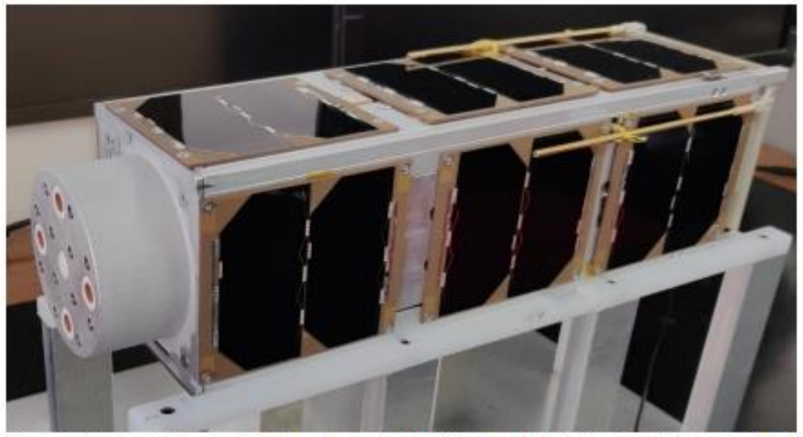


Figure 2 From left to bottom right. PETRUS 68J (top), PETRUS 34J (bottom), PETRUS 51J (top), PETRUS 17J (bottom), PETRUS 5J, and the GreenCube propulsion module with four PETRUS 1J thrusters.



[1]

The GreenCube satellite on its integration stand with the PETRUS propulsion mounted on the left.

Additional comments:

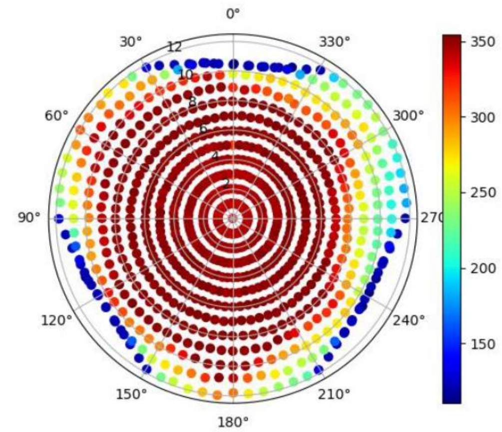
[Reference 1][Aug 2022][Thruster information]
Within the PETRUS development six different breech fed coaxial PPTs were developed, tested, and characterized. The pulse energy reaches from 0,8J to 68J. Focus of this work was to achieve a reliable miniaturized PPT for CubeSat applications, which is why a 5J thruster was the base for the investigations. Larger scaled PETRUS versions were designed to determine their scaling behaviour for possible future missions. With the opportunity to be onboard the 3U CubeSat mission GreenCube of the University of Rome, the PETRUS 1J propulsion system was developed and will be the first of this family of thrusters developed at IRS to be tested in orbit. Especially, restrictions such as power consumption, system mass and volume ("tuna can") drove the PETRUS 1J design. Next to the thrusters a miniaturized PPU was developed. Baseline for the PETRUS 1J PPU was the laboratory prototype of PETRUS 5J. To know about the performance of the propulsion system on-ground tests at IRS as well as ESA ESTEC were successfully performed. With the flight data from the GreenCube mission in near future these data will be correlated.
GreenCube is a 3U CubeSat aimed at testing an autonomous laboratory for microgreens cultivation on-board a CubeSat platform. The satellite mission has been conceived by the S5Lab research group at Sapienza University of Rome, together with ENEA and University of Naples "Federico II" and the coordination and support by the Italian Space Agency.
The spacecraft design will allocate 2 CubeSat units (approximately 20x10x10 cm) for the cultivation laboratory, consisting in a pressurized vessel containing all the resources, sensors and actuators and actual volume that will be occupied by the growing plants during the experiment execution. The GreenCube payload unit i.e., the Biological Life Support System hosting the microgreens cultivation system, is comprised in an aluminium shell that will be pressurized at 0.5 atm. This pressure will allow the cultivation of the plants, yet mitigating the risks related to flying pressurized vessels on-board a nano-satellite platform due to its reduced pressure

References:
[1] Schafer, F., Skalden, J., Montag, C., Herdrich, G., Laufer, R., Santoni, F., "In-orbit testing of the coaxial pulsed plasma thruster PETRUS on GreenCube," IEPC-2022-569.

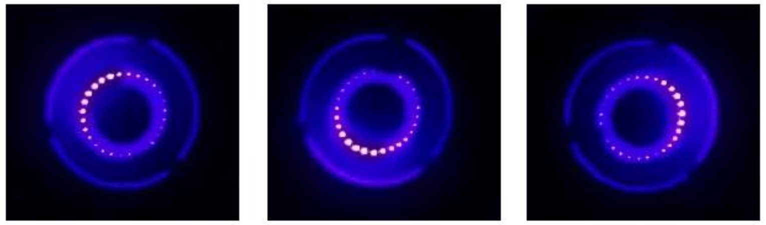
NO	7	NO
Comm. avail.	TRL	Aerospace-tested

Nano AR³ (previously named IFM NanoThruster SE) [1 of 2]
Enpulsion

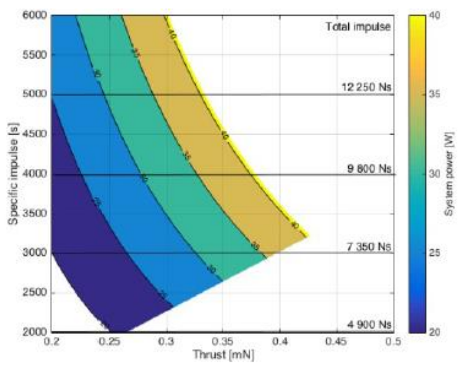
Propulsion Technology	Field Emission Electric Propulsion (FEEP)
Manufacturer/Country	FOTEC/ENPULSION (AUSTRIA), ENPULSION Inc. (US)
TRL	6
Size (including PPU)	0.6U to 1U, 720g (dry), 950g (wet) [1]
Design satellite size	1U and larger
Isp (s)	2000 to 6000 s [1]
Thrust type/magnitude	350 uN (continuous, nominal, at 40W power), 200 uN (continuous, nominal, at 20W power) [1] 5000 N*s (impulse, total), dynamic thrust range 10 uN to 0.4 mN [1]
Delta-V (m/s)	2000 m/s for 3 kg spacecraft, 525 m/s for 15 kg spacecraft (specs taken from IFM Nano heritage thruster)
Propellant	Indium
Power consumption (W)	40W (operational, including neutralizer) [1], 3 to 5W (standby) [5]. 12V or 28V input power. System can be throttled via power.
Flight heritage (if any)	Has not flown, but is based heavily on heritage IFM Nano, which has flown. Projected for Blue Canyon 6U Agile MicroSat (to be launched late 2021) [2] Projected for ABEX mission [3]
Commercially available	YES. Several models are now available for immediate delivery. "Base model" is ~$75K [1] Now available as stock item on SmallSat Catalog by Orbital Transports [3]
Last updated	*09/2022*



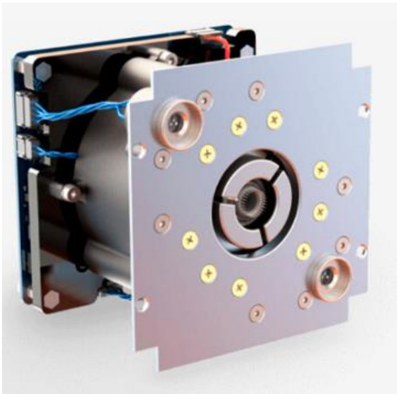
Thrust vectoring capability of the *ENPULSION NANO AR³*



[1]



Depending on available power, the user can choose from any operational point - Data shown corresponds to 12 V configuration



Additional comments on following charts…

References:
[1] https://www.enpulsion.com/
[2] https://www.enpulsion.com/news/mit-lincoln-lab-cooperation-on-the-6u-agile-microsat-mission/
[3] https://smallsatnews.com/2021/05/18/smallsat-thruster-modules-from-enpulsion-now-in-orbital-transports-smallsat-catalog/
[4] Fuchs, J., Halvorson, M., Lopez, V., "An overview of the alabama burst energetics explorer (ABEX) mission)," Small satellite conference 2021, SSC21-WKII-04.

Comm. avail.	7 TRL	NO Aerospace-tested

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Nano AR^3 (previously named IFM NanoThruster SE) [2 of 2]
Enpulsion

Additional comments:

[Reference 1][July 2019][General company info]
For 15 years, FOTEC has followed a technology push from ESA developing a FEEP propulsion technology for a very niche market of scientific satellites in formation flight. ENPULSION was founded in 2016 as a FOTEC spin-out to scale the production of this thruster to several hundred units per year. The IFM Nano Thruster is a mature technology, developed under ESA contracts for 15 years. In this time more than 100 emitters have been tested and an ongoing lifetime test has demonstrated more than 18,000 h of firing without degradation of the emitter performance. The technology is scalable, and multiple IFM units can be clustered for a variety of mission needs.

This thruster is based on the IFM Nano Thruster design (see corresponding charts in this survey), and expands the performance towards active thrust vector control, without moving parts. The IFM NanoThruster SE uses differential emission throttling within the proprietary crown ion emitter to actively control the emitted ion beam and therefore thrust. A spatial map of the thrust vectoring capabilities of the IFM NanoSE is shown on the company's website and also on this chart.

[Reference 2][Jan 2021][General company info]
[Nov 2019] We are very proud to announce that on September 23 2019, ENPULSION was selected by MIT Lincoln Laboratory to develop the Agile MicroSat thruster technology. The Agile MicroSat mission will demonstrate the potential for reliable low altitude performance of CubeSats. Small satellite manufacturer and mission services provider Blue Canyon Technologies (BCT) has been selected to design and manufacture the 6U Agile MicroSat. Funded by the U.S. Air Force, the launch is planned for late 2021.

ENPULSION is proud to take a part in this project as a provider of high-quality thruster solutions which are of critical importance for the success of this advanced mission. For this purpose, ENPULSION will deliver a thruster offering active thrust vector control without moving parts, the IFM Nano Thruster SE. This effect is achieved by the segmented extractor which enables the steering of the beam and achieves precise thrust pointing. This modification of the IFM Nano Thruster is also available for pre-order on the company's website www.enpulsion.com.

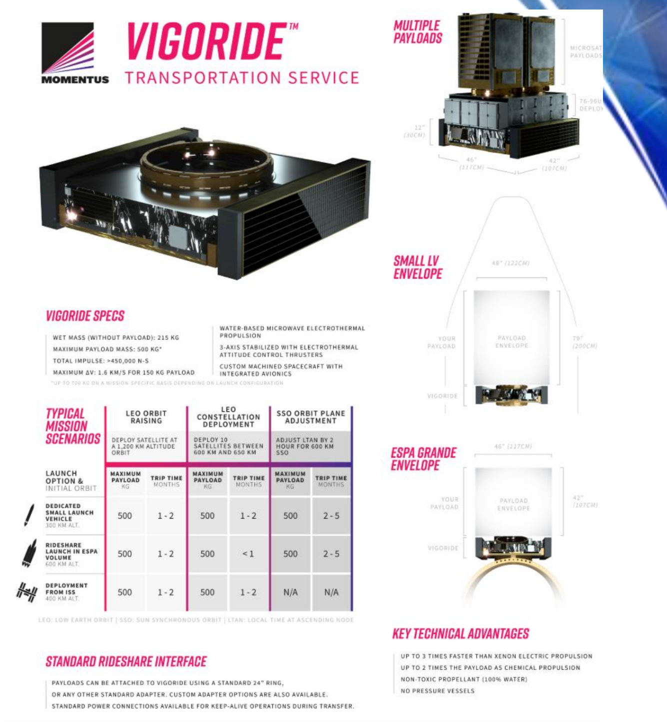
References:
[1] https://www.enpulsion.com/
[2] https://www.enpulsion.com/news/mit-lincoln-lab-cooperation-on-the-6u-agile-microsat-mission/

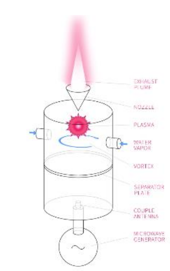
	7	NO
Comm. avail.	TRL	Aerospace-tested

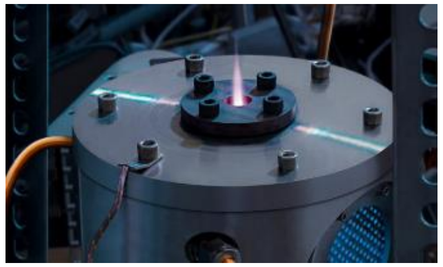
DISTRO A: Approved for public release. OTR-2024-00338

Momentus Microwave Electro-Thermal (MET) Water Thruster [1 of 6]
VIGORIDE Transportation Service

Propulsion Technology	Water thruster ****NOTE MOMENTUS DOES NOT MARKET THEIR PROPULSION DEVICE ON ITS OWN. RATHER, THEY ARE SELLING A TRANSPORTATION SERVICE.**
Manufacturer/Country	Momentus (USA)
TRL	7 (no specific thruster performance noted, but customer payloads have been delivered. Propulsion system will be comprehensively tested in the Dec 2022 launch [6])
Size (including PPU)	Wet mass = 215 kg [1], Maximimum payload mass = 500 kg
Design satellite size	100kg +
Isp (s)	457s [3]
Thrust type/magnitude	>450,000 N*s [1].
Delta-V (m/s)	>1600 km/s for 150 kg payload [1]
Propellant	Water
Power consumption (W)	35W [3]
Flight heritage (if any)	Tech Demo “CubeSat Momentus X1” launched July 2019, aboard El Camino Real, integrated by Astro Digital. No technical on-orbit data available, only manufacturer’s claim of success. Vigoride (“Vigoride-3”)to launch Dec 2020 [4], now delayed [5], launched May 2022 [6] Second Vigoride to launch Dec 2022 aboard SpaceX Transporter-6 [6] Third Vigoride launched April 2023 [7] “Vigoride-5” launched Jan 2023, “Vigoride-6” launched April 2023. [8]
Commercially available	YES
Last updated	12/2023







Additional comments:

[Reference 2][March 2019][Momentus company]

July 2018 - SAN FRANCISCO — Mikhail Kokorich, the space industry investor who founded Russian small satellite builder Dauria Aerospace, is the founder and president of Momentus, a Silicon Valley startup focused on water plasma propulsion. Momentus plans to demonstrate Vigor, its first water plasma thruster, by sending it into orbit in February 2019 on a 16-unit cubesat launched from a Russian Soyuz rocket. In 2020, Momentus plans a flight demonstration of the Ardor thruster it is developing for its Ardoride propulsion system to power 500 to 1,000-kilogram spacecraft. For now, Momentus’s Ardor technology is undergoing laboratory testing, Kokorich said by email. “We are developing the first in-space rockets powered by water plasma engines,” Kokorich said. “We use solar energy to heat water with microwaves up to the sun’s surface temperature and eject the superheated gas through the nozzle to create thrust. One of the main problems we solved is how to make sure that plasma will not vaporize the chamber walls and nozzle.” Momentus is participating in Y Combinator, a startup accelerator based in Mountain View, California. After Y Combinator’s demonstration day in August, the culmination of the three-month program, Momentus will announce plans to attract investment, including its fundraising goal, Kokorich said. Kokorich, who founded a home products retail chain in Russia before moving to the United States, is also a co-founder of Astro Digital, an Earth imaging and analysis firm based in Mountain View, and an investor in Helios Wire, a satellite-enabled internet of Things startup in Vancouver.

References:

[1] https://momentus.space/development/
[2] https://spacenews.com/momentus-developing-water-engines/
[3] Verbal statements and charts during Electrospray and Future of EP Workshop in May 2019, held at LA AFB.
[4] Small Sat 2020, virtual public forum
[5] https://spacenews.com/momentus-delays-first-vigoride-launch/
[6] https://smallsatnews.com/2022/09/21/momentus-spaces-vigoride-osv-completes-vibration-testing-5th-mission-update-regarding-their-inaugural-vigoride-mission/
[7] https://smallsatnews.com/2023/04/16/momentus-vigoride-6-orbital-service-vehicle-osv-launches-via-the-spacex-transporter-7-mission/
[8] https://smallsatnews.com/2023/07/31/momentus-deploys-all-payloads-from-vigoride-6-mission-offers-updates/

Comm. avail.	7* TRL	NO Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Momentus Microwave Electro-Thermal (MET) Water Thruster [2 of 6]

Additional comments:

[Reference 1][March 2019][Momentus news]
Feb 2018 - MOUNTAIN VIEW, CALIFORNIA – Exolaunch, the German launch services provider formerly known as ECM Space, signed a contract to pay in-space transportation startup Momentus more than $6 million to move satellites in low Earth orbit in 2020 with a service called Vigoride and from low Earth to geosynchronous orbit in 2021 with Vigoride Extended.
With Vigoride, Exolaunch will send "cubesat and microsatellite constellations to multiple orbits, giving clients an unprecedented flexibility of satellite deployment, reducing the price of launch, and giving access to orbits not typical for ridesharing vehicles," Dmitriy Bogdanov, Exolaunch chief executive, said in a statement. "We also plan to deliver smallsats to geosynchronous orbit using the Vigoride Extended service. Momentus will enable us to service a larger segment of the market by enabling our customers to reach custom orbits in an efficient and cost-effective manner." Vigoride, with a preliminary pricetag of $1.2 million, is designed to move satellites with a mass of 250 kilograms or less to new destinations in low Earth orbit. For example, "you could put different satellites at different altitudes," Mikhail Kokorich, Momentus founder and president, told SpaceNews at the SmallSat Symposium. Vigoride Extended, with a preliminary price of $4.8 million, will move satellites with a mass of 300 kilograms from low Earth orbit to geostationary transfer orbit, geostationary orbit or the moon, said Kokorich, the entrepreneur who founded Russian small satellite builder Dauria Aerospace, co-founded Astro Digital, an Earth imaging and analysis firm, and invested in Helios Wire, a satellite-enabled internet-of-things startup. Momentus plans to conduct an in-orbit demonstration of its key technology, a water-plasma engine, in March or April. After extensive laboratory testing, Momentus engineers are confident the technology works but this type of water plasma engine has never flown in space, said Negar Feher, Momentus product and business development vice president. Momentus' orbital transport vehicle is housed in a 61 by 71 by 25 centimeter aluminum bus with a fueled mass of 80 kilograms. In addition to the Exolaunch contract, Momentus has nonbinding letters of intent worth about $400 million for its in-space transportation services, Feher said.

[Reference 2][May 2019][Thruster technology]
"This thruster uses microwave power at 17.8 GHz for plasma production within a resonant cavity. Water is utilized as the propellant, unlike previous MET models that have used helium, ammonia, and hydrazine decomposition products. Prior miniaturization efforts have resulted in a CuMET version that can be integrated into a 3U CubeSat bus. An overview of a proposed implementation is presented. Redesign of the CuMET allows for implementation of the thruster block into the "tuna can" volume available in the CubeSat standard, increasing either propellant or secondary payload space onboard. The theoretical underpinnings of water as a propellant in an MET are also detailed, including challenges faced in testing and discovered through analysis of the MET flow and heating system. Continuing work involves the development of viable spacecraft microwave signal sources and an adequate heater configuration for water vapor production aboard a spacecraft."
"The microwave electrothermal thruster (MET) works on the principle of microwave power being injected into a resonant cavity to produce plasma that is exhausted from a nozzle. A TM011z resonant mode is established within the cylindrical cavity, as shown in Fig. 1. Propellant inlets are placed near the top, where the nozzle is located, and a vertical flow is induced around the primary plasma formation region. An antenna for injecting the microwave power is at the bottom of the cavity, which region is separated from the propellant vortex by a dielectric separation plate. Electric fields are maximized at the bottom and top of the cavity, and breakdown occurs producing a plasma at the nozzle since the bottom is separated and held at a higher pressure."
"An early concept of the CuMET's integration and implementation as part of a working CubeSat platform has been outlined. Design points for the development of an improved vaporization and vapor delivery system have also been determined, such that laboratory testing of a water CuMET may be done to adequately characterize water's behavior in the resonant cavity. A forced flow-through pump system and addition of increased insulation in the flow system should greatly increase efficiency in the system, as well as vapor quality and delivery. Moving forward, trades must be conducted on the balance of thermal and fluid-flow parameters in the vaporization system. Optimal fluid residence time for the production of a high-quality vapor will drive the specifications of stop-gap and filling valves populating the vaporization chamber.
Estimates for the total required system volume and power have been provided. The water CuMET's operational parameters fit within the accommodations of a 3U CubeSat bus. Mission profile as well as system architecture development will be integrated into an upcoming Penn State CubeSat mission."

References:
[1] https://spacenews.com/momentus-first-vigoride-customer/
[2] Galluci, S., Micci, M., Bilen, S., "Design of a Water-Propellant 17.8-GHz Microwave Electrothermal Thruster," IEPC-2017-296

Comm. avail.	TRL	Aerospace-tested
(cart icon)	7*	NO

DISTRO A: Approved for public release. OTR-2024-00338

Momentus Microwave Electro-Thermal (MET) Water Thruster [3 of 6]

Additional comments:

[Reference 1][May 2019][Momentus company and status]
In May, 2019, Philip Mainwaring (Head of Propulsion, Momentus) and Michael Micci (Penn State), gave a joint talk at the Electrospray and Future of EP Workshop entitled “Medium Isp, High Thrust, and Thrust Density Electric Propulsion Using Water Propellant”.
In 2017, Momentus began commercialization of the Microwave Electrothermal Thruster (MET) developed at Penn State by Sergio Gallucci, Michael Micci, and Sven Bilen. Momentus is VC-funded, and currently has 12 employees. They raised $8.3M in seed money last year. Instead of selling propulsion, they specialize in selling space transportation services (i.e. delivering customer payloads to specified orbits using their own bus).
In July 2019, they plan to launch their water thruster as a tech demo. It is a 35W, 10 GHz model named “Vigor”. The Isp for this model is 457s using water vapor.
Momentus has not made any direct thrust measurements.

[Reference 2][June 2019][Missions]
“Momentus is preparing to demonstrate its water plasma propulsion system on an Astro Digital 16-unit cubesat scheduled to launch July 5 on a Russian Soyuz rocket from Vostochny Cosmodrome. Two more Momentus launches are slated for 2020. The first Vigoride Extended mission is set for 2021.”

[Reference 3][Aug 2019][Funding and missions]
SAN FRANCISCO – Momentus, a Silicon Valley in-space transportation startup, raised $25.5 million in its Series A funding round announced July 17, 2019. Momentus launched its first demonstration mission July 5 on a Russian Soyuz rocket alongside dozens of small satellites and Russia’s Meteor M2-2 weather satellite. Mikhail Kokorich(founder and CEO) declined to comment on that ongoing demonstration. “In the past 18 months, Momentus has rapidly matured their water plasma propulsion system to deliver the world’s safest and most affordable in-space transportation services,” Dakin Sloss, Prime Movers Lab founder and general partner, said in a statement. “They recently launched their first demonstration and are on track to radically reshape the landscape of the space economy.” Momentus is preparing to expand its staff, research and manufacturing facilities. The company is moving most of its development in-house and investing in vertical integration, Kokorich said.

[Reference 4 and 5][Nov 2019][Thruster mission and status]
SAN FRANCISCO – Silicon Valley startup Momentus’ is reporting success in on-orbit testing of water plasma propulsion and other key elements of its Vigoride in-space transportation vehicle. “The on-orbit testing has demonstrated for the first time that microwave electrothermal plasma technology has the potential to achieve high specific impulse using water propellant,” Momentus CEO Mikhail Kokorich told SpaceNews. “Water plasma propulsion is now technologically mature enough to be baselined for operational in-space transportation missions.”
For the next few months, Momentus plans to continue firing the water plasma thruster and performing in-space maneuvers on the El Camino Real spacecraft launched in July. Engineers will compare the results of on-orbit testing with results of ground tests to validate the company’s models and analysis, Kokorich said by email. El Camino Real is a 16-unit cubesat integrated by Astro Digital, a spacecraft manufacturer and geospatial data analysis firm based in Santa Clara, California.
During one operation, water froze throughout the spacecraft’s propulsion lines. “The system proved to be highly resilient and post-freezing, all units were successfully verified to operate as expected,” Kokorich said. “El Camino Real has performed numerous hot thruster firings on-orbit since it launched in early July and the company has collected a wealth of valuable telemetry.” Momentus revealed the first El Camino Real test results on Twitter. “El Camino Real is performing as expected!” the company tweeted Sept. 9. “This successfully demonstrates for the first time in-space water plasma propulsion, and also demonstrates the technology, which has the highest specific impulse among other water-based propulsion.”

[**Reference 6][Dec 2020][Company info]**
Momentus and Australian rocket company Gilmour Space Technologies have reached a multi-million dollar agreement for launch and orbital transport services, the companies announced Nov. 30. Gilmour Space has the option to book up to three missions with Momentus orbital transfer vehicle Vigoride between 2023-2025, and Momentus has agreed to purchase one dedicated launch on an Eris launch vehicle. The specific dollar value of the agreement was not disclosed. Gilmour Space’s Eris rocket is designed for lift-off capability to LEO in the 300 kg class starting in 2022.

References:
[1] Verbal statements and charts during Electrospray and Future of EP Workshop in May 2019, held at LA AFB.
[2] https://spacenews.com/momentus-vigoride-extended-line/
[3] https://spacenews.com/momentus-raises-25-5-million/
[4] https://space.skyrocket.de/doc_sdat/momentus-x1.htm
[5] https://spacenews.com/momentus-el-camino-real-results/
[6] https://www.satellitetoday.com/launch/2020/12/04/australias-gilmour-space-partners-with-momentus-for-in-orbit-transfer-on-future-launches/

Comm. avail.	TRL	Aerospace-tested
	7*	NO

DISTRO A: Approved for public release. OTR-2024-00338

Momentus Microwave Electro-Thermal (MET) Water Thruster [4 of 6]

Additional comments:

[Reference 1][Feb 2021][Company info]
CEO Mikhail Kokorich has resigned as Director and Founder of Momentus. The departure of Kokorich is see as the company attempting to ameliorate their regulatory reviews by the U.S. government, given that Kokorich is a Russian citizen and that fact had caused some concerns regarding foreign ownership of the company and US national security. Dawn Hawms will be taking his place. She was Momentus' Chief Revenue Officer.

[Reference 2][Feb 2021][Company info]
Momentus Inc. ("Momentus" or the "Company") and Qosmosys, a new venture founded in Singapore last year, have announced a service agreement for two 3UXL protoflight cubesats in 2022, followed by two options in 2023. Momentus will provide the orbital maneuvering services necessary to deliver the spacecraft to a circular or elliptical orbit, depending on each mission requirement. Qosmosys has its specific platform design, dubbed Zeus, which will be built with major contributions from NuSpace in Singapore.

[Reference 3][March 2021][Flight info]
In a Jan. 4 statement, Momentus said the flight of its first Vigoride tug, which was to be part of the payloads on a Falcon 9 dedicated rideshare mission launching as soon as Jan. 14, will be delayed to later in the year because it was unable to get approval from the Federal Aviation Administration for the mission. Momentus did not disclose in its announcement the payloads on the mission, known as Vigoride-1 or VR-1. However, in a Federal Communications Commission filing in June, the company said the vehicle would carry five cubesats, ranging in size from 1.8 to 4.4 kilograms each, from Aurora Propulsion Technologies, SatRevolution, SpaceManic and Steamjet Space Systems.

[Reference 4][April 2021][Company info – Exolaunch terminates contact with Momentus]
In 2019, Exolaunch agreed to pay in-space transportation startup Momentus more than $6 million to move satellites in low Earth orbit in 2020 with a service called Vigoride, and from low Earth to geosynchronous orbit in 2021 with Vigoride Extended.

Vigoride's operational debut had been slated for SpaceX's Jan. 24 Transporter-1 mission but was pulled off that launch after delays in completing an interagency review.

Exolaunch said it terminated the agreement with Momentus in 2020 when it became apparent that expected timing parameters would not be met. The company added there is now no contractual relationship between Exolaunch and Momentus.

[Reference 5][Oct 2022][Mission information]
Momentus Space, Inc. has completed vibration testing of the firm's Vigoride Orbital Service Vehicle that is scheduled to launch on the SpaceX Transporter-6 mission in December of 2022. The December flight will mark Momentus' second demonstration mission. The vehicle will carry payloads for customers Caltech and Qosmosys. In addition to deploying customer payloads, Momentus will aim to comprehensively test Vigoride in space, including its water-based, propellant propulsion system.

[Reference 6, 7][April 2023][Mission information]
Momentus Inc. (NASDAQ: MNTS), on April 14th., launched their third, Vigoride Orbital Service Vehicle (OSV) to LEO aboard the SpaceX Transporter-7 mission — the company established contact with the Vigoride vehicle and confirmed that both solar arrays are deployed and the vehicle is generating power and the batteries are charging. The Vigoride-6 mission is delivering two satellites to a custom orbit for the NASA LLITED mission. Momentus will use their Electrothermal Thruster (MET) propulsion technology that uses water as a propellant to change the orbital inclination of the Vigoride OSV to support these deliveries.

Momentus Inc. (NASDAQ: MNTS) has successfully completed the initial test sequence on-orbit of the company's pioneering Microwave Electrothermal Thruster (MET) that relies on solar power and uses distilled water as a propellant. The MET is the Vigoride Orbital Service Vehicle's (OSV) primary propulsion method that produces thrust by expelling extremely hot gases through a rocket nozzle. Unlike a conventional chemical rocket engine, which creates thrust through a chemical reaction, the MET is designed to create a plasma and thrust using solar power to drive a microwave energy source that heats the water propellant. Momentus has two patents in support of this proprietary propulsion technology.

References:
[1] https://smallsatnews.com/2021/01/26/momentus-founder-director-resigns-new-ceo-named/
[2] https://smallsatnews.com/2021/01/22/momentus-to-provide-orbital-maneuvering-services-to-qosmosys/
[3] https://spacenews.com/momentus-delays-first-vigoride-launch/
[4] https://spacenews.com/exolaunch-entering-orbital-debris-market-with-eco-friendly-space-tugs/
[5] https://smallsatnews.com/2022/09/21/momentus-spaces-vigoride-osv-completes-vibration-testing-5th-mission-update-regarding-their-inaugural-vigoride-mission/
[6] https://smallsatnews.com/2023/04/16/momentus-vigoride-6-orbital-service-vehicle-osv-launches-via-the-spacex-transporter-7-mission/
[7] https://smallsatnews.com/2023/04/03/momentus-propulsion-system-completes-initial-in-space-tests/

Comm. avail.	TRL	Aerospace-tested
	7*	NO

DISTRO A: Approved for public release. OTR-2024-00338

Momentus Microwave Electro-Thermal (MET) Water Thruster [5 of 5]

Additional comments:

[Reference 1][June 2023][Company news]
Momentus Inc. (NASDAQ: MNTS) has signed an agreement with Apogeo Space to provide orbital transportation services for nine satellites that are part of Apogeo's planned, 100-satellite, Internet of Things (IoT) constellation. Apogeo Space aims to build a constellation of smallsats that are capable of providing connectivity to IoT devices across the globe. The delivery with Momentus represents the second batch of nine satellites and another key step toward the creation of the 100-satellite network. The constellation is scheduled to enter service by the second half of 2023.

[Reference 2][June 2023][Company news]
Momentus Inc. (NASDAQ: MNTS) has signed a contract with Lunasonde to deliver their Picacho CubeSat to orbit. Lunasonde is a sub-surface imaging company with the goal of making underground resources – such as water and minerals – easier to locate. The Picacho CubeSat is a tech demo of Lunasonde's sensors and will measure the power spectral density of low-frequency radio signals in the ionosphere that will help inform designs for the company's future satellites. Picacho will fly on the Vigoride-7 spacecraft targeted to launch on the SpaceX Transporter-9 mission in October 2023.

Momentus currently has three Vigoride Orbital Service Vehicles in orbit. The Company has flights scheduled through the end of 2024.

[Reference 3][June 2023][Company news]
Momentus Inc. (NASDAQ: MNTS) has deployed the Qosmosys Zeus-1 payload from the company's Vigoride-5 Orbital Service Vehicle and is now providing comprehensive hosted payload support services for Caltech's Space-based, Solar Power Project payload. The Qosmosys Zeus-1 payload was deployed to orbit on May 10, 2023. Effective May 15, 2023, Momentus is providing on-orbit support to Caltech, including providing data, communication, commanding and telemetry, and resources for optimal picture taking and solar cell lighting. Momentus will also be performing thrusting maneuvers so Caltech can measure the behavior of their experiments. Caltech's Space Solar Power Demonstrator project onboard Momentus' Vigoride-5 spacecraft comprises three separate experiments. The experiments include:
DOLCE (Deployable on-Orbit ultraLight Composite Experiment): A structure measuring 6 feet by 6 feet that demonstrates the architecture, packaging scheme and deployment mechanisms of the modular spacecraft that would eventually make up a kilometer-scale constellation forming a power station.
ALBA: A collection of 32 different types of photovoltaic (PV) cells, to enable an assessment of the types of cells that are the most effective in the punishing environment of space.
MAPLE (Microwave Array for Power-transfer Low-orbit Experiment): An array of flexible lightweight microwave power transmitters with precise timing control focusing the power selectively on two different receivers to demonstrate wireless power transmission at distance in space.

References:
[1] https://smallsatnews.com/2023/06/05/momentus-to-deliver-9-iot-sats-to-orbit-for-apogeo-space/
[2] https://smallsatnews.com/2023/05/29/momentus-to-deliver-lunasonde-tech-demo-payload-to-orbit-3/
[3] https://smallsatnews.com/2023/05/19/momentus-deploys-qosmosys-satellite-starts-comprehensive-on-orbit-support/

🛒	7*	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Momentus Microwave Electro-Thermal (MET) Water Thruster [6 of 6]

Additional comments:

[Reference 1][Sep 2023][Mission information]
Momentus Inc. (NASDAQ: MNTS) has signed a contract with FOSSA Systems (“FOSSA”), a Spanish company that offers global, low-power, Internet of Things (IoT) connectivity and in-space services to provide hosted payload services, starting in 2024 — the contract also includes two options for additional hosted payloads. The hosted payloads will strategically complement FOSSA’s existing IoT satellite constellation with additional capacity and serve as a technology demonstrator platform independent of the future satellite launches FOSSA has scheduled for 2024 and 2025.

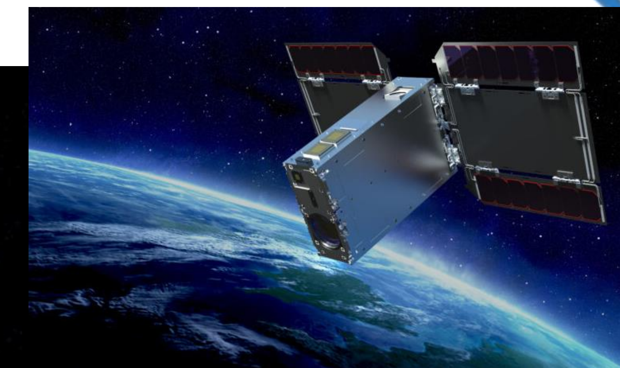
[Reference 2][Dec 2023][Company information]
Momentus Inc. (NASDAQ: MNTS) has closed the firm’s previously announced agreement with a single investor that is an existing holder of warrants to purchase shares of common stock of the Company for cash (the “Existing Warrants”), wherein the investor agreed to exercise the Existing Warrants to purchase up to a maximum of 2,904,269 shares of common stock at an exercise price of $2.00 per share, plus an additional $0.25 consideration per share, resulting in gross proceeds of approximately $6.5 million, before deducting offering fees and other expenses payable by the Company.

References:
[1] https://smallsatnews.com/2023/08/25/momentus-to-provide-hosted-payload-services-for-fossa-systems/
[2] https://smallsatnews.com/2023/11/13/momentus-closes-warrant-inducement-transaction-for-million-in-gross-proceeds/

	7*	NO
Comm. avail.	TRL	Aerospace-tested

Pale Blue Resistojet

Propulsion Technology	Water resistojet
Manufacturer/Country	Pale Blue (JPN)
TRL	7
Size (including PPU)	~1U (1.4 kg wet mass)
Design satellite size	3U+
Isp (s)	
Thrust type/magnitude	5.6 mN [1]
Delta-V (m/s)	
Propellant	water
Power consumption (W)	22W [1]
Flight heritage (if any)	EYE launched Jan 2023 [1]
Commercially available	YES
Last updated	04/2023



[1]

Additional comments:

[References 1 and 2][April 2023][General information]
Pale Blue's water-based propulsion system aboard "EYE" was launched by SpaceX on January 3rd 2023 and has been currently orbiting earth in LEO. The propulsion system operated for approximately 2 minutes on March 3rd 2023, and the company confirmed successful thrust from the obtained data.

STAR SPHERE Project, led by Sony Group Corporation, is planning to roll out a space photography service in 2023. The satellite will use Pale Blue's thruster to enter the target orbit before service launch.

References:
[1] https://pale-blue.co.jp/news/314/
[2] https://smallsatnews.com/2023/03/14/pale-blues-water-based-propulsion-system-successfully-performs-on-orbit/

7 | NO
Comm. avail. | TRL | Aerospace-tested

B20 SmallSat Propulsion Thruster, 20N

Propulsion Technology	Bi-prop
Manufacturer/Country	Dawn Aerospace (Netherlands/New Zealand)
TRL	4-5
Size (including PPU)	2U (not including tanks)
Design satellite size	3U and above
Isp (s)	>285s
Thrust type/magnitude	7.3N at -5C, 13.4N at 15C, 20N at 35C [2] 150 N*s (max impulse bit)
Delta-V (m/s)	
Propellant	Nitrox oxide (N2O) + propene (C3H6)
Power consumption (W)	12W
Flight heritage (if any)	D-Orbit's ION Satellite launched Jan 2023 on Transporter-1 [5]
Commercially available	Yes. Website quotes $40K, 6 months lead time [2]
Last updated	05/2023

Dawn's B20 Thruster on orbit. © D-Orbit

Dawn's B20 Thruster on orbit. © D-Orbit

[5]

Nominal thrust
20 N

Specific impulse
>285 s

Propellants
Nitrous oxide (N2O) and propene (C3H6)

Thrust, range
7.3 N at -5°C
13.5 N at 15°C
19.8 N at 35°C

Minimum impulse bit
< 1 N.s
< 400 mN.s cold gas N2O
< 50 mN.s cold gas C3H6

Maximum impulse bit
150 N.s

Nominal power
12 W

Regulatory
REACH compliant and ITAR free

Health monitoring
Temperature sensor

Operational temperature
-5°C to 35°C

Cold-start capable
Yes

Thruster dimensions
167 x 70 x 41 mm

Mounting
3x M5 threaded holes

Valve configuration
Single seat (standard)
Dual seat (premium)

Dry mass, single seat
400 g

Dry mass, dual seat
560 g

Inlet pressure, range
Oxidiser 27.7 to 72.0 bar
Fuel 5.0 to 14.7 bar

Flow rate, range
Oxidiser 2.3 to 6.9 g/s
Fuel 0.26 to 0.88 g/s

Mixture ratio, nominal
8.5 to 9.2

Mixture ratio, range
6.0 to 11.0

Max operating frequency
4 Hz

Nozzle expansion ratio
100

Qualified number of starts
12,000

Qualified accumulated burn life
93,000 N.s

Droplet formation in plume and backflow
None

[2]

Additional comments:

[Reference 1][Dec 2020][General information]
Dawn Aerospace has been awarded "Hi-Tech Start-up Company of the Year" at the 2020 NZ Hi-Tech awards hosted on August 21st. Dawn Aerospace is developing technology to access space in a more scalable and sustainable way than is currently possible with traditional rockets. Their "spaceplanes", such as the Mk-II Aurora, will one-day launch satellites into space. It is the second rocket-powered aircraft or "spaceplane" produced by Dawn Aerospace. It will be capable of flights to above 100km altitude, the border to space, before returning to land at an airport. Upon landing, it can be refuelled and flown again within hours. It will be the first vehicle ever to be capable of such a feat multiple times per day. Dawn Aerospace also produces non-toxic propulsion for use on satellites themselves. These provide mobility to satellites long after delivering them to space. They allow the satellites to maintain their orbits, dodge space debris, and at the end of the satellites life, renter the Earth's atmosphere in a controlled manner.
[Reference 4][Feb 2022][General information]
Dawn Aerospace is providing satellite propulsion to hyperspectral imaging company Pixxel, who is building a health monitor for the planet through a constellation of hyperspectral imaging small satellites. In the last 12 months, Dawn has had several propulsion systems launched to space, with a total of 21 thrusters, powering a variety of satellites, including cubesats and OTV's. At the end of 2021, the company announced it had over one hundred of its 1N and 20N "green" thrusters in production, with this projected to triple over the next twelve months.
[Reference 5][April 2023][Flight information]
Six thrusters were onboard D-Orbit's ION Satellite Carrier. The companies have been working together since early-2019.Since launching on SpaceX's Transporter-1 mission in January, D-Orbit's operations team fired the six Dawn Aerospace B20 thrusters, validated attitude and orbit control strategies and algorithms, analyzed post-firing changes of orbital parameters and performed flight dynamics processes. The resulting orbit-changing manoeuvres succeeded in changing the altitude by up to 10km, while also demonstrating ION's ability to change the local time of the ascending node (LTAN).

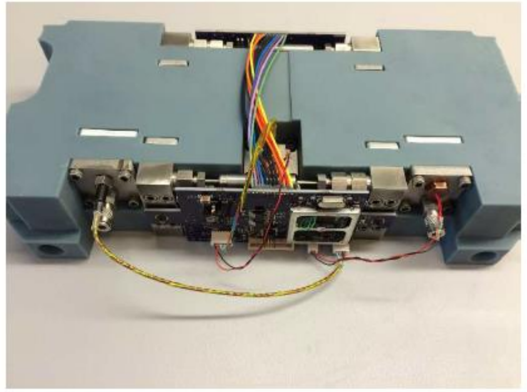
References:
[1] https://www.dawnaerospace.com/blog/start-up-of-the-year-2020
[2] https://www.dawnaerospace.com/products/p/smallsat-propulsion
[3] Publicly distributed newsletter – Dec 2020
[4] https://smallsatnews.com/2022/02/08/dawn-aerospace-propulsion-to-empower-pixxels-hyperspectral-imaging-smallsats/
[5] https://www.dawnaerospace.com/latest-news/b20-thrusters-proven-in-space

Comm. avail.	7 TRL	NO Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Lightsey cold-gas thruster (BioSentinel, SunRise, SWARM-EX, VISORS) [1 of 2]

Propulsion Technology	Cold-gas
Manufacturer/Country	Georgia Tech
TRL	7
Size (including PPU)	~1-2U 0.7 U for the Swarm-EX vehicle [7]
Design satellite size	6U (BioSentinel)
Isp (s)	30s [1]
Thrust type/magnitude	50 to 60 mN thrust, total impulse = 60 N*s[1]
Delta-V (m/s)	5.9 m/s for the BioSentinel vehicle 15 m/s for the Swarm-EX vehicle [7]
Propellant	Refrigerant R-236fa
Power consumption (W)	
Flight heritage (if any)	Launched NASA BioSentinel aboard Artemis-1 (2022) Identical or similar systems to be launched aboard SunRISE (to be launched Q4 2024), SWARM-EX (to be launched 2024), and VISORS missions (TBD) [5]
Commercially available	NO
Last updated	12/2023



[3]

SunRISE specs

Metric	Value
Thrust* (0.15s Pulse)	32 mN
Specific Impulse	42.2 s
Dry Mass	1.2 kg
Propellant Capacity	330 g

[6]

Additional comments:
[Reference 1][June 2020][Thruster information]
The structure of the thruster consists of a 3D-printed component and give steel manifolds attached to the printed component and sealed with O-rings. The 3D-printed structed is printed using the selective laser ablation (SLA) technique, and is made from Accura Bluestone. Bluestone is a ceramic-like composite with a relatively high ultimate tensile strength of 66 Mpa. The printed structure contains two propellant tanks, the main tank and the plenum, as well as the seven nozzles and the propellant feed pipes.
In order to validate the thruster’s design and performance, an engineering prototype unit was fabricated and tested at the Georgia Institute of Technology in early 2015. The thruster testing was carried out in the Space Systems Designs Lab (SSDL), in a microTorr-level thermal vacuum chamber, using a custom-built torsional pendulum thrust stand.

References:

[1] Stevenson, T., Lightsey, G., “Design and characterization of a 3D-printed attitude control thruster for an interplanetary 6U CubeSat,” Small Satellite Conference SSC16-V-5, 2016.
[2] https://www.nasa.gov/centers/ames/engineering/projects/biosentinel.html
[3] Sorgenfrei, M., Stevenson, T., Lightsey, G., “Performance characterization of a cold gas propulsion system for a deep space cubesat,” AAS17-141.
[4] Dono, A., Alvarellos, J., Napoli, M., Shih, P., Smith, M., Fusco, J., “BioSentinel deep space cubesat mission,” Conference Proc. from Interstellar Small Sat Conference, May 2023.
[5] Wood, S., Lightsey, G., “Refill strategy for two-tank cold gas systems,” Small Satellite Conference, 2023 poster session.
[6] Martineau, R., Smith, T., Felt, M., Weston, C., Rusch, B., Fowler, R., Brown, E., Farmer, A., Nielsen, T., Thompson, C., Kirkman, A., Fluckiger, P., Morrison, S., Wittner, D., Picha, F., Weiss, J., Daniel, N., Wood, S., Glaser, M., “Lessons learned during the implementation of a cold gas propulsion system for the SunRISE mission,” SSC23-VI-04.
[7] Tong, K., Hart, S., Glaser, M., Wood, S., Hartigan, M., Lightsey, E., “Design to delivery of additively manufactured propulsion systems for the Swarm-EX mission,” SSC23-VI-06.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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Lightsey cold-gas thruster (BioSentinel, SunRise, SWARM-EX, VISORS) [2 of 2]

Additional comments:

[Reference 1][May 2023][Mission information]
On November 16th 2022 BioSentinel successfully deployed from ICPS and the navigation team started to receive tracking data from the DSN and ESA antennas. The spacecraft performed a nominal lunar flyby which provided the pertinent energy to achieve a final earth-trailing heliocentric orbit. delta v=4.2 m/s after unloading momentum, with a delta v total of 5.9 m/s over the 6 month mission. There was a tumbling anomaly shortly after deployment which caused the s/c to enter safe mode. The team was able to recover and prop system performed nominally for the remainder of the mission.

[Reference 2][Dec 2023][Design improvements]
This paper discusses a new refill strategy. The propellant, R-236fa, is stored as a saturated liquid-vapor mixtures in the main tank. A refill valve connects a plenum to the main tank. The plenum is kept below saturation pressure to store gaseous R-236fa for actuation.

[Reference 3][Dec 2023][SunRISE information]
The SunRISE mission utilizes a two-phase cold gas propulsion system, which provides several advantages over other cold gas systems but experienced challenges during assembly and testing. Since 2020, Georgia Tech Research Corporation (GTRC), Utah State University Space Dynamics Laboratory (SDL), and the Jet Propulsion Laboratory (JPL) have implemented several improvements to the SunRISE propulsion system. The SunRISE propulsion system leverages an additively manufactured monolithic structure, commercial off-the-shelf (COTS) valves and transducers, and the benign working fluid R-236fa to provide a suitable propulsion system for the SunRISE mission.
This source provides a very thorough listing of lessons learned during the engineering and testing process for SunRISE's propulsion system.

[Reference 4-5][Dec 2023][Swarm-EX information]
Space Weather Atmospheric Reconfigurable Multiscale Experiment CubeSat (SWARM-EX) is a collaboration between six colleges and universities (University of Colorado Boulder, Stanford, University of South Alabama, Western Michigan University, Olin, and Georgia Tech). Together, we are constructing three 3U CubeSats that will be launched in 2024 and be used to collect atmospheric data.
Mission requirements necessitate a propulsion system that provides each spacecraft with 15 m/s of ΔV and a maximum thrust greater than 5 mN in a volume of roughly 0.7U (7 cm x 10 cm x 10 cm). Unlike many other CubeSat-scale cold gas propulsion systems which are used to provide attitude control and perform reaction wheel desaturation burns, the primary objective of the SWARM-EX propulsion system (SEPS) is to provide ΔV during maneuvers

References:
[1] Dono, A., Alvarellos, J., Napoli, M., Shih, P., Smith, M., Fusco, J., "BioSentinel deep space cubesat mission," Conference Proceedings from Interstellar Small Sat Conference, May 2023.
[2] Wood, S., Lightsey, G., "Refill strategy for two-tank cold gas systems," Small Satellite Conference, 2023 poster session.
[3] Martineau, R., Smith, T., Felt, M., Weston, C., Rusch, B., Fowler, R., Brown, E., Farmer, A., Nielsen, T., Thompson, C., Kirkman, A., Fluckiger, P., Morrison, S., Wittner, D., Picha, F., Weiss, J., Daniel, N., Wood, S., Glaser, M., "Lessons learned during the implementation of a cold gas propulsion system for the SunRISE mission," SSC23-VI-04.
[4] https://www.osstp.org/swarm-ex
[5] Tong, K., Hart, S., Glaser, M., Wood, S., Hartigan, M., Lightsey, E., "Design to delivery of additively manufactured propulsion systems for the Swarm-EX mission," SSC23-VI-06.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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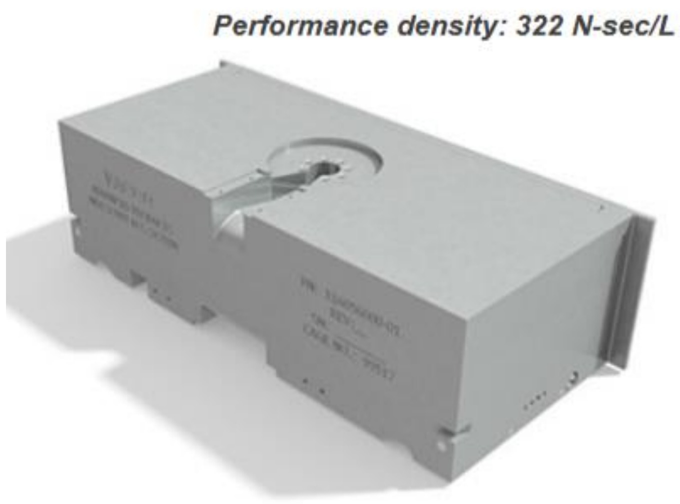
LiciaCube/NEA Scout Propulsion System [1 of 2]
VACCO

Propulsion Technology	Cold gas
Manufacturer/Country	VACCO (USA)
TRL	7
Size (including PPU)	2U
Design satellite size	6U and larger
Isp (s)	40s (estimated from similar thrusters)
Thrust type/magnitude	150 mN total (6X 25 mN cold gas thrusters) 500 N*s (impulse, total)
Delta-V (m/s)	37 m/s for 14 kg CubeSat (NEA Scout)
Propellant	Refrigerant R-134A or R-236FA
Power consumption (W)	1.1W (standby), 55W (warmup), 9W (operating)
Flight heritage (if any)	Launched on LiciaCube on Artemis-1 (2022), performed nominally [4] Launched on NEA-Scout on Artemis-1 (2022) but s/c had communication failure [5]
Commercially available	YES
Last updated	*09/2023*



Vacco's NEA Scout Propulsion System

Additional comments:

[References 1-3][Jan 2019][General info]
VACCO's cold gas Micro Propulsion System (MiPS) provides attitude control and orbital maneuvering. NASA's NEA Scout program utilizes VACCO's cold gas system to achieve highly reliable propulsion while observing an asteroid. The VACCO NEA Scout MiPS is approximately 2U in volume and uses six 25 mN cold gas thrusters to develop 500 N-sec of total impulse that provides 37 m/s of delta-v for a 14 kg CubeSat. Each thruster independently operates to perform both delta-v and ACS maneuvers through an integrated microprocessor controller.
NEA-Scout (Near Earth Asteroid Scout) is a cubesat mission by the NASA Marshall Space Flight Center to perform a slow flyby and rendezvous maneuver with a Near Earth Asteroid (NEA) and characterize it in a way that is relevant to human exploration. This mission is based on the JPL Deep Space NanoSat 6U cubesat Bus and features an 80 m^2 solar sail. The payload will consist of a Commercially available 4-band spectrometer. NEA-Scout will perform several lunar fly-bys before beginning the cruise phase to the asteroid. The maximum earth distance will be about ~0.35 AU and the solar distance will be about ~0.9-1.1 AU. NEA-Scout is to perform at least one close, slow flyby (<10 m/s). NEA-Scout is one of 13 CubeSats planned to be carried with the Orion EM1 mission into a heliocentric orbit in cis-lunar space on the maiden flight of the SLS (Block 1) iCPS launch vehicle in 2019.
[Reference 5][Dec 2019][Flight info]
NEA-Scout is one of 10 cubesats carried with the Artemis 1 (Orion CM-002) mission into a heliocentric orbit in cis-lunar space on the maiden flight of the SLS (Block 1) iCPS launch vehicle in November 2022. No signals were received after deployment.

References:

[1] http://space.skyrocket.de/doc_sdat/nea-scout.htm
[2] http://www.cubesat-propulsion.com/wp-content/uploads/2017/08/X16056000-data-sheet-080217.pdf
[3] http://www.cubesat-propulsion.com/nea-scout-propulsion-system/
[4] Gomez, L., Gai, I., Lombardo, M., Gramigna, E., Zannoni, M., "Navigation of LiciaCube: Challenges and lessons learned," Conference proceedings, Interstellar SmallSat Conference, May 2023.
[5] https://space.skyrocket.de/doc_sdat/nea-scout.htm

	7	NO
Comm. avail.	TRL	Aerospace-tested

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LiciaCube/NEA Scout Propulsion System [2 of 2]
VACCO

Additional comments:

[References 1][May 2023][Mission info]
LiciaCube News
On September 11, 2022, the CubeSat was released from the DART piggyback dispenser and started its independent approach to the system. A few hours later, the navigation operations of LICIACube kicked off. For the following 15 days, different orbital and desaturation maneuvers were designed and executed, leading LiciaCube towards the predefined location to observe DART's impact on Dimorphos. On September 26, 2022, about 168 seconds after DART's impact, LiciaCube flew by the asteroid at ~59 km and 6.1 km/sec, capturing images of the impact, the ejecta plume and the non-sun-lit side of Dimorphos, becoming the first CubeSat to flyby an asteroid in deep space. After the impact, the spacecraft continued on its trajectory while downloading the acquired images to the Mission Control Centre until December 23, 2022, when following an ASI decision, the spacecraft was commanded to execute the end-of-life procedure, and subsequently the end of mission was declared.

[Reference 5][September 2023]][Mission information]
Argotec has been honored for the reliability and technical excellence of the company's LICIACube mission with the American Institute of Aeronautics and Astronautics Small Satellite Mission of the Year award.

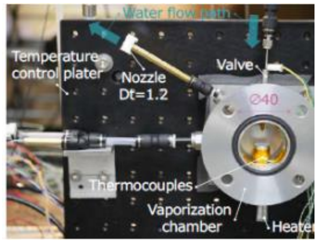
References:
[1] http://space.skyrocket.de/doc_sdat/nea-scout.htm
[2] https://smallsatnews.com/2023/08/17/liciacube-named-aiaa-small-satellite-mission-of-the-year/

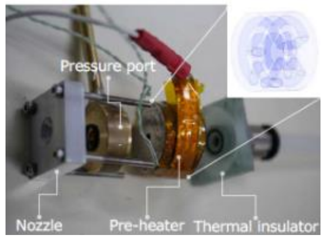
	7	NO
Comm. avail.	TRL	Aerospace-tested

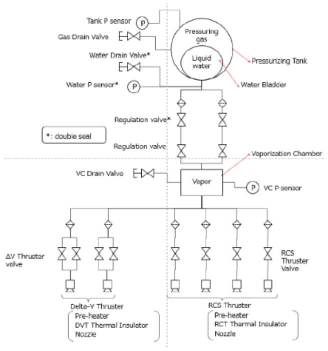
DISTRO A: Approved for public release. OTR-2024-00338

Aquarius (Aqua Resistojet Propulsion System) [1 of 3]

Propulsion Technology	Water resistojet
Manufacturer/Country	University of Tokyo (Japan)
TRL	7
Size (including PPU)	2U, 1.2 kg wet mass, 0.8 kg dry mass [3]
Design satellite size	6U (~14 kg)
Isp (s)	70 s [3], 86 s demonstrated on EQUULEUS [7]
Thrust type/magnitude	4 mN (depends on power), 0.22 mN/W (thrust to power ratio), 0.5 mN*s (min impulse bit), 250 N*s (tot impulse) [3] 6 mN demonstrated on EQUULEUS [7]
Delta-V (m/s)	54 m/s for 6U CubeSat [3]
Propellant	Water, 0.4 kg [3]
Power consumption (W)	<20W
Flight heritage (if any)	AQUARIUS (aka AQT-D) (Sep 2019) [3], EQUULEUS aboard Artemis-1 (2022) [2, 4, 5] SPHERE-1 EYE (6U CubeSat, Launched 2023) [6]
Commercially available	No
Last updated	*12/2023*







Additional comments:

[Reference 1][Jan 2019][General info and mission info]

AQUARIUS consists of 3 main components: a tank, a vaporization chamber, and thruster-heads. Inside the tank, a bladder is inserted, which is a kind of rubber balloon, storing 1.2 kg of water inside. Pressurized gas and water are separated by the bladder. Nominal temperature of the tank is 283-293K. The vaporization chamber made of aluminum is manufactured using 3D printing technology. Nominal temperature and pressure of the vaporization chamber are around 293K and less than 4.0 kPa. The thruster-head consists of 3 components: a thermal insulator, a pre-heater, and a nozzle. Saturated water vapor is heated to around 393K at the pre-heater which is also manufactured by using 3D printing technology to make a helical flow path in it. Thruster performance was evaluated using a horizontal torsional thrust stand. Aquarius was integrated with EQUULEUS and was tested for more than one hour of thruster operation. This was successful. Vibration testing of the spacecraft was also completed and was successful.

References:

[1] Asakawa, J., Koizumi, H., Nishii, K., Takeda, H., Funase, R., Komurasaki, K., “Development of the water resistojet propulsion system for deep space exploration by the cubesat EQUULEUS,” SSC17-VII-04.

[2] https://space.skyrocket.de/doc_sdat/equuleus.htm

[3] Asakawa, J., et al., “AQT-D: Demonstration of the water resistojet propulsion system by the ISS-Deployed CubeSat,” SSC19-WKV-07.

[4] Roma, K., Shibukawa, T., Matsushita, S., Mishimoto, S., Sekine, H., Fujimori, A., Moriai, I., Funase, R., “Thermal operation for the 6U deep space cubesat EQUULEUS in the initial critical phase,” Small satellite conference, Poster SSC23-WP1-12, 2023.

[5] Funase, R., Nakajima, S., Kawabata, Y., Fuse, R., Sekine, H., Koizumi, H., “EQUULEUS: Initial operation results of an Artemis-1 Cubesat to the earth-moon lagrange point,” SSC23-WV22-03.

[6] Nakagawa, Y., Iwakawa, A., Kameyama, S., Kikuchi, T., Yaginuma, K., Asakawa, J., Koizumi, H., “On-orbit demonstration of the water resistojet propulsion system on commericla 6U-Sat SPHERE-1 EYE,” SSC23-VI-02.

[7] Fujimori, A., Sekine, H., Ataka, Y., Moriai, I., Akiyama, M., Murohara, M., Koizumi, H., Funase, R., “AQUARIUS: The world’s first water-based thruster enabled 6U CubeSat to complete lunar flyby,” SSC23-VI-05.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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Aquarius (Aqua Resistojet Propulsion System) [2 of 3]

Additional comments:

[Reference 1][Jan 2019][Mission info]
EQUULEUS (Equilibrium Lunar-Earth point 6U Spacecraft) is a small lunar mission designed jointly by the Japan Aerospace Exploration Agency (JAXA) and the University of Tokyo. It will measure the distribution of plasma that surrounds the Earth to help scientists understand the radiation environment in the region of space around Earth. It will also demonstrate low-energy trajectory control techniques, such as multiple lunar flybys, within the Earth-Moon Lagrangian points (EML). EQUULEUS is equipped with the AQUARIUS propulsion system consisting of eight water thrusters also used for attitude control and momentum management. The spacecraft will carry 1.5 kg of water, and the complete propulsion system occupies about 2.5 units out of the 6 units total spacecraft volume. The scientific payload consists of three instruments:
PHOENIX (Plasmaspheric Helium ion Observation by Enhanced New Imager in eXtreme ultraviolet), a small UV telescope to operate in the high-energy extreme ultraviolet wavelengths. DELPHINUS (DEtection camera for Lunar impact PHenomena IN 6U Spacecraft), a camera connected to the PHOENIX telescope to observe lunar impact flashes and near-Earth asteroids, as well as potential 'mini-moons' while positioned at the Earth-Moon Lagrangian point L2 (EML2) halo orbit. CLOTH (Cis-Lunar Object Detector within Thermal Insulation) to detect and evaluate the meteoroid impact flux in the cislunar space by using dust detectors mounted on the exterior of the spacecraft. EQUULEUS is one of 13 cubesats planned to be carried with the Orion EM1 mission into a heliocentric orbit in cis-lunar space on the maiden flight of the SLS (Block 1) iCPS launch vehicle in 2019.

[Reference 2][Aug 2019][Mission info and thrust characterization]
AQUARIUS (AQUA ResIstojet propUlsion System) was proposed as the water propulsion system using a room temperature evaporation system. AQUARIUS consists of a tank, a vaporizer, and two types of thrusters, designed within 2.5U and storing 1.2 kg of water. It is to be installed on the 6U deep space exploration CubeSat: EQUULEUS (EQUilibriUm Lunar-Earth point 6U Spacecraft) and launched by SLS (Space Launch System) EM-1 in 2020.
AQT-D (AQua Thruster-Demonstrator) is a 3U CubeSat for a demonstration of 1U-size water-micro propulsion system, named AQUARIUS-1U. The propulsion concept and fundamental design were based on proposed AQUARIUS. AQT-D will be launched to the ISS (International Space Station) in the middle of 2019. This spacecraft will also be the world's first ISS-deployed CubeSat installing the propulsion system. The safety of water enables for ISS-deployed CubeSat to install a propulsion system. Deployment of CubeSats from the ISS is quite attractive because of the constant launch opportunity, low-cost, and user-friendly launch environment. However, ISS-deployed CubeSats have short lifetime due to the low altitude and air drag force. Installing a water micro-propulsion system on CubeSats can overcome this crucial issue. In addition, AQT-D has a role as a pre-cursor of EQUULEUS in terms of propulsion technology demonstration.

[Reference 3][Dec 2019][Flight info]
AQT-D is a 3U CubeSat for a demonstration of a water resistojet propulsion system developed by The University of Tokyo. The small propulsion system, named AQUARIUS-1U (AQUA ResIstojet propUlsion System 1U) is installed into a 1U volume using water as a propellant . The project completed the design and assembly of the AQT-D flight model. AQUARIUS-1U was fired on a pendulum-type thrust balance, and its performance was directly characterized in both a stand-alone test and an integrated test using an entire spacecraft system. — The AQT-D 3U CubeSat was delivered to JAXA to be launched to the ISS by the HTV-8 (HII Transfer Vehicle-8) flight of JAXA in September 2019.

[Reference 4][Dec 2019][Flight info]
HTV-8 (H-II Transfer Vehicle)/Kounotori-8 Mission
Launch: On 24 September 2019 at 16:05 UTC on Japan's Kounotori H-II Transfer Vehicle's eighth journey to the International Space Station aboard an H-IIB carrier rocket has begun following a successful second attempt. The launch from the Tanegashima Space Center followed a standdown due to a pad fire during its initial countdown two weeks ago. Mitsubishi Heavy Industries, Ltd. (MHI) launched the H-IIB Launch Vehicle No. 8 (H-IIB F8). H-IIB F8 flight proceeded nominally

References:
[1] https://space.skyrocket.de/doc_sdat/equuleus.htm
[2] Asakawa, J., et al., "AQT-D: Demonstration of the water resistojet propulsion system by the ISS-Deployed CubeSat," SSC19-WKV-07.
[3] https://directory.eoportal.org/web/eoportal/satellite-missions/a/aqt-d
[4] https://directory.eoportal.org/web/eoportal/satellite-missions/content/-/article/htv-8

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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Aquarius (Aqua Resistojet Propulsion System) [3 of 3]

Additional comments:

[Reference 1-2][Dec 2023][Flight info]
EQUULEUS was launched into deep space by NASA's SLS on November 16, 2022. It has an engineering mission to demonstrate low-energy orbit maneuvering to EML2, a libration orbit around the second Earth-Moon lagrange point using the water propulsion system AQUARIUS. The initial critical phase in EQUUELSU was a series of operational procedures associated with the first delta-V maneuver, which generated the largest thrust throughout the entire mission, taking place about 38 hrs after separation for entering the transfer orbit to EML2. This orbit control was followed by several thrust correction maneuver operations to compensate for thrust errors. Telemetry data confirmed that the thrust correction maneuvers were successful. There was some discrepancy between the ground test and on-orbit thermal telemetry, which is being investigated by the team.
The delta-V maneuver was successfully completed, achieving a total delta-V of 6.48 m/s. The propulsion system demonstrated an average thrust of 5.94 ± 0.21 mN. Subsequently, precise trajectory control maneuvers were carried out, resulting in a successful lunar flyby. As a result of these initial operations, AQUARIUS became the world's first water propulsion system to successfully control its orbit in deep space.

[Reference 3][Dec 2023][Flight info]
SPHERE-1 EYE, a 6U CubeSat developed by Sony Group Corporation, was launched at the beginning of 2023. The satellite included a water resistojet propulsion system, which is designed for orbit raising after the initial checkout. The water resistojet propulsion system consists of a tank, a vaporizer, nozzles, a control board, and a power processing unit. The form factor of the propulsion system is 1.25 U, the wet mass is 1.4 kg, and the achievable total impulse of the system is 170 Ns or higher. A unique design of the water propulsion system is a vaporization chamber generating steam at room temperature and low pressure, under 10 kPa. The performance measured on the ground shows a thrust of 2.7 mN, and a specific impulse of 60 s. A qualification test campaign including vibration, shock, thermal, throughput, and system performance tests was conducted, followed by acceptance tests. On-orbit demonstration was conducted on March 3rd and 16th for all four nozzles and the thrust generation was confirmed. The estimated thrust on orbit was 6.1 – 7.2 mN. Comparison between the on-orbit results and the ground tests demonstrated the functionality of the system as anticipated.

References:
[1] Roma, K., Shibukawa, T., Matsushita, S., Mishimoto, S., Sekine, H., Fujimori, A., Moriai, I., Funase, R., "Thermal operation for the 6U deep space cubesat EQUULEUS in the initial critical phase," Small satellite conference, Poster SSC23-WP1-12, 2023.
[2] Fujimori, A., Sekine, H., Ataka, Y., Moriai, I., Akiyama, M., Murohara, M., Koizumi, H., Funase, R., "AQUARIUS: The world's first water-based thruster enabled 6U CubeSat to complete lunar flyby," SSC23-VI-05.
[3] Nakagawa, Y., Iwakawa, A., Kameyama, S., Kikuchi, T., Yaginuma, K., Asakawa, J., Koizumi, H., "On-orbit demonstration of the water resistojet propulsion system on commericla 6U-Sat SPHERE-1 EYE," SSC23-VI-02.

NO	7	NO
Comm. avail.	TRL	Aerospace-tested

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Lunar Flashlight Propulsion System/Green MiPS [1 of 2]

Propulsion Technology	Green Monopropellant
Manufacturer/Country	~~VACCO (USA). Incorporates 100 mN HPGP thrusters from Bradford ECAPS/OrbitalATK/NGC~~ Georgia Tech (USA)/Plasma Processes (USA)/NASA Marshall [3,4,5]
TRL	7* (The system was flown, but encountered FOD issues on orbit that prevented the mission from being successful, however, the thrusters themselves performed, some deltaV was executed, and root cause was identified.) [6]
Size (including PPU)	3U
Design satellite size	6U and larger
Isp (s)	~220s (estimated from comparable thrusters)
Thrust type/magnitude	400 mN (continuous, nominal), 3320 N*s (impulse, total)
Delta-V (m/s)	237 m/s for 14 kg CubeSat. Only 16 m/s was delivered on orbit [6]
Propellant	ADN green propellant (LMP-103S), or Air Force green (AF-M315E)
Power consumption (W)	10W (standby, max), 1W (standby, typical- health/status monitoring) 35W (warm-up), 15W (operational)
Flight heritage (if any)	Artemis-1 (launched Dec 2022)
Commercially available	Unclear from website
Last updated	*12/2023*

VACCO's Lunar Flashlight Propulsion System

Additional comments:
[Reference 1, 2][Jan 2019][General information]
VACCO's green mono-propellant Micro Propulsion System (MiPS) provides a highly reliable solution for a fully self-contained CubeSat attitude control and main propulsion system. JPL's Lunar Flashlight program will use VACCO's MiPS configured for ADN green propellant to perform its Lunar surveying mission. The VACCO Lunar Flashlight MiPS is approximately 3U in volume and uses four 100 mN thrusters to develop 3,320 N-sec of total impulse that provides 237 m/s of delta-v for a 14 kg CubeSat. Each thruster independently operates to perform both delta-v and ACS maneuvers controlled by an integrated microprocessor controller. Lunar Flashlight is a mission that was selected in 2014 by NASA's Advanced Exploration Systems (AES) by a team from the Jet Propulsion Laboratory, UCLA, and Marshall Space Flight Center. This innovative, low-cost concept will map the lunar south pole for volatiles and demonstrate several technological firsts, including being the first CubeSat to reach the Moon, the first planetary CubeSat mission to use green propulsion, and the first mission to use lasers to look for water ice.

References:
[1] http://www.cubesat-propulsion.com/lunar-flashlight-propulsion-system/
[2] http://space.skyrocket.de/doc_sdat/lunar-flashlight.htm
[3] Andrews, D., Huggins, G., Lightsey, E., Cheek, N., Lee, N., Talaksi, A., Peet, S., Littleton, L., Patel, S., Cavender, D., Williams, H., McQueen, D., Baker, J., Kowalkowski, M., "Design of a green monopropellant propulsion system for the lunar flashlight cubesat mission," SSC20-IX-07
[4] Marshall, W., Cavender, D., Maynard, A., Zuttarelli, P., "State of the Art in Green Propulsion – 2020," In-Space Chemical Propulsion TIM – September 2020, DISTRO A: Approved for public release
[5] http://www.ssdl.gatech.edu/research/projects/lunar-flashlight-propulsion-system
[6] Smith, C., Cheek, N., Burnside, C., Baker, J., Adell, P., Picha, F., Kowalkowski, M., Lightsey, E., "The journey of the lunar flashlight propulsion system from launch through end of mission," SSC23-VI-03.

Comm. avail.	7* TRL	NO Aerospace-tested

Lunar Flashlight Propulsion System [2 of 2]

Additional comments:

[Reference 1][Dec 2019][Flight info]
From reference 2, the mission was originally planned to be one of the 13 cubesats aboard the iCPS launch vehicle in 2019. However, the launch date has now been moved to 2021.

[Reference 2][Aug 2020][Thruster system design]
Georgia tech has been supporting thruster design, including tank, manifold, thermal control, fluid control, and additive manufacturing options.

[Reference 3][October 2021][Flight status]
Lunar Flashlight, being developed at NASA's Jet Propulsion Laboratory to look for water ice deposits on the moon using lasers. That spacecraft is in danger of missing the Artemis 1 because of delays in the development of its propulsion system, JPL spokesperson Ian O'Neill said Aug. 20.
"Due to significant issues during testing of the originally procured Lunar Flashlight propulsion system, the mission switched to development of an alternative. This change occurred late in the project and delayed mission readiness," NASA said in a statement about the cubesat. The pandemic then slowed development of the new propulsion system, which uses a "green" nontoxic propellant, by a group led by the Georgia Institute of Technology.
JPL has received the propulsion system, but O'Neill said it wasn't clear that the system would be fully integrated and tested in time to launch on Artemis 1. "NASA is also exploring several near-term commercial launch opportunities for Lunar Flashlight in case it does not make Artemis 1," the agency stated.

[Reference 4][October 2021][Controller development]
While there were no project guidelines specifically requiring high-reliability space-rated parts, it was required that the controller be designed to withstand the expected radiation profile of the mission. The propulsion system sits at one end of the spacecraft, so one face of the controller is inherently shielded by the bulk of the spacecraft. The other five faces are shielded by a 2 mm-thick titanium 6Al4V shell. The lifetime total ionizing dose (TID) with this configuration was estimated to be under 10 kRad.
The flight boards underwent vibration and thermal vacuum acceptance testing. One unit has now been installed into a flight propulsion system by Georgia Tech and is awaiting integration into the spacecraft.

[Reference 5][May 2023][Mission info]
WASHINGTON — NASA has ended the mission of a cubesat intended to go into orbit around the moon but which was unable to do so because of problems with its propulsion system.
NASA's Jet Propulsion Laboratory announced May 12 the end of the Lunar Flashlight mission, five months after its launch. The spacecraft was unable to go into its planned polar orbit around the moon because its propulsion system could not produce the required thrust.
Engineers spent several months trying to troubleshoot the problem, identified shortly after its December 2022 launch. They suspected that debris of some kind was blocking propellant lines, reducing the amount of propellant reaching the thrusters.
NASA said May 5 that they were making one final effort to clear the obstructions by increasing fuel pump pressures "far beyond" operational limits while opening and closing valves. That technique, tried on one of the spacecraft's four thrusters, had shown some success, "inconsistently producing some increased levels of thrust."
However, those efforts weren't enough to keep the spacecraft in the vicinity of the moon, leading JPL to bring the mission to an end. Mission planners had, by that point, ruled out placing the spacecraft into a near-rectilinear halo orbit around the moon, but hoped to be able to place it into a distant Earth orbit that allowed for monthly flybys of the moon.
How the debris got into the propulsion system is not clear. In a recent interview, Daniel Cavender, who was the project manager for the cubesat's propulsion system at NASA and is now director of Rubicon Space Systems, a division of Plasma Processes LLC that is commercializing that propulsion system, noted the constraints imposed by the 6U cubesat design limited engineers' ability to put filters into the system.
"Because of the size constraints, we could not put filters everywhere. So, we relied heavily on precision cleaning, inspections and contamination controls. But there was a process slip at some point," he said. The data from the cubesat, he noted, was consistent with ground tests of thrusters with debris in their propellant lines.
Lunar Flashlight was the first spacecraft to go beyond Earth orbit to use a non-toxic "green" propellant called Advanced Spacecraft Energetic Non-Toxic, or ASCENT, developed at the Air Force Research Laboratory. Cavender noted that the thrusters worked well until the debris problem starved them of propellant, calling it a "significant validation in space."
NASA emphasized other technologies that Lunar Flashlight successfully tested. They included a new flight computer called Sphinx that can operate at low power levels and survive the radiation environment of deep space, and an upgraded radio called Iris.

[Reference 6][Dec 2023][Mission info]
A full debrief is found in this reference, including the most likely source of mission failure, debris in the propellant flow path.

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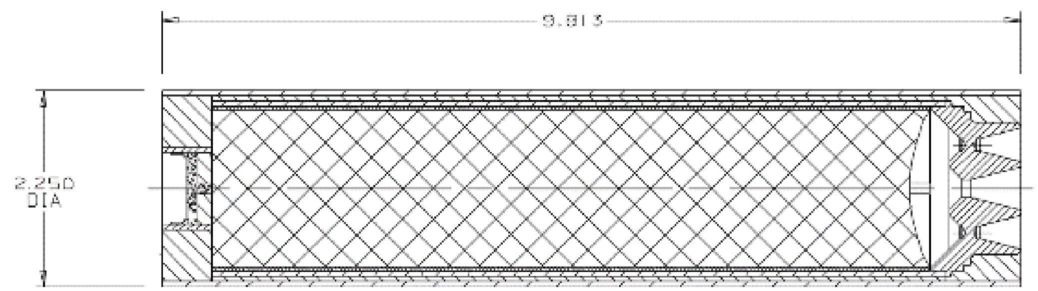
	7*	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

30s Motor
Industrial Solid Propulsion

Propulsion Technology	Solid rocket motor
Manufacturer/Country	Industrial Solid Propulsion (ISP) (USA)
TRL	6
Size (including PPU)	10” (25.4 cm) L x 2.25” (5.7 cm) DIA (~2.5U), 1 kg
Design satellite size	3U or larger
Isp (s)	187s
Thrust type/magnitude	37N (average thrust) 67N (maximum thrust) 1000 N*s (impulse, total)
Delta-V (m/s)	~300 m/s for 3kg spacecraft
Propellant	80% solids HTPB/AP
Power consumption (W)	n/a
Flight heritage (if any)	Proof-of-concept flight vehicle (did not go into space) (2013) [3] Optical target at Kirtland AFB. Space applications unknown [1-3]
Commercially available	YES
Last updated	*06/2020*

Device Name: 30 second duration motor
Application: Optical target
Prime Contractor: Phillips Laboratory, Kirtland Air Force Base, New Mexico
ISP Part Number: 8024-30-1000



*It is unclear whether this rocket has any heritage in space.

Additional comments:

[Reference 1-3][Jan 2019][General info]
As the name describes, this rocket burns for 30 seconds. It is an end-burning grain type and contains about 50% propellant, by weight. This rocket motor is used as an optical target at Kirtland AFB on the HABE program. The propellant has an enhanced signature in the visible and IR ranges. Operational temperature limits have not been established. It is unclear whether this rocket has any heritage in space.
Industrial Solid Propulsion makes a whole family of solid rocket motors, of which this is the smallest.
A sub-orbital test flight was conducted to determine whether jet paddles could control such a rocket vehicle. The proof-of-concept flight vehicle flew a test flight on August 28, 2013. The flight demonstrated that a jet paddle system can effectively control the attitude of small rocket vehicles.

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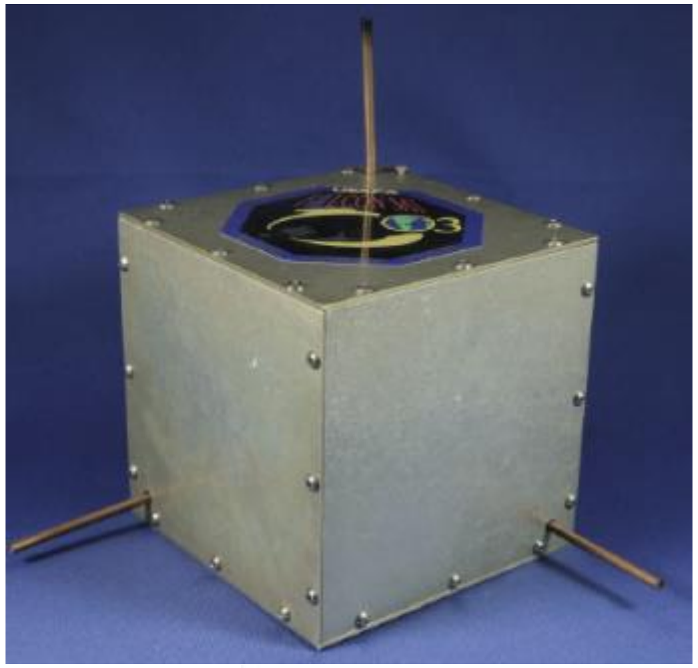
6 | NO
Comm. avail. | TRL | Aerospace-tested

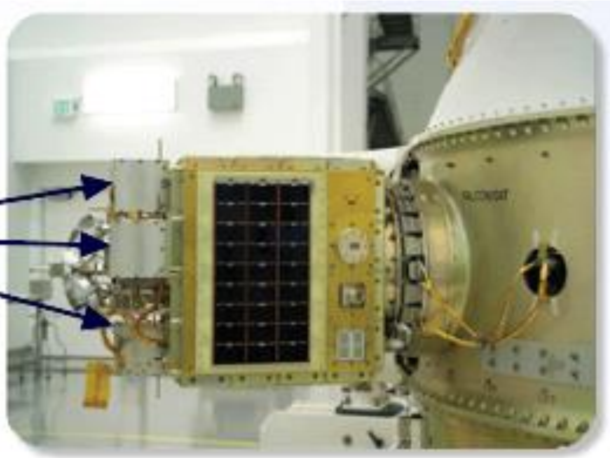
μPPT-1 Micro Propulsion Attitude Control System (MPACS)
Busek

Propulsion Technology	Micro-PPT
Manufacturer/Country	Busek (US)
TRL	6 Lab-tested with ground test data. Flown but no on-orbit data reported.
Size (including PPU)	1U
Design satellite size	>3U
Isp (s)	400-800s, 827 s (average)
Thrust type/magnitude	80 μN*s (impulse)
Delta-V (m/s)	65 m/s
Propellant	Solid Teflon
Power consumption (W)	2-5W
Flight heritage (if any)	FalconSat3 (2007)
Commercially available	YES
Last updated	*01/2019*



Micro-PPT unit

MPACS units loaded on FalconSat-3, prior to launch (photo courtesy of Col. Timothy Lawrence, USAFA)



Additional comments:

[Reference 1-3][Jan 2019][General thruster info]
No moving parts and no pressurized containers. Low power consumption make this thruster attractive for small satellites. 4 mPPT's were flown on FalconSat-3. Mission status unknown. No on-orbit data found, although manufacturer's website reports operational success.

References:
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Comm. avail.	6	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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Palomar Micro Propulsion System (XSOE10220-01)
VACCO/Boeing

Propulsion Technology	Cold gas
Manufacturer/Country	VACCO/BOEING (USA)
TRL	6
Size (including PPU)	1U
Design satellite size	3U
Isp (s)	50s (calculated from manufacturer's spec)
Thrust type/magnitude	35 mN (continuous) 85 N*s (impulse, total, butane) 56 N*s (impulse, total, N2O, cold gas) 141 N*s (impulse, total, N2O, decomposing) 0.75 mN*s (impulse, minimum)
Delta-V (m/s)	34 m/s for 1 kg spacecraft
Propellant	Butane (can use others as well), N2O
Power consumption (W)	<5W
Flight heritage (if any)	None known
Commercially available	YES
Last updated	*12/2023*

Palomar system, designed to sit in the center of a 3U CubeSat

Max Operating Pressure	150 psia
Proof Pressure	225 psia
Burst Pressure	375 psia
Thrust	35 mN
Internal Leakage	3.0 scc/hr
External Leakage	1.0 x 10 $^{-6}$ scch
Operating Temperature	0°C to +50°C
Non-Operating Temperature	-10°C to +60°C
Vibration	23 Grms
Cycle Life	120,000 firings
Total Impulse	85 N/sec
Minimum Impulse Bit	0.75 mN/sec
Operating Voltage	4.75 to 5.25 vdc
Peak Power	<5 watts (two thrusters)
Dry Mass	890 grams
Propellant Mass	173 grams
Total Mass	1,063 grams

Additional comments:

[References 1-4][Jan 2019][Thruster info]
Manufacturer claims to have tested over 200,000 thruster firings in a simulated space environment, and is designed to occupy the center of a 3U CubeSat. Palomar, designed in collaboration with Boeing, is a MiPS-type thruster, and is primarily a reaction control system with thrusters arranged so that use of all six degrees of freedom (DoF) in rotation and translation are possible. Additional propellant is available by stretching the tank lobes, allowing for a custom propulsion system mass and volume based on specific mission needs. Upgrades to other propellants available.
Unit was delivered to Boeing for ground test and evaluation 2006.

[Reference 5][Dec 2023][Applications]
This system was recently seen baselined as a potential "Octopus" orbital debris removal application.

References:

[1] Mueller, J., Hofer, R., Ziemer, J., "Survey of Propulsion Technologies Applicable to CubeSats," JANNAF, Colorado Springs, CO, 2010.
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[3] http://www.cubesat-propulsion.com/palomar-micro-propulsion-system/
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6 NO

Comm. avail. TRL Aerospace-tested

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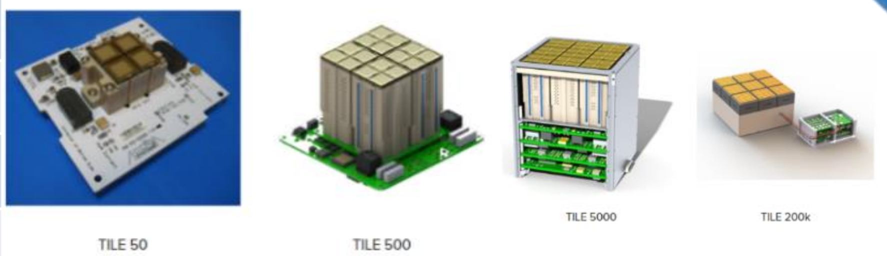
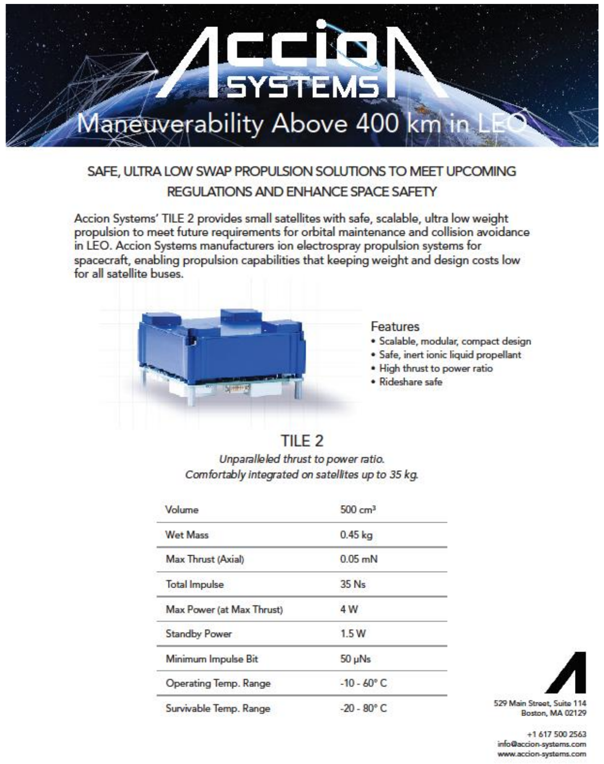
Ion Electrospray Propulsion System (iEPS)/TILE [1 of 3]
MIT/Espace/Accion

Propulsion Technology	Ionic liquid electrospray
Manufacturer/Country	MIT/Espace/ Commercialized by Accion (USA)
TRL	6. Lab-tested with ground test data. Flown but no on-orbit data reported.
Size (including PPU)	Range from 0.25U to 6U, scalable
Design satellite size	>1U
Isp (s)	1250 to 1500 s
Thrust type/magnitude	20 to 200,000+ N*s (impulse), 0.05 to 10 mN (continuous), model-dependent
Delta-V (m/s)	100 to 1000 m/s (scalable)
Propellant	Ionic liquid (EMI-BF4 and others)
Power consumption (W)	1.5 to 280 W (depending on size)
Flight heritage (if any)	AeroCube8 (IMPACT, 2015 – MIT hardware) Irvine01 (Nov 2018), Irvine02 (Dec 2018 – Both flew Accion's TILE unit) Scheduled delivery for DoD demonstration (Accion TILE unit, Sept 2019) [6] BeaverCube (to be launched October 2020, now 2021) [8,9] Astro Digital Tenzing satellite (to be launched June 2021) [11] NanoAvionics rideshare (flying Accion's Tile 3, launched July 2021) [10, 12]
Commercially available	YES
Last updated	*05/2023*



Various versions of iEPS/TILE available from Accion Systems



Maneuverability Above 400 km in LEO

SAFE, ULTRA LOW SWAP PROPULSION SOLUTIONS TO MEET UPCOMING REGULATIONS AND ENHANCE SPACE SAFETY

Accion Systems' TILE 2 provides small satellites with safe, scalable, ultra low weight propulsion to meet future requirements for orbital maintenance and collision avoidance in LEO. Accion Systems manufacturers ion electrospray propulsion systems for spacecraft, enabling propulsion capabilities that keeping weight and design costs low for all satellite buses.

Features
- Scalable, modular, compact design
- Safe, inert ionic liquid propellant
- High thrust to power ratio
- Rideshare safe

TILE 2

Unparalleled thrust to power ratio.
Comfortably integrated on satellites up to 35 kg.

Volume	500 cm^3
Wet Mass	0.45 kg
Max Thrust (Axial)	0.05 mN
Total Impulse	35 Ns
Max Power (at Max Thrust)	4 W
Standby Power	1.5 W
Minimum Impulse Bit	50 μNs
Operating Temp. Range	-10 - 60° C
Survivable Temp. Range	-20 - 80° C

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www.accion-systems.com

Additional comments:

[References 1-4] [Jan 2019][General info]
These small thrusters are a compact ion electrospray propulsion system. They have a small footprint and are scalable. They can use various ionic liquids as propellant. Many of the candidate ionic liquids are non-toxic and have negligible vapor pressure so they can be carried in an un-pressurized container. Ion electrosprays accelerate ions from ionic liquids using strong electric fields. A high voltage is applied between a sharp tip coated with propellant and an extractor aperture positioned directly above. The ions accelerate through the downstream extraction aperture, exiting the spacecraft and providing thrust. There are no moving parts or valves. The thrusters can be operated in impulse or continuous firing mode. Many publications on the MIT thruster exist in the scientific community.
The core technology (based on MIT's design and hardware) have been tested at The Aerospace Corporation in support of AeroCube8 and AeroCube12.
[Reference 5] [Oct 2018] [Company information]
Boeing's venture capital fund is leading a $3 million investment round for Accion Systems, a Boston-based startup whose electric propulsion system for satellites could get its next in-space test early as next month. Joining Boeing HorizonX Ventures in the Series B round is GettyLab, a Bay Area venture fund focusing on innovations in science and technology.
[Reference 7][Aug 2020][Company information]
A new Accion CEO has been named, Peter Kant.

References:

[1] Tile data sheet: https://www.accion-systems.com/tile
[2] MIT electrospray information: http://spl.mit.edu/electrospray-thruster-engineering
[3] D. Krejci, F. Mier-Hicks, C. Fucetola, P. Lozano, A. Hsu Schouten and F. Martel, "Design and characterization of a scalable ion electrospray propulsion system," IEPC-2015-149.
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[5] https://www.geekwire.com/2018/boeing-leads-3m-round-boost-accion-systems-electric-space-propulsion-system/
[6] Statements made at Electrospray and Future of EP workshop, held at LA AFB, organized by AFRL (POC Dan Eckhardt), May 2019. Distribution statement A
[7] SmallSat 2020, Virtual public forum
[8] Schroeder, M., Womack, C., Gagnon, A., "Maneuver planning for demonstration of a low-thrust electric propulsion system," Small Sat Conference, 2020, virtual talk. Paper SSC20-VII-02.
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[11] https://smallsatnews.com/2021/04/19/accion-systems-in-space-propulsion-system-set-for-june-launch-with-astro-digital-starfish-space-via-spacex-rideshare-mission/
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Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Ion Electrospray Propulsion System (iEPS)/TILE [2 of 3]
MIT/Espace/Accion

Additional comments:

[Reference 1][Jan 2019][Flight information]
The Irvine 01 is a 1U CubeSat built by a team of students from five high schools, with guidance from universities and industry experts. It was originally manifested on a Dnepr rocket in 2017. As the availability of Dnepr had become doubtful, it had been moved to an Indian PSLV-XL for launch in 2018. Eventually it was again moved to an Electron Curie (Rocket Lab) launch. Irvine 01 carried Accion's electronics (PPU) with mass models for the thrusters. Irvine02 was launched on Spaceflight Industry's SSO-A multi-satellite launch on a Falcon-9 v1.2 (Block 5) rocket. Irvine02 is the first commercial demonstration of Accion's electrospray system. It carried both Accion's PPU and thrusters. The PPU for both these CubeSats was made by eSpace.

[Reference 2][May 2019][Status of thrusters and flight updates]
At the Electrospray and Future of EP Workshop in May 2019, Accion (Luis Perna) gave a presentation on the status of Accion and its thrusters. Accion is currently up to 30 employees. He said that the thrusters had run up to 2500 hrs. They now have 8 vacuum chambers, each with the ability to pump down to lower than 1E-7Torr, allowing them the ability to scale up production/manufacturing.
In terms of launches and deliveries, he stated that Irvine 01 replied with telemetry, but Irvine 02 satellite failed to turn on (not due to a thruster PPU error). He did not say what sort of telemetry Irvine 01 replied with. In September 2019, they are due to deliver a TILE unit for an undisclosed DoD mission.
The emitter manufacturing technology has been upgraded from “Robu” (traditional laser-ablative porous glass micro-machining) to “Silcor”. “Silcor” gives much nicer emitter peaks with radii tips on the order of 6 um, height >400 um. He would not reveal what the “Silcor” material was, nor would he reveal the machining process, stating that at this point, it was proprietary technology.
He gave a summary of upcoming goals:
- Summer 2019 -> test 5 to 15 frozen designs
- Near future -> develop/install diagnostics such as ToF, RPA, thrust stands, droplet/neutral species detection, develop thrust densification up to 300 mN/m^2

[Reference 3][Jan 2021][Missions]
NanoAvionics has signed a contract with Accion Systems to host their propulsion system, TILE 3, on-board the firm's new rideshare mission for a demonstration flight in 2021. Accion Systems procured this flight as the culmination of an ongoing US government sponsored propulsion program. The smallsat for the rideshare mission is based on NanoAvionics flight-proven M6P bus and will include several customer payloads that can fit the 4U payload volume. The rideshare mission is the fourth in a series of NanoAvionics rideshare missions and will be arranged by NanoAvionics US. The expected launch will be during the last half of 2021.
“NanoAvionics is the perfect partner for the TILE 3 launch as a space proven product,” said Peter Kant, CEO of Accion Systems. “We selected a demonstration partner that would fully represent the commercial potential of TILE 3. While this initial flight will provide propulsion to the 6U M6P, TILE 3 is designed to offer full propulsion capabilities to a wide variety of small satellites and we are excited to provide that capability to NanoAvionics' line of satellite bus products.”

[Reference 4][April 2021][Company info]
Accion Systems has signed a new partnership agreement with NanoAvionics US Inc. — the TILE in-space propulsion system will be listed as a preferred option for all appropriate missions that require electric in-space propulsion and Accion Systems will provide preferred pricing to NanoAvionics US Inc.

[Reference 4][May 2021][Upcoming flight]
Astro Digital's Tenzing satellite is a rideshare satellite, hosting several payloads. Also included are two TILE 2 ion electrospray propulsion systems that will test on-orbit maneuvers in LEO and will test proximity operations maneuvers supported by Starfish Space software. As part of the mission, Accion Systems and Starfish Space will complete an on-orbit proximity operations demonstration. The team will combine Starfish's CEPHALOPOD software and Accion's TILE 2 thrusters, both already a part of the Tenzing mission, to work together to perform the first ever demonstration of rendezvous and proximity operations trajectories using low-thrust electric propulsion.

References:

[1] https://space.skyrocket.de/doc_sdat/irvine-01.htm https://space.skyrocket.de/doc_sdat/irvine-02.htm https://www.greaterirvinechamber.com/ambassador-of-the-month-archive/p/item/8290/irvine-cubesat-stem-program-successfully-launches-first-two-high-school-studentbuilt-cubesat-in-the-west-coast
[2] Statements made at Electrospray and Future of EP workshop, held at LA AFB, organized by AFRL (POC Dan Eckhardt), May 2019. Distribution statement A.
[3] https://smallsatnews.com/2020/10/12/nanoavionics-contracts-accion-systems-for-the-tile-3-smallsat-propulsion-system-for-upcoming-rideshare-mission/
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Comm. avail. TRL Aerospace-tested

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Ion Electrospray Propulsion System (iEPS)/TILE [3 of 3]
MIT/Espace/Accion

Additional comments:

[Reference 1][July 2021][NanoAvionics launch]
NanoAvionics was all geared up for the SpaceX Transporter-2 rideshare launch at the end of June, with several satellite missions from their customers that will have a positive impact on businesses and communities in remote regions on Earth, as well as pioneering an ionic liquid electrospray propulsion system. Among the applications onboard are also the world's first, 1U-sized, hyperspectral imager and a new high-gain X-band antenna.

The first of the two smallsats, named "D2 / Atlacom-1," that were onboard Transporter-2 was a shared 6U satellite mission dedicated to an on-orbit demonstration of new satellite technologies as well as several, novel, satellite applications. They included the world's first 1U-sized hyperspectral imager to be ever flown, a new 1U tiled ionic liquid electrospray (TILE) propulsion system, a new high-gain X-band antenna and an upgraded X-Band downlink transmitter. The mission comprises "HyperActive," an international consortium and its partners, and an electric propulsion demonstration by Accion Systems.

[Reference 2, 3][July 2021][Company news]
Accion Systems close series C funding to the tune of $42 million.
Tracker Capital, "a venture capital firm linked to the group that bought hypersonic vehicle maker Stratolaunch, has taken a majority stake in space propulsion startup Accion Systems." The firm "acquired 51% of Accion Systems after leading its $42 million funding round, supporting plans to scale up its Tiled Ionic Liquid Electrospray (TILE) thrusters for larger satellites." Accion Systems CEO Peter Kant "said [the company's] scalable thrusters are coming to the market as the propulsion industry evolves, from being built around how to get satellites into space and then keeping them in a position such as low-Earth-orbit, to today where megaconstellations and servicers are increasing demand for moving objects around in space."

Tracker Capital is a stage-agnostic venture capital investor that principally invests in high-potential technology growth companies and was founded by Stephen Feinberg, who is also Co-Founder and Co-CEO of Cerberus Capital Management.

[Reference 4][Aug 2022][Flow control]
This paper reports on the preliminary development of an electrowetting MEMS-fabricated liquid flow regulator that can operate in zero gravity vacuum environments to provide reliable propellant management for electrospray propulsion systems.

References:

[1] https://smallsatnews.com/2021/07/06/two-nanoavionics-built-smallsats-were-passengers-on-the-spacex-transporter-2-mission-launch-to-successful-orbit/
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Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

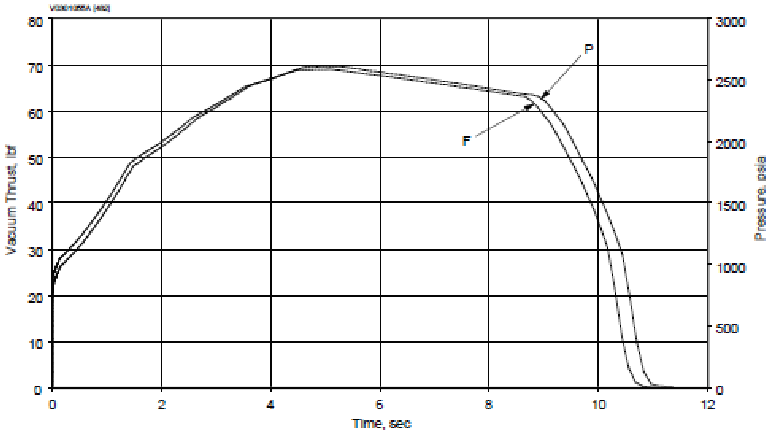
STAR-4 (STAR-4G) Series Solid Rocket Motors
Northrop Grumman

Propulsion Technology	Solid rocket motor
Manufacturer/Country	Orbital ATK (now Northrop Grumman) (USA)
TRL	5-6
Size (including PPU)	5.5” (14 cm) L x 4.5” (11.4 cm) DIA, (~1.5U)
Design satellite size	3U and larger
Isp (s)	276s
Thrust type/magnitude	258 N (thrust, average), 300 N (thrust, max) 2600 N*s (impulse, total)
Delta-V (m/s)	480 m/s for 10 kg spacecraft (calc)
Propellant	TP-H-3399, Graphite-epoxy composite case. [2] Typically HTPB (Hydroxyl-terminated Polybutadiene) matrix with Al fuel and Ammonium perchlorate oxidizer.
Power consumption (W)	n/a
Flight heritage (if any)	None
Commercially available	YES
Last updated	*01/2021*

STAR Motor Performance and Experience Summary

STAR Designation	Model Number	Nominal Diameter		Total Impulse, lb_f-sec	Effective Specific Impulse, lb_f-sec/lb_m	Propellant Weight		Propellant Mass Fraction	Tests	Flights
		in.	cm			lb_m	kg			
3	TE-M-1082-1	3.18	8.08	281.4	266.0	1.06	0.48	0.42	26	3
3A	TE-M-1089	3.18	8.08	64.4	241.2	0.27	0.12	0.14	2	3
4G	TE-M-1061	4.45	11.30	595	269.4	2.16	0.98	0.65	2	0
5*	TE-M-500	5.05	12.83	895	189.0	3.8	1.72	0.87	4	11
5A	TE-M-863-1	5.13	13.02	1,289	250.8	5.05	2.27	0.49	6	3
5C/5CB	TE-M-344-15 TE-M-344-16	4.77 4.77	12.11 12.11	1,252 1,249	268 262.0	4.55 4.62	2.06 2.10	0.47 0.47	245 20	686 160
5D	TE-M-989-2	4.88	12.39	3,950	256.0	15.22	6.90	0.68	13	3
5F	TE-M-1198	4.85	12.32	2,216	262.9	8.42	3.82	0.37	9	194
6	TE-M-541-3	6.2	15.75	3,077	287.0	10.7	4.85	0.80	47	238
6A*	TE-M-542-3	6.2	15.75	2,063	285.3	7.2	3.27	0.72		
6B	TE-M-790-1	7.32	18.59	3,686	269.0	13.45	6.10	0.60	8	18

Star 4G motor



Additional comments:

[Reference 1] [Jan 2021][Thruster info]
According to NGC website: This STAR motor was developed and tested in January 2000 under a NASA Goddard Space Flight Center program for a low-cost, high mass fraction orbit adjust motor for use in deploying constellations of very small satellites (nanosatellites). The first static test of the STAR 4G prototype motor was conducted 8 months after program start. The motor is designed to operate at high chamber pressure and incorporates a noneroding throat insert to maximize specific impulse.
NGC reports the production status as “in development”, as of Jan 2021.

[Reference 2][July 2019][Testing history]
This reference places the TRL at 9, stating that “solid motors have been used since the dawn of the space age. STAR 4G is a newer developments of lower TRL. Proven technology with many catalogued existing motor options. May require dedicated development for smaller spacecraft matching required masses, thrusts, burn times, g-loads.”

References:

[1] https://www.northropgrumman.com/Capabilities/PropulsionSystems/Documents/NGIS_MotorCatalog.pdf
[2] Mueller, J., Ziemer, J., Hofer, F., Wirz, R., O’Donnell, T., “A Survey of Micro-Thrust Propulsion Options for Microspacecraft and Formation Flying Missions,” Cube Sat 5th Annual Developers Workshop, San Luis Obispo, CA, 2008.

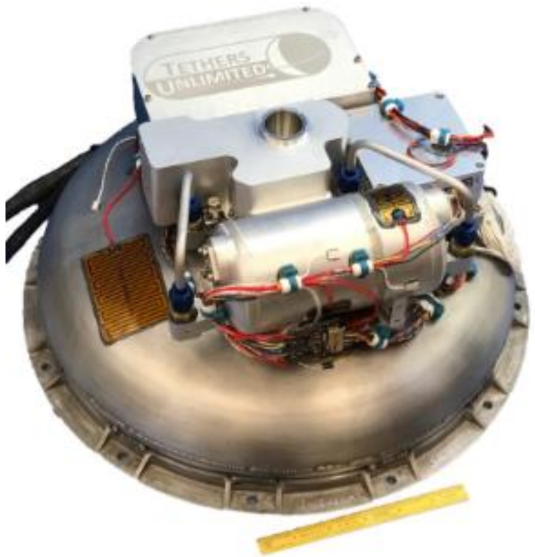
6 NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

HYDROS-M
Tethers Unlimited/Lee

Propulsion Technology	Electrolysis
Manufacturer/Country	Tethers Unlimited (USA)
TRL	6
Size (including PPU)	191 mm L x 381 mm DIA (~22U)
Design satellite size	up to 180 kg
Isp (s)	310 s
Thrust type/magnitude	1.2N (average), 1.75 N*s (impulse, per event), 18000 N*s (impulse, total)
Delta-V (m/s)	HYDROS-M: 200 m/s for 100 kg spacecraft
Propellant	Water
Power consumption (W)	7-40W
Flight heritage (if any)	Delivered to commercial customer (2017)
Commercially available	YES
Last updated	*01/2021*



Two models of HYDROS

HYDROS-M

Additional comments:

[Reference 1-4][Jan 2019][General info]
In 2016, Tethers Unlimited, Inc. (TUI) announced that it has signed a Public-Private Partnership with NASA to deliver a HYDROS™ propulsion system for a CubeSat mission. Concurrently, TUI has signed an associated contract to provide three HYDROS thrusters sized for Millennium Space Systems' (MSS) ALTAIR™ class microsatellites to support three different flight missions. Total contract value for the two efforts is $2.2M. TUI delivered the first flight unit of the HYDROS-M thruster to its commercial customer Nov 2017.
From news article (Parabolic Arc), "NASA has selected TUI's HYDROS-C thruster for demonstration on the first Pathfinder Technology Demonstration (PTD) CubeSat mission, planned for launch in early 2019. The HYDROS-C thruster, developed under a NASA Small Business Innovation Research (SBIR) contract and matured to flight-readiness under a NASA Tipping Point Technologies Public-Private Partnership, is a revolutionary space propulsion technology that uses water as propellant."

References:
[1] James, K., Bodnar, M., Freedman, M., Osborne, L., Grist, R., Hoyt, R., "HYDROS: High Performance Water-electrolysis Propulsion for CubeSats and MicroSats," AAS17-145, 2017.
[2] http://www.tethers.com/HYDROS.html
[3] http://www.parabolicarc.com/2016/08/03/tethers-unlimited-signs-contracts-deliver-hydros-waterpropelled-thrusters/
[4] http://www.parabolicarc.com/2018/06/30/nasa-selects-tuis-hydrosc-thruster-ptd-cubesat-mission/

🛒	6	NO
Comm. avail.	TRL	Aerospace-tested

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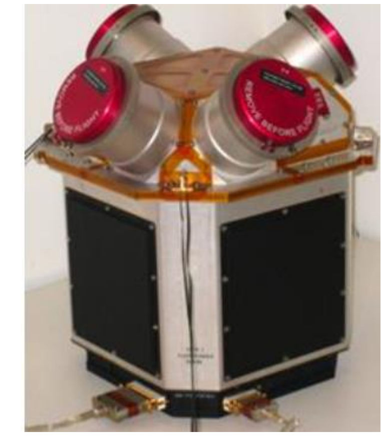
BET-1mN Electrospray/Colloid [1 of 2]
Busek

Propulsion Technology	Electrospray/Colloid
Manufacturer/Country	Busek (USA)
TRL	6-7
Size (including PPU)	1U
Design satellite size	3U and larger
Isp (s)	400 to 1300s
Thrust type/magnitude	1mN (max), 0.7 mN (nominal, continuous), 605 N*s (impulse, total)
Delta-V (m/s)	150 m/s for 4 kg CubeSat
Propellant	Ionic Liquid, EMI-IM (speculated)
Power consumption (W)	10 to 15W
Flight heritage (if any)	None known Many components have flight heritage and were successful on ST7-DRS Lisa Pathfinder (cathode, thruster design, and valve design) (2015)
Commercially available	YES
Last updated	*01/2021*

Busek's BET-1mN electrospray thruster



LISA thrusters (Ref. 4)

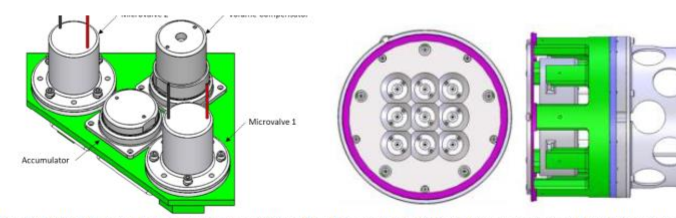


Figure 3. Flow Control Assembly (left) consisting of an Accumulator, Volume Compensator, and two Microvalves. Baseline preliminary thruster head design (right) for LISA consisting nine individual capillary emitters.

Additional comments:

[Ref 1-3][Jan 2019][Thruster design and missions]
This is a colloid thruster (not a true electrospray) that is less than 1U in size and can deliver thrust up to 1 mN at ISPs from 400 to 1300s. It can deliver 150 m/s of delta-v for a standard 3U CubeSat. The propellant is an ionic liquid (not specified) but is probably EMI-IM. It requires higher voltages than the MIT/Espace/Accion thruster to operate (about 10 kV as compared to ~2kV for the iEPS system). The 8.5 cm x 8.5 cm x 6 cm module consumes under 15W power to deliver a thrust up to 1.0mN, at ISPs ranging from 400 s to over 1300 s. The in-situ optimization of performance output provides significant mission flexibility and versatility. The Electrospray Thruster System features a precision micro-valve, leveraged from ST7 design heritage, and rugged flight electronics. In 2008 Busek delivered to NASA's JPL eight electrospray thrusters clusters for the NASA/ESA LISA Pathfinder mission, ST7. This technology demonstration mission has been undertaken to prepare for the Laser Interferometry Space Antenna (LISA), which is a gravity wave observatory. ST7 required extremely low-noise thrusters, which Busek was able to produce and demonstrate. Busek won the 2008 paper of the year award for their thruster design work in support of Lisa Pathfinder.

References:
[1] Demmons, N., Hruby, V., Spence, D., et al. "ST7-DRS Mission Colloid Thruster Development," AIAA JPC conference, AIAA 2008-4823.
[2] http://www.busek.com/index_htm_files/70008500%20BET-1mN%20Data%20Sheet%20RevH.pdf
[3] http://www.busek.com/flightprograms__st7.htm

Comm. avail.	TRL	Aerospace-tested
	6	NO

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BET-1mN Electrospray/Colloid [2 of 2]
Busek

Additional comments:

[Reference 1][Oct 2019][LISA Pathfinder thruster design and improvements for future builds]
The recently completed European Space Agency Lisa Pathfinder (LPF) mission was a significant success with regards to demonstrating technologies necessary for development of a platform suitable for space-based gravitational wave detection. As part of the NASA Space Technology 7 (ST7) program, a Disturbance Reduction System (DRS) was developed and flown on LPF to demonstrate a precision attitude control system consisting of: two Colloid Micro-Thruster (CMT) Clusters developed by Busek Company in cooperation with JPL, each comprising four fully independent colloid thrusters and associated electronics, and an Integrated Avionics Unit (IAU) developed by JPL, containing drag-free control algorithms developed at NASA Goddard Space Flight Center (GSFC). During LPF flight operations the ST7-DRS system met all system-level requirements, with over 20,000 hours of cumulative operation being demonstrated across the eight colloid thrusters. This was an unprecedented success for such a rapidly developed technology and efforts have pivoted to preparation for the follow-on mission. Lessons learned from development, flight hardware production, and flight operations were compiled and prioritized with regards to their relevance for LISA. Updates have focused on adding redundancy (e.g. series/parallel valve configurations and redundant thruster heads), improved assembly yield to support larger scale production, and repackaging to meet updated spacecraft designs. New and updated feed system elements have been fabricated and assembly processes validated, providing preliminary production yield data for the future flight build. Components were subjected to vibration and thermal testing environments and proper function verified. Next steps entail component integration into major subassemblies, and continued environmental testing.

[Reference 2][June 2020][Flight info]
The Space Technology 7 Disturbance Reduction System (ST7-DRS) is a NASA technology demonstration payload as part of the ESA LISA Pathfinder (LPF) mission, which launched on December 3, 2015. The ST7-DRS payload includes colloid microthrusters as part of a drag-free dynamic control system (DCS) hosted on an integrated avionics unit (IAU) with spacecraft attitude and test mass position provided by the LPF spacecraft computer and a gravitational reference sensor (GRS) as part of the LISA Technology Package (LTP). The objective of the DRS was to validate two technologies: colloid micro-Newton thrusters (CMNT) to provide low-noise control capability of the spacecraft, and drag-free flight control. The CMNT were developed by Busek Co., Inc., in a partnership with NASA Jet Propulsion Laboratory (JPL), and the DCS algorithms and flight software were developed at NASA Goddard Space Flight Center (GSFC). ST7-DRS demonstrated drag-free operation with less than 10nm/√Hz level precision spacecraft position control along the primary axis of the LTP using eight CMNTs that provided 5-30 μN each with ≤0.1 μN precision. The DCS and CMNTs performed as required and as expected from ground test results, meeting all Level 1 requirements based on on-orbit data and analysis. DRS microthrusters operated for more than 2400 hours in flight during commissioning activities, a 90-day experiment and the extended mission. This mission represents the first validated demonstration of electrospray thrusters in space, providing precision spacecraft control and drag-free operation in a flight environment with applications to future gravitational wave observatories like the Laser Interferometer Space Antenna (LISA).

References:
[1] Demmons, N., Alvarez, N., Wood, Z., Strain, W., Ziemer, J., "Colloid micro-thruster (CMT) component development and testing towards meeting LISA Mission Requirements," IEPC-2019-255.
[2] Zeimer, J., Marrese-Reading, C., Dunn, C., Romero-Wolf, A., Cutler, C., Javidnia, S., Le, T., Li, T., Franklin, G., Barela, P., Hsu, O., Maghami, P., O'Donnell, J., Slutsky, J., Thorpe, J., Demmons, N., Hruby, V., LISA Pathfinder Team (ESA), "Colloid Microthruster Flight Performance Results from Space Technology 7 Disturbance Reduction System," IEPC 2017.

	6	NO
Comm. avail.	TRL	Aerospace-tested

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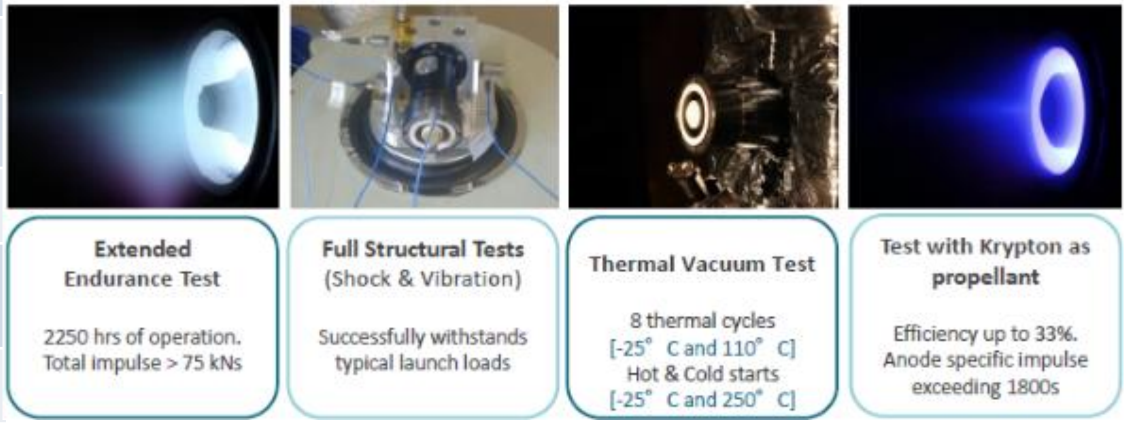
HT100 Hall Effect Thruster
Alta-Space/SITAEL [1 of 2]

Propulsion Technology	Hall Effect Thruster (HET)
Manufacturer/Country	Alta-Space, now (SITAEL) (ITALY)
TRL	5-6
Size (including PPU)	~1U, <0.5 kg
Design satellite size	6U and larger. Likely limited by power draw. S-75 platform (to be used for uHETSat) is 75 kg [6]
Isp (s)	1000-1600s [Ref 1-3], Max 1350 s [4]
Thrust type/magnitude	6 to 18 mN [Ref 1-3], 5-15 mN [4] 75 kN*s (impulse, total, demonstrated via 2250 hr lifetime test)
Delta-V (m/s)	
Propellant	Xenon, Krypton, Iodine [5]
Power consumption (W)	120W to 350W, 28V, 2.5A peak current
Flight heritage (if any)	None known. uHETSat (µHETSat) (projected, launch date now 2021, was 2019) [7]
Commercially available	YES
Last updated	*01/2021*

SITAEL's HT100 thruster



Additional comments:

[References 1-3][Jan 2019][General info]

Alta and Alma space merged into SITAEL in 2015. According to SITAEL's website (product sheet acquired via email inquiry), "HT100 Hall Effect Thruster (HET) is the smallest and lowest power HET ever developed in Europe, whose performance and characteristics represent the state-of-the-art of this technology. Based on permanent magnets, HT100 is designed to perform orbit control tasks on micro-satellites and AOCS tasks on mini-satellites. HT100 thruster unit and all the key sub-system components are fully based on European, ITAR-free technologies. The thruster unit can be offered with its HC1 S-type hollow cathode, 300 W max PPU and a dedicated fluidics based on flight-proven valves."

Manufacturer claims efficiency up to 40%, and demonstrated lifetime of 2200 hrs/ 75kN*s at 200W. The thruster weighs <500g, and requires a feed pressure of 25 mbar. Operating voltages are 300V.

[Reference 4][Oct 2019][Testing]

Manufacturer reports HT100 has been extensively tested in the past 2 years, and is Sitael's baseline and most advanced electric thruster. The thruster has undergone extended endurance tests, full structural tests (shock and vibration), thermal vacuum testing, and validation using krypton as a propellant. For the lifetime test, the thruster was operated at a fixed operating power level of 210W, resulting in a slightly accelerated lifetest. The HT100 at beginning of life provided a thrust of 10 mN, and at the end of the test, after a total firing time of 2240 hr, the value was 15% lower. The total impulse accumulated at the end of the test was 75 kN*s. The beam remained focused and no major variations of its orientation were detected.

References:

[1] Stanzione, V., Melega, N., Misuri, T., "IOV Mission of a Mini-Hall Effect Thruster (HET), on-board S-50 Micro-Satellite Class Platform," Poster at Annual Small Satellite Conference, 2016, SSC16-P4-02
[2] Manufacturer emailed product sheet
[3] www.sitael.com
[4] Misuri, T., "Low power electric propulsion at Sitael," International workshop on ion propulsion and accelerator industrial applications, Presentation, 2017.
[5] Misuri, T., "Sitael low power electric propulsion systems for small satellites," EPIC Workshop, Presentation, 2018.
[6] https://space.skyrocket.de/doc_sdat/myhetsat.htm
[7] https://www.rocketlaunch.live/launch/uhetsat

Comm. avail.	6	NO
Comm. avail.	TRL	Aerospace-tested

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HT100 Hall Effect Thruster
Alta-Space/SITAEL [2 of 2]

Additional comments:

[Reference 1, 2][Oct 2019][Flight information]
The µHETsat project is currently under development at SITAEL S.p.A. in collaboration with the European Space Agency (ESA) and the Italian Space Agency (ASI). It represents one of the first applications of a Hall Effect based, low power electric thruster (so-called HET), on-board a microsatellite platform (µsat). The flight segment of this mission is based on the SITAEL low cost S-75 micro-platform that has been adapted to carry out the in orbit validation of the SITAEL HT-100 low power thruster system which represents also the µHETsat payload. The mission is validating both the SITAEL bus (S-75 platform) and SITAEL low power Hall Effect Thruster (HT100). Virgin Orbit has been contracted to launch the satellite on their LauncherOne rocket.

[Reference 3][Oct 2019][Flight information]
Sitael is collaborating with Rafael (an Israeli company) under the Micro-satellite Electric Propulsion System (MEPS) project. The goal of the MEPS project, which is funded by European Space Agency (ESA) and the Israeli Space Agency (ISA), is to design, manufacture and qualify an electric propulsion system for micro-satellites. The goal is for MEPS to be qualified for space in coming years.

[Reference 4][Oct 2019][Thruster qual status]
Several tests have been carried out on the TU and separately on the cathode unit, in order to assess their performance, evaluate their lifetime and the compliance with all mission requirements. Three main issues were addressed with these experiments:
1. The evaluation of TU global performance, in terms of thrust level, specific impulse and steady-state behaviour.
2. The evaluation of TU lifetime, in terms of total number of operating hours and total number of On/Off cycles.
3. The characterization of the ignition transients, with the definition of an ignition sequence which is repeatable, reliable and well within the mission constraints (i.e. in terms of available power, start-up time, etc…).

Through two successive test campaigns (Structural Tests and Thermal Vacuum Test) the thruster unit EQM has been validated versus typical launch loads and space environment thermal conditions. HT100 Thruster Unit full ground qualification is in its final stage, waiting for the completion of the second round of environmental tests that is now in progress. This paper presented the whole qualification path that has been followed by the thruster unit since 2017, focusing the attention on those steps that turned out to be more complex and somewhat tricky (like the choice of a mission-optimal position for the cathode; the design, manufacturing and in-house qualification of a high-performance, small-size heater; the process of coupling the thruster unit with the rest of the propulsion system and the efforts necessary to identify a solid ignition sequence). HT100 thruster unit has been put together for the first time in the framework of uHETSat programme, but its key components (anode and cathode) were developed well before on internal R&D activities, with some crucial test-session already taking place between 2014 and 2016 (such as the life-test carried out on the HT100 thruster, operating it with an industrial cathode at a power level in excess of 200W for 2250 hours). uHETSat started in June 2016 and, after the first months spent defining the system requirements, the programme entered its core phase with the development and qualification of the propulsion system which is also the mission payload (uHETSat is an IOD/IOV mission aimed at testing in orbit a low power electric propulsion system). Initially the thruster unit was relying on externally provided cathodes, but considering the difficulties to find a product that could be reliable and compliant with the stringent constraints posed by the uHETSat platform, in 2017 SITAEL started to advance the TRL of its HC1 cathode. In the last two years, HC1 was transformed from a simple development model into a qualification model, maintaining its core design but modifying all the interface, the structural design and developing from scratch a dedicated heater able to withstand thousands of cycles.

The qualification test campaign is now approaching its end and, to be ready in no time after its completion, a PFM of the thruster unit has already been procured and assembled. If there are no setbacks, by the end of the year the PFM will be accepted for flight, marking a pivotal moment for Sitael.

[Reference 5][March 2021][Thruster testing]
An iodine version of this thruster is being tested by the University of Vienna (Austria).

References:
[1] Misuri, T., "Sitael low power electric propulsion systems for small satellites," EPIC Workshop, Presentation, 2018.
[2] https://space.skyrocket.de/doc_sdat/myhetsat.htm
[3] Franco, D., Lev, D., Appel, L., "Recent development of the CAM200 low power hall thruster," IEPC-2017-247.
[4] Misuri, T., Ducci, C., Gregucci, S., Pedrini, D., Cannelli, F., Cesari, U., Nania, F., Vicini, A., Pace, G., Magistro, F., Cenni, J., Dignani, J., Farauanu, C., Quaranta, V., Tiseo, B., Orefice, M., Bruno, G., "SITAEL HT100 thruster unit, full ground qualification," IEPC-2019-A655.
[5] Paganucci, F., Saravia, M., Vinci, A., Bernazzani, L., "I2HET: Development of an iodine-fed hall effect thruster," IEPC, 2019.

🛒	6	NO
Comm. avail.	TRL	Aerospace-tested

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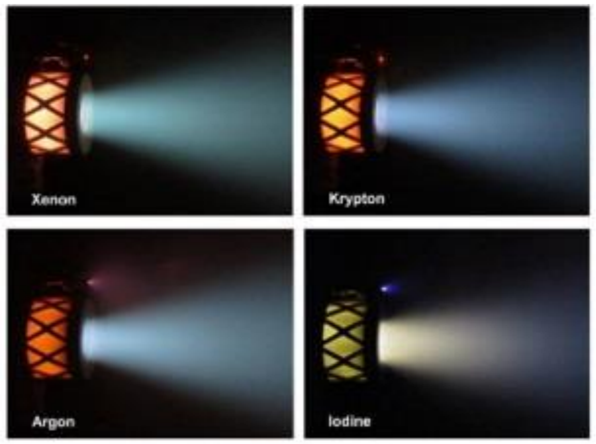
BIT-1, BIT-3 RF Ion Thrusters [1 of 3]
Busek

Propulsion Technology	RF ion thruster
Manufacturer/Country	Busek (USA)
TRL	5-6
Size (including PPU)	~1U (BIT-1), ~3U (BIT-3)
Design satellite size	3U (BIT-1), 6U and larger (BIT-3)
Isp (s)	1600 (BIT-1), 2100 (BIT-3)
Thrust type/magnitude	185 uN (BIT-1), 1.15 mN(BIT-3)
Delta-V (m/s)	2500 m/s for 14 kg spacecraft (BIT-3)
Propellant	Xenon, Krypton, Argon, Iodine, Hydrogen, Nitrogen, Helium
Power consumption (W)	28W (BIT-1), 50 to 75W (BIT-3)
Flight heritage (if any)	BIT-3 is projected to fly on Lunar IceCube aboard Artemis-1 using iodine propellant (2019, now 2021 – vehicle has been delivered) [4] Launched on LunarH-Map aboard Artemis-1 using iodine propellant (2022) but valve stuck [5, 8] First on-orbit firings of the BIT-3 are expected to be late in 2022. [6] 24 Generation II units delivered with launches anticipated in mid-2023. [7]
Commercially available	YES
Last updated	*05/2023*



BIT-1 and BIT-3 thrusters

Additional comments:

Continued on next chart(s)

References:
[1] Tsay, M., Frongillo, J., Model, J., Zwahlen, J>, Paritsky, L., “Flight Development of Iodine BIT-3 RF Ion Propulsion System for SLS EM-1 CubeSats,” 30th AIAA USU Conference on Small Satellites, 2016.
[2] Tsay, M., Frongillo, J., Model, J., Zwahlen, J., Paritsky, L., “Maturation of Iodine-Fueled BIT-3 RF Ion Thruster and RF Neutralizer,” 52nd AIAA JPC, AIAA 2016-4544.
[3] http://www.busek.com/technologies__ion.htm
[4] https://directory.eoportal.org/web/eoportal/satellite-missions/l/lunar-icecube
[5] https://directory.eoportal.org/web/eoportal/satellite-missions/l/lunah-map
[6] Tsay, M., Terhaar, R., Emmi, K., Barcroft, C., “Volume production of Gen-2 iodine BIT-3 ion propulsion system,” IEPC-2022-267
[7] Email correspondence with P. Hruby [March 2023]
[8] Hardgrove, G., “LunaH-Map: Early operations, science data and technology demonstrations,” Conference Proceedings: Interstellar Small Sat Conference, 2023.

🛒	6	NO
Comm. avail.	TRL	Aerospace-tested

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BIT-1, BIT-3 RF Ion Thrusters [2 of 3]
Busek

Additional comments:

[References 1-3][Aug 2019][General info]
These RF ion thrusters come in two small-satellite flavors: BIT-1 and BIT-3, which require 10W and 60W, respectively. The BIT-1 delivers 2150s Isp and 100 uN thrust. The BIT-3 is capable of 1.4mN and 3500s. The delta-v is dependent on the propellant tank size. Propellants used can be Xenon, Krypton, Argon, and Iodine. Both models use an RF cathode (BRFC-1). Key advantages include fast start-up and rapid thrust response to the input RF power. Busek is also developing high-efficiency RF power supplies to couple with the thrusters. Performance results were verified with xenon and iodine propellant using a highly-accurate torsional thrust stand. As an optional add-on, Busek has developed an innovative thruster gimbal capable of desaturating reaction wheels as part of the Attitude Control System (ACS). Advances in the BIT-3 thruster and BRFC-1 neutralizer are complemented by major breakthroughs in the flight electronics. The BIT-3 power processing unit (PPU) features a ~90% efficient RF power supply with radiation-tolerant components. The state-of-the-art electronics package is highly efficient and compact.

[Reference 6][Jan 2021][General information]
Busek is developing an iodine-fueled RF ion propulsion system that will fly on two 6U CubeSats missions as part of NASA's upcoming SLS EM-1 launch in 2019. The 70W-nominal propulsion system utilizes a 2.5cm-grid-diameter RF ion thruster "BIT-3" and a micro RF cathode "BRFC-1" as the neutralizer. Other notable subsystem components include a custom thruster gimbal capable of 2-axis, ±10 o actuation, a lightweight tank designed for 87% propellant fraction, and a State-of-the-Art miniature Power Processing Unit (PPU) with >84% overall efficiency. The 1.5kg-dry/3.0kg-wet system, self-contained within an ultra lightweight aluminum chassis, is expected to produce 0.66-1.24mN thrust and 1,400-2,640sec Isp, at 56-80W throttleable PPU input power. When given sufficient power to operate, it can provide up to 37kN-sec total impulse and 2.9km/s deltaV for a 6U/14kg CubeSat. This paper details various subsystem-and system-level integrated testing results to date, including integrated mechanical system hot fire and gimbal-chassis random vibration test. The second part of the paper focuses on the development and testing of the flight PPU subsystem, including a demonstration of thruster-cathode hot fire with the full suite of PPU breadboards. Within the PPU subsystem, further details are presented regarding the innovative, dual-channel RF amplifier that has recorded a class-leading 90% DC-to-RF power conversion efficiency.

[Reference 4][June 2020][Flight info - Lunar IceCube]
Lunar IceCube, while primarily a science mission, will demonstrate technologies that will enable future interplanetary exploration with small satellite platforms including radiation-hardened subsystems, a precise ranging transponder/transceiver, a capable attitude determination and control system, a high power solar array and an innovative electric propulsion system (EP). The EP (Busek BIT-3 Iodine engine) generates 1.2 km/s-1 of ΔV and, combined with an innovative low energy manifold trajectory, allows the spacecraft to reach lunar orbit from Earth escape with minimal energy. The 13 secondary payloads to be deployed on Artemis 1, including Lunar IceCube, will usher in a new era of solar system exploration with small satellite platforms.
The BIT-3 RF ion thruster is regarded as the world's first gridded ion thruster ever to operate on iodine propellant.

The expected performance of the iodine BIT-3 system is currently based on actual thrust and Isp data obtained with I2 propellant, with some estimation on the heater power consumption and FM PPU efficiency. The flight BIT-3 system will be throttleable between 56 and 80 W at the PPU input and capable of accepting 28-37 V unregulated voltage and RS-485 command. Expected thrust and Isp within this power range are 0.66-1.24 mN and 1,400-2,640 s, respectively. The 80 W max power is not outrageous for 6U CubeSats, as current SOA (State-of-the-Art) solar array for 6U can generate up to 120 W prime power at 1 AU distance from the Sun. When given sufficient power, the iodine BIT-3 system can provide a 6U/14 kg CubeSat an unprecedented ΔV capability of 2.9 km/s. The BIT-3 system has also been recognized as having the highest volumetric impulse (total impulse per unit volume) among all SOA CubeSat propulsion options.

[Reference 5][June 2020][Flight info – LunaH-map]
LunaH-Map is equipped with an EP (Electric Propulsion) system for orbit transfer and station keeping, developed by Busek Co. Inc. of Natick, MA. The BIT-3 (Busek Ion Thruster – 3 cm grid) propulsion system uses solid-storable iodine as propellant, a pioneering technology that can enable a wide variety of deep-space CubeSat missions. The ability to use iodine as propellant is a game-changer for CubeSat propulsion, because iodine can be stored as a dense solid (4.9 g/cc), and its torr-level storage and operating vapor pressure is safe to launch while allowing for very lightweight and conformal tanks. In contrast, legacy EP propellant xenon has to be stored as highly compressed gas (>2,000 psi) and requires bulky, spherical-shaped pressure vessels that are unfavorable for a CubeSat's unique form factors. Busek's BIT-3 ion thruster and its complementary cathode neutralizer also hold the distinction of being the world's first EP device ever to fire on iodine propellant, and its performance has been verified on the ground via direct thrust measurement.

References:

[1] Tsay, M., Frongillo, J., Model, J., Zwahlen, J>, Paritsky, L., "Flight Development of Iodine BIT-3 RF Ion Propulsion System for SLS EM-1 CubeSats," 30th AIAA USU Conference on Small Satellites, 2016.
[2] Tsay, M., Frongillo, J., Model, J., Zwahlen, J., Paritsky, L., "Maturation of Iodine-Fueled BIT-3 RF Ion Thruster and RF Neutralizer," 52nd AIAA JPC, AIAA 2016-4544.
[3] http://www.busek.com/technologies__ion.htm
[4] https://directory.eoportal.org/web/eoportal/satellite-missions/l/lunar-icecube
[5] https://directory.eoportal.org/web/eoportal/satellite-missions/l/lunah-map
[6] Tsay, M., Model, J., Barcroft, C., Frongillo, J., Zwahlen, J., Feng, C., "Integrated testing of iodine BIT-3 RF ion propulsion system for 6U CubeSat applications," IEPC-2017-264.

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Comm. avail.	TRL	Aerospace-tested

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BIT-1, BIT-3 RF Ion Thrusters [3 of 3]
Busek

Additional comments:

[Reference 1][Aug 2022][Thruster characterization- endurance testing]
An Engineering Qualification Model (EQM) of the iodine-fueled, radio-frequency (RF) ion propulsion system “BIT-3” was subjected to a long-duration wear test. A total of 3,543 hours of hot firing was accumulated, with demonstrated total impulse being 12.3 kN-sec. The BIT-3 thruster and its innovative RF neutralizer cathode ran in various thrust settings (from 65 to 75W) and duty cycles, including a continuous burn lasting 764 hours. Average iodine flow rate, as measured by a digital scale in-situ, was 52 µg/sec. This translates to a total Isp of 2,150 sec at the maximum 75W system input power. Post-test inspections show the iodine tank’s propellant consumption behavior was not affected by gravity or ground-test setup, and C.G. shift over time would be along the thrust axis. The thruster and cathode’s discharge chambers were found to have accumulated small layers of metallic coating. The coating is not expected to impact RF coupling efficiency within the life of the system. The thruster’s accelerator grid exhibited noticeable erosion, with its diameter enlarging by 29%, but it was difficult to determine whether the erosion was caused by the initial burn-in period or by the nature of the ion optics design.

[Reference 2][Aug 2022][Thruster design evolution]
Busek delivered three (3) iodine-fueled BIT-3 CubeSat ion propulsion systems in late 2019, following four years of development. With the initial Non-Recurring Engineering (NRE) work complete, Busek has since improved the BIT-3 design and optimized it for robustness, manufacturability, and cost. The Gen-2 BIT-3 is currently in volume production, with 24 flight units already delivered.
Gen-2 hardware is similar to Gen-1 hardware, but differs in several ways:
- The iodine tank was redesigned to improve stiffness by 2x and significantly improve manufacturability. This change helped reduce tank fabrication costs by at least 3x. However, the design-for-manufacturing did have a negative tradeoff on mass, and the Gen-2 tank is 24% heavier than its predecessor.
- The Gen-2 valve design was a complete departure from the 3rd party-supplied Gen-1 valve, in both its working mechanism and material selection. Although there was a growth in size and mass, significant improvement was realized in the areas of iodine compatibility and operational robustness. In-house manufacturing also drastically brought down valve cost by about 90%.
- The Gen-2 system eliminates the gimbal design in favor of a simplified thruster mounting platform. This decision was made, in part, to accommodate the valve’s size growth, but it was also driven by market analysis. Most microsatellite customers do not need gimballed thrusters for LEO operations. Eliminating the complex gimbal mechanism made the BIT-3 system simpler to fabricate and test, ultimately resulting in lower production cost and more competitive sales pricing.

Overall, the Gen-2 system wet mass is about 105g heavier than the Gen-1, but its design-for-manufacturing and streamlined, in-house fabrication approach bore fruit in the ability to produce at volume. Currently, a Gen-2 flight system can be delivered to the customer in 10 months, with one-thruster-per-week cadence afterward. Combined with bulk material purchasing, pricing for each Gen-2 system can be as low as 20% of the Gen-1 cost.
The Gen-2 design was rigorously and expeditiously qualified in Busek’s upgraded testing facilities. The qualification program included environmental exposure to random vibration, shock, and thermal vacuum, with hot-fire tests at full thrust before and after exposure. Following qualification, the Gen-2 proceeded to flight-model manufacturing. To meet an urgent customer need, Busek stood up its first volume production program. 24 Gen-2 thruster units have now been delivered, with the ability to produce one unit per week going forward. An acceptance test regimen based on the qualification tests has been incorporated into the BIT-3 production sequence. Unit-to-unit comparisons of acceptance data demonstrate the quality and repeatability of the production program and the functionality of the PPU and the flight software. Reflected RF power has successfully been limited to 1.5% for the thruster circuit and 4% for the cathode circuit. The first on-orbit firings of the BIT-3 are expected to be in late 2022.

[Reference 3][March 2023][Mission information]
BIT-3: RF Ion (iodine) – 24 Generation II units delivered with launches anticipated in mid-2023. The Generation I unit on LunaH-Map (Artemis-1) contained a 3rd party valve which was a known, communicated risk, and unfortunately the customer was not permitted the time to allow Busek to swamp-in a GenII design.

[Reference 4][May 2023][Mission information]
The propulsion system (onboard LunaH) was unable to achieve ignition. Preliminary telemetry from the propulsion system indicates this is likely from a stuck valve due to extended storage of the spacecraft of more than 1 year. Momentum is being currently managed on the spacecraft via attitude changes and solar pressure. The propulsion system has heaters to condition the valve to unstick it, however, to date attempts at raising tank and valve temperatures have been unsuccessful. EOM will be end of May 2023 unless ignition is achieved. Contacts 2X per week continue to attempt ignition. If the propulsion system is unable to achieve ignition, the spacecraft will continue on a ballistic heliocentric orbit with a close approach to the Earth-Moon system occurring in 2039.

References:
[1] Tsay, M., “3500-hour wear test result of BIT-3 RF ion propulsion system,” IEPC-2022-255.
[2] Tsay, M., Terhaar, R., Emmi, K., Barcroft, C., “Volume production of Gen-2 iodine BIT-3 ion propulsion system,” IEPC-2022-267.
[3] Email correspondence from P. Hruby [March 2023]
[4] Hardgrove, G., “LunaH-Map: Early operations, science data and technology demonstrations,” Conference Proceedings: Interstellar Small Sat Conference, 2023.

Comm. avail.	6	NO
Comm. avail.	TRL	Aerospace-tested

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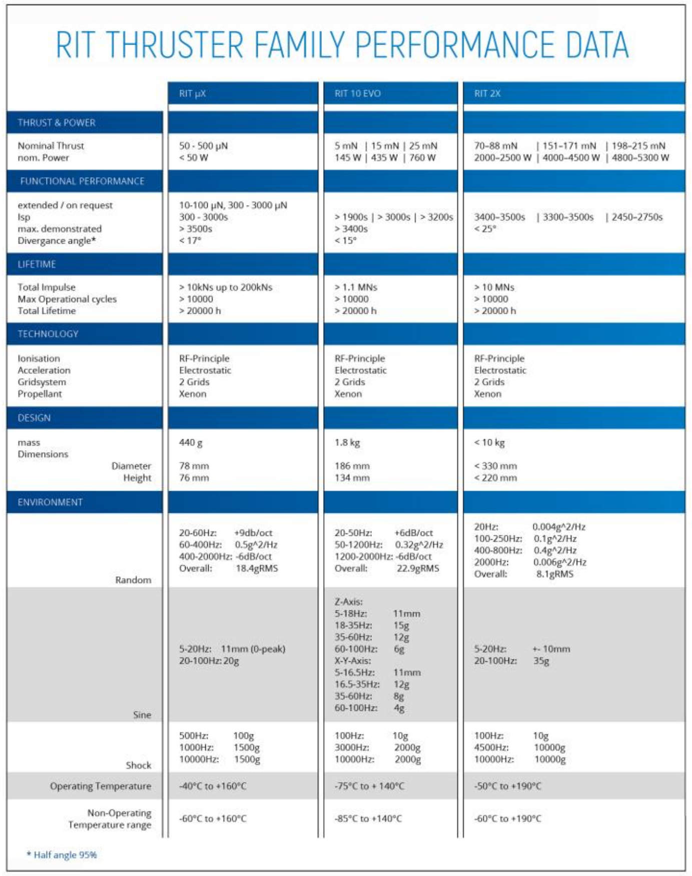
RIT µX (Radiofrequency Ion Thruster) (RIT-uX)
Ariane Group

Propulsion Technology	RF Ion Thruster
Manufacturer/Country	Ariane Group (Airbus/Safran) (FRANCE/GERMANY)
TRL	6
Size (including PPU)	<1U (440g dry mass)
Design satellite size	3 kg or larger (speculated)
Isp (s)	300 to 3000 s (3500s, demonstrated)
Thrust type/magnitude	50 to 500 uN (continuous, nominal), <0.1 uN (thrust resolution) 10,000 N*s (impulse, total)
Delta-V (m/s)	>3000 m/s (calculated using 4 kg wet spacecraft, with 500g Xe)
Propellant	Xenon
Power consumption (W)	<50W
Flight heritage (if any)	None known
Commercially available	YES
Last updated	*08/2022*



RIT THRUSTER FAMILY PERFORMANCE DATA

	RIT µX	RIT 10 EVO	RIT 2X
THRUST & POWER			
Nominal Thrust nom. Power	50 - 500 µN < 50 W	5 mN | 15 mN | 25 mN 145 W | 435 W | 760 W	70–88 mN | 151–171 mN | 198–215 mN 2000–2500 W | 4000–4500 W | 4800–5300 W
FUNCTIONAL PERFORMANCE			
extended / on request Isp max. demonstrated Divergance angle*	10-100 µN, 300 - 3000 µN 300 - 3000s > 3500s < 17°	> 1900s | > 3000s | > 3200s > 3400s < 15°	3400–3500s | 3300–3500s | 2450–2750s < 25°
LIFETIME			
Total Impulse Max Operational cycles Total Lifetime	> 10kNs up to 200kNs > 10000 > 20000 h	> 1.1 MNs > 10000 > 20000 h	> 10 MNs > 10000 > 20000 h
TECHNOLOGY			
Ionisation Acceleration Gridsystem Propellant	RF-Principle Electrostatic 2 Grids Xenon	RF-Principle Electrostatic 2 Grids Xenon	RF-Principle Electrostatic 2 Grids Xenon
DESIGN			
mass Dimensions Diameter Height	440 g 78 mm 76 mm	1.8 kg 186 mm 134 mm	< 10 kg < 330 mm < 220 mm
ENVIRONMENT			
Random	20-60Hz: +9db/oct 60-400Hz: 0.5g^2/Hz 400-2000Hz: -6dB/oct Overall: 18.4gRMS	20-50Hz: +6dB/oct 50-1200Hz: 0.32g^2/Hz 1200-2000Hz: -6dB/oct Overall: 22.9gRMS	20Hz: 0.004g^2/Hz 100-250Hz: 0.1g^2/Hz 400-800Hz: 0.4g^2/Hz 2000Hz: 0.006g^2/Hz Overall: 8.1gRMS
Sine	5-20Hz: 11mm (0-peak) 20-100Hz: 20g	Z-Axis: 5-18Hz: 11mm 18-35Hz: 15g 35-60Hz: 12g 60-100Hz: 6g X-Y-Axis: 5-16.5Hz: 11mm 16.5-35Hz: 12g 35-60Hz: 8g 60-100Hz: 4g	5-20Hz: +- 10mm 20-100Hz: 35g
Shock	500Hz: 100g 1000Hz: 1500g 10000Hz: 1500g	100Hz: 10g 3000Hz: 2000g 10000Hz: 2000g	100Hz: 10g 4500Hz: 10000g 10000Hz: 10000g
Operating Temperature	-40°C to +160°C	-75°C to + 140°C	-50°C to +190°C
Non-Operating Temperature range	-60°C to +160°C	-85°C to +140°C	-60°C to +190°C

* Half angle 95%

Photo of the RIT uX thruster. It is the smallest in a family of RIT thrusters produced by Ariane Group

[3]

Additional comments:

[Reference 1-3][Jan 2019][General info]

The radio frequency Ion thruster uses a high-frequency electromagnetic field to ionize xenon gas atoms to form a plasma containing free 'light' electrons and 'heavy' positive ions. The heavy positive ions are then accelerated by an electrostatic field before being ejected to cause thrust. After the ions have been ejected from the thruster, electrons are added from a neutralizer. The plasma is thereby neutralized which prevents the satellite from becoming charged.

Ariane Group makes a family of RF thrusters, and RIT µX is the smallest in the family. It is optimal for orbital maneuvers requiring high precision. The divergence angle of the plume is roughly 17 degrees, and lifetime has been tested to more than 10,000 operational cycles and >20,000 hrs. It has also been qualification tested (vibration, thermal cycling) extensively.

In the light of upcoming ESA science missions there is the request for an extended thrust dynamic targeting 50-2500µN. The work on adequate ion optics began in 2014. Several different configurations for the RIT uX exist. Two IOS configurations, one with 61 channels and the other one with 121 have been successfully tested. For the 61 channel configuration a maximum thrust dynamic from 32 to 2500µN has been demonstrated and the 121 channel configuration war operated from 62-3200µN. A coupled system test for the configuration with 61 channels was successfully performed and presently an endurance test is running in the electric propulsion laboratory of ESA's technology center ESTEC (Noordwijk, NL).

[Reference 2][Aug 2022][Testing]

A coupling test with 2 RIT-uX thrusters for studying the effects of grid-erosion and cluster operation is reported. The endurance test showed no unexpected increase of power consumption of the thrusters when operated in cluster mode.

References:

[1] Leither, H., Altmann, D., Porst, J., Lauer, D., "Six Decades of Thrust – The Ariane Group Radiofrequency Ion Thrusters and Systems Family," IEPC-2017-027
[2] Leither, H., Killinger R., Bassner, H., Muller, J., Kukies, R., "Development of the Radio Frequency Ion Thruster RIT XT- A Status Report," IEPC-01-104
[3] http://www.space-propulsion.com/brochures/electric-propulsion/electric-propulsion-thrusters.pdf
[4] Leiter, H., Altmann, C., Lauer, D., Feili, D., Amo, J., Massoti, L., "Recent development of the RIT-uX thruster and system," IEPC-2022-252.
[5] Holste, K., Henning, T., Nauschutt, B., Klar, P., Spemann, D., Scholze, F., Eichhorn, C., Leiter, H., Dietz, P., Bosch-Borras, E., "Endurance and coupling test of the RIT-uX," IEPC-2022-247.

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NO

Comm. avail. TRL Aerospace-tested

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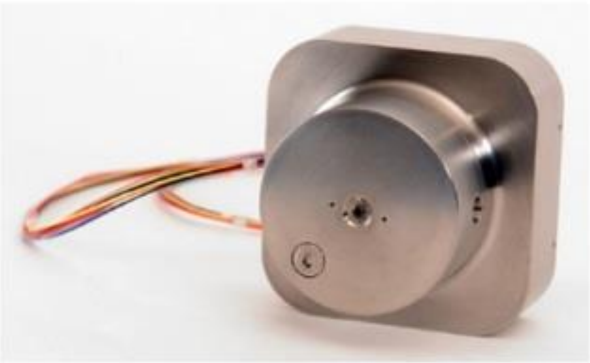
Propulsion Unit for CubeSat (PUC-SO2, PUC184-SO2, AFRL PUC-1U) CU Aerospace/VACCO/AFRL [1 of 2]

Propulsion Technology	Warm/cold gas thruster
Manufacturer/Country	CU Aerospace/VACCO/AFRL (USA)
TRL	5
Size (including PPU)	Various sizes, from 0.25U to 1U
Design satellite size	1U and larger
Isp (s)	70 s
Thrust type/magnitude	5 mN (continuous, nominal) 180 N*s (impulse, 0.25U model) 320 N*s (impulse, 0.5U model) 593 N*s (impulse, 1U model) 1 mN*s (impulse, minimum) Thruster can thrust for 20 minutes continuously, and then requires 10 min of cooldown.
Delta-V (m/s)	48 m/s (4 kg spacecraft, 0.25U model), 85 m/s (4 kg spacecraft, 0.5U model) 167 m/s (4 kg spacecraft, 1U model)
Propellant	SO2 (Sulfur Dioxide), stored as liquid. Other propellants possible
Power consumption (W)	15W (warm gas), 8W (cold gas), 0.055W (standby)
Flight heritage (if any)	None known
Commercially available	YES, ~10 month lead time
Last updated	*01/2021*



Photograph 0.25U Propulsion Unit for CubeSats (Model: PUC-184-SO2)

Warm Gas Mode: 5.4 mN, 70 sec Isp, 15 watts				
Unit	Total Impulse (N/sec)	Delta-V, 3 kg CubeSat (meters/sec)	Delta-V, 4 kg CubeSat (meters/sec)	Dry Mass (grams)
0.25U	183	64	47	434
0.50U	320	121	87	568
1U	595	234	167	835

[4]

Additional comments:

[Reference 1-4][Jan 2019][General info]

This thruster was developed under a partnership between VACCO, AFRL and CU Aerospace. The thruster valves have been tested to 75,000+ cold gas firings. SO2 propellant is non-flammable, chemically stable, and self-pressurizing, and is stored onboard as a liquid. The CU Aerospace/VACCO Industries Propulsion Unit for CubeSats (PUC) was developed as a medium thrust, medium impulse thruster system to enable CubeSat orbital maneuvering, formation flying, and rendezvous. The 0.25U PUC casing is all-welded titanium, and comes fully integrated with all necessary propulsion subsystems, including controller, power processing unit, micro-cavity discharge thruster, propellant valves, heaters, sensors, and software. The unit is software-configurable to operate over a wide range of power, thrust, and impulse levels. System setpoints, system status, and firing telemetry are accessible and configurable through an RS422 serial interface. The baseline system fits within a compact 350 cm3 volume (0.25U+“hockey puck”), with an 89 mm x 89 mm cross-section, leaving clearance for solar panels and magnetic torquers. PUC may be expanded from 0.25U to any desired length, providing significant potential for increased propellant capacity and ΔV capability, compared with the baseline 0.25U design. The 0.25U PUC draws 15 W when using a microcavity discharge (MCD) to heat the high-density, self-pressurizing liquid SO2 propellant, coupled to an optimized micronozzle to provide 5 mN thrust at 70 s Isp, a 4 kg CubeSat ΔV of 48 m/s, and demonstrates negligible component wear and constant lifetime operations. A dedicated propellant heater provides for continuous operation below +5°C ambient temperature. Cold gas operation can be used for small impulse operations. On-orbit update of system parameters is provided, including thrust duration, plenum pressure, MCD power level temperature & fault set-points. Manufacturer claims life span as 2 years from propellant load.

References:

[1] Carroll, D., Cardon, J., Burton, R., et al. “Propulsion Unit for CubeSats (PUC),” 62nd JANNAF Propulsion Meeting, 2015.
[2] http://www.cuaerospace.com/Portals/2/SiteContent/pdfs/datasheets/PUC/PUC-SO2%20(Rev140722).pdf
[3] http://www.cuaerospace.com/technology-products/compact-small-satellite-propulsion-unit-cubesats
[4] http://www.cubesat-propulsion.com/propulsion-unit/

Comm. avail.	6 TRL	NO Aerospace-tested

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Propulsion Unit for CubeSat (PUC-SO2, PUC184-SO2) CU Aerospace/VACCO/AFRL [2 of 2]

Additional comments:

[Reference 1][Jun 2020][General info]
The Propulsion Unit for CubeSats (PUC) system was designed and fabricated by CU Aerospace and VACCO Industries under contract with the U.S. Air Force to supply two government missions. The system was acquired for drag makeup capability to extend asset lifetime in LEO. The system utilizes SO2 as a self-pressurizing liquid propellant. The propulsion system electrothermally heats the propellant using a micro-cavity discharge (MCD) and expels the propellant through a single nozzle. It can alternatively use R134a or R236fa propellants, but only in a cold-gas mode with reduced performance. Eight (8) flight units were delivered to the Air Force in 2014. It is unknown if any of the units have flown.

[Reference 2][Jan 2021][General info]
Development hardware has been extensively tested including 75000+ cold gas firings in a vacuum chamber.

References:
[1] NASA 2020 SOA for Small Satellites (POC Gabriel Benavides). https://www.nasa.gov/smallsat-institute/sst-soa-2020/in-space-propulsion
[2] https://satcatalog.com/datasheet/VACCO%20-%20AFRL%20PUC-1U.pdf

Comm. avail.	TRL	Aerospace-tested
	6	NO

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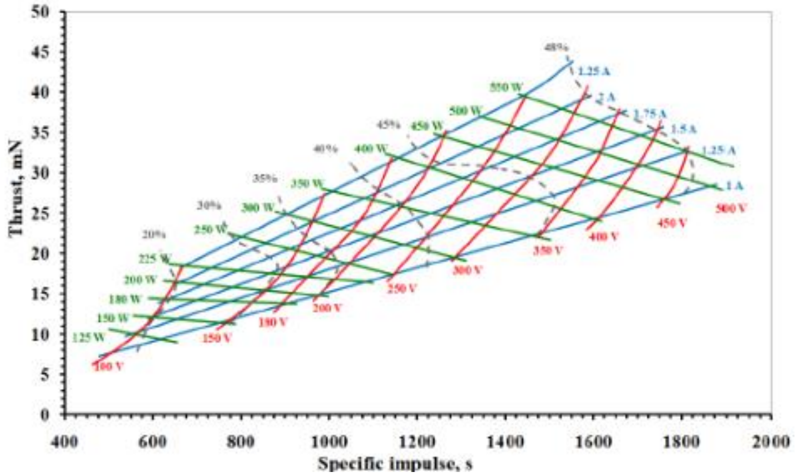
PlaS-40

Propulsion Technology	Hall thruster
Manufacturer/Country	Fakel (Russia)
TRL	5-6
Size (including PPU)	1.5U, 1.2 kg
Design satellite size	
Isp (s)	500 to 1800 s
Thrust type/magnitude	7 to 43 mN
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	100 to 650W
Flight heritage (if any)	None known
Commercially available	Unclear, manufacturer claims EM model development
Last updated	*01/2021*

Performances	Value
Discharge volatge, V	100…500
Discharge current, A	1.00…2.25
Discharge power, W	100…650
Thrust, mN	up to 44
Specific impulse, s	up to 1880
Efficiency, %	up to 50
Power-to-thrust ratio, W/mN	13…18
Mass, kg	1.2
Overall dimensions, mm	167x100 x87

PlaS-40 thruster after manufacturing and during operation



PlaS-40 thruster after 200 hrs operation time

Additional comments:

[Reference 1-2][Jan 2019][Development]

Creation of high-pulse electric propulsion with the thrust specific impulse higher than 2500 s was made at EDB Fakel (Kaliningrad) in 1999-2000. Back at that time in frames of contractual works with Atlantic Research Corporation (ARC, USA) a high-voltage thruster experimental model was developed based on the separate modified elements and assembly units of the PPS 1350R and based on the anode new design scheme, and this model was conventionally named as SPT-1. The proposed design scheme of the SPT-1 thruster high-voltage experimental model, according to the authors, is a new type of Hall-effect thrusters. It is stipulated by the fact that this thruster discharge chamber (DCh) is combined: DCh exit part is formed by dielectric rings and its bottom part is made metallic by means of the walls of the adjoining hollow anode-gas distributor. On the basis of the research tests results of the hollow magnet anode plasma thruster laboratory models at EDB Fakel, a parametric family of the PlaS-type of thrusters conceptual models with the power from 100 W to 6 kW was developed, namely: PlaS-34, PlaS-40, PlaS-55 and PlaS-120CM.

The first developed thruster of PlaS parametric family is PlaS-40. This thruster is the most investigated and tested and has status of engineering model. As shown by test, PlaS-40 thruster efficiently and stably operates in the discharge power range from 100 to 650 W. Maximum thrust determined at the anode flow rate of 2.58 mg/s and at the discharge voltage of 300 V is 44.0 mN. Minimum power-to-thrust is 12.3 W/mN and corresponds to discharge current of 2.0 A and discharge voltage of 150 V. The total specific impulse calculated with an allowance for the discharge power and power consumption for magnet field generation, and also with an allowance for cathode flow rate and for the level of vacuum chamber pressure is 1880 s at maximum discharge voltage of 500 V and power of 500 W. Efficiency increases significantly at the discharge voltage increase up to 250 V followed by stabilization of the value up to ~35% for anode gas flow of 1.32 mg/s and ~47% for anode gas flow 2.58 mg/s.

[Reference 3][Jan 2019][Test results]

Thrust efficiency up to 50%, development level at EM (Engineering Model).

References:

[1] Bernikova, M., Gopanchuk, V., “Parametric family of the PlaS-type thrusters: development status and future activities,” IEPC-2017-39.
[2] Potapenko, M., Gopanchuk, V., Olotin, S., “PlaS-40 development status: new results,” IEPC-2015-99/ISTS-2015-b-99.
[3] www.fakel-Russia.com

NO	6	NO
Comm. avail.	TRL	Aerospace-tested

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Roll-Out De-Orbiting device (RODEO)

Propulsion Technology	Passive de-orbit
Manufacturer/Country	Composite Technology Development, Inc. (USA)
TRL	6
Size (including PPU)	Very small, the 3U size is 140 cm^3, or 96g [4]
Design satellite size	Variations for 3U, Nanosat (15kg), up to SmallSat (100kg) [4]
Isp (s)	n/a
Thrust type/magnitude	Propellant-less
Delta-V (m/s)	n/a
Propellant	n/a
Power consumption (W)	
Flight heritage (if any)	RocketSat-8 (suborbital, 2012) [1,2]
Commercially available	Yes
Last updated	01/2021

Deployment progression for 3U CubeSat RODEO [2]

During deployment on RocketSat-8 [4]

Additional comments:

[Reference 1, 2][March 2019][Device information]

Use of small and very small spacecraft is rapidly becoming more common. Methods to intentionally deorbit these spacecraft at the end of useful satellite life are required. A family of mass efficient Roll-Out DeOrbiting devices (RODEO™) was developed by Composite Technology Development, Inc. (CTD). RODEO™ consists of lightweight film attached to a simple, ultra-lightweight, roll-out composite boom structure. This system is rolled to stow within a lightweight launch canister, allowing easy integration to the small satellite bus. The device is released at the end of useful lifetime and the RODEO™ composite boom unrolls the drag sail in a matter of seconds. This dramatically increases the deployed surface area, resulting in the higher aerodynamic drag that significantly reduces the time until reentry. A RODEO™ flight demonstration was recently conducted as part of the Colorado Space Grant Consortium's (COSGC) RocketSat-8 program, a program to provide students hands-on experience in developing experiments for space flight. The experiment was ultimately a success and RODEO™ is now ready for future CubeSat missions.

[Reference 4][Jan 2021][Flight information]

On RocketSat-8, full deployment was achieved, but was off-nominal. RODEO encountered moisture absorption due to extended exposure (a few weeks) to extremely high humidity prior to launch. However, this would not be an issue for orbital flight.

References:

[1] https://sst-soa.arc.nasa.gov/12-passive-deorbit-systems
[2] Turse, D., Keller, P., Taylor, R., Reavis, M., Tupper, M., Koehler, C., "Flight testing of a low cost de-orbiting device for small satellites," Proceedings of the 42nd Aerospace Mechanisms Symposium, NASA, 2014.
[3] https://www.ctd-materials.com/home/composite-booms-and-boom-deployers/#tab-id-2
[4] Turse, D., Reavis, M., Keller, P., Koehler, C., "Flight Testing of a Low-cost De-orbiting Device for small satellites," Presented at 2015 CubeSat Workshop, Small Satellite Conference, Logan, UT. https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3296&context=smallsat

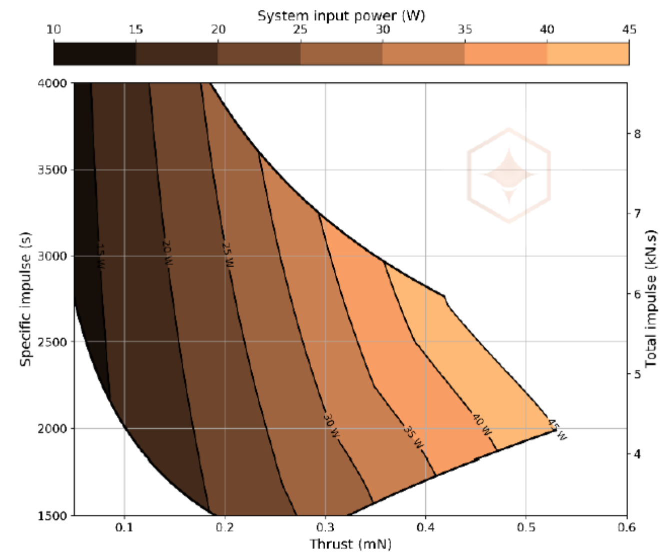
Comm. avail.	6	NO
	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Nano IR^3

Propulsion Technology	FEEP
Manufacturer/Country	Enpulsion (AUT)
TRL	6
Size (including PPU)	1U
Design satellite size	3U and larger
Isp (s)	2000 s (see performance envelope) [1]
Thrust type/magnitude	500 uN (max, see performance envelope) [1]
Delta-V (m/s)	
Propellant	Indium
Power consumption (W)	40 to 45W (at 500 uN thrust and 2000s Isp) [1]
Flight heritage (if any)	None known
Commercially available	YES Now available as stock item on SmallSat Catalog by Orbital Transports [2]
Last updated	06/2021

DYNAMIC THRUST RANGE	10 TO 500 µN
NOMINAL THRUST	500 µN
SPECIFIC IMPULSE	1,500 TO 4,000 s
PROPELLANT MASS	220 g
TOTAL IMPULSE	MORE THAN 4,000 Ns
POWER AT NOMINAL THRUST	45 W INCL. NEUTRALIZER
OUTSIDE DIMENSIONS	98.0 x 99.0 x 95.3 mm
MASS (DRY / WET)	<1200 / <1420 g
TOTAL SYSTEM POWER	8 – 45 W
HOT STANDBY POWER	3.5 W
COMMAND INTERFACE	RS422 / RS485
TEMPERATURE ENVELOPE (NON-OPERATIONAL)	-40 TO 95°C
TEMPERATURE ENVELOPE (OPERATIONAL)	-20 TO 40 °C
SUPPLY VOLTAGE	12 V, 28 V, OTHER VOLTAGES UPON REQUEST



Depending on available power, the user can choose from any operational point. Performance model is based on heritage *ENPULSION NANO* and modified to the *ENPULSION NANO IR^3* parameters.

Additional comments:

[Reference 1][March 2021][Thruster information]
The Enpulsion Nano IR3 is based on the Enpulsion Nano. Incorporation of lessons learned from a large number of acceptance test campaigns and in-orbit performance verifications led into an updated electronics design, thermostructural concept, and software functionality. The result is that the Nano IR3 features increased reliability, radiation tolerance, and environmental resilience, and is configured to enable higher-thrust operating points.

References:
[1] https://www.enpulsion.com/order/nano-ir3/
[2] https://smallsatnews.com/2021/05/18/smallsat-thruster-modules-from-enpulsion-now-in-orbital-transports-smallsat-catalog/

	6	NO
Comm. avail.	TRL	Aerospace-tested

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XCGT

Propulsion Technology	Xenon Cold Gas thruster
Manufacturer/Country	Maxar, Moog (USA)
TRL	6-7
Size (including PPU)	<1U
Design satellite size	1U and larger
Isp (s)	20
Thrust type/magnitude	1N
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	
Flight heritage (if any)	2019
Commercially available	YES
Last updated	01/2021

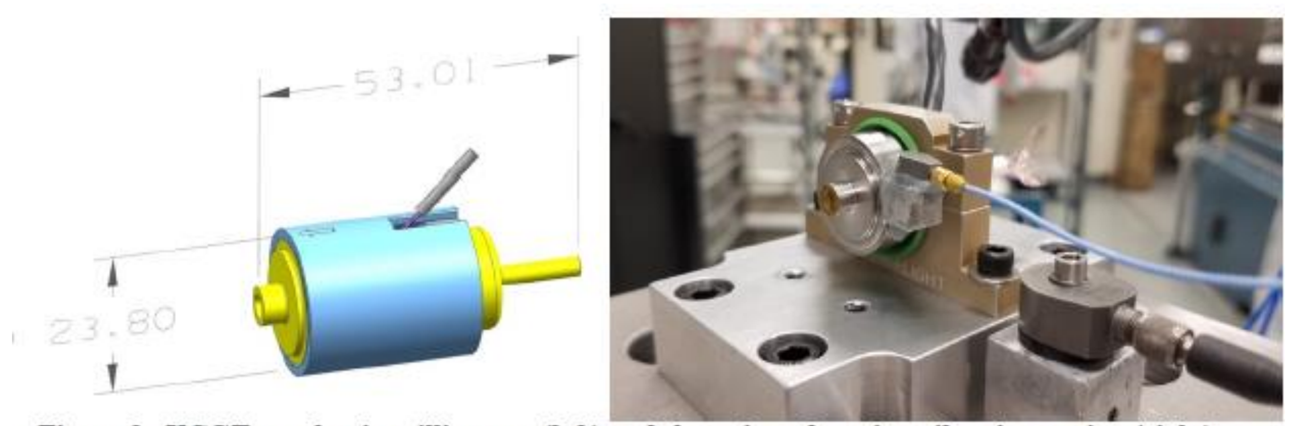
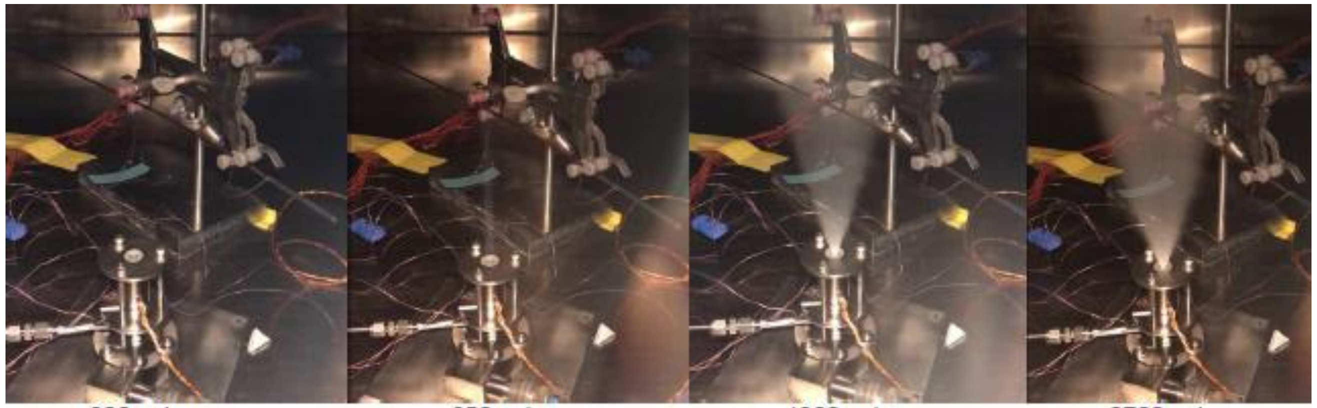


Figure 2. XCGT envelop in millimeters (left) and the unit undergoing vibration testing (right).



Additional comments:

[Ref 1][Oct 2019][Thruster status]
In place of a dedicated, and expensive, chemical system for this singular beginning of life application, a simple solution developed by Maxar is to use xenon cold gas thrusters (XCGT) directly connected to the primary propellant tanks. Such a system is low-cost, low-risk, low-power, and easily integrated with existing spacecraft infrastructure and manufacturing processes. The XCGTs for this application were designed and built by Moog Inc and are based on heritage single-seat solenoid valves. Developmental testing showed that they operate up to 2700psi inlet pressures with 2.8N of thrust with a specific impulse of 22sec at 21C. The thrust decreases with pressure, while both the thrust and specific impulse are highly dependent on temperature and have non-linear features at the Xenon critical point. An overview of the use of the XCGT to correct satellite tip-off rotation, and a performance summary of the thruster will be reviewed, including performance predictions as compared to test results.
The problem of high launch vehicle tipoff rates with large all electric propulsion GEO spacecraft requires a relatively high thrust, low power solution. Maxar solved this issue with Moog built Xenon cold gas thrusters, directly connected to the Xenon tanks. Developmental testing at varying pressures and temperatures showed good correlation between theory and experiment. This solution for this singular BOL operation was simple, light weight, low risk, and low cost. The first Maxar all-EP spacecraft utilizing the Moog Xenon Cold Gas Thrusters was launched in 2019.

References:
[1] John, I., Warner, D., Neff, K., McCormick, S., “Xenon cold gas thruster (XCGT),” IEPC-2019-941.

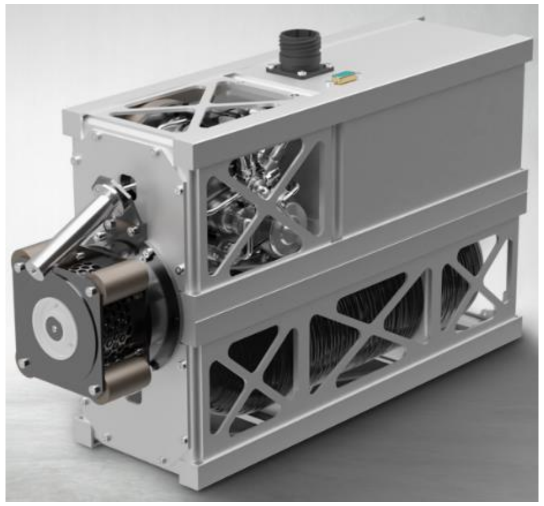
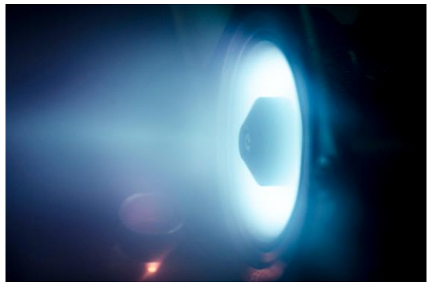
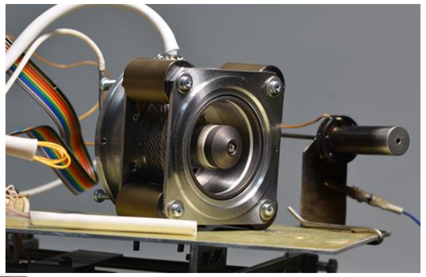
6 NO

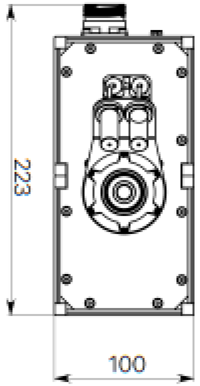
Comm. avail. TRL Aerospace-tested

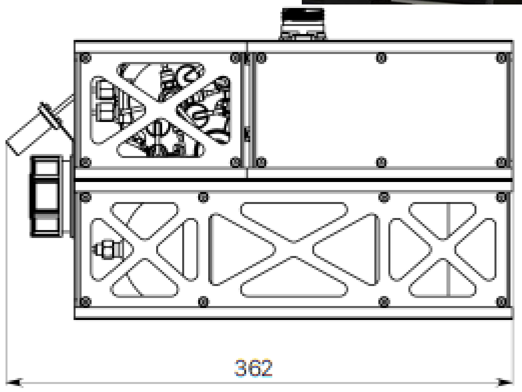
DISTRO A: Approved for public release. OTR-2024-00338

SPS-25 [1 of 2]

Propulsion Technology	Hall effect thruster
Manufacturer (Country)	SETS (UKR)
TRL	5
Size (including PPU)	~10cm x 22cm x 36cm (dry mass 6 kg)
Design satellite size	Small Sat (up to 500 kg)
Isp (s)	1200s
Thrust type/magnitude	5 - 11 mN
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	150 – 230 W
Flight heritage (if any)	None
Commercially available	YES
Last updated	*03/2021*





All pictures [SETS website]

Additional comments:

[Reference 1-7][September 2020][Overview]
Space Electric Thruster Systems (SETS) is a Ukrainian based EP company focusing on SmallSat HET applications. They develop the entire EP system string which includes the Hall effect thruster (HET), Xenon Feed System (XFS), and Power Processing Unit (PPU) characterized in [1]. SETS makes two flight EP strings: the SPS-40 for medium/large satellites weighing up to 1 ton for station-keeping [2] and the SPS-25 for SmallSats up to 500 kg [1],[3]. SETS produces two HET designs: the ST40 and ST25 to satisfy the two satellite mass categories. The ST25 is the low power option (250W max) used on SPS-25. The ST25 with one cathode weighs ~ 750 g. The PPU is designed to support either the SPS-40 or SPS-25 requiring an input spacecraft bus voltage of 28 VDC though no spec sheet is available to confirm this or other performance properties. The XFS is compatible with various propellants (N2,He, Ar, Air) and is designed to regulate anode/cathode flow rates as given in [7]. SETS has a US office in Austin, TX but is HQ'ed in Ukraine.

[Reference 1][September 2020][Performance]
Full performance of the SPS-25 string is presented in [1]. Thruster efficiency is 25%.

References:

[1] https://sets.space/wp-content/uploads/2020/02/IAC-19C444x50659.pdf
[2] https://sets.space/wp-content/themes/sets-space/images/product-sheet/SPS40.pdf
[3] https://sets.space/wp-content/themes/sets-space/images/product-sheet/SPS25.pdf
[4] https://sets.space/wp-content/themes/sets-space/images/product-sheet/ST25.pdf
[5] https://sets.space/electric-propulsion-system-sps-25-with-hall-thruster/
[6] https://sets.space/ppu/
[7] https://sets.space/wp-content/themes/sets-space/images/product-sheet/XFS.pdf

Comm. avail.	6	NO
	TRL	Aerospace-tested

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SPS-25 [2 of 2]

Additional comments:

[Reference 1][March 2021][Company news]

SETS to debut its TAL thruster EP string in spring of 2021 along with Firefly Aerospace's 1st launch out of Vandenberg AFB

On December 22, 2020, SETS, a Noosphere Ventures aerospace company, announced it will undergo field testing in LEO as part of a debut launch of the Firefly Aerospace Alpha rocket, which is scheduled for the beginning of 2021 from Vandenberg AFB. "The goal of the first SETS mission is to demonstrate and confirm the space worthiness and performance of the system under real conditions, and receive the necessary telemetry," commented SETS CEO Viktor Serbin.

The 200 W SPS-25 propulsion system is a proprietary technology developed by SETS, and is composed of an ST-25 Hall-effect thruster (HET), modular Xenon Feed System (XFS), fuel tank, and Power Processing Unit (PPU). The system is intended to transport spacecraft to their final orbit following payload separation.

"The SETS system was developed in order to increase the working duration of satellites and assist in safe deorbiting. This is incredibly important, as minimizing orbital debris in near-Earth space is a necessity for the continued development of space technologies," said Noosphere Ventures founder Max Polyakov.

References:

[1] https://sets.space/sets-to-demonstrate-in-space-performance-as-part-of-firefly-aerospace-s-debut-alpha-launch/

	6	NO
Comm. avail.	TRL	Aerospace-tested

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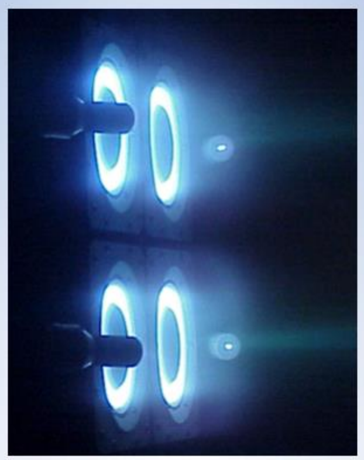
BHT-600

Propulsion Technology	Hall thruster
Manufacturer/Country	Busek (USA)
TRL	6
Size (including PPU)	Thruster mass 2.6 kg
Design satellite size	Small Sat (ESPA)
Isp (s)	1500 s
Thrust type/magnitude	39 mN
Delta-V (m/s)	
Propellant	Xenon, iodine, krypton
Power consumption (W)	300 to 800 W, nominal 600W
Flight heritage (if any)	None BHT-600: initial flight model with 100kRAD PPU integrated and awaiting 2023 launch [2]
Commercially available	YES
Last updated	06/2021

BHT-600 Hall Effect Thruster



Multiple BHT-600 in a Cluster

BHT-600 During NASA Glenn Research Center Test

Additional comments:

[Reference 1][June 2021][Thruster information]
The BHT-600 is a mature propulsion system featuring high performance and compatibility with flight proven heritage components (cathodes, PPUs, and feed systems). The BHT-600 is especially suited for ESPA-class spacecraft and offers high performance over long-life, as well as operation on xenon or iodine propellants. The thruster is TRL-6. The BHT-600 produces ~39mN thrust at 600W power at a specific impulse of ~1,500 seconds. As of July 2019, a BHT-600 engineering model at NASA's Glenn Research Center has accumulated 4,000 hours of operation (equating to ~40 kg Xe propellant throughput). Performance over this timeframe has not resulted in a discernable drop in thrust or specific impulse typically seen in other thruster designs. A hybrid BHT-600i (iodine anode, xenon cathode) has also been demonstrated for over one thousand hours of operation. Busek provides complete and fully integrated Hall Effect thruster systems, including cathode, power processing unit, digital control unit, and propellant management systems.

References:
[1] http://busek.com/index_htm_files/70000701B.pdf
[2] Email correspondence with Pete Hruby, March 2023.

	6	NO
Comm. avail.	TRL	Aerospace-tested

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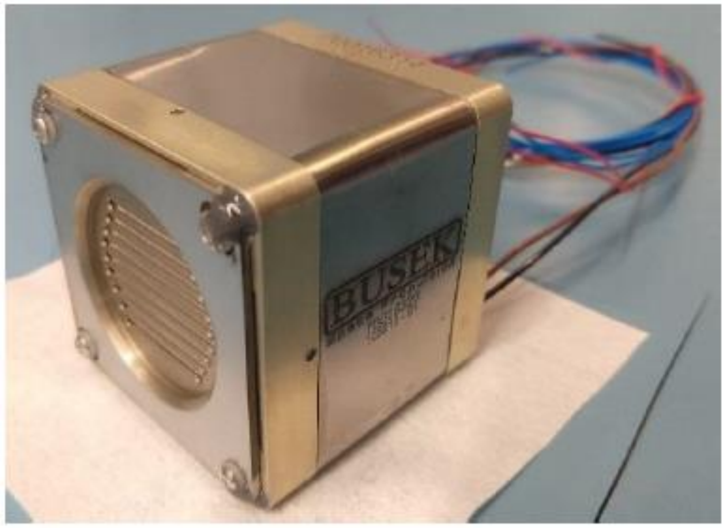
BET-300-P [1 of 2]
Busek

Propulsion Technology	Electrospray
Manufacturer/Country	Busek
TRL	5
Size (including PPU)	1U
Design satellite size	3U and larger
Isp (s)	800 to 1000 s [1, 2], 850s [3]
Thrust type/magnitude	5 to 150 uN (variable), in 400 nN steps, ~135 N*s (impulse, total) [1, 2] 55 uN nominal, 92 N*s (impulse, total) [3]
Delta-V (m/s)	
Propellant	EMI-Im [3]
Power consumption (W)	<3W
Flight heritage (if any)	None known
Commercially available	Yes
Last updated	*06/2022*



[3]

Additional comments:

[Reference 1] [Jan 2019][Company information]
Busek Company will develop advanced CubeSat propulsion and Hall Effect thrusters (HETs) with the help of NASA funding.
The space agency has selected the Massachusetts-based company for five Small Business Innovation Research (SBIR) Phase 1 awards. The contracts are worth up to $125,000 apiece over 13 months.
The three proposals focused on CubeSats and small satellites include:
•a low impulse bit electrospray thruster control system;
•a compact high performance plasma propulsion system (CHPPPS); and,
•an iodine-compatible photocathode for RF ion thrusters.
The passive electrospray thruster control "will enable extremely fast thruster operations and thereby unprecedented minimum impulse bits. Busek's BET-300-P thruster is under active development as a precision reaction control system (RCS) which will provide orders of magnitude improvements over state-of-the-art alternative attitude control systems (ACS) for CubeSats and small spacecraft," the proposal summary stated.

[Reference 2] [Jan 2019][Thruster info]
The BET-300-P is passively fed propellant at a rate established by a balance between traction due to an applied electric field, fluid viscosity and capillary forces internal to the thruster's propellant reservoir. In this state, stable flow rates are sufficiently low to yield an ion-dominated beam with high charge to mass ratio and thereby high specific impulse. Propellant is stored exclusively within the thruster body in a manner which specifically targets evolution towards high impulse density storage, while retaining features necessary to maintain consistent propellant flows and unambiguous fluid containment. In comparison, the CMNT thrusters aboard LISA Pathfinder were supplied propellant from pressurized tanks at a flow rate regulated by piezoelectric valves. The droplet dominated beam generated by that system led to a specific impulse of 150-250s compared with the 1000s for the BET-300-P. Combined, the simple feed system and high specific impulse of the BET-300-P permit a compact thruster system: approximately 5 cm cubed including all flow-regulation hardware and sufficient propellant for up to 135 Ns of impulse (corresponding to >1000Ns/U). The system therefore provides enhanced impulse density compared with, for example, cold-gas reaction control systems (RCS). Emission current and bean energy is regulated by a single applied voltage between the propellant and extractor electrode, with the latter held at ground. Thrust efficiency was in the range of 20 to 30%. Higher efficiency and specific impulse were observed at low thrust.

References:
[1] http://www.parabolicarc.com/2018/06/11/busek-sbirs/
[2] Courtney, D., Alvarez, N., Demmons, N., "Electrospray thrusters for small spacecraft control: pulsed and steady state operation," AIAA proceedings, 2018.
[3] Fedkiw, T., Wood, Z., Demmons, N., Courtney, D., "Environmental and lifetime testing of the BET-300-P Electrospray Thruster," AIAA Propulsion and Energy, 2020.

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Comm. avail. TRL Aerospace-tested

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BET-300-P [2 of 2]
Busek

Additional comments:

[Ref 1, 2][Oct 2019][Thruster diagnostics]
Busek has developed tomographic plume diagnostics and characterized the thruster at high speed modulation.

[Reference 3][March 2021][Thruster ground testing results]
The BET-300-P has been updated to an engineering model design, and its lifetime performance has been evaluated. The engineering model thruster was subjected to a series of environmental exposure tests, followed by demonstration of the full thruster life. The thruster was shown to be able to tolerate NASA GEVS qual level vibrations, as well as prolonged exposure to elevated humidity. The thruster was operated for 461 hours at a nominal thrust of 55 uN, with a total impulse of 91.8 N*s. The thruster performance varied over the course of life testing, but the average specific impulse was 850s, average thrust to power was 65 uN/W, and average propulsive efficiency was 25%.

[Reference 1][June 2022][Thruster information]
4X BET-300's are joined together in Busek's new BET-MAX unit (it has its own separate spec sheet)

References:

[1] Courtney, D., Wood, Z., Fedkiw, T., "Reconstructing electrospray plume current spatial distributions using computed tomography," IEPC-2019-A-787.
[2] Courtney, D., Wood, Z., Gray, S., Model, J., "High speed transient characterization of the Busek BET-300-P electrospray thruster," IEPC-2019-A-788.
[3] Fedkiw, T., Wood, Z., Demmons, N., Courtney, D., "Environmental and lifetime testing of the BET-300-P Electrospray Thruster," AIAA Propulsion and Energy, 2020
[4] BET-MAX information, public flyer from IEPC 2022 distributed by Peter Hruby

Comm. avail.	6 TRL	Aerospace-tested

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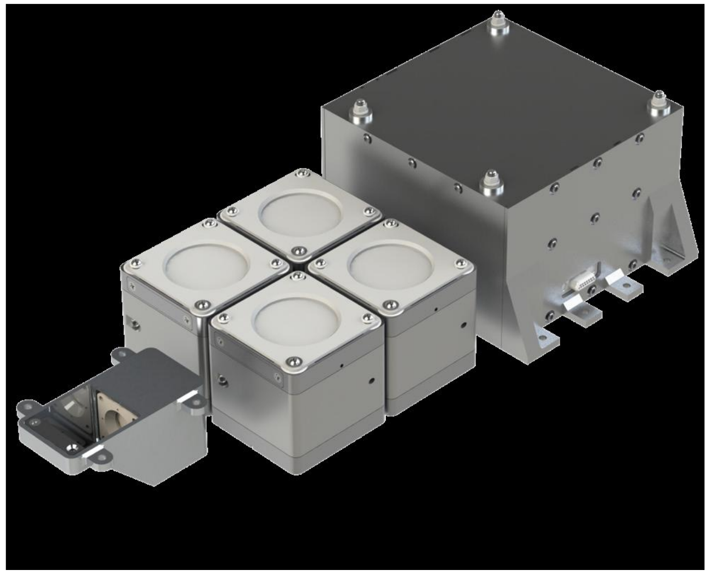
BET-MAX

Propulsion Technology	Electrospray
Manufacturer/Country	Busek (USA)
TRL	6
Size (including PPU)	~0.75U
Design satellite size	3U and larger
Isp (s)	850s to 2300s (depending on configuration)
Thrust type/magnitude	4X 150 uN (but operationally ~300 uN)
Delta-V (m/s)	
Propellant	EMI-IM
Power consumption (W)	~100W (throttleable)
Flight heritage (if any)	None Multi-axis electrosprays system; first flight set (4 thrusters, 1 cathode, 1 PPU) delivered to customer and awaiting integration. [3]
Commercially available	YES
Last updated	03/2023



[1]

Additional comments:

[Reference 1, 2][June 2022][Thruster info]
Busek's BET-MAX precision reaction control system seeks to provide the high-resolution control afforded by electrospray propulsion technology. Up to four 125cm3 BET-300P thrusters per centralized PPU can be positioned as desired to provide attitude or orbital control within platforms as small as 3U. Each thruster can provide throttled continuous thrust from <1µN up to 150µN with sub-µN resolution over the full range. The thruster modules include propellant storage -sufficient propellant to provide over 100Ns of impulse- and all associated feed components.

References:
[1] https://www.busek.com/bet-300p
[2] Demmons, N., "Qualification of the BET-MAX electrospray propulsion system," IEPC-2022-196
[3] Email correspondence with P. Hruby [March 2023]

Comm. avail.	TRL	Aerospace-tested
	6	NO

DISTRO A: Approved for public release. OTR-2024-00338

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Monofilament Vaporization Propulsion (MVP) [1 of 2]
CU Aerospace

Propulsion Technology	Electrothermal
Manufacturer/Country	CU Aerospace (USA)
TRL	5-6
Size (including PPU)	1U
Design satellite size	3U or larger
Isp (s)	>100s demonstrated 66s [4]
Thrust type/magnitude	4.5 mN (continuous, nominal) [4] 280 N*s total impulse [4] 0.16 mN/W power Maximum thrusting time =15 min, after which 2 min of resting time is required.
Delta-V (m/s)	150 m/s for 4 kg spacecraft
Propellant	Polyoxymethylene (POM, tradename Delrin), 660g [2]
Power consumption (W)	13.5W average power with peak 45 W [4]
Flight heritage (if any)	None known Slated for DUPLEX NASA Tipping point program, Q1 2023 [3,4]
Commercially available	YES, ~12 month lead time [2]
Last updated	*12/2023*

[4]

Item	"Flight-like" MVP Performance	"Flight" MVP Performance
Propulsion system dimensions	10.0 x 10.0 x 11.57 cm^3	9.0 x 9.0 x 11.43 cm^3
Propulsion system volume	1157 cm^3	926 cm^3
System lifetime	Not propellant limited	
Spacecraft temperature range	Not propellant limited (survived – 20°C to + 70°C)	
Propellant	POM (Delrin), gaseous MW = 30	
Power to MVP system when firing	45 W	39 W
Power to superheater PPU	40 W	36 W
PPU efficiency	0.74	0.85
Power to superheater	30 W	30.6 W
Duty Cycle	30% (3 min on, 7 min off)	30% (3 min on, 7 min off)
Propellant Mass	516 g	433 g
Dry Mass	622 g	622 g
Total propulsion wet mass	1138 g	1055 g
Nominal mass flow rate	7 mg/s	7 mg/s
Total thrust time	20.5 hr	17.2 hr
Specific Impulse	66 s	66 s
Primary Thrust	4.5 mN	4.5 mN
Total impulse	334 N-s	280 N-s
Volumetric total impulse	290 N-s/liter	302 N-s/liter
Spacecraft ΔV, M(initial) = 4 kg	89 m/s	75 m/s

Additional comments:

[Reference 1,2][Jan 2019][General info]

The CUA Monofilament Vaporization Propulsion (MVP) system is an electrothermal thruster that uses a space-rated plastic as propellant. This approach enables CUA to deliver competitive delta-v to CubeSat customers at a substantially lower cost and dramatically lower risk profile than traditional liquid or gaseous propulsion systems having pressure vessels. In a 1U form factor, MVP provides a total impulse of 540 N-s with a peak continuous thrust of 6.7 mN. MVP is in the late stages of development on a NASA Phase II SBIR program.

MVP draws from 3D printing technology to feed propellant. A preheat is required before firing (~3 minutes), but once warmed the "ready" state is maintained with minimal power draw and thermal loading. When firing, the micro-resistojet uses approximately 30 W. Propellant fiber is mechanically drawn from a fixed spool into the extruder where it evaporates. Lower thrust and power levels are available but at reduced specific impulse. Propellant metering is precise, but evaporation time results in "softer" starts and stops. As a consequence, minimum impulse bit is inherently larger than gaseous propulsion systems with fast-actuating valves, and is still being characterized. This represents the largest trade-off for the reduced system cost, complexity, and risk.

References:

[1] Woodruff, C., Carroll, D., King, D., Burton, R., Hefmanowski, N., "Monofilament Vaporization Propulsion (MVP) – CubeSat propulsion system with inert polymer propellant," SSC18-III-09, SmallSat Conference, 2018.
[2] http://www.cuaerospace.com/technology-products/compact-small-satellite-propulsion-unit-cubesats
[3] Small Sat 2020, public virtual forum
[4] Woodruff, C., Parta, M., King, D., Woodruff, A., Burton, R., Carroll, D., "Monofilament vaporization propulsion (MVP) flight-like system performance," IEPC-2022-575.

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NO

Comm. avail. TRL Aerospace-tested

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Monofilament Vaporization Propulsion (MVP) [2 of 2]
CU Aerospace

Additional comments:

[Reference 1,2][Aug 2020][General info]
They (CU Aerospace) will receive $1.7 million from NASA to build and test a six-unit CubeSat equipped with two different propulsion systems. "DUPLEX will test two of CU Aerospace's thrusters in space to provide flight heritage for these new, innovative systems, significantly lowering risk for future customers while dramatically raising the Technology Readiness Level," says David L. Carroll, CU Aerospace founder and current president. NearSpace Launch will be responsible for the CubeSat bus, power system, radios, and much of the electronics. The delivery of the DUPLEX spacecraft to NanoRacks is anticipated in February 2022 for future launch.
DUPLEX will fly the FPPT and the MVP systems.

[Reference 3][Aug 2022][Qualification status]
CUA has made major strides forward in developing the MVP electrothermal thruster which consumes an inert polymer propellant fiber. This technology retains performance characteristics competitive with other warm gas systems, but enables more accessibility to micropropulsion via dramatically reduced cost and the elimination of range safety concerns (no pressure vessel and an inert propellant). The MVP system draws from extrusion 3D printer technology and CUA's micro-resistojet CHIPS technology. Despite undergoing depolymerization and two separate phase changes, the system power requirements are manageable, demonstrating typical specific thrusts of 0.17 mN/W, and a long-term stable specific impulse of 66 s. Higher specific impulse is achievable [Woodruff, 2018], but at the cost of significantly reduced operational life and total impulse. CUA has now developed a self-contained flight system that can be modified to best meet customer needs. A 0.93U MVP with 280 N-s of total impulse is being integrated for flight on CUA's NASA-funded DUPLEX CubeSat, presently manifested for launch in Q1 2023.

References:
[1] https://aerospace.illinois.edu/news/nasa-funds-long-standing-partners-cubesat-development
[2] Small Sat 2020 Virtual public forum
[3] Woodruff, C., Parta, M., King, D., Woodruff, A., Burton, R., Carroll, D., "Monofilament vaporization propulsion (MVP) flight-like system performance," IEPC-2022-575.

6 | NO

Comm. avail. | TRL | Aerospace-tested

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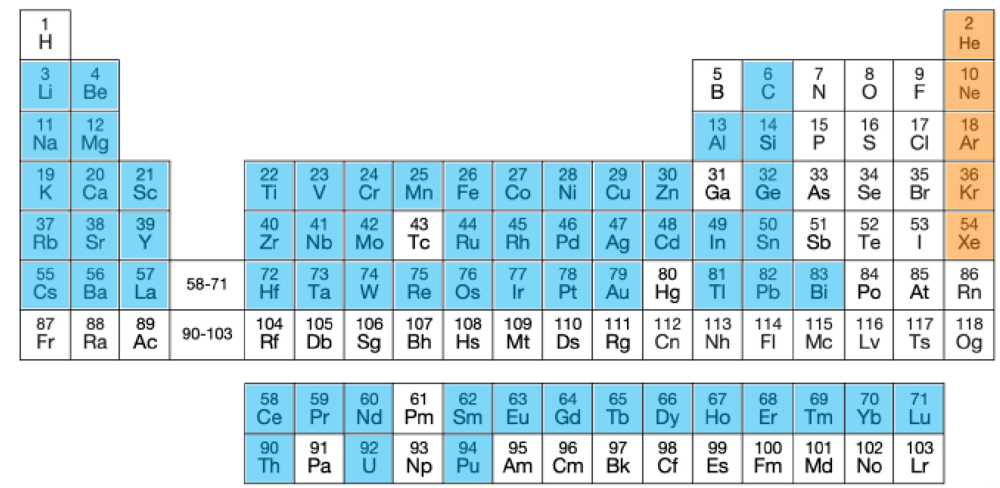
Neumann Drive ND-15 (Gen1) [1 of 2]

Propulsion Technology	Metal PPT
Manufacturer/Country	Neumann Space Australia (AUS)
TRL	6
Size (including PPU)	~1U
Design satellite size	3U+
Isp (s)	Molybdenum ~1800s
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Molybdenum, Aluminum, propellant agnostic to some extent although performance may vary depending on propellant [6]
Power consumption (W)	
Flight heritage (if any)	None First launch scheduled for June 2023 [4] Projected to launch on the SSTL CarbSAR satellite 2024 [5] Projected to launch with Spire Global [7]
Commercially available	Yes
Last updated	12/2023

[3]



[6]

Additional comments:
[References 1-3][April 2023][General information]
Neumann Space is working with partners at CisLunar Industries to demonstrate that debris can be economically recycled on-orbit, turned into propellant for our thrusters, and then used to move debris around – either by putting it into a space disposal orbit where it rapidly and safely falls to an altitude where it can safely burn up during re-entry, or delivering the debris to an orbital recycling centre for further processing.
The Neumann Drive uses our patented Centre-Triggered Pulsed Cathodic Arc Thruster (CTPCAT) technology to convert a solid conductive fuel rod into plasma and produce thrust. The system can use a range of conductive fuels giving unprecedented control over propulsion performance.

References:
[1] https://neumannspace.com/
[2] https://smallsatnews.com/2023/03/14/neumann-drive-propulsion-system-now-integrated-onto-australias-skykraft-satellite-2/
[3] https://smallsatnews.com/2023/03/02/australian-space-companies-achieve-critical-propulsion-technology-commercialization-milestone/
[4] https://smallsatnews.com/2023/06/06/neumann-space-signs-contract-with-space-inventor-to-provide-greater-access-to-space/
[5] https://smallsatnews.com/2023/08/09/sstl-neumann-space-partner-to-test-australian-made-propulsion-system-on-demo-mission/
[6] Neumann, P., Despotellis, S., Astier, H., “Propellant variety and affordability: a strength of pulsed cathodic arc propulsion systems,” Small satellite conference SSC23-P4-02.
[7] https://smallsatnews.com/2023/12/06/australian-government-funding-to-accelerate-neumann-space-space-tech-development-with-spire-global/

Comm. avail.	TRL	Aerospace-tested
	6	NO

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Neumann Drive ND-15 (Gen1) [2 of 2]

Additional comments:

[References 1][June 2023][General information]
Neumann Space has signed a contract with smallsat manufacturer, Space Inventor, that will enable the firm to gain greater access to space as part of their in-orbit demonstration (IOD) program. As part of the contract, Space Inventor will provide Neumann Space with the opportunity to integrate the nexgen Neumann Drive® as an IOD payload on board a 6U EDISON smallsat scheduled for launch in the second half of 2024.
The EDISON Mission is a part of the European Space Agency's Pioneer program, designed to support emerging companies seeking to provide new and innovative satellite communications technologies and services.
The companies will collaborate to test, demonstrate, and verify ease of integration, ease of operation and the performance of the Neumann Drive® whose unique propulsion technology uses solid metallic propellant.

[Reference 2][September 2023][Mission information]
SSTL and Neumann Space will commence work this year to integrate the nexgen Neumann Drive® as an IOD payload on board the SSTL CarbSAR satellite that is scheduled for launch during the second half of 2024. The companies will collaborate over the course of the mission to test, demonstrate and verify the performance of the Neumann Drive® whose unique propulsion technology uses a solid metallic propellant.
The opportunity to be a part of the CarbSAR Demo Mission will provide Neumann Space with the ability to further grow its space heritage and is an active demo of SSTL's commitment to collaborate with the Australian Space industry to stimulate local growth and competitiveness.
The CarbSAR Demo Mission is a partnership between SSTL and Oxford Space Systems to build and launch an OSS Wrapped Rib antenna mounted to an SSTL CarbSAR satellite. This mission is designed to prove a groundbreaking Synthetic Aperture Radar (SAR) concept with implications for near to medium term, UK defence, ISR strategies.

[Reference 3][Dec 2023][Ground testing and characterization]
A representative anode-cathode array was placed in a vacuum chamber, and instruments measured current conducted to ground from the chamber walls, which acted as a Faraday Cup. The results showed that no excess charge leaves the thruster head and returns to building ground, and that the plasma neutralizes to one part in 10,000. This shows that the exhaust of a pulsed cathodic arc thruster is self-neutralizing, and that an exhaust neutralization system is unnecessary.

[Reference 4][Dec 2023][Upcoming flight]
Neumann Space is a founding partner of the Australian Space Manufacturing Network (ASMN) project led by Gilmour Space Technologies and made possible through funding under the Australian Government's Modern Manufacturing Initiative (MMI) Collaboration stream. Neumann Space will use Australian Government funding received under this program to work together with Spire on this mission to rapidly adapt, integrate, launch and verify the performance of the next generation Neumann Drive® on-board one of Spire's proven satellite platforms.

References:

[1] https://smallsatnews.com/2023/06/06/neumann-space-signs-contract-with-space-inventor-to-provide-greater-access-to-space/
[2] https://smallsatnews.com/2023/08/09/sstl-neumann-space-partner-to-test-australian-made-propulsion-system-on-demo-mission/
[3] Neumann, P., Despotellis, S., Scholten, D., Mostert, J., Astier, H., "Verification of exhaust quasineutrality in a pulsed cathodic arc thruster testbed," Small Satellite Conference, poster SSC23-P2-01
[4] https://smallsatnews.com/2023/12/06/australian-government-funding-to-accelerate-neumann-space-space-tech-development-with-spire-global/

🛒	6	NO
Comm. avail.	TRL	Aerospace-tested

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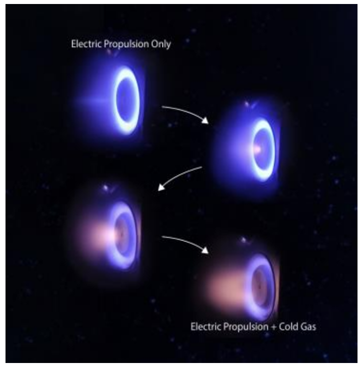
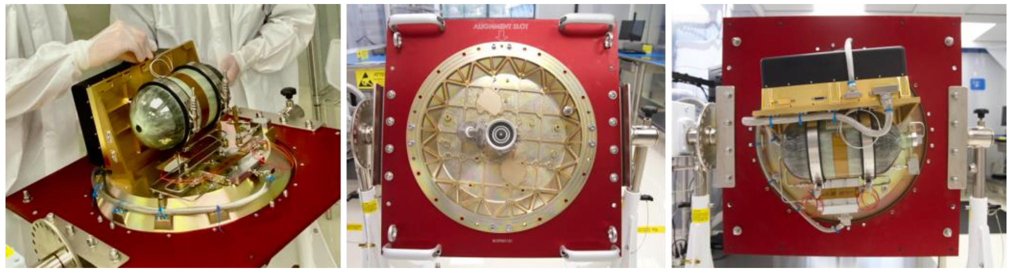
Orbion Aurora [1 of 2]

Propulsion Technology	Hall-effect Thruster (HET) [optional cold gas mode]
Manufacturer/Country	Orbion Space Technology (USA)
TRL	6
Size (including PPU)	Total dry mass for HET, PPU, with propellant management system and harness is 8.3 kg [1]
Design satellite size	>12U (70 to 500 kg) [1]
Isp (s)	918s at 100W discharge power, 1295 at 300W discharge power [1]
Thrust type/magnitude	Throttleable from 5.2 mN at 100 W discharge power to 19.2 mN at 300 W discharge power. 2,000 mN at 7 W in cold-gas mode for agile collision avoidance maneuvers. [1]
Delta-V (m/s)	1,000 m/s for 200 kg s/c [1]
Propellant	Xenon, Krypton [1]
Power consumption (W)	115 to 355 W (throttleable), 28V unregulated [1]
Flight heritage (if any)	None (in-space operations planned for 2024) [2]
Commercially available	YES. PPU available in 3 variants to meet radiation tolerance requirements across multiple orbits. [1] Aurora is optionally available as a complete, bolt-in propulsion subsystem integrated to a customer provided flight structure with COTS tank and service valve [1]
Last updated	12/2023 Revisions with vendor approval

1,000s to be built in certified factory [3]



Cold gas dual mode [4]



Custom Integrated Modules [1]

Discharge Power (W)	m_a (mg/s)	Thrust (mN)	I_{sp} (s)
100	0.52	5.2	918
150	0.67	8.1	1112
200	0.85	10.8	1180
250	1.03	14.0	1261
300	1.37	19.2	1295

[1]

Additional comments on next charts…

	6	NO
Comm. avail.	TRL	Aerospace-tested

Orbion Aurora [2 of 2]

Additional comments:

[Reference 5][Jun 2021][Company info]
WASHINGTON — Orbion Space Technology, a Michigan-based supplier of electric propulsion for small satellites, announced June 24 it has raised $20 million in Series B funding. The new funding is to scale up production of plasma thrusters for small satellites.

[Reference 4][Aug 2021][News]
SAN FRANCISCO — Orbion Space Technology announced a U.S. Air Force contract to develop and demonstrate high-thrust propulsion to help small satellites quickly dodge satellites or space debris. The Phase 2 Small Business Innovation Research contract awarded by the Air Force AFWERX program supports Orbion's work on El Matador, a collision avoidance feature that "allows a spacecraft to elegantly step out of the way and avoid the horns of an incoming threat," said Brad King, Orbion founder and CEO.

[Reference 6][Jun 2022][News]
SAN FRANCISCO — Orbion Space Technology will supply a propulsion system for a U.S. Space Force prototype weather satellite, under a contract with General Atomics Electromagnetic Systems (GA-EMS). In February, the Space Force announced the selection of General Atomics and Orion Space Solutions to each develop and launch demonstration satellites to gather global weather imagery and data on cloud characteristics. The General Atomics satellite will rely on Orbion's Aurora Hall-effect plasma thruster system for orbit raising and orbit maintenance, Orbion executives told SpaceNews. The Aurora system also will propel the 400-kilogram satellite out of orbit at the conclusion of its mission.

[Reference 3][Oct 2022][News]
Orbion Space Technology held a ribbon-cutting ceremony at their AS9100 certified manufacturing facility in Houghton Michigan. Patented special test equipment deployed in this factory brings production capacity up to over 1,000 plasma thrusters per year.

[Reference 1][Nov 2023][Company Info]
The Orbion Aurora is a fully integrated Hall-effect propulsion system, comprised of a magnetically shielded thruster for ultra-long life and high total impulse, power processing unit, propellant management assembly, harness assembly, and storage tank. The spacecraft interface is simple: A 28-volt unregulated power connection and an RS-422 data connection. We can either provide propulsion system components separately so you can locate them as desired within your spacecraft volume, or we can integrate the complete system on an element of the spacecraft structure you provide. Decades of laboratory testing and in-space heritage have proven that Hall-effect thrusters (HETs) possess an unrivaled combination of high thrust, specific impulse, and reliability. The Orbion Aurora is the next step in Hall-effect technology. Aurora was designed from the ground-up to be an affordable, reliable, mass-produced product. We didn't just design a new thruster – instead, we designed an entirely new process.
Orbion can design a custom packaging solution to integrate Aurora with your spacecraft. We can even perform the integration labor and inspections: send us a spacecraft panel and we return it to you with a fully integrated and fueled propulsion system ready to bolt on to your spacecraft.

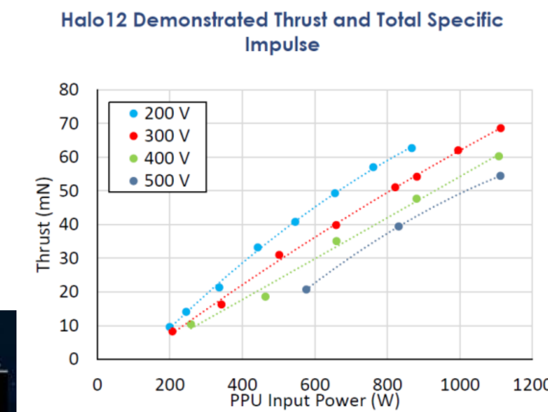
References:

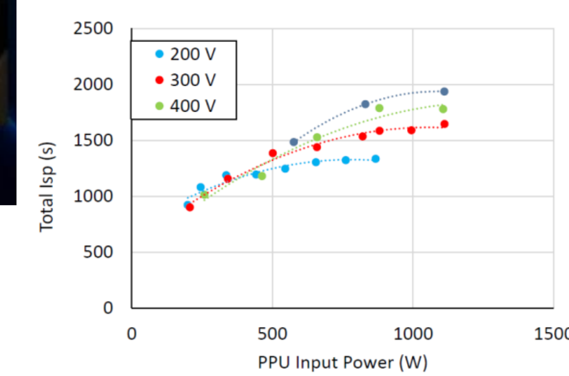
[1] https;//orbionspace.com/product/ [including Aurora System Specification available via download]
[2] Correspondence with Orbion [Greg Orndorff]. Nov 2023 to update this compendium
[3] https://www.linkedin.com/posts/lyon-brad-king-ab3a48126_orbion-space-technology-held-a-ribbon-cutting-activity-6983541009586515970-NKm4/?utm_source=share&utm_medium=member_desktop
[4] https://spacenews.com/orbion-sbir-el-matador/
[5] https://spacenews.com/satellite-propulsion-supplier-orbion-raises-20-million-in-series-b-funding/
[6] https://spacenews.com/orbion-ga-ems-weather-satellite/

Comm. avail.	TRL	Aerospace-tested
	6	NO

Exoterra Halo12

Propulsion Technology	Hall effect thruster
Manufacturer/Country	Exoterra (USA)
TRL	4-5
Size (including PPU)	3.4 kg
Design satellite size	ESPA
Isp (s)	1200-1950s [1]
Thrust type/magnitude	15 to 68 mN [1]
Delta-V (m/s)	
Propellant	Xenon (Krypton is an alternative)
Power consumption (W)	355 to 1110W [1]
Flight heritage (if any)	None
Commercially available	YES
Last updated	12/2023





Additional comments:

[Reference 1][Oct 2021][Thruster information]
Exoterra was founded in 2011.
The Halo12 thruster has completed environmental testing to levels encompassing a wide range of launch vehicles and spacecraft architectures. Life testing is ongoing with a projected lifetime of 28,000 hrs. Halo12 is expected to complete qualification testing in 2021.

[Reference 2][Dec 2023][Ground testing]
Recent progress in the flight qualification of the MaSMi-EM/Halo12 Hall thruster has been summarized. The MaSMi-EM Long Duration Wear Test, which previously achieved 100 kg of xenon propellant throughput, will be extended to further qualify the service life capability of thruster. Ongoing investigations including LIF measurements, magnetic field mapping, and physics-based modeling seek to understand the root cause of asymmetric front pole erosion observed in the wear test thruster, raising the possibility that future units could have even longer life if the issue can be eliminated. Cathode life modeling using the OrCa2D code showed that orifice plate and keeper face erosion are not expected to be important life limiting factors for realistic mission throttle profiles. Heaterless cathode ignitions have been studied both in the wear thruster and in a stand-alone cathode test fixture, demonstrating reliable startups late in the thruster's life. Finally, quantitative reliability analysis was carried out to calculate the thruster's random failure rate in flight, including the contribution from micrometeoroid impacts.

References:
[1] https://exoterracorp.com/products/electric-propulsion-systems/
[2] Chaplin, V., Simmonds, J., Byrne, M., Goebel, D., Loz-Ortega, A., Lobbia, R., Mikellides, I., Hofer, R., Zhu, B., Ratliff, J., Conversano, R., "Extended life qualification of the magnetically shielded miniature (MaSMi) hall thruster," SSC23-VI-01.

6 NO

Comm. avail. TRL Aerospace-tested

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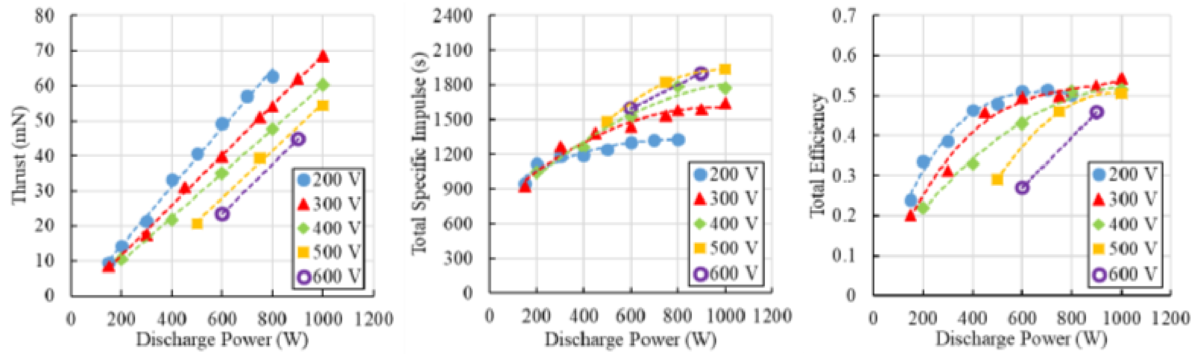
ASTRAEUS Hall thruster [1 of 2]

Propulsion Technology	Hall thruster
Manufacturer/Country	JPL and Exoterra (USA) [5]
TRL	4* [*Thruster only, PPU has lower TRL]
Size (including PPU)	
Design satellite size	100 kg?
Isp (s)	1200 to 2000s [4]
Thrust type/magnitude	10 to 70 mN, throttleable [4]
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	100 to 1000 W
Flight heritage (if any)	None known
Commercially available	Not through JPL. Licensed through Exoterra as Halo12. [5]
Last updated	12/2023

MaSMi-EM SN001 Hall thruster fabricated, assembled, and delivered by Apollo Fusion.

[4]



Additional comments:

[Reference 1-4][Aug 2020][General info]
NASA's Jet Propulsion Laboratory in California is developing the Ascendant Sub-kW Transcelestial Electric Propulsion System, or ASTRAEUS, small satellite HET system for interplanetary missions, targeting a throttle range of 150 to 1,000 watts and 100-kilogram xenon throughput, peak system efficiency greater than or equal to 50%, and dry mass less than or equal to 10 kg for the thruster, PPU, flow controller and gimbal. Apollo Fusion, Inc. has been awarded an exclusive, worldwide commercial license to NASA Jet Propulsion Laboratory's (JPL) MaSMi (Magnetically Shielded Miniature) Hall thruster, the world's first low-power (=1.0 kW) magnetically shielded Hall thruster. MaSMi has demonstrated class-leading performance with a peak total efficiency of 54%, a peak total specific impulse of 1940 s, and an estimated throughput capability of >150 kg Xe. MaSMi is a key component of JPL's ASTRAEUS (Ascendant Sub-kW Transcelestial Electric Propulsion System), a low-power electric propulsion (EP) system optimized for use on smallsats. In support of ASTRAEUS, Apollo was awarded a contract to manufacture three engineering model MaSMi-EM thrusters for JPL this summer. ASTREAUS will carry an ultra-compact heaterless laB6 hollow cathodes and electromagnets, both of which employ designs bespoke to ASTRAEUS, as they represent the highest failure risks for the thruster. Through parallel long-duration wear and ignition tests, the ASTRAEUS cathode demonstrated invariant discharge performance over more than 5000 hrs of operation at its maximum operating current of 4A and demonstrated more than 25,0000 ignition cycles. The ASTRAEUS electromagnets completed their environmental qualification through a demonstration of more than 1200 deep thermal cycles with no indication of coil degradation. ASTRAEUS's prototype power processing units has demonstrated more than 92% total power conversion efficiency and class-leading power density and specific power density of 4.5 Wcm^3 and 1670 W/kg, respectively.

References:
[1] https://aerospaceamerica.aiaa.org/year-in-review/explosive-growth-in-electric-propulsion/
[2] https://www.spacedaily.com/reports/Apollo_Fusion_Inc__Lands_NASA_JPL_License_and_Manufacturing_Contract_999.html
[3] Conversano, R., Barchowsky, A., Vorperian, V., Chaplin, V., Becatti, G., Carr, G., Stell, C., Loveland, J., Goebel, D., "Cathode and electromagnet qualification status and power processing unit development update for the ascendant sub-kW transcelestial electric propulsion system, "Small Sat Conference, SSC20-VI-10.
[4] Conversano, R., Reilly, S., Kerber, T., Brooks, J., Goebel, D., "Development of and acceptance test preparations for the thruster component of the ascendant sub-kW transcelestial electric propulsion systems (ASTRAEUS)," IEPC-2019-283.
[5] Chaplin, V., Simmonds, J., Byrne, M., Goebel, D., Lopez-Ortega, A., Lobbia, R., Mikellides, I., Hofer, R., Zhu, B., Ratliff, Conversano, R., "Extended life qualification of the magnetically shielded miniature (MaSMi) hall thruster," SSC23-VI-01.

NO	6	NO
Comm. avail.	TRL	Aerospace-tested

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ASTRAEUS Hall thruster [2 of 2]

Additional comments:

[Reference 1][Oct 2021][Thruster ground testing]
The thruster component of the Ascendant Sub-kW Transcelestial Electric Propulsion
System successfully completed a propellant throughput demonstration of 72 kg Xe in a longduration wear test planned to eventually exceed 100 kg. The thruster has been operated for a total of 5450 h over three operating conditions: 3287 h at 300 V – 1000 W, 1745 h at 500 V – 1000 W, and 417 h at 400 V – 600 W. A total of 1.2 MN-s of impulse has been demonstrated to date. Thrust, telemetry, and temperature measurements periodically recorded at four operating conditions spanning 200 – 500 V and 200 – 1000 W revealed constant performance across the full test duration. The erosion of the downstream faces of the thruster was observed to be higher than anticipated after the first 5032 h of thruster operation. This issue was traced to the application of sub-nominal magnetic field strengths throughout the LDWT, caused by an electrical-related ground-support equipment issue, which resulted in a downstream shift of the discharge plasma and enhanced erosion of the thruster's pole covers. Nevertheless, the thruster performance and operational behaviour remained unaffected. High-fidelity plasma simulations of the erosion of the thruster's downstream faces, supported by prior short-duration wear testing, suggest a theoretical lifetime capability of >30 kh at both the 500 V – 1000 W and 400 V – 600 W conditions, corresponding to a propellant throughput capability of >310 kg Xe & >260 kg Xe, respectively, and a total impulse capability of >5.9 MN-s and >3.9 MN-s, respectively. The test was voluntarily paused after 68 kg Xe and 72 kg Xe throughput, respectively, to take erosion measurements at the 500 V and 400 V operating conditions.

See entry for Halo12

References:

[1] Conversano, R., Arestie, S., Lobbia, R., Lopez-Ortega, A., Chaplin, V., Reilly, S., Goebel, D., "Long-duration wear testing of the ASTRAEUS Hall thruster, Phases II and III: 72 kg Xe throughput and 1.2 MN-s total impulse," AIAA Propulsion and energy forum, 2021.

NO	6	NO
Comm. avail.	TRL	Aerospace-tested

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MEPSI/Micro-Propulsion System (MiPS)
VACCO

Propulsion Technology	Cold gas
Manufacturer/Country	VACCO
TRL	5-6
Size (including PPU)	0.25U
Design satellite size	1U
Isp (s)	65 s
Thrust type/magnitude	53 mN (nominal, continuous) 23 N*s (impulse, total) 0.53 mN*s (impulse, minimum)
Delta-V (m/s)	34 m/s for 1 kg spacecraft
Propellant	Butane (can use others, nitrogen)
Power consumption (W)	4-6 VDC
Flight heritage (if any)	None known
Commercially available	YES
Last updated	*01/2021*

MEPSI propulsion system by VACCO

Max Operating Pressure	150 psia	Minimum Impulse Bit	0.53 mN-sec
Proof Pressure	225 psia	Operating Voltage	4.0 to 6.0 vdc
Burst Pressure	375 psia	Tank Pressure Sensor Output	0.5 to 3.5 vdc
Thrust	53 mN @ 20ºC	Gas Tank Pressure Sensor Output	0.5 to 3.5 vdc
Internal Leakage	3.6 scc/hr GN2 @ 20ºC	Coil Resistance	5.3 +/- 0.5 Ω coil
External Leakage	1.0×10^{-6} scc/hr GN2 @ 20ºC	Pull-in Voltage	3.5 vdc max @ 20°C
Operating Temperature	0°C to +60°C	Drop Out Voltage	1.0 vdc min @ 20°C
Vibration	16 Grms	Mass	456 grams (dry)
Cycle Life	80,000 cycles		

Additional comments:

[Reference 1-5][Jan 2019][General info]
The MEPSI unit has 5 thrusters, and is a cold-gas thruster designed for 1U CubeSats. Using Chemically Etched Micro System (ChEMS™) technology, VACCO has produced a complete CubeSat propulsion system including propellant storage, pressurization, distribution and thrusters. This simple, highly integrated design uses a self-pressurizing liquid propellant that is expelled as a gas. The manufacturer reports that the system has been tested to 43,000 minimum impulse firings. It has an all-welded titanium construction, and integrated pressure and temperature sensors.

References:

[1] Mueller, J., Hofer, R., Ziemer, J., "Survey of Propulsion Technologies Applicable to CubeSats," JANNAF, Colorado Springs, CO, 2010.
[2] Cardin, J., Coste, K., Williamson, D., Gloyer, P., "A Cold Gas Micro-Propulsion System for CubeSats," 17th Annual AIAA/USU Conference on Small Satellites, 2003.
[3] http://www.cubesat-propulsion.com/vacco-systems/
[4] http://www.cubesat-propulsion.com/wp-content/uploads/2015/10/Mepsi-micro-propulsion-system.pdf
[5] http://space.skyrocket.de/doc_sdat/mepsi.htm

Comm. avail.	5	NO
	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Standard & End-mounted Micro-propulsion System (X14029003) VACCO

Propulsion Technology	Cold gas/warm gas
Manufacturer/Country	VACCO (USA)
TRL	5
Size (including PPU)	0.25U to 1U (various models available)
Design satellite size	1U, 3U
Isp (s)	40s
Thrust type/magnitude	10 mN (continuous, nominal) 33 to 250 N*s (impulse, total – various models) 93 to 312 N*s (impulse, total – tuna-can model) 0.05 mN*s (impulse, minimum)
Delta-V (m/s)	20 (cold gas) to 40 m/s (warm gas) for 5 kg CubeSat
Propellant	R134 or R236FA refrigerant
Power consumption (W)	9 to 12 VDC, <10W (operational), 0.25W (stand-by)
Flight heritage (if any)	A variation of this was flown on MEPSI (2002)
Commercially available	YES
Last updated	*01/2021*

VACCO's standard micropropulsion system (standard, left and tuna-can, right)

Part Number	Size	Depth (mm)	"Wet" Mass (grams)	Total Impulse (N-sec)
X14029003-1	0.3U	30	542	44
X14029003-4	0.5U	50	743	103
X14029003-7	0.8U	80	1044	191
X14029003-9	1U	100	1245	250

Operating Parameters

Nominal Thrust	10 mN @ 20°C	Vibration	16 Grms
Specific Impulse	40 sec	Minimum Impulse Bit	0.05 mN-sec
Total Impulse	44 to 250 N-sec	Operating Voltage	9.0 to 12.6 vdc
Internal Leakage	<1 x 10^3 sccs GHe	Mass (Including Propellant)	542 grams (wet)
External Leakage	<1 x 10^{-6} sccs GHe	Stand-By Power	0.25 watts
Operating Temperature	0°C to +60°C	Maximum Steady-State Power	10 watts

Additional comments:

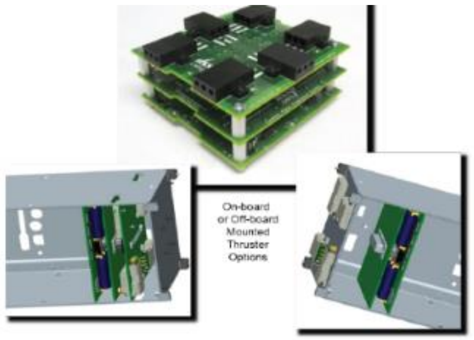
[Reference 1-5][Jan 2019][General thruster info]
This thruster is a cold-gas thrusters with 5 nozzles for pitch, yaw, and roll control. The VACCO Standard Micro-Propulsion System (MiPS) is a low-cost, cold gas propulsion system designed for CubeSats. Using Chemically Etched Micro System (ChEMS™) technology, VACCO has produced a complete propulsion system including propellant storage, pressurization, distribution, thrusters, and controller. This simple, highly integrated design uses a self-pressurizing liquid propellant that is expelled as a gas. The thruster is available either in a standard configuration, or a tuna-can style. The thruster can be adapted to be a warm-gas thruster

References:
[1] http://www.cubesat-propulsion.com/standard-micro-propulsion-system/
[2] http://www.cubesat-propulsion.com/wp-content/uploads/2015/10/standard-micro-propulsion-system.pdf
[3] http://www.cubesat-propulsion.com/end-mounted-standard-mips/
[4] http://www.cubesat-propulsion.com/wp-content/uploads/2015/10/End-mounted-standard-mips.pdf
[5] http://mstl.atl.calpoly.edu/~bklofas/Presentations/DevelopersWorkshop2015/Day_Micro_Propulsion.pdf
[6] https://www.vacco.com/images/uploads/pdfs/MiPS_standard_0714.pdf

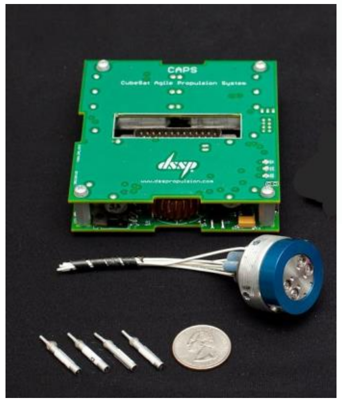
	5	NO
Comm. avail.	TRL	Aerospace-tested

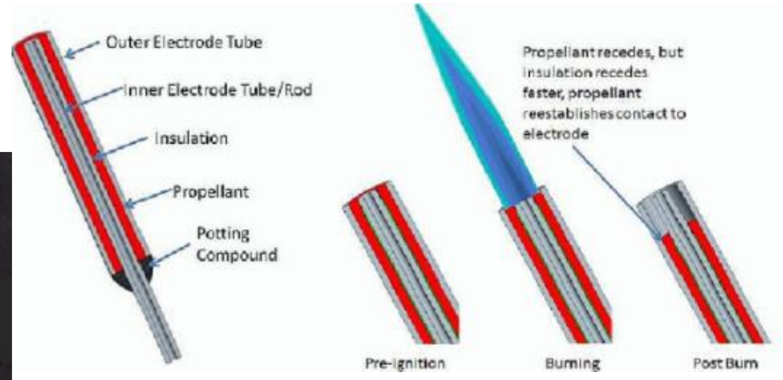
CubeSat Agile Propulsion System (CAPS/CAPS-3)
Digital Solid State Propulsion (DSSP)

Propulsion Technology	Solid rocket motors
Manufacturer/Country	DSSP (US)
TRL	5 Lab tests with ground test data. Flown and commands for thruster firing are reported, but no on-orbit data reported in public literature.
Size (including PPU)	<0.5U
Design satellite size	>1U. SpinSat weighed 57 kg
Isp (s)	Up to 900s
Thrust type/magnitude	~300 mN total (average), Duration 2 ms, 0.21 mN*s (impulse, minimum bit), 0.82 mN*s (impulse, maximum bit), 0.125 N*s (impulse, total)
Delta-V (m/s)	
Propellant	HIPEP-501A
Power consumption (W)	0.1 W (arming), 0.01 W (standby). 5-12 VDC supply.
Flight heritage (if any)	SpinSat, 2014
Commercially available	YES
Last updated	*03/2021*



DSSP CAPS-3 thrusters onboard the SPINSAT, launched by the Naval Research Laboratory





[2]

Additional comments:

[Reference 1-4][Jan 2019][General thruster info]
Thrust variation +/- 10%. Number of pulses per thruster >250. Maximum shot frequency = 0.04 Hz. Temperature limits -30C to 60C. Up to 12 thrusters can be controlled with a single PPU, and can be arrange according to the customer's needs. It as the first propellant safe enough to be taken into the ISS before final deployment. SpinSat's mission was to demonstrate and characterize the on-orbit performance of ESP (Electrically-controlled Solid Propellant) technology in space. However, no on-orbit data could be found in the open literature.
It was launched by the Naval Research Laboratory in partnership with DSSP. A microthruster consists of two coaxial electrodes separated by ~1 mm of ESP. ESPs have the unique property that they are ignited only by the application of electric current. Unlike conventional rocket motor propellants that are difficult to control and extinguish, ESPs can be ignited reliably at precise intervals and durations. Moreover, the technology is attractive because it requires no moving parts and the propellant is insensitive to flames or electrical sparks. The center electrode is a stainless steel rod and the outer electrode is a hollow aluminum case. The total length is 13 mm, which amounts to 0.1 gram of propellant.
In total, 72 thrusters formed the propulsion system of the SPINSAT spacecraft. Six of them were included in each of the twelve plugs strategically located around the bus. Performance characterization is done by firing the thrusters in pairs and measuring the changes in the spin rate by both on-board and on-ground assets

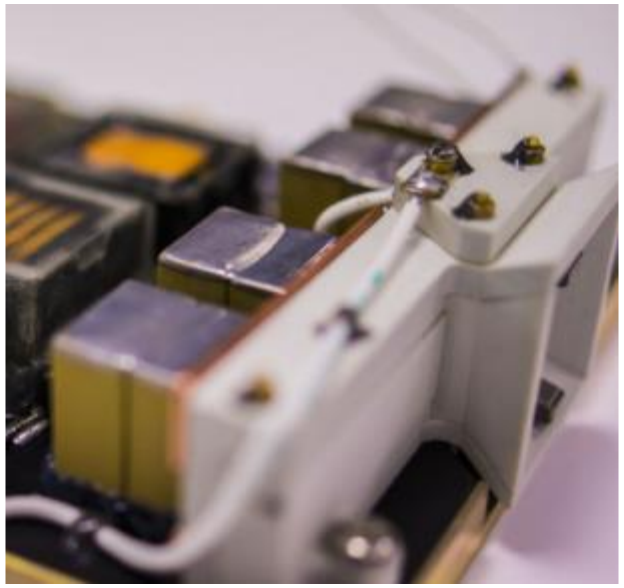
References:
[1] https://static1.squarespace.com/static/59de9c9c18b27ddf3bac610a/t/5a3a9c5d9140b78b7a1768e9/1513790563886/Brochure+Inlet+CAPS+3+Website.pdf
[2] https://www.dsspropulsion.com/propellant-products/
[3] https://directory.eoportal.org/web/eoportal/satellite-missions/s/spinsat
[4] Nicholas, A., Finne, T., Galysh, I., "SpinSat Mission Overview," 27th Annual AIAA Conference on Small Satellites. SSC13-I-3.

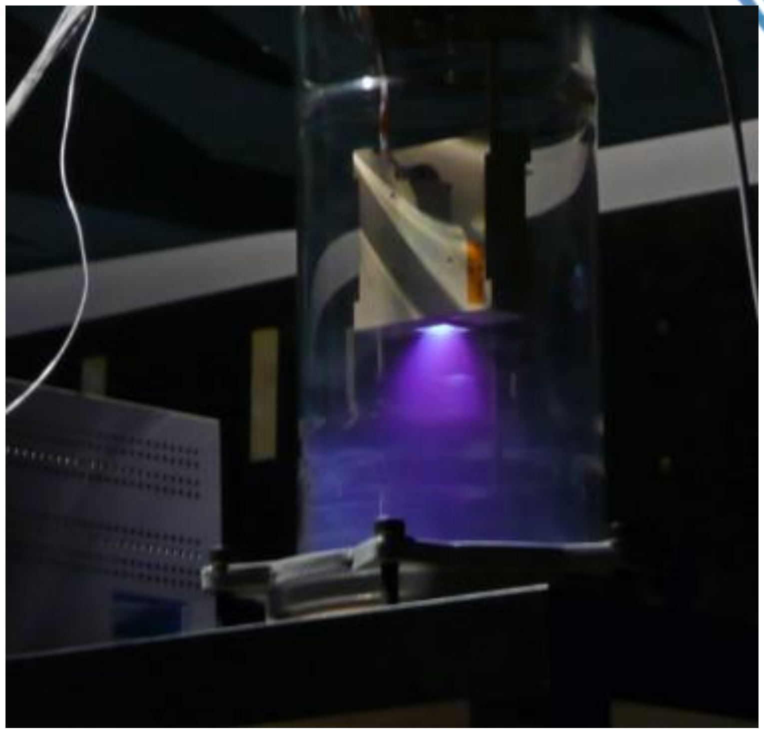
Comm. avail.	5	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

CubeSat Micro-Pulsed Plasma Thruster (CMPPT/PPTCUP)
ClydeSpace/ESA/Mars Space

Propulsion Technology	Pulsed Plasma Thruster (PPT)
Manufacturer/Country	ClydeSpace, ESA, MarsSpace (SCOTLAND)
TRL	5-6
Size (including PPU)	<0.5U (various models available, customizable)
Design satellite size	1U, 3U
Isp (s)	600-700s
Thrust type/magnitude	40 microN, 42 N*s, 63 N*s (impulse, total, two models)
Delta-V (m/s)	11 m/s for a 3U (4 kg)
Propellant	Teflon (PTFE), ~7g
Power consumption (W)	2.7W
Flight heritage (if any)	None known
Commercially available	YES
Last updated	*03/2021*





CubeSat Pulsed Plasma Thruster
Customizable, depending on mission requirements

Additional comments:

[Reference 1-6][Jan 2019][General info]

From manufacturer's website, "Developed in concert with Mars Space and recently flight-qualified under an ESA funded qualification program, our micro pulsed plasma thruster has been developed to support all potential CubeSat applications which require low thrust delta-v capability.
Our simulations suggest that the PPT could maintain altitude of a CubeSat in a 450KM circular orbit approximately 60% longer than without propulsion. Our simulations analysis has shown that the µPPT would perform well as an actuator to support formation flying between 3U CubeSats."
This is a 0.3U thruster unit utilizing solid Teflon propellant. The PPT consists of two main components: the discharge chamber and the high voltage/control electronics. The discharge chamber design consists of the propellant, physical discharge chamber, sparkplug and electrodes. The electronics consists of two converters to generate the required excitation voltages and the control circuitry for the firing process. The unit is designed to interface with standard CubeSat electronics. Several online sources say that the thrusters have undergone testing up to 1M shots in a vacuum chamber simulating real LEO conditions.

In 2015, the unit was quoted as $19K. The price has since been removed from the website. A quote can be obtained by inquiring.
From Ciarelli (2015), at the University of Southampton, thermal cycling, vibration, Electro Magnetic Compatibility (EMC) and lifetime tests were performed. Vibration test results showed that the module sustains the mechanical vibrations during launch and Electro-Magnetic (EM) noise levels during discharge were mostly compliant with guidelines.

As of March 2021, I could no longer find this product online as commercially available.

References:

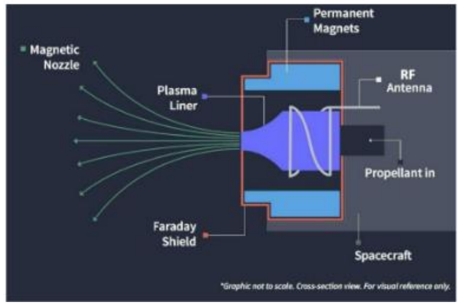
[1] Ciarelli, S., Coletti, M., Gabriel, S., "Results of the qualification test campaign of a pulsed plasma thruster for Cubesat propulsion (PPTCUP)," Acta Astronautica, 2016.
[2] Clark, C., Guarducci, F., Colletti, M., Gabriel, S., "An Off-the-shelf Electric Propulsion System for CubeSats," 25th Annual AIAA/USU Conference on Small Satellites, SSC11-VI-12.
[3] https://www.clyde.space/products/50-cubesat-pulsed-plasma-thruster
[4] http://mstl.atl.calpoly.edu/~bklofas/Presentations/SummerWorkshop2013/Clark_Power_PPT.pdf
[5] https://www.esa.int/spaceinimages/Images/2018/06/CubeSat_micro-pulsed_plasma_thruster
[6] https://mars-space.co.uk/ppt

NO	5	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

RIDER
Phase Four

Propulsion Technology	RF plasma thruster
Manufacturer/Country	Phase Four (USA)
TRL	5-6
Size (including PPU)	1U
Design satellite size	3U and larger
Isp (s)	80 to 470s
Thrust type/magnitude	~0.4 to 2.3 mN (40 to 160W), depending on propellant flow rate. 2300 N*s (impulse, total, max)
Delta-V (m/s)	~500 m/s (calculated, using 4 kg s/c wet weight with 500g propellant and Isp = 500s)
Propellant	Xenon (~500g)
Power consumption (W)	40 to 160 W (2 W for standby)
Flight heritage (if any)	None
Commercially available	YES
Last updated	*02/2022*



Schematic of the inside of the thruster


Photo of the thruster firing inside Phase Four's chamber.

Additional comments:

[Reference 1-4][Jan 2019][General info]

The Phase Four RFT is an electrodeless RF propulsion engine that scales from the mass, volume and power budget of Cube Satellites up to larger satellite applications. Figure 1 shows a diagram of the core components of The RFT and Figure 2 shows an image of The RFT-2 unit firing in the Phase Four laboratory. Propellant (nominally xenon gas) is injected into a “plasma liner” at a fixed mass flow rate, which is wrapped in an RF antenna with a proprietary geometry. The liner-antenna assembly is housed inside a series of permanent magnets that generate a fixed magnetic field inside the liner and out of the liner's exit orifice. A high frequency radio signal is applied to the antenna and the “near field” radiation under the antenna inside the liner ignites the gas into a plasma, and subsequently heats the plasma propellant. The hot xenon plasma then expands rapidly in all directions inside the liner. Similar to how a chemical rocket engine nozzle directs the hot propellant, the magnetic field inside the liner and in the near-region of the liner exit is designed to direct the hot plasma out of the exit orifice, generating thrust.

The baseline RFT system includes a thruster, power processing unit, propellant storage and management unit, and engine controller. It uses radio frequency waves to efficiently ionize and heat xenon plasma. Magnetic fields then direct the plasma out of the engine nozzle, producing thrust. The P4 Radio Frequency Thruster (RFT) is a new system designed for small satellites while being scalable to large satellite and even launch vehicle applications. The RFT was inspired by technology developed at The University of Michigan and licensed exclusively to Phase Four for commercialization.

Phase Four says they have a flight planned for 2018. As of June, no information can be found yet on a flight.

They have also reported that NASA has purchased one of their thrusters (to be delivered in 2019).

[Reference 5][Feb 2022][General info]

P4 has informed us that Rider is no longer available.

References:

[1] Siddiqui, M., “Updated Performance Measurements of the Phase Four RF Thruster,” 34th Space Symposium, 2018.
[2] Siddiqui, M., Cretel, C., Synowiec, J., Hsu, A., Young, J., Spektor, R., “First Performance Measurements of the Phase Four RF Thruster,” IEPC-2017-431.
[3] http://phasefour.io/wp-content/uploads/2017/06/SPEC.pdf
[4] https://www.prnewswire.com/news-releases/phase-four-signs-contract-with-nasa-to-vet-its-propulsion-system-for-upcoming-small-satellite-missions-300654094.html
[5] Email correspondence with Umair, Jan 2022, public information

5

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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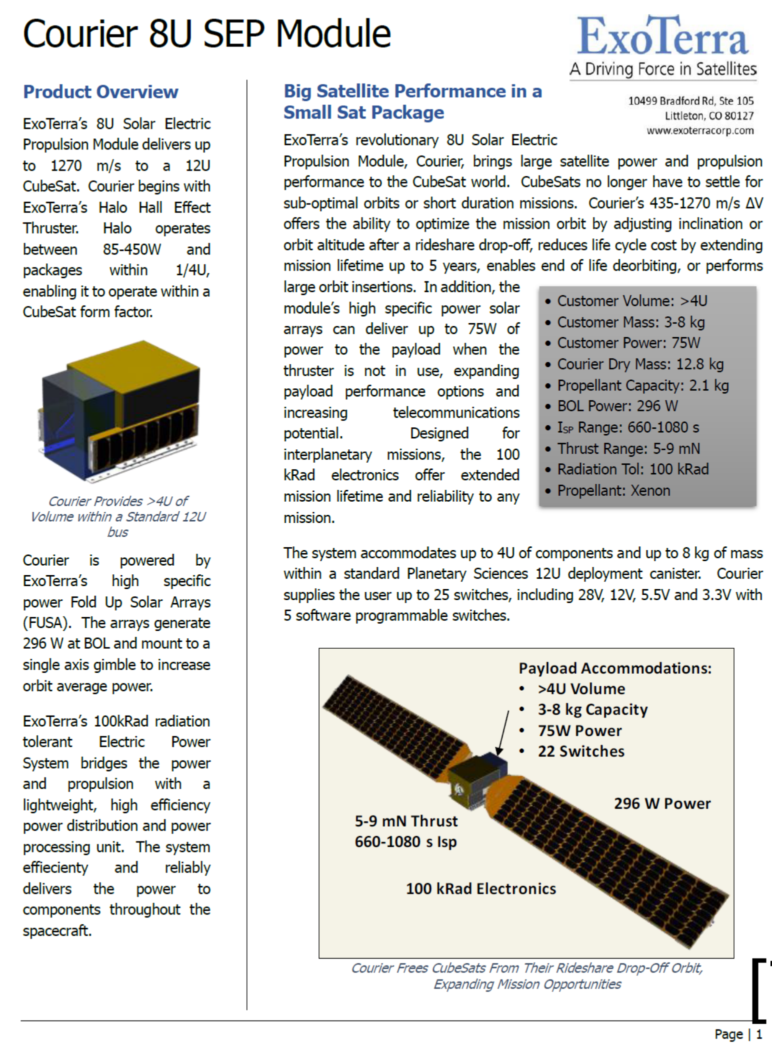
Halo Hall effect thruster/Courier Solar Electric Propulsion – SEP – Module ExoTerra [1 of 3]

Propulsion Technology	Hall Effect Thruster
Manufacturer/Country	Exo-Terra/ExoTerra/Exoterra (USA)
TRL	5
Size (including PPU)	<1/4U, <0.65 kg, total system is 4-9U [6] Courier SEP is ~12 kg dry mass [7]
Design satellite size	6U or larger Courier SEP is designed for 12U spacecraft [7]
Isp (s)	Halo delivers 700 to 1500s [6] Courier SEP delivers 660-1080s [7]
Thrust type/magnitude	4 to 34 mN, 48-100 kN*s (total impulse) [6] Courier SEP delivers 5-9 mN [7]
Delta-V (m/s)	
Propellant	Xenon, Krypton
Power consumption (W)	75W to 400W
Flight heritage (if any)	None Courier projected to fly on NASA Tipping point program (delayed, was 2019)
Commercially available	YES, ~$200K each
Last updated	*03/2021*


Courier 8U SEP Module

ExoTerra
A Driving Force in Satellites

10499 Bradford Rd, Ste 105
Littleton, CO 80127
www.exoterracorp.com

Product Overview

ExoTerra's 8U Solar Electric Propulsion Module delivers up to 1270 m/s to a 12U CubeSat. Courier begins with ExoTerra's Halo Hall Effect Thruster. Halo operates between 85-450W and packages within 1/4U, enabling it to operate within a CubeSat form factor.

Courier Provides >4U of Volume within a Standard 12U bus

Courier is powered by ExoTerra's high specific power Fold Up Solar Arrays (FUSA). The arrays generate 296 W at BOL and mount to a single axis gimble to increase orbit average power.

ExoTerra's 100kRad radiation tolerant Electric Power System bridges the power and propulsion with a lightweight, high efficiency power distribution and power processing unit. The system effieciency and reliably delivers the power to components throughout the spacecraft.

Big Satellite Performance in a Small Sat Package

ExoTerra's revolutionary 8U Solar Electric Propulsion Module, Courier, brings large satellite power and propulsion performance to the CubeSat world. CubeSats no longer have to settle for sub-optimal orbits or short duration missions. Courier's 435-1270 m/s ΔV offers the ability to optimize the mission orbit by adjusting inclination or orbit altitude after a rideshare drop-off, reduces life cycle cost by extending mission lifetime up to 5 years, enables end of life deorbiting, or performs large orbit insertions. In addition, the module's high specific power solar arrays can deliver up to 75W of power to the payload when the thruster is not in use, expanding payload performance options and increasing telecommunications potential. Designed for interplanetary missions, the 100 kRad electronics offer extended mission lifetime and reliability to any mission.

- Customer Volume: >4U
- Customer Mass: 3-8 kg
- Customer Power: 75W
- Courier Dry Mass: 12.8 kg
- Propellant Capacity: 2.1 kg
- BOL Power: 296 W
- I_{SP} Range: 660-1080 s
- Thrust Range: 5-9 mN
- Radiation Tol: 100 kRad
- Propellant: Xenon

The system accommodates up to 4U of components and up to 8 kg of mass within a standard Planetary Sciences 12U deployment canister. Courier supplies the user up to 25 switches, including 28V, 12V, 5.5V and 3.3V with 5 software programmable switches.

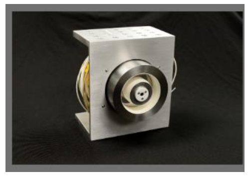
Payload Accommodations:
- >4U Volume
- 3-8 kg Capacity
- 75W Power
- 22 Switches

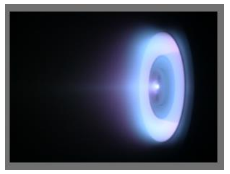
296 W Power
5-9 mN Thrust
660-1080 s Isp
100 kRad Electronics

Courier Frees CubeSats From Their Rideshare Drop-Off Orbit, Expanding Mission Opportunities

Page | 1

[7]





Additional comments:

[Reference 1-5][Jan 2019][General info]

ExoTerra was formed in 2011 and has 16 engineers. They offer engineering and consulting services in structural, mechanical, systems design/analysis, thermal protection/analysis, and electrical engineering. They build components, subsystems, and fully-integrated buses for CubeSats and small satellites.

ExoTerra and the Space Science Institute were selected by NASA to study the use of a CubeSat to observe Dust Storms on Mars. The award is part of NASA's Deep Space Small Satellite program to investigate the use of small satellites in space exploration to reduce mission cost. The mission uses ExoTerra's Solar Electric Propulsion system to place the CubeSat in an Aerostationary orbit above the planet for the first time. From this vantage, the vehicle can continuously monitor the formation and decay of dust storms throughout a Martian year. ExoTerra will perform the satellite design for the mission.

Also, ExoTerra is chosen to fly to an asteroid with their 300W system, also under NASA funding. ExoTerra will flight test a 300-watt solar electric propulsion system that uses iodine in place of xenon gas. Iodine can be launched as an inert solid and then vaporized into an ionized gas once in orbit, which removes the risk to the launch vehicle. Launching as a dense solid instead of a gas also increases the amount of propellant that can be stored in the same volume on the spacecraft. ExoTerra's demonstration mission will attempt a flyby of a near-Earth asteroid with an instrumentation payload provided by Deep Space Industries of Moffett Field, California.

References:

[1] Moses, J., Pierce, D., Seablom, M., Petro, A., "An Overview of the NASA/Science Mission Directorate CubeSat Activities," SSC16-XI-01, SmallSat Conference, 2016.
[2] https://exoterracorp.com/?p=114
[3] http://projects-web.engr.colostate.edu/ionstand/research/research.php
[4] https://www.nasa.gov/press-release/nasa-establishes-new-public-private-partnerships-to-advance-us-commercial-space
[5] http://www.spacedaily.com/reports/ExoTerra_to_become_first_privately_owned_space_company_to_fly_to_an_asteroid_999.html
[6] VanWoerkom, M., Gorokhovsky, V., Pulido, G., Pettigrew, R., Seidcheck, A., Williams, J., Farnell, C., "Performance of ExoTerra's Halo micro electric propulsion system for microsatellites," AIAA Propulsion and Energy Forum, 2019.
[7] https://exoterracorp.com/wp-content/uploads/2019/05/ExoTerra-Data-Sheet-8U-SEP-Module-REV-1.pdf

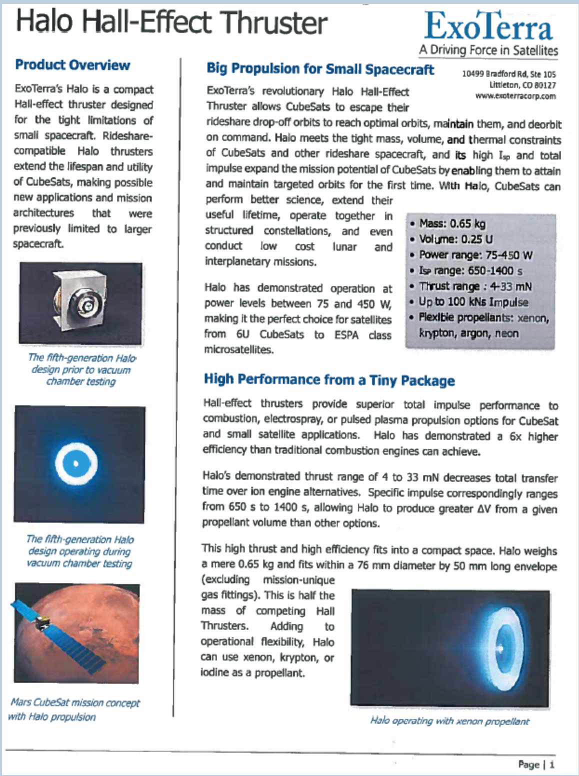
DISTRO A: Approved for public release. OTR-2024-00338

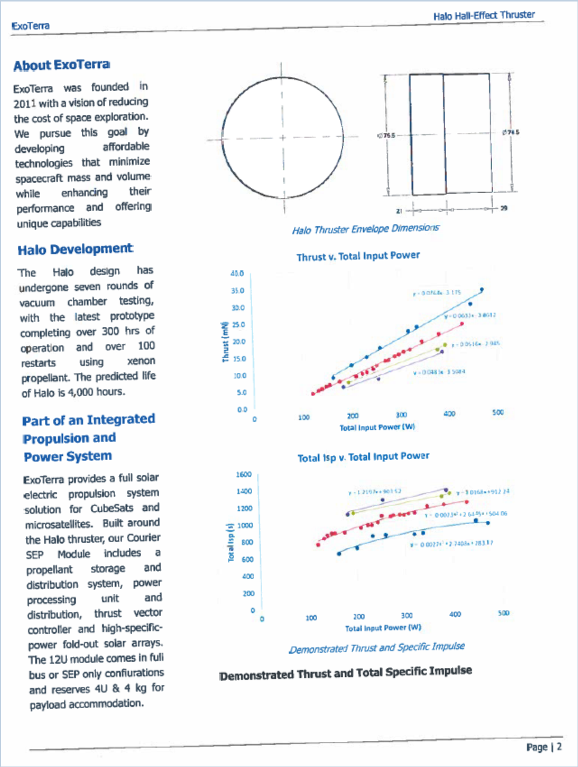
Comm. avail.	TRL	Aerospace-tested
	5	NO

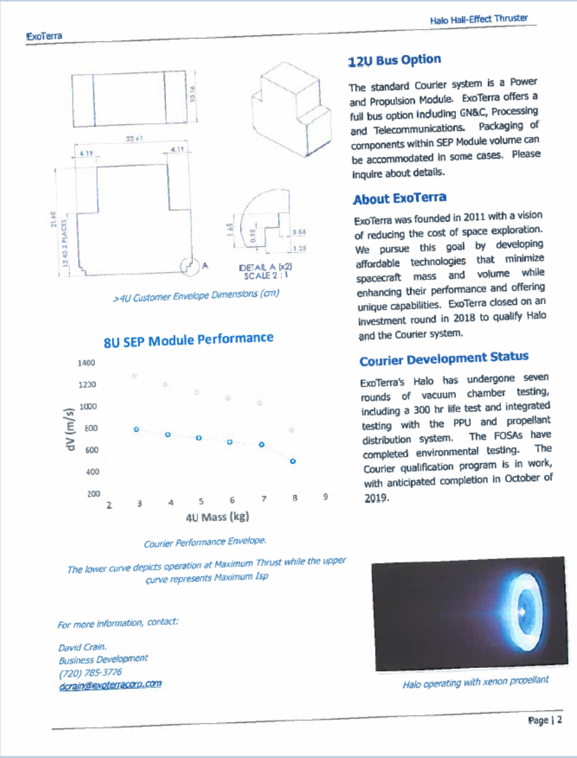
Halo Hall effect thruster/Courier Solar Electric Propulsion – SEP – Module ExoTerra [2 of 3]

Additional comments:

[Reference 1][Aug 2019][Company and thruster updates]
Their Hall thruster are now commercially available and priced at ~$200K. They are roughly 2U in size and run from 75W to several hundred W. They were previously using iodine but have now moved to exclusively xenon. They have approximately 20 employees in Colorado. Many of them work as part-time consultants in the EP field.







References:
[1[Public conversations at Small Sat 2019, publicly distributed fliers.

Comm. avail. | 5 TRL | NO Aerospace-tested

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Halo Hall effect thruster/Courier Solar Electric Propulsion – SEP – Module ExoTerra [3 of 3]

Additional comments:

[Reference 1][June 2020][Thruster testing]
Three separate rounds of testing have been performed over the last 18 months, using steadily improved thrusters: Performance Testing, Life Testing, and Integrated Testing. Performance testing occurred in 2017 and focused on exploring its operating envelope using the Halo-C iteration. Initial Life testing with Halo-D was performed in June of 2018 and focused on understanding the erosion rates to project lifetime. Integrated testing using Halo-E concluded in January 2019 and focused on demonstrating operation with the full PPU and representative propellant distribution system.

[Reference 2][June 2020][Thruster testing]
ExoTerra's Modular Micro Electric Propulsion (μ-EP) system enables more ambitious NASA, DoD and commercial CubeSats applications with a high-impulse, radiation tolerant propulsion option. The μ-EP system packages into 6-9U depending on specific mission requirements. ExoTerra's magnetically shielded Halo Micro Hall-Effect Thruster operates between 85-450 W and generates between 4-33 mN of thrust at an Isp ranging from 700-1500 s. The thruster itself occupies less than 1/4U of volume and weighs <.65 kg, providing a significantly smaller option for its power class. Depending on tank size and operating point, we deliver over 100 kNs of impulse. The accompanying propellant storage and distribution system uses a Composite Overwrap Pressure Vessel (COPV) to minimize distribution system volume and mass. Powering the system is ExoTerra's high-efficiency power processing unit (PPU), with a demonstrated 96-98% efficiency, mass under 0.45 kg, and 100 krad radiation tolerance to survive transit through the Van Allen belts. ExoTerra recently concluded several rounds of testing of its Micro Electric Propulsion system for CubeSats, including performance testing of the thruster operating envelope, initial life testing, integrated system testing, and is currently undergoing qualification testing. The performance testing demonstrated an operating range between 85-450 W and 150-500 V with up to 40% efficiency, providing operating capabilities for low power CubeSats up to microsat scale satellites. The initial life testing operated for 300 hrs. The resulting data provided evidence of magnetic shielding at the operating point and projected a lifetime of >2000 hrs, resulting in total impulses up to 100 kNs. The integrated testing successfully demonstrated the ability of the PPU, propellant distribution system and thruster to work in concert and provided data on overall system efficiency, with demonstrated PPU efficiencies of up to 98%. Qualification testing is currently in work. Results from the qualification unit's functional testing show thrust measurements in line with prior testing and significant improvements to Isp and total efficiency.

[Reference 3, 4][June 2020][Flight info]
In January 2020, ExoTerra was awarded a NASA Tipping Point- Topic 3: Efficient and affordable propulsion systems. This proposal was to develop a modular, fully integrated, miniature Hall thruster system primarily designed for 12U CubeSats for "Courier".

The "Courier" 8U SEP Module delivers up to 1270 m/s to a 12U CubeSat. Courier begins with ExoTerra's Halo Hall Effect Thruster. The system accommodates up to 4U of components and up to 8 kg of mass within a standard Planetary Sciences 12U deployment canister.

References:
[1] VanWoerkom, M., Gorokhovsky, V., Pulido, G., Pettigrew, R., Seidcheck, A., Williams, J., Farnell, C., "Performance of ExoTerra's Halo micro electric propulsion system for microsatellites," AIAA Propulsion and Energy Forum, 2019.
[2] VanWoerkom, M., Gorokhovsky, V., Pulido, G., Pettigrew, R., and Seidcheck, A., "Test Results of ExoTerra's Halo Micro Electric Propulsion System," 36th IEPC, Vienna, Austria, 2019.
[3] https://govtribe.com/vendors/exoterra-resource-llc-exoterra-6bae9
[4] https://exoterracorp.com/wp-content/uploads/2019/05/ExoTerra-Data-Sheet-8U-SEP-Module-REV-1.pdf

Comm. avail.	TRL	Aerospace-tested
	5	NO

DISTRO A: Approved for public release. OTR-2024-00338

CDM-1
Digital Solid State Propulsion (DSSP)

Propulsion Technology	Solid rocket motor
Manufacturer/Country	DSSP (US)
TRL	5-6
Size (including PPU)	~1U
Design satellite size	4kg (3U)
Isp (s)	235
Thrust type/magnitude	226 N*s (impulse, total) 76.5 N (average over burn time) 190 N (thrust, maximum)
Delta-V (m/s)	50 m/s for a 4 kg
Propellant	AP/HTPB
Power consumption (W)	<5W
Flight heritage (if any)	None
Commercially available	YES
Last updated	*03/2021*

MOTOR DIMENSIONS
Motor diameter, cm....................................6.40
Motor length, cm.......................................4.70

MOTOR PERFORMANCE (STP)
Burn time/action time, sec..............................2.98
Ignition Delay time, sec..................................10.8
Total impulse, N-sec......................................226.4
Effective vacuum specific impulse, sec..............235
Burn time average thrust, N.............................76.5
Maximum thrust, N...186.8

MOTOR WEIGHT, grams
Total loaded..459.5

IGNITION SETTINGS,
Peak Current Draw ,A.....................................1.0
Power Supply Required, VDC...........................5

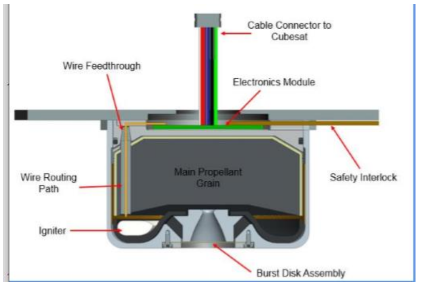
TEMPERATURE LIMITS
Operation...-13° to 50°C
On Orbit Survival...............................-24° to 61.5°C

PROPELLANT TYPE..........................AP/HTPB

PRODUCTION STATUS..........Qualified for Flight

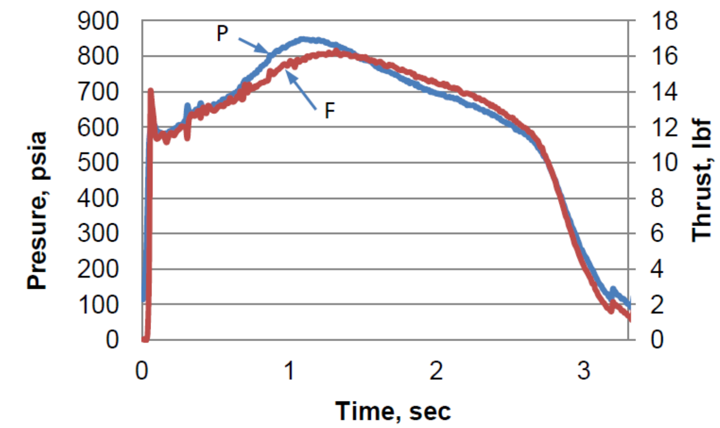
SHIPPING CLASSIFICATION....... DOT Class 1.4C


One of the CDM-1 units firing in the vacuum chamber



Section view of the CDM-1 motor


DSSP's CDM-1 solid rocket motor



Additional comments:

[References 1-3][Dec 2019][General info]
Digital Solid State Propulsion (DSSP) was given the challenge of developing a propulsion unit that can deliver >47.5 m/s of delta-V to a 3U CubeSat, but limited to 5W from a 5V bus and to the "tuna can" of the 3U+ configuration without intruding into the interior volume of the spacecraft. The design that followed was an AP/HTPB fueled solid rocket motor in an end-burning configuration with a NaClO3 igniter that requires 5W from a 5V bus to ignite. The unit mounts to the aft end of a 3U CubeSat structure using 4X Pumpkin Solar Panel clips.

Ideal for a single delta-v maneuver or a rapid de-orbit. The adapter plate is designed for easy mounting of the motor to any standard CubeSat (or small-sat) structure. The motor diameter is 6.4 cm, and the length is 4.7 cm, and weights close to 500 g when loaded with propellant. Temperature limits are -25C to 60C. Burn times are about 3 seconds, with an ignition delay of 11 seconds. The ignitor is NaClO3, and requires 5W from a 5V bus to ignite.
The motors have been tested in the laboratory, including thermal cycling and performance (thrust measurements). However, they have not flown on any missions.

References:
[1] https://static1.squarespace.com/static/59de9c9c18b27ddf3bac610a/t/5a3aa16053450a5b8b608431/1513791844223/Brochure+Inlet+CDM+1+Website.pdf
[2] https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=3261&context=smallsat
[3] https://www.dsspropulsion.com/

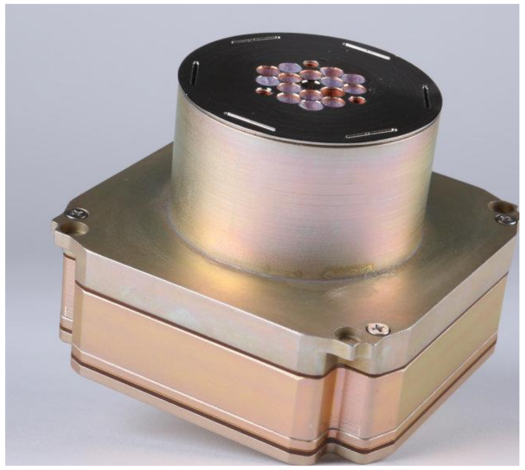
	5	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

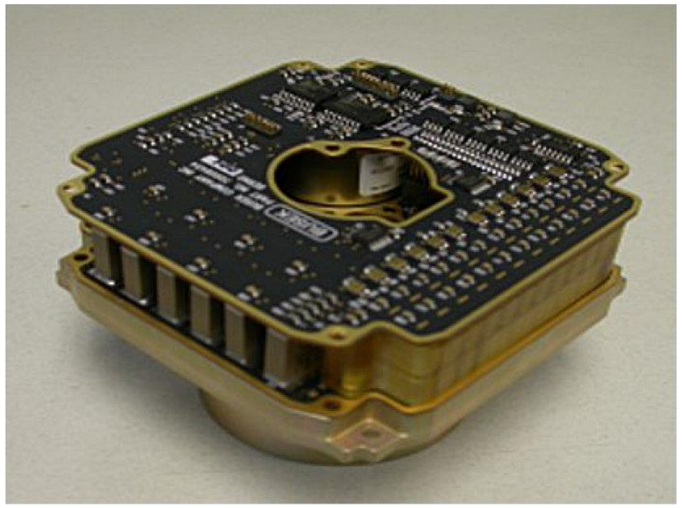
DISTRO A: Approved for public release. OTR-2024-00338

Basic micro-Pulsed Plasma Thruster, BmP-220
Busek

Propulsion Technology	Pulsed Plasma Thruster
Manufacturer/Country	Busek (USA)
TRL	5 (estimated). Some components have flight heritage
Size (including PPU)	10cm x 10cm x 7cm, <500 g [2]
Design satellite size	
Isp (s)	536 s
Thrust type/magnitude	220 N*s (impulse, total) 0.02 mN*s (impulse, minimum) 20 uN (continuous, nominal) [1]
Delta-V (m/s)	
Propellant	Teflon (PTFE), 40g
Power consumption (W)	7.5W (7 Hz), 1.5W (1 Hz)
Flight heritage (if any)	None known. However, some components have flown (Busek's PPT technology successfully flew on FalconSat-3, 2007)
Commercially available	YES
Last updated	*03/2021*



Busek's Micro Pulsed Plasma Thruster



Integrated PPU

Additional comments:

[Reference 1-3][Jan 2019][General info]

The basic micro-pulsed plasma thruster configuration was created and patented by the AFRL in response to the Air Force's need for efficient, low-mass propulsive ACS for small spacecraft. The hardware and design were transitioned to Busek for advanced engineering and flight hardware development under the IHPRPT program, a collaboration of Air Force, NASA and industry. The resulting three-axis MPACS (Micro-Propulsion Attitude Control System) was built, tested and delivered for launch in 2007. Four of these units have successfully flown on the USAFA FalconSat-3 satellite. The BMP-220 is based on the MPACS and is a rugged, precision propulsion technology that has continued development and miniaturization at Busek Co, Inc.

References:

[1] Krejci, D., Lozano, P., "Space Propulsion Technology for Small Spacecraft," Proceedings of the IEEE, 2018.
[2] http://www.busek.com/technologies__ppt.htm
[3] http://www.busek.com/flightprograms__fs3.htm

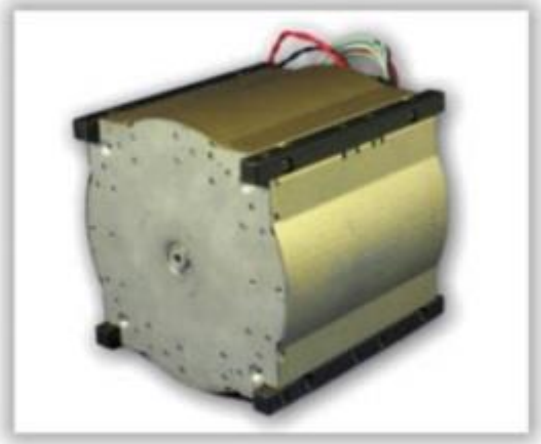
Comm. avail.	TRL	Aerospace-tested
	5	NO

DISTRO A: Approved for public release. OTR-2024-00338

Ammonia Micro-Resistojet
Busek

Propulsion Technology	Electrothermal Micro-Resistojet
Manufacturer/Country	Busek (USA)
TRL	5 Some components have flown and have higher TRLs.
Size (including PPU)	1U
Design satellite size	3U and larger
Isp (s)	150s primary, 80s for each of the 8 ACS units; Total Impulse = 790s
Thrust type/magnitude	14 mN max (10 mN along primary axis and 0.5 mN from each of the 8 ACS thrusters) 400 N*s (impulse, total, primary) 23N*s (impulse, total, ACS)
Delta-V (m/s)	60 m/s for 4 kg CubeSat
Propellant	Ammonia, R-134A, or R-236fa refrigerants
Power consumption (W)	3 to 15 W
Flight heritage (if any)	None known
Commercially available	Yes
Last updated	*03/2021*

Electrical	
System Power	3 - 15 W
Input Voltage	+5 VDC
Mechanical	
System Mass	< 1.25 kg
System Volume	< 1.0 U
System Dimensions	< 9 cm x 9 cm x 10 cm
Performance	
Total Impulse:	404 N-s, primary 23 N-s, ACS
Nominal Thrust:	2-10 mN, primary 0.5 mN, ACS
Nominal ISP:	150 s, primary 80 s, ACS
Delta-V	60 m/s (assuming 4 kg CubeSat), primary 6 m/s, ACS
TRL	5



Additional comments:

[Reference 1][March 2021][General info]
Through an AFRL-Kirtland sponsored SBIT, Busek has developed an integrated primary and attitude control propulsion system. The Busek Micro-Resistojet (MRJ) leverages flight and SBIR design efforts for miniature low power valves and power management electronics. The 9 cm x 9 cm x 10 cm system is capable of throttling performance based on available power, ranging from 3 to 15W, delivering up to 10 mN along the primary axis and 0.5 mN from each of the eight ACS thrusters. Specific impulse is 150 seconds for the primary thruster, and 80 seconds for each ACS thruster. The MRJ features safe, non-toxic propellant and lifetime is constrained only by propellant storage.

References:
[1] http://www.busek.com/technologies__therm.htm

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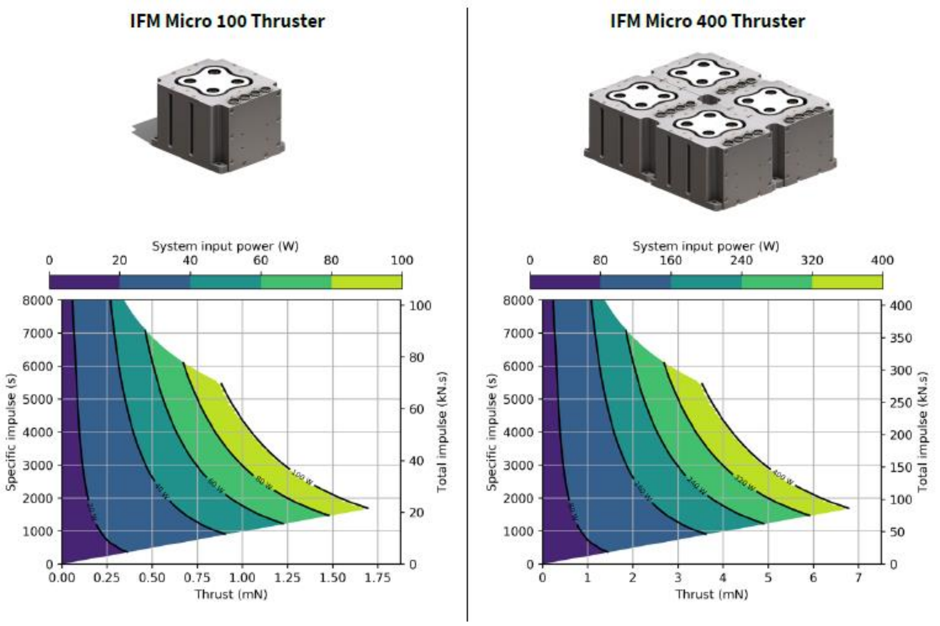
NO

Comm. avail. TRL Aerospace-tested

Micro R^3 (previously named IFM Micro Thruster modular units/ IFM Micro 100/200/400/600) Enpulsion [1 of 3]

Propulsion Technology	Field Emission Electric Propulsion (FEEP)
Manufacturer/Country	FOTEC/ENPULSION (AUSTRIA), ENPULSION Inc. (US)
TRL	5-6 (estimated)
Size (including PPU)	Each Micro 100 unit is ~1.5U Each Micro 100 unit weighs 1.7 (dry) 3 kg (wet)
Design satellite size	3U and larger
Isp (s)	1500 to 6000 s
Thrust type/magnitude	1 mN (continuous, nominal) [1] 75 uN to 1.5 mN (dynamic range, nominal) [1] >50 kN*s (at 4000s Isp, impulse, total)
Delta-V (m/s)	
Propellant	Indium
Power consumption (W)	20-100W (operational), 5-10W (standby) [1]
Flight heritage (if any)	None at this time, based on heritage IFM Nano technology which has flown. Launched on OHB Sweden GMS-T Satellite (launched in 2021) [3]
Commercially available	Yes. Website gives price starting at $95K. As of March 2021, pricing information is no longer shown on website [1] Now available as a stock item on SmallSat Catalog by Orbital Transports [2]
Last updated	*03/2023*



IFM Micro-thruster, for small and medium-sized spacecrafts. [1]

Additional comments:

[Reference 1][July 2019][General company info]

For 15 years, FOTEC has followed a technology push from ESA developing a FEEP propulsion technology for a very niche market of scientific satellites in formation flight. ENPULSION was founded in 2016 as a FOTEC spin-out to scale the production of this thruster to several hundred units per year. The IFM Nano Thruster is a mature technology, developed under ESA contracts for 15 years. In this time more than 100 emitters have been tested and an ongoing lifetime test has demonstrated more than 18,000 h of firing without degradation of the emitter performance. The technology is scalable, and multiple IFM units can be clustered for a variety of mission needs.

This thruster is based on the IFM Nano Thruster design (see corresponding charts in this survey) and is a scaled version of the technology to target small and medium sized spacecrafts. The IFM Micro 100 Thruster is engineered in a modularity approach, with units clustering easily together to form building blocks that can be arranged for various mission profiles. You can thus combine four IFM Micro 100 thrusters for an IFM Micro 400. Radiation tolerant options for the power processing unit are available for different mission applications and reliability levels. In the IFM Micro 400 thruster, the four segments of the thruster can be controlled individually and provide a significant capability to vary the effective thrust footprint.

References:

[1] https://www.enpulsion.com/
[2] https://smallsatnews.com/2021/05/18/smallsat-thruster-modules-from-enpulsion-now-in-orbital-transports-smallsat-catalog/
[3] https://www.enpulsion.com/news/ohb-sweden-selected-electric-propulsion-by-enpulsion-for-their-eis-mission/

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NO

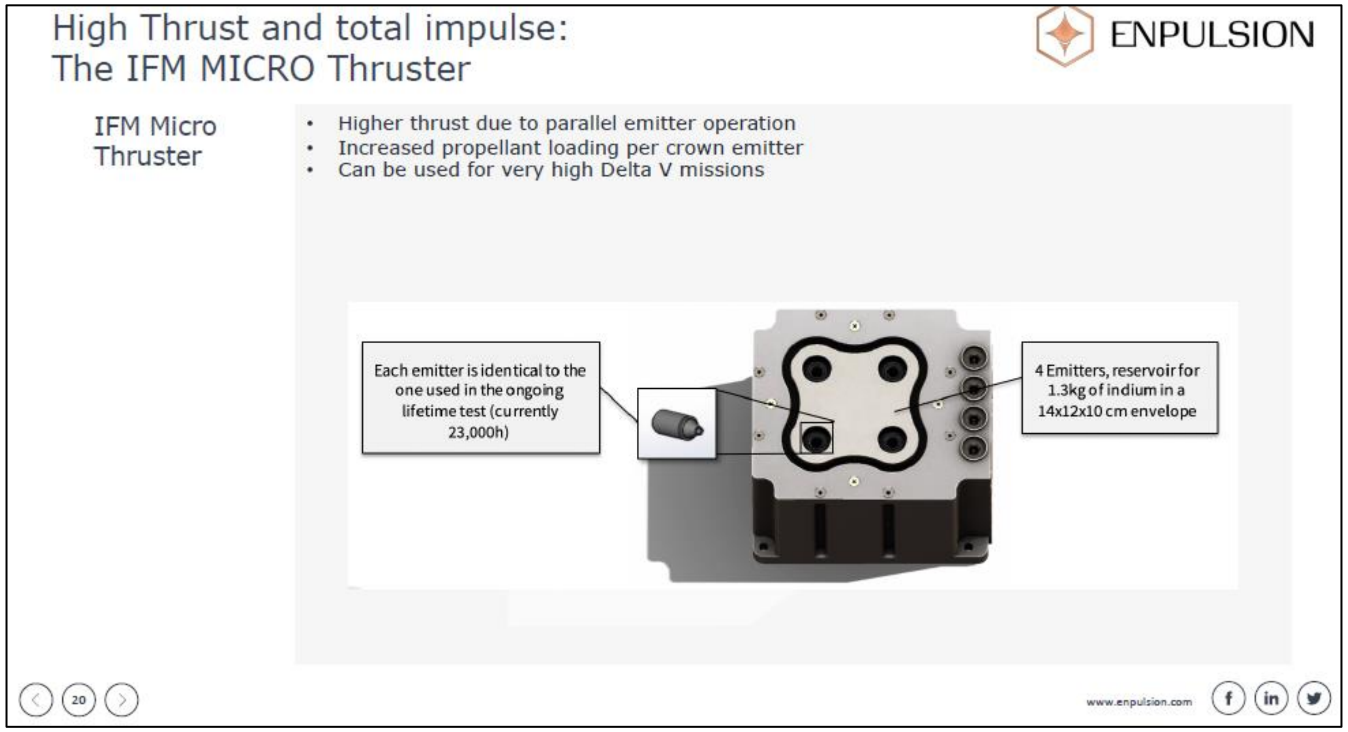
Comm. avail. TRL Aerospace-tested

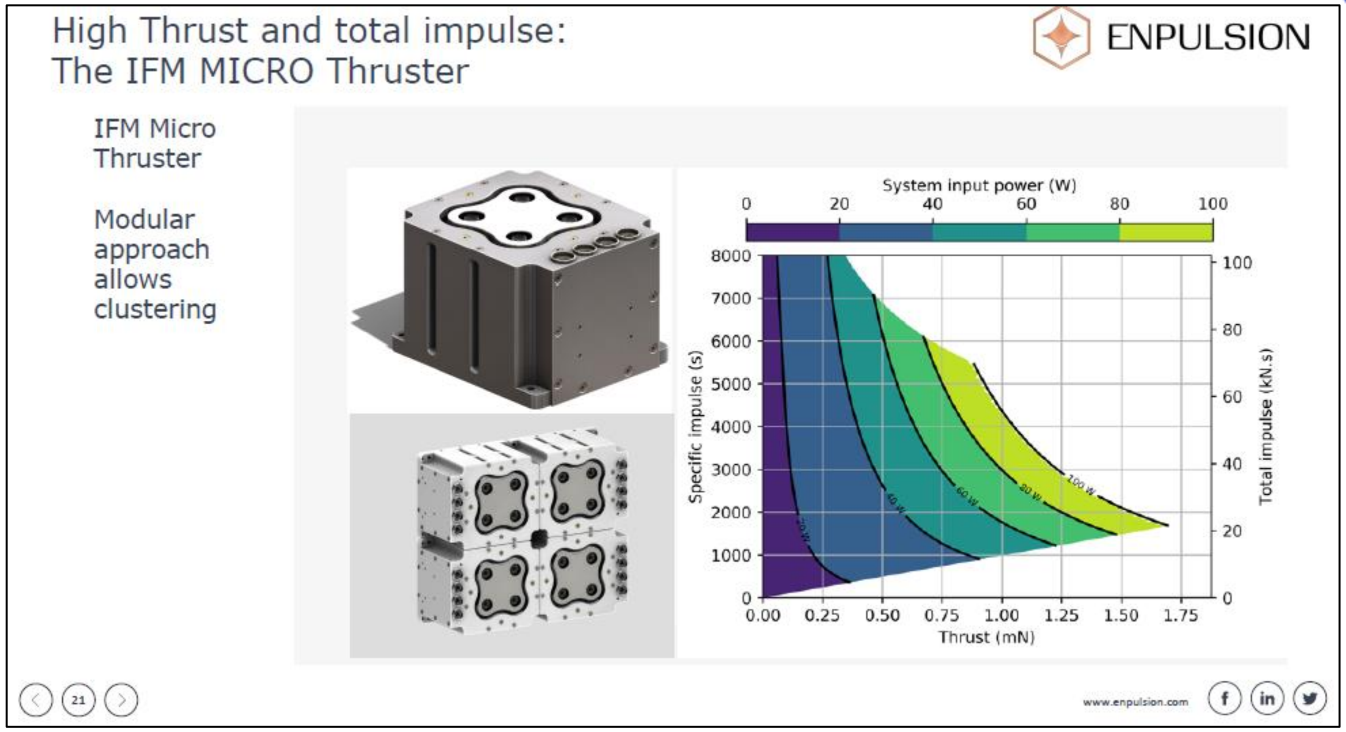
DISTRO A: Approved for public release. OTR-2024-00338

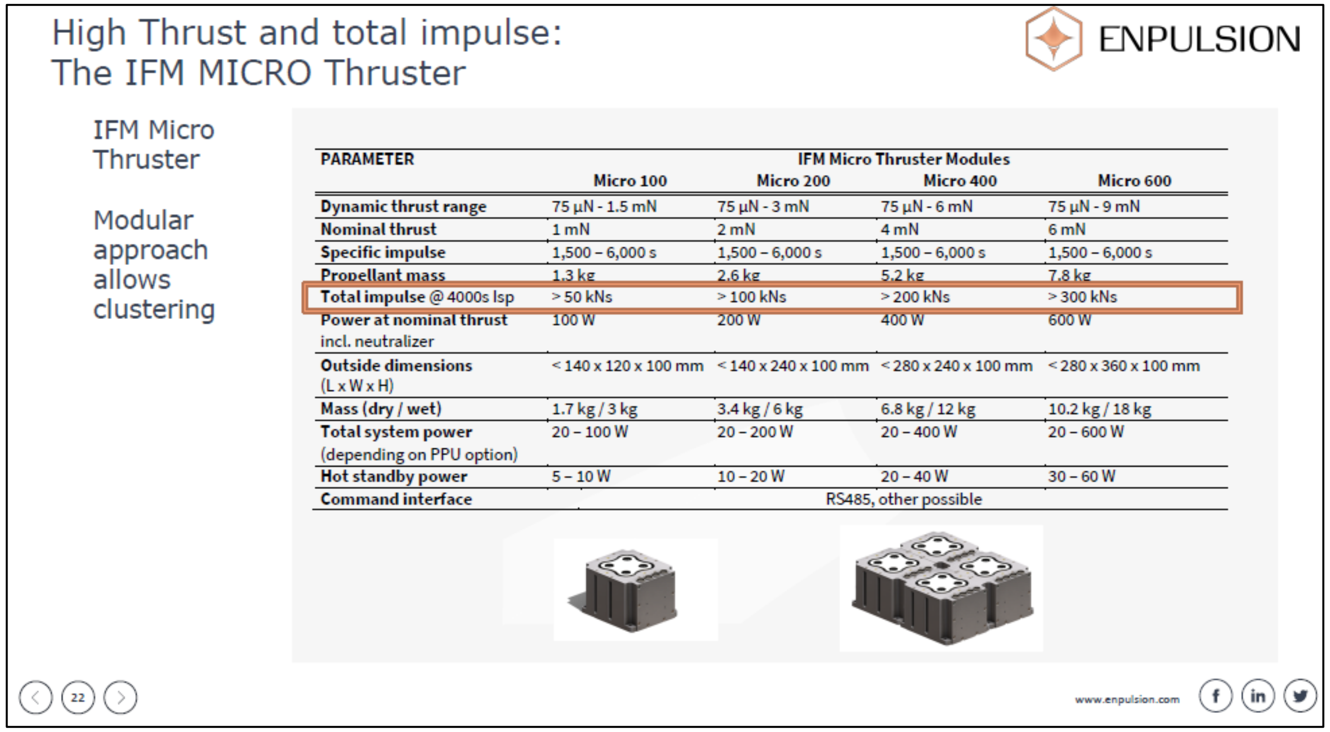
Micro R³ (previously named IFM Micro Thruster modular units/ IFM Micro 100/200/400/600) Enpulsion [2 of 3]

Additional comments:

[Reference 1][Aug 2019][On-orbit demonstration data]







PARAMETER	IFM Micro Thruster Modules			
	Micro 100	Micro 200	Micro 400	Micro 600
Dynamic thrust range	75 µN - 1.5 mN	75 µN - 3 mN	75 µN - 6 mN	75 µN - 9 mN
Nominal thrust	1 mN	2 mN	4 mN	6 mN
Specific impulse	1,500 – 6,000 s	1,500 – 6,000 s	1,500 – 6,000 s	1,500 – 6,000 s
Propellant mass	1.3 kg	2.6 kg	5.2 kg	7.8 kg
Total impulse @ 4000s Isp	> 50 kNs	> 100 kNs	> 200 kNs	> 300 kNs
Power at nominal thrust incl. neutralizer	100 W	200 W	400 W	600 W
Outside dimensions (L x W x H)	< 140 x 120 x 100 mm	< 140 x 240 x 100 mm	< 280 x 240 x 100 mm	< 280 x 360 x 100 mm
Mass (dry / wet)	1.7 kg / 3 kg	3.4 kg / 6 kg	6.8 kg / 12 kg	10.2 kg / 18 kg
Total system power (depending on PPU option)	20 – 100 W	20 – 200 W	20 – 400 W	20 – 600 W
Hot standby power	5 – 10 W	10 – 20 W	20 – 40 W	30 – 60 W
Command interface	RS485, other possible			

References:
[1] Krecji, D., Schonherr, T., Reissner, A., “Direct thrust measurements and In-orbit demonstration of the IFM Nano Thruster,” Interplanetary Small Symposium (San Luis Obispo), 2019. Public-released charts.

5

NO

Comm. avail. TRL Aerospace-tested

Micro R3 (previously named IFM Micro Thruster modular units/ IFM Micro 100/200/400/600) Enpulsion [3 of 3]

Additional comments:

[Reference 1][Aug 2022][Thruster testing]
The Micro R3 has been exposed to a series of mechanical loads on the vibration facility at Fotec, thermal vacuum at acceptance level, electromagnetic compatibility. Full total ionizing dose testing has not been conducted yet, however, some preliminary tests show no destructive events up to LETth of 35 MeV*cm^2/mg. Upsets were recovered by either internal protection (hardware and software) or restarting the unit. Preliminary testing has been done to assess the precision of the thrust model and thrust balance. The qual model was verified over a wide range of thrust values from 0.3 to 1 mN on an engineering thruster. Endurance testing is scheduled for Q3 and Q4 of 2022. Some preliminary testing on engineering models have shown no degradation.

[Reference 2][March 2023][Mission information]
OHB Sweden selected electric propulsion by ENPULSION for their EIS mission
Wr. Neustadt, Austria, Feb 1st, 2023 – In December 2022 OHB Sweden and ENPULSION have signed a dedicated sales contract on a Horizon2020 IOV/IOD Mission called EIS making it the next important milestone in a long and very successful cooperation between the two companies.

Proven concept
After having delivered ENPULSION's propulsion products to previous OHB Sweden's InnoSat microsatellite platform missions, OHB Sweden now decided to order a next series of ENPULSION thrusters for its EIS mission. OHB Sweden and ENPULSION have very successfully worked together on previous missions, including the Arctic Weather Satellite (AWS) programme, using the ENPULSION NANO R3 thrusters, as well as the GMS-T satellite, launched in 2021, in which the ENPULSION MICRO R3 thrusters are being used. The AWS is a part of ESA's Earth Watch programme, and the AWS satellite will be the proto-flight model for a possible constellation of satellites. The launch of the AWS is planned for 2024.

EIS mission
The fourth mission to be realized using the InnoSat platform is the European IOD/IOV Satellite (EIS) mission. EIS will host a single experiment from the Belgian company AMOS called "ELOIS". OHB Sweden acts as the satellite prime, carrier/platform provider, system integrator and overall ground segment responsible (incl. operations). For this mission, OHB Sweden will again rely fully on its existing flight proven InnoSat platform with a minimum of adaptations and will again be using the ENPULSION NANO R3 thrusters. The EIS satellite is under a contract with the European Space Agency funded by the European Commission. The launch of EIS is planned for early 2024.

References:
[1] Grimaud, L., Schonherr, T., Vasiljevich, I., Reissner, A., Krejci, D., Seifert, B., "Qualification status update of the MICRO R3 and Nano R3 FEEP thrusters," IEPC-2022-200.
[2] https://www.enpulsion.com/news/ohb-sweden-selected-electric-propulsion-by-enpulsion-for-their-eis-mission/

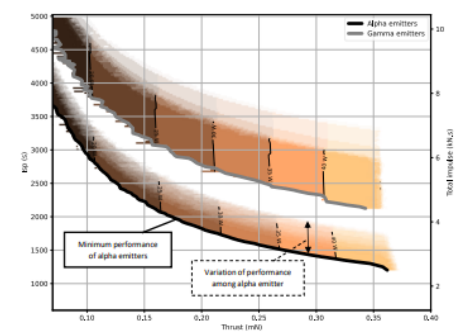
Comm. avail.	TRL	Aerospace-tested
	5	NO

Nano R³ [1 of 2]

Propulsion Technology	FEEP
Manufacturer/Country	Enpulsion (AUT)
TRL	5
Size (including PPU)	1U
Design satellite size	3U and larger
Isp (s)	4000 s (see performance envelope) [1]
Thrust type/magnitude	150 uN (max, see performance envelope) [1]
Delta-V (m/s)	
Propellant	Indium
Power consumption (W)	40 to 45W (at 500 uN thrust and 2000s Isp) [1]
Flight heritage (if any)	None known Projected for OHB Sweden’s AWS [launch planned for 2024] [3] Projected for OHB Sweden EIS mission [launch planned for 2024][3]
Commercially available	YES
Last updated	03/2023

	FLIGHT HERITAGE	ROBUST	VERSATILE	POWERFUL	DURABLE
DYNAMIC THRUST RANGE	10 µN TO 350 µN	10 µN TO 350 µN	10 µN TO 0.35 mN	10 µN TO 500 µN	200 µN - 1.35 mN
NOMINAL THRUST	330 µN	350 µN	350 µN	500 µN	1 mN
SPECIFIC IMPULSE	2,000 TO 6,000 s	2,000 TO 6,000 s	2,000 TO 6,000 s	1,500 TO 4,000 s	1,500 - 6,000 s
PROPELLANT MASS	220 g ± 5%	220 g	220 g	220 g	1.3 kg
TOTAL IMPULSE	MORE THAN 5,000 Ns	MORE THAN 5,000 Ns	MORE THAN 5,000 Ns	MORE THAN 4,000 Ns	MORE THAN 50,000 Ns
TOTAL SYSTEM POWER	8 – 40 W	8 – 40 W	8 – 40 W	8 – 45 W	30 - 120 W
POWER AT NOMINAL THRUST (incl. Heating and Neutralizer)	40 W	40 W	40 W	45 W	90 - 100 W
OUTSIDE DIMENSIONS	Fully Integrated System: 100.0* x 100.0* x 82.5 mm *can be customized	Fully Integrated System: 98.0 x 99.0 x 95.3 mm	Fully Integrated System: 98.0 x 99.0 x 95.3 mm	Fully Integrated System: 98.0 x 99.0 x 95.3 mm	Thruster head: 140 x 120 x 98.6 mm PPU box: 140 x 120 x 34.0 mm
MASS (DRY / WET) including PPU	680 / 900 g	< 1200 / < 1420 g	< 1230 / < 1450 g	<1200 / < 1420 g	2.6 kg / 3.9 kg
HOT STANDBY POWER	3.5 W	3.5 W	3.5 W	3.5 W	10 - 15 W
SUPPLY VOLTAGE	12 V or 28 V *other upon request*	12 V or 28 V *other upon request*	12 V or 28 V *other upon request*	12 V or 28 V *other upon request*	28 V
COMMAND INTERFACE	RS422 or RS485	RS422 or RS485	RS422 or RS485	RS422 or RS485	RS422 or RS485

DYNAMIC THRUST RANGE [1]	10 TO 350 µN
NOMINAL THRUST	350 µN
SPECIFIC IMPULSE	1,500 TO 5,000 s
PROPELLANT MASS	220 g
TOTAL IMPULSE[2]	MORE THAN 4,000 Ns
POWER AT NOMINAL THRUST	45 W INCL. NEUTRALIZER
OUTSIDE DIMENSIONS	98.0 x 99.0 x 95.3 mm
MASS (DRY / WET)	<1180 / <1400 g
TOTAL SYSTEM POWER	15 – 45 W
HOT STANDBY POWER[3]	4 - 7 W
COMMAND INTERFACE	RS422 / RS485
SUPPLY VOLTAGE	12 V, 28 V, OTHER VOLTAGES UPON REQUEST



Depending on available power the user can choose from any operational point - data shown is for 12 V configuration

Additional comments:

[Reference 1][Aug 2022][Thruster information]
The ENPULSION NANO R3 is the next-generation FEEP system based on the flight-proven success story that is the ENPULSION NANO (formerly: IFM Nano Thruster). Incorporation of lessons learned from a large number of acceptance test campaigns and inorbit performance verifications led into an updated electronics design, thermostructural concept, and software functionality. The resulting product – the ENPULSION NANO R3 – features increased reliability, radiation tolerance, and environmental resilience

[Reference 2][Aug 2022][Thruster information and testing]
Qualification testing has been carried out on the Nano R3. Nano R3 QM was subjected to a series of vibrational loads in 3 axes. Thermal vacuum testing was conducted for a total of 7 On-cycles at 350 uN. Endurance testing is planned for later this year. In addition, EMC qualification was doncuted in 2021 and 2022 at Seibersdorf Laboratories. We believe that this is concludes that FEEP thrusters do not produce a significant plasma cloud which can have impacts on electromagnetics behavior of the system in flight. Overall, the test campaign was successful, with a minor violation at 75 kHz and related harmonics for the conduction emission part at full operational load. Total ionizing dose testing was done also at Seibersdorf.

References:
[1] https://www.enpulsion.com/wp-content/uploads/ENP2019-086.F-ENPULSION-NANO-R%C2%B3-Product-Overview.pdf
[2] Grimaud, L., Schonherr, T., Vasiljevich, I., Reissner, A., Krejci, D., Seifert, B., “Qualification status update of the Micro R3 and Nano R3 FEEP thrusters,” IEPC-2022-200
[3] https://www.enpulsion.com/news/ohb-sweden-selected-electric-propulsion-by-enpulsion-for-their-eis-mission/

🛒	5	NO
Comm. avail.	TRL	Aerospace-tested

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Nano R^3 [2 of 2]

Additional comments:

[Reference 1][March 2023][Missions information]
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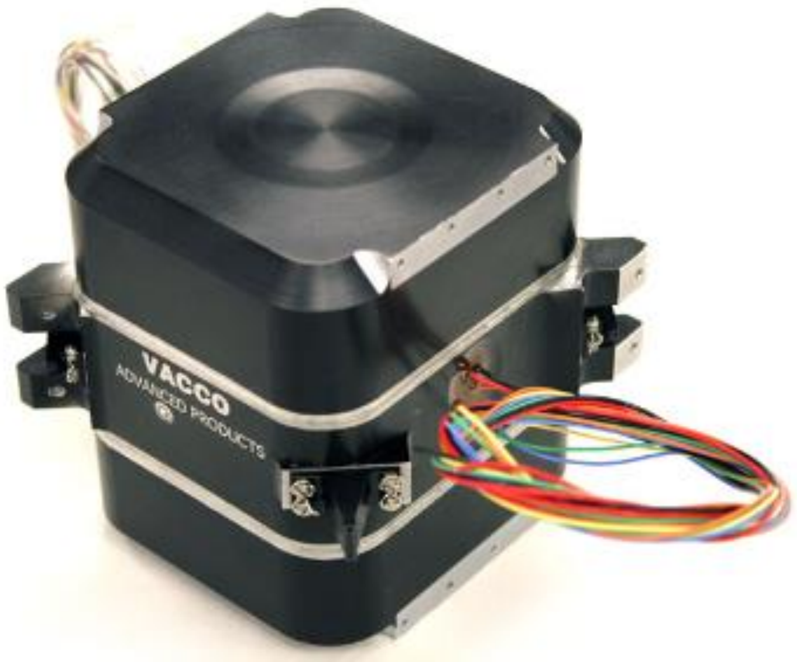
References:
[1] https://www.enpulsion.com/news/ohb-sweden-selected-electric-propulsion-by-enpulsion-for-their-eis-mission/

	5	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

C-POD (CPOD) Micro CubeSat Propulsion System (MiPS)
VACCO

Propulsion Technology	Cold gas
Manufacturer/Country	VACCO (USA)
TRL	5-6
Size (including PPU)	1U
Design satellite size	3U and larger, CPOD will be 4 kg [3]
Isp (s)	40s
Thrust type/magnitude	190 N*s (impulse, total), 200 mN (total) = 8X 20-30 mN thrusters (continuous, nominal, each), 0.2 mN*s (impulse, minimum)
Delta-V (m/s)	
Propellant	R134a refrigerant
Power consumption (W)	5W (operational), 0.25W (standby)
Flight heritage (if any)	None to date Projected to fly on CPOD (originally mid-2020, now delayed to 2021) [3]
Commercially available	YES
Last updated	*03/2021*



C-POD Micro Propulsion unit, with 8X 25 mN thrusters arranged at its corners for precise proximity operations.

Additional comments:

[Reference 1-4][Jan 2019][Thruster info]

VACCO's NASA C-POD Micro Propulsion System is a self-contained unit designed to occupy the center of a 3U CubeSat. A total of eight 25 mN thrusters in groups of two at four corners of the module allows for precise rendezvous and proximity operations with full CubeSat attitude control. The NASA CubeSat propulsion module uses R134a propellant, which self-pressurizes over the normal operating temperature range and helps to ensure range safety. This smart system is designed to interface with the spacecraft through an RS422 data bus for command and control. The NASA C-POD Micro CubeSat Propulsion System can be scaled down from 0.8U based upon the mission and payload requirements. Valve response time is better than 2 ms.

CPOD (Cubesat Proximity Operations Demonstration), formerly known as PONSFD (Proximity Operations Nano-Satellite Flight Demonstration), is a two satellite cubesat mission by Tyvak Nanosatellite Systems LLC to demonstrate proximity and rendezvous operations with cubesat class satellites. The objective of the PONSFD mission is to design, develop, and demonstrate rendezvous and proximity operations to a support inspection missions utilizing a CubeSat. The Program represents a 10× reduction in space vehicle size and program cost for a proximity operations flight experiment. Both satellites will be launched together in a joint 6U configuration and will separate in orbit, before they begin operations.

Each satellite contains a VACCO built self-contained Micro Propulsion System, which is mounted in the center of a 3U CubeSat. It features eight fast response, low power 25 mN cold gas thrusters. CPOD is funded by the Small Spacecraft Technology Program within the NASA Space Technology Mission Directorate and was selected in 2013 for a launch in NASA's ELaNa program.

From Bowen (2015), "The multi-thruster propulsion system utilizes a mature design that was developed by VACCO industries and tested extensively (70,000+ firings) in a vacuum by the US Air Force Research Lab."

References:

[1] Bowen, J., Villa, M., Williams, A., "CubeSat based rendezvous, proximity operations, and docking in the CPOD mission," Small Satellite Conference, 2015. SSC15-III-5.
[2] http://www.cubesat-propulsion.com/reaction-control-propulsion-module/
[3] http://space.skyrocket.de/doc_sdat/cpod.htm
[4] https://www.nasa.gov/directorates/spacetech/small_spacecraft/cpod_project.html

Comm. avail.	5 TRL	NO Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

CubeSat High Impulse Propulsion System (CHIPS)
CU Aerospace/VACCO (1 of 2)

Propulsion Technology	Resistojet/warm gas/cold gas
Manufacturer/Country	CUAerospace (USA)/VACCO (USA)
TRL	5
Size (including PPU)	Various models (0.6U to 1.5U)
Design satellite size	3U and larger
Isp (s)	R236FA: 66s (warm), 38s (cold), R134W: 76s (warm), 52s (cold), ACS model: 47s
Thrust type/magnitude	R236FA: 17 mN (warm, continuous), 22 mN (cold, continuous), 498 N*s (warm, impulse), 287 N*s (cold, impulse) R134A: 31 mN (warm, continuous), 31 mN (cold, continuous), 472 N*s (warm, impulse), 323 N*s (cold, impulse) 0.2 mN*s (impulse, minimum) Thruster can thrust for 10 minutes continuously, and then requires 6 min of cool-down
Delta-V (m/s)	R236FA: 138 m/s (warm), 80 m/s (cold), R134A: 129 m/s (warm), 88 m/s (cold)
Propellant	R134A or R236fa Refrigerant
Power consumption (W)	~25W
Flight heritage (if any)	None to date [Vacco's valves flew on the MARCO mission (NASA, 2018)]
Commercially available	YES
Last updated	*03/2021*

Additional comments:

[Reference 1-4][Jan 2019][General info]

The CU Aerospace / VACCO CubeSat High Impulse Propulsion System (CHIPS) offers a miniaturized and well-integrated small-satellite propulsion solution, including both a main thruster and three-axis attitude control system (ACS). The ACS system is a 4-thruster array and has a pointing accuracy of 1.2 degrees and can control roll, pitch, yaw, and –Z. CHIPS achieves a high total-impulse-to-volume ratio by leveraging CU Aerospace's high-efficiency resistojet technology, VACCO Industries' compact frictionless valve technology, and self-pressurizing, non-toxic, and inert propellants. Waste heat from the electronics and resistojet is efficiently and regeneratively recovered to evaporate propellant, resulting in a system temperature rise of only ~1°C per 10 minutes of operation. The baseline CHIPS is a 1U, fully-throttleable system. System set-points, system status, and firing telemetry are all accessible and configurable through an RS-422 serial interface. CU Aerospace offers an optional battery module to simplify integration with existing low-power CubeSat buses. CHIPS may be customized to meet customer-specific mission requirements.

Vacco valves (but not the CHIPS system) were flown on the MarCO mission in 2018 and results were presented at the SmallSat conference. A slight leak was detected from a thruster on marCO-B following a blow-down maneuver for thruster characterization early in the mission. After characterizing the leak, and altering onboard behaviors to account for it, the team adopted a slightly different strategy for the second spacecraft. First, in anticipation that the leak might not end, or could change in the future, the spacecraft performs regular plenum chamber blowdowns at specified attitudes to keep the spacecraft pushing towards Mars. This reduces the need for extensive thruster firing. The team is continuously to characterize the leaky thruster, as well as slightly tweak the flyby location, as of 2018.

It is unclear whether the CHIPS system utilizes these leaky valves still.

The manufacturer claims the life span as 2 years from propellant load.

References:

[1] Klesh, A., Clement, B., Colley, C., Essmiller, J., Forgette, D., Krajewski, J., Marinan, A., Martin-Mur, T., et al., "MarCO: Early Operations of the First CubeSats to Mars," SSC18-WKIX-04, SmallSat Conference, 2018.
[2] Hejmanowski, N., Woodruff, C., Burton, R., Carroll, D., Palla, A., Cardin, J., "CubeSat High Impulse Propulsion System (CHIPS) Design and Performance," 63rd JANNAF Propulsion Meeting, 2016.
[3] Hejmanowski, N., Woodruff, C., Burton, R., Carroll, D., Cardin, J., "CubeSat High Impulse Propulsion System (CHIPS)," 62nd JANNAF Propulsion Meeting, 2015.
[4] http://www.cuaerospace.com/Portals/2/SiteContent/pdfs/datasheets/CHIPS/CHIPS-Brochure-170718.pdf?ver=2017-07-18-234056-717

Comm. avail.	5 TRL	NO Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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CubeSat High Impulse Propulsion System (CHIPS)
CU Aerospace/VACCO (2 of 2)

Additional comments:

[Reference 2][Jan 2019][TRL level, risk assessment]
RISK ASSESSMENT AND MITIGATION
Overall technical risk of the CHIPS thruster unit is low and has been substantially mitigated through testing on the NASA-funded Phase II SBIR project. Additionally, the TRL 7 PUC thruster systems [Carroll, 2015] already delivered to the Air Force by the CU Aerospace-VACCO team have validated many of the proposed technologies (valves, welds, materials compatibility, control boards, pressure vessel testing, etc.) through testing. The CHIPS super-heater cartridge and associated drive electronics are a primary focus of the ongoing SBIR effort and have been validated through testing to TRL 5 at this time. Resistojet thrusters as a class are at TRL 9. Liquid propellant resistojets have been extensively ground and flight tested [Morren, 1988; Sweeting,1999]. Micronozzle performance has been well-characterized as a function of Reynolds number, and the CHIPS nozzle (Re = 1600) will be operating at a demonstrated high efficiency [Whalen, 1987]. Super-heater performance is based on extremely well-known heat transfer performance for internal turbulent convective flow (Re = 7500, Nusselt No. = 25.8) to a constant temperature wall. Evaporator performance is based on the effect of microgravity on pool boiling [Kim, 2002; Lee, 1997], and on the strong absorption by liquid R134a of infrared radiation [Pikkula, 2004]; R236fa should be similar. In-house testing at CUA has effectively mitigated the risk in propellant selection on materials compatibility. These propellants are well known and benign, and thus inherently carry very low risk. R236fa and R134a are benign, non-toxic, non-hazardous refrigerants, so they are not hazardous materials. The CHIPS hardware also contains no hazardous materials. Further, R236fa can be removed from the air by the International Space Station (ISS) filtration system, making it a candidate for deployment from ISS (whereas R134a cannot be so filtered on ISS). The primary safety risk with CHIPS is pressure, but this is predominantly mitigated by the use of R236fa propellant rather than R134a. R236fa requires more preheating because of its lower vapor pressure, and its Isp performance is worse than R134a. However, with R236fa, the overall total impulse will be similar (Fig. 8) and more importantly, the propellant tank will be below 100 psig at the CHIPS maximum expected operating pressure (MEOP) under worst-case temperature conditions of 65ºC, so it is not a hazardous pressure system [AFSPCMAN 91-710, Vol. 3 Chap. 12]. This is extremely low compared with pressures routinely encountered in the space industry and does not present a serious safety issue. As such, R236fa is now considered as the baseline propellant choice (R134a was the original baseline propellant). The primary pressure hazard occurs if the system is erroneously over-filled with liquid R236fa, sealed, then raised in temperature. Liquid refrigerant is relatively incompressible and pressure will increase rapidly potentially exceeding burst pressure causing external leakage. This safety issue is mitigated by using fill methods that leave a prescribed minimum amount of vapor in the system. The correct propellant load is easily verified by simply measuring the mass of the system .To address a filling error, the aluminum alloy system will be designed to plastically deform then leak before burst. The maximum temperature limit will be determined for a system inadvertently filled with 100% liquid. This information will be incorporated into ground handling and storage procedures for a fueled system. Should a larger structural margin be desired, the all-welded titanium propellant tank design for CHIPS has already been validated in our PUC thruster system.

Failure of the warm-gas functionality of the primary thruster is mitigated by operating the system in cold gas mode, which is still capable of satellite maneuvering and limited de-orbiting using solar warming of the propellant.
The thruster system will have triple physical and electronic timer inhibits and can only be activated via ground command, to guarantee the CHIPS unit cannot have extended uncontrolled firing in case of failure. For example, one option to limit thrust duration on any flight unit design is to include real time clock (RTC) electrical inhibits on the primary propellant feed valve.

References:

[1] Klesh, A., Clement, B., Colley, C., Essmiller, J., Forgette, D., Krajewski, J., Marinan, A., Martin-Mur, T., et al., "MarCO: Early Operations of the First CubeSats to Mars," SSC18-WKIX-04, SmallSat Conference, 2018.
[2] Hejmanowski, N., Woodruff, C., Burton, R., Carroll, D., Palla, A., Cardin, J., "CubeSat High Impulse Propulsion System (CHIPS) Design and Performance," 63rd JANNAF Propulsion Meeting, 2016.
[3] Hejmanowski, N., Woodruff, C., Burton, R., Carroll, D., Cardin, J., "CubeSat High Impulse Propulsion System (CHIPS)," 62nd JANNAF Propulsion Meeting, 2015.
[4] http://www.cuaerospace.com/Portals/2/SiteContent/pdfs/datasheets/CHIPS/CHIPS-Brochure-170718.pdf?ver=2017-07-18-234056-717

	5	NO
Comm. avail.	TRL	Aerospace-tested

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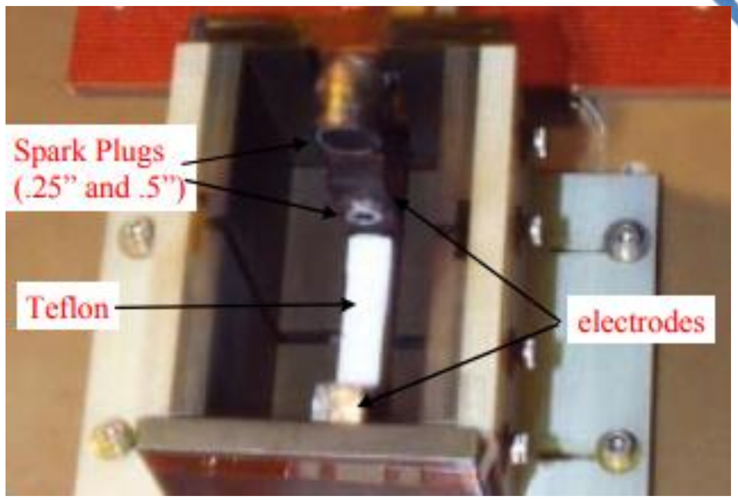
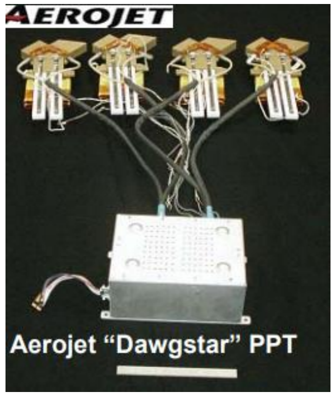
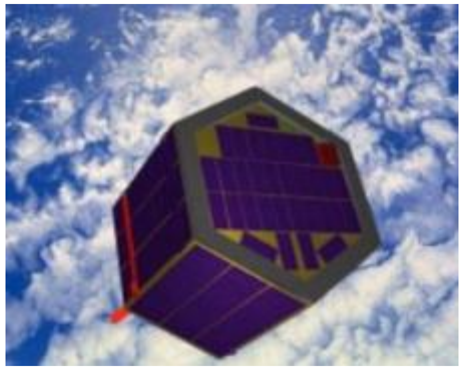
“Dawgstar” PPT

Propulsion Technology	Pulsed Plasma Thruster (PPT)
Manufacturer/Country	Primex/General Dynamics (now Aerojet) (USA)/University of Washington
TRL	4-5
Size (including PPU)	1-2U (1kg)
Design satellite size	1U and larger (designed for university 10kg s/c)
Isp (s)	400 - 625s
Thrust type/magnitude	0.07 mN (thrust, continuous), 66 uN*s (impulse-bit, typical), 3000 N*s (impulse, total) [1-4] 112 uN (maximum thrust), 56 uN*s (impulse bit, typical), 1125 N*s (impulse, total), [5]
Delta-V (m/s)	~67 m/s (design)
Propellant	Teflon, 0.03 kg/thruster (design spec) [5]
Power consumption (W)	13W for 2 thrusters firing simultaneously [5]
Flight heritage (if any)	None, “Dawgstar” delivered but never flown.
Commercially available	No
Last updated	*03/2021*



Thruster prototype





UW Dawgstar Nanosatellite

Additional comments:

[Reference 1-2, 6][Jan 2019][General info]

The thruster is a miniaturized version of EO-1 thruster, which had flown. EO-1 is a larger (>100kg) satellite which demonstrated the use of PPTs for S/C precision-pointing. It was designed for the “Dawgstar” nanosatellite mission, designed by University of Washington. The UW Dawgstar had 8 thrusters for 5-axis control in order to save mass. The system contained 4 clusters of 2 thrusters each, with one capacitor per pair. One PPU with high voltage switches will power the entire system. “Dawgstar” was the only satellite in ION-F that had propulsive capability. The thruster has a reported 3% efficiency. Contamination concerns related to Teflon propellant largely refuted by EO-1 mission, but need to be re-evaluated for each mission for extensive firings near sensitive surfaces such as optics.

[Reference 3][Jan 2019][Flight info]

ION-F (Ionospheric Observation Nanosatellite Formation) was a three-satellite nanosatellite program conducted by Utah State University, University of Washington and Virginia Polytechnic. The three nanosatellites, one from each university (USUSat (Utah State University), DawgStar (University of Washington) and HokieSat (Virginia Polytechnic)), were to weigh about 10 kg each. The goals of the ION-F alliance program were: 1) Basic research mission of investigating global ionospheric effects which affect the performance of space based radars, and other distributed satellite measurements, 2) Formation flying and local communication in a constellation, including upgrade from a three nanosatellite constellation to four nanosatellites, 3) Baseline new technologies including micro-thrusters, attitude control, advanced tether system, and an Internet based operations center, 4) Internet control of a distributed space system. They were to fly on the same Space Shuttle mission as the 3CS satellites (2002), but were all cancelled, although Dawgstar was delivered.

[Reference 4][Jan 2019][Flight info]

Information on the EO-1 mission. EO-1 is a large (>100 kg) satellite that utilized mainly hydrazine thrusters but carried PPTs as a secondary system for demonstration. The PPTs it carried consumed roughly 100W, weighed 5 kg, and produced 460 N*s total impulse. Specific impulse was approximately 650-1400s (estimated). A series of fine pitch pointing maneuvers were performed after the end of the primary imaging mission. Flight operations of the EO-1 PPT began on January 4, 2002. As of June 15, 2002, a total of 26.9 hours of operation and almost 97,000 pulses have been logged, including several image acquisitions and continuous control of the pitch attitude of the spacecraft for over 9 hours for 5.5 orbits. This was the first flight demonstration of PPT throttling. Spacecraft pitch attitude was controlled to well within the 30 arcsec requirement during image acquisition and was generally within 10 arcsec. In addition, sensitive tests with images of the dark Earth have detected no evidence of electromagnetic interference from the discharge or light pollution from the plume even though the ALI instrument was known to have very sensitive electronic components.

References:

[1] Campbell, M., Schetter, T., “Formation Flying Mission for the UW Dawgstar Satellite,” IEEE 2000.
[2] Mueller, J., Ziemer, J., Hofer, F., Wirz, R., O’Donnell, T., “A Survey of Micro-Thrust Propulsion Options for Microspacecraft and Formation Flying Missions,” Cube Sat 5th Annual Developers Workshop, San Luis Obispo, CA, 2008.
[3] https://space.skyrocket.de/doc_sdat/ion-f.htm
[4] https://directory.eoportal.org/web/eoportal/satellite-missions/e/eo-1
[5] https://eo1.gsfc.nasa.gov/new/miscPages/TechForumPres/25-PPT.pdf
[6] Rayburn, C., Campbell, M., Hoskins, W., Cassady, R., “Development of a micro pulsed plasma thruster for the dawgstar nanosatellite,” AIAA-2000-3256.

NO	5	NO
Comm. avail.	TRL	Aerospace-tested

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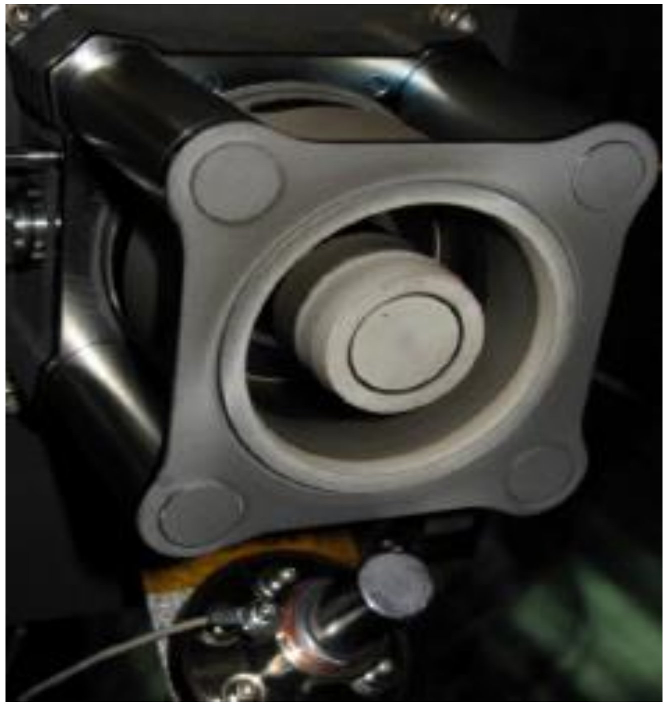
CAM200 Low Power Hall Thruster

Propulsion Technology	Hall thruster
Manufacturer/Country	Rafael/Asher Space Research Institute (ASRI) (Israel)
TRL	5
Size (including PPU)	
Design satellite size	
Isp (s)	900 s at 100W, 1500 s at 250W [1]
Thrust type/magnitude	6 mN at 100W, 14 mN at 250W, >60 kN*s (impulse, total) [1]
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	100 to 300W, 150 to 400V
Flight heritage (if any)	None known
Commercially available	NO
Last updated	*03/2021*


CAM200 engineering model

Additional comments:

[Reference 1][Dec 2019][Thruster development]
During the past few years CAM200 was designed and tested by Rafael in cooperation with the Asher Space Research Institute (ASRI) implementing the gained knowledge of previous ASRI work on Hall Thrusters. During development tests CAM200 Hall thruster exhibited outstanding performance at the low power operating range, from 100 to 300 W. Following the preliminary laboratory model tests phase CAM200 thruster entered the next development phase in which an Engineering Model (EM) was designed, manufactured and tested at Rafael, Israel. During the past year the CAM200 EM model was tested in order to validate the MEPS project vibration requirements, ECSS requirements and manufacturability requirements and proceed to the next project phases. CAM200 takes part in the joint European-Israeli Micro-satellite Electric Propulsion System (MEPS) project. The goal of the MEPS project, which is funded by European Space Agency (ESA) and the Israeli Space Agency (ISA), is to design, manufacture and qualify an electric propulsion system for micro-satellites. MEPS, which is planned to be qualified for space in coming years, is collaboration between Rafael and the Italian electric propulsion company, Sitael. Performance characterization at Sitael and ion flux measurements in the thruster plume are presented in detail. The next steps involve raising the TRL by running a full CAM200-QM (qualification model) under the MEPS project specifications. Thruster efficiency is 43%.
[Reference 2][Dec 2019][Thruster testing]
We present the CAM200 thruster performance maps and emphasize the unusually high performance; i.e. thrust, Isp and efficiency (12mN, 1,550sec and 45% @200W respectively). We present the vibration test campaign in which we examined the possible effects of the maximum expected launch loads on thruster performance and structural integrity. Using resonance sweeps we show that the thruster's structural Eigen frequencies are well above the minimum allowed value of 140 Hz. Additionally, no performance degradation, due to applying launch loads, was observed. Lastly, the thruster's structural integrity was preserved throughout all vibration tests.
[Reference 3][Mar 2021][Thruster testing]
Thruster performance was recorded at an independent research facility, and measurement of the ion flux in the thruster plume was executed.

References:

[1] Franco, D., Lev, D., Appel, L., "Recent development of the CAM200 low power hall thruster," IEPC-2017-247.
[2] Lev, D., Franco, D., Eytan, R., Appel, L., "Performance characterization and vibration test of the CAM200 Low Power Hall Thruster," AIAA-JPC, 2016.
[3] Franco, D., Lev, D., Appel, L., "Performance validation and plume divergence of the CAM200 low power hall thruster," Aeronautics and Aerospace Open Access Journal, Vol. 2, 2018.

NO	5	NO
Comm. avail.	TRL	Aerospace-tested

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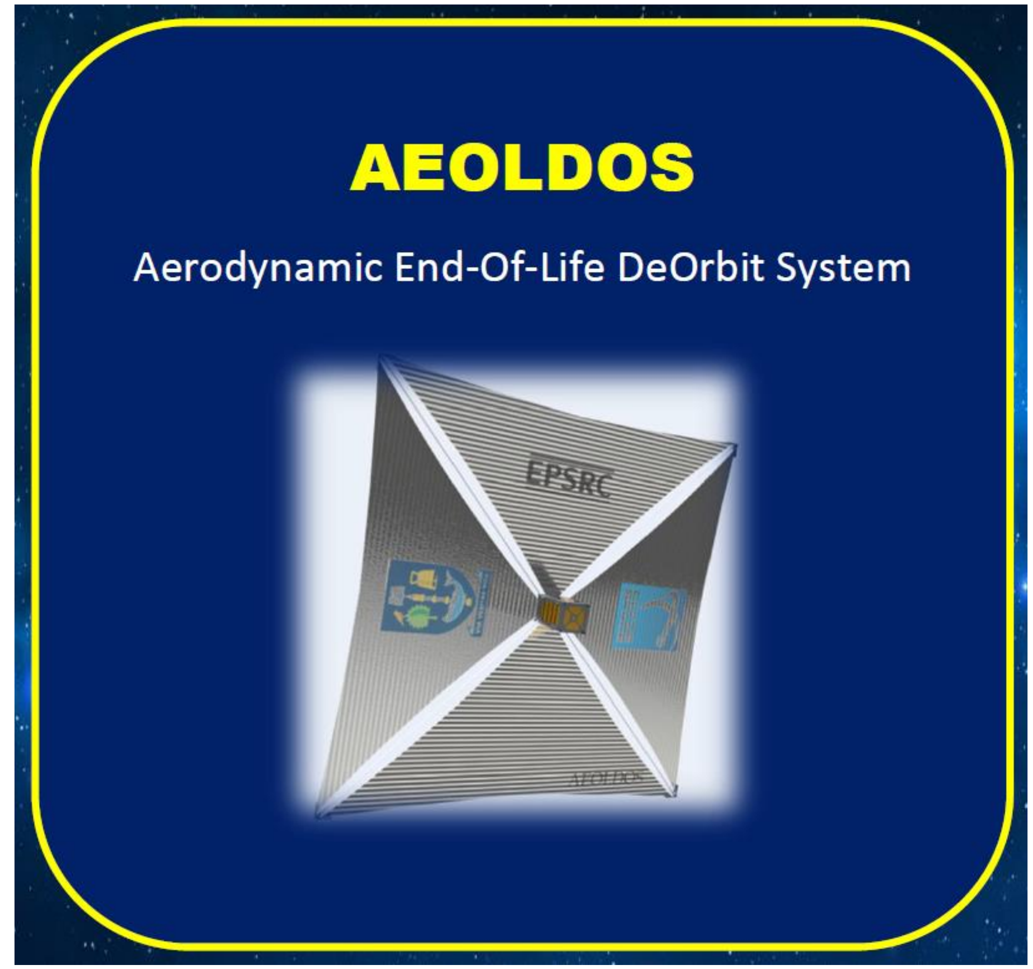
Aerodynamic End-of Life Deorbit system for CubeSats (AEOLDOS)

Propulsion Technology	Passive de-orbit
Manufacturer/Country	AAC-Clyde/University of Glasgow/Clyde Space (UK)
TRL	5
Size (including PPU)	0.4U [4]
Design satellite size	1 to 3U
Isp (s)	n/a
Thrust type/magnitude	Propellant-less
Delta-V (m/s)	n/a
Propellant	n/a
Power consumption (W)	
Flight heritage (if any)	None known
Commercially available	Yes
Last updated	03/2019



Additional comments:

[Reference 1, 2][March 2019][Device information]
AEOLDOS is a lightweight, foldable 'aerobrake' made from a membrane supported by boom-springs that open the sail to generate aerodynamic drag against the extremely thin upper atmosphere that still exists in near-Earth space. As the satellite falls out of orbit the aerodynamic effects increase, causing the CubeSat to harmlessly burn up during its descent. This ensures that it does not become another piece of potentially harmful space debris. The module deploys a 1.5 m2 aerobrake membrane on command or as part of a pre -planned end-of-mission disposal sequence. Re -entry times from LEO are vastly reduced, enabling higher missions and ensuring compliance with debris mitigation recommendations and requirements.
SWAPPABLE SAIL CARTRIDGES: The aerobrake is made up from four triangular sails supplied pre-folded in identical sealed cartridges to fit into the four sides of the module. We provide cartridges for ground testing and space-certified materials for flight applications.
PETAL-HUB DEPLOYMENT SYSTEM: Tape-springs provide self-actuated deployment after many years in space, Soft-stop technology reduces shock at end-of-deployment, minimizing damage to the tape-springs and enabling multiple test deployments of the module.
RADIAL SAIL-CASTING DOORS: Four rigid doors ensure the membrane remains safely stowed in both the P-POD and in service. A single, synchronized unlocking and radial deployment action extends the sails when required.
FULL DESIGN FLEXIBILITY: AEOLDOS provides one facet for solar cells in an end-stack configuration and offers generous service pass-through channels for mid-stack applications.

References:
[1] https://sst-soa.arc.nasa.gov/12-passive-deorbit-systems
[2] https://www.clyde.space/products/59-aerodynamic-end-of-life-deorbit-system-for-cubesats
[3] Harkness, P., McRobb, M., Lutzkendorf, P., Milligan, R., Feeney, A., Clark, C, "Development status of AEOLDOS- A deorbit module for small satellites," Advances in Space Research, 2014.
[4] https://www.youtube.com/watch?v=lZ3ZqUvG2dw

	5	NO
Comm. avail.	TRL	Aerospace-tested

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REGULUS [1 of 2]

Propulsion Technology	RF thruster
Manufacturer/Country	T4i (Technology for Propulsion and Innovation) (ITALY), a University of Padua Spin-off
TRL	4-5
Size (including PPU)	1.5U
Design satellite size	3U and above
Isp (s)	550s at 50W [2]
Thrust type/magnitude	0.25 to 0.6 mN (0.6 mN at 50W) [2]
Delta-V (m/s)	
Propellant	Iodine (but can also work with CO2, Argon, Xenon) [3]
Power consumption (W)	20-60W (50W nominal)
Flight heritage (if any)	None Projected flight Unisat-7 in Q2/Q3 2020, now 2021 [4]
Commercially available	YES, website says flight-qualified unit available from Dec 2019 [3]
Last updated	12/2021

[2]

Additional comments:

[Ref 1][Oct 2019][Thruster development]
The REGULUS MEPT (Magnetically Enhanced Plasma Thruster) is a cathode-less RF thruster specifically designed for CubeSat propulsion. The cathode-less concept is a relatively new technology which is particularly suited for CubeSat propulsion solutions thanks to its simple design. Specifically, the main components of a cathode-less thruster are: (i) a dielectric tube inside which the neutral gas propellant is ionized, (ii) a RF antenna working in the MHz range which provide the power to ionize the gas, and (iii) magnets which produce a magneto-static field that enhances the plasma confinement and provides the magnetic nozzle effect downstream the source exhaust. The principal features which make a cathode-less thruster suitable for CubeSat propulsion are: (i) a very simple structure, which helps limit the cost of the system; (ii) absence of electrodes immersed in the plasma; (iii) adaptability to different propellants by simple geometric reconfiguration; (iv) no need for a neutralizer because the ejected plasma is neutral.
REGULUS is a complete electric propulsion unit fed with iodine propellant. REGULUS has a mass below 3 kg and an envelope of 1.5U; it is intended to propel satellites ranging from 6U CubeSats up to 150 kg SmallSats, and for CubeSat carriers. REGULUS integrates the MEPT with its subsystems, namely electronics, fluidic line, and thermos-structural. First, the MEPT concept has been illustrated and the thruster tested with both xenon and iodine. The two propellants have shown comparable performances, and that 0.6 mN thrust and 600 s specific impulse can be achieved at 50 W input power if MEPT is operated with iodine. Second, the subsystems (i.e., electronics, fluidic line, and thermos-structural) have been described and some qualification tests have been discussed. More specifically, the electronics performs the control and conditioning of the overall system communicating with the bus via CANbus and/or I2C via CSP protocol. Functional tests have been performed on the fluidic line in vacuum and at ambient temperature (20-30°C); the testing campaign in a variable temperature environment (-40°C/+80°C) is currently ongoing. In addition, REGULUS has successfully undertook sinusoidal and random vibration tests, along with thermal balance and thermal bake out. Finally, the qualification tests on REGULUS will be completed by October 2019, subsequently a Flight Model will be manufactured and delivered by December 2019. An IoD (In-orbit Demonstration) is planned by Q2/Q3 2020 on board Unisat-7, a microsatellite operated by the Italian company GAUSS.

References:

[1] Manente, M., Trezzolani, F., Mantellato, R., Scalzi, D., Schiavon, A., Souhair, N., Duzzi, M., Barato, F., Cappellini, L., Barbato, A., Paulon, D., Selmo, A., Bellomo, N., Gloder, A., Toson, E., Minute, M., Magarotto, M., Paravin, D., "REGULUS: Iodine fed plasma propulsion system for small satellites," IEPC-2019-417.
[2] Small Sat 2020, virtual public forum
[3] https://www.t4innovation.com/electric-thrusters/
[4] https://space.skyrocket.de/doc_sdat/unisat-7.htm

	5	NO
Comm. avail.	TRL	Aerospace-tested

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REGULUS [2 of 2]

Additional comments:

[Ref 1][Dec 2021][Company information]
T4i and Spacety Luxembourg have signed a Memorandum of Understanding (MoU) to set the framework for several intended collaborations regarding Electric Propulsion and flight opportunities.
There are common fields of interests between the two companies. T4i is developing plasma thrusters in different sizes to accommodate the entire spectrum of smallsats, while Spacety Luxembourg is both offering flight opportunities for T4i IOD missions and looking for innovative, robust, and reliable iodine-based electric propulsion systems for their SAR constellation. In addition, this agreement formalizes the mutual interest in collaborating for future space missions and the possibility for T4i to capture the growing demand arising in the Chinese constellations market through this partnership with Spacety.

References:

[1] https://smallsatnews.com/2021/08/14/mou-signed-between-t4i-spacety-luxembourg-for-electric-propulsion-mission-flight-opportunities/

	5	NO
Comm. avail.	TRL	Aerospace-tested

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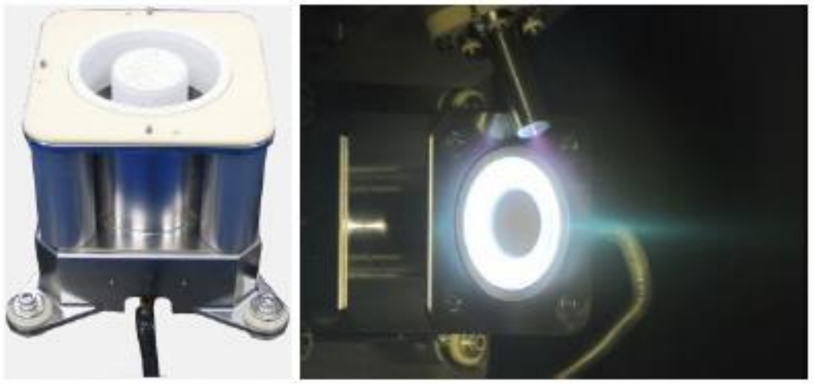
R-200/R-200EPS [1 of 2]

Propulsion Technology	Hall effect thruster
Manufacturer/Country	Rafael (Israel)
TRL	5-6
Size (including PPU)	
Design satellite size	~50 kg class
Isp (s)	800 -1200s [1]
Thrust type/magnitude	5-15 mN [1]
Delta-V (m/s)	
Propellant	Xenon, Krypton
Power consumption (W)	150-350W [1], endurance tested at 250W [2], powered range up to 600W [3]
Flight heritage (if any)	None, derivative of VENUS R-400EPS which has flown.
Commercially available	NO
Last updated	07/2022



Property	Value
Power	150-350 Watt
Thrust (Xe)	5-15 mN
Isp (Xe)	800-1200 sec
Propellant	Xe, Kr
Total Impulse (Xe)	> 200 kNs

[1]

Additional comments:

[Reference 1][Jan 2021][Thruster development/flight]
Recently, Rafael has been developing the R-200EPS, a full Hall thruster based EP system in the 150-350W power range. The R-200EPS is an improved derivative of the R-400 EPS (in orbit aboard the VENUS satellite), and consists of a low power thruster unit, based on hall thruster and hall cathode, PPU, and a propellant management assembly (PMA). Rafael's heritage and experience in high volume of production was implemented in the R-200EPS. To overcome the low mass utilization efficiency issues associated with low power Hall thrusters, the R-200HT includes a non-conventional configuration. The thruster consists of co-axial anodes and an elongated discharge channel. The co-axial anode configuration creates radial electric fields in the near anode region. This electric field pattern repels the ions towards the discharge channel center in the ionization region and lowers the ion flux into the walls.
Early Development Models (DM) and Engineering Models (EM) of the R-200 underwent a development program that included proof of concept tests, experimental and numerical validation of physical mechanisms, wall material selection, performance testing, thruster engineering model structural, thermal, and magnetic simulations followed by an engineering model production, as well as full performance mapping. Following these development phases, a Qualification model (QM) of the thruster was produced. The R-200-QM Hall thruster is presently at the end of a meticulous qualification program that included steady state performance characterization, ignition tests, shock and vibration tests, and post shock and vibration test operation. To date the thruster successfully passed all qualification tests.
The R-200 thruster, as part of the R-200 EPS, is scheduled for launch in 2021/2022.
The cathode that accompanies the R-200 thruster is the R-200 ARC-1A. The ARC-1A will soon start a lifetime experiment with the R-200 Hall thruster, and will undergo steady state operation of over 1,000 hrs and performance several hundred ignitions.

References:
[1] Lev, D., Zimmerman, R., Shoor, B., Appel, L., Ben-Ephraim, M., Herscovitz, J., Epstein, O., "Electric propulsion activities at Rafael in 2019," IEPC-2019-600.
[2] Lev, D., Franco, D., Zimmerman, R., Tordjman, M., Auslender, B., Epsteain, O., "96 kN-sec endurance test of the R-200 low power hall thruster," IEPC-2022-399
[3] Lev, D., Franco, D., Auslender, B., Epstein, O., "Extension of the operation envelope of the R-200 low power hall thruster," IEPC-2022-357

NO	5	NO
Comm. avail.	TRL	Aerospace-tested

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R-200/R-200EPS [2 of 2]

Additional comments:

[Reference 1][July 2022][Thruster testing]
The R-200 low power Hall thruster unit passed a 96 kNs endurance test in which it operated at one operation point of 250 W (275 V) while anode mass flow rate adjusted to maintain constant power. The test was performed at Rafael, while the initial performance validation was conducted at ESTEC. At the end of the endurance test the thruster exhibited excellent performance and did not reach its end-of-life. Throughout the endurance test performance was measured 5 times in the 100-250 W discharge power range, ceramic channel profile was measured 6 times to assess the erosion rate, thrust was continuously tracked multiple times a day, an ignition test was conducted twice (0 kNs and 60 kNs) and sensitivity to operational parameters was checked twice (12 kNs and 65 kNs). Two notable events occurred during the test – a cathode keeper breach and a ceramic channel breach. The keeper electrode was replaced, and cathode position adjusted. After the ceramic channel breach the thruster continued to operate regularly, and with no performance degradation, even after the inner pole was exposed to the plasma discharge. The thruster generated a constant thrust of 13 mN throughout the entire test while the Isp decreased from 1,250 sec at the beginning of life to 1,160 sec at the end of test. Performance degradation of less than 10% was spotted at all operation points in the 100-250 W discharge power range throughout the experiment. Both ignition tests were successful. Using channel profile geometry data a simple erosion model was constructed to predict possible breaching points and allow for an improved channel design. The information gathered during this endurance test campaign was used to redesign the cathode keeper and inner ceramic channel profile. A subsequent test of the improved thruster unit design showed an expected lifetime of over 200 kNs.

[Reference 2][July 2022][Thruster testing]
In the 200-600 W discharge power range the measured thrust was inversely proportional to the discharge voltage. The highest thrust was approximately 32.5 mN and was measured at 600 W with discharge voltage of 300 V. Specific impulse is proportional to the discharge voltage and power. The lowest measured specific impulse is approximately 980 sec at 200 W and 200 V while the highest is 1,850 sec at 600 W and 600 V as expected. Thrust efficiency at this power regime showed an increasing-decreasing behavior with the highest efficiency being 0.4 at a power level of 500 W. for the nominal discharge voltage of 300 V the efficiency does not drop below 0.3 for all of the examined high power levels.

References:
[1] Lev, D., Franco, D., Zimmerman, R., Tordjman, M., Auslender, B., Epsteain, O., “96 kN-sec endurance test of the R-200 low power hall thruster,” IEPC-2022-399
[2] Lev, D., Franco, D., Auslender, B., Epstein, O., “Extension of the operation envelope of the R-200 low power hall thruster,” IEPC-2022-357

NO	5	NO
Comm. avail.	TRL	Aerospace-tested

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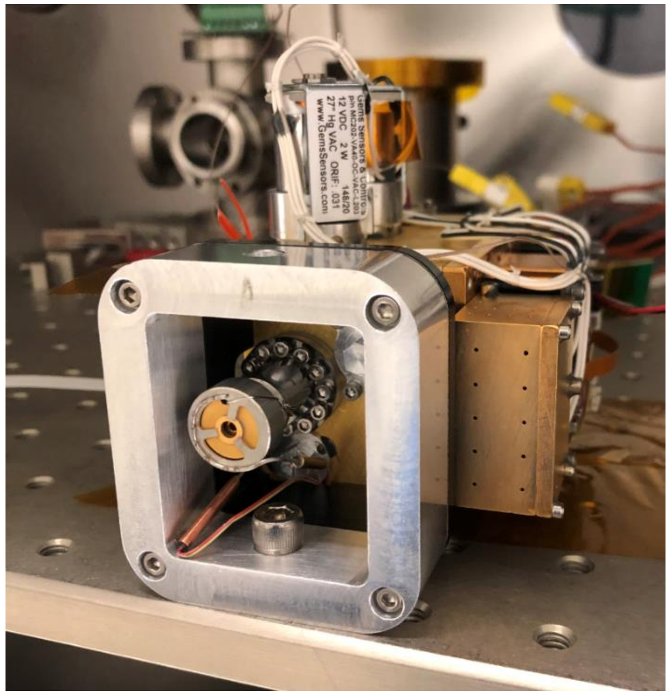
HyPer [1 of 2]

Propulsion Technology	Monopropellant Thruster
Manufacturer/Country	The Aerospace Corporation (USA)
TRL	5
Size (including PPU)	< 0.6U
Design satellite size	Small Sat, Slingshot is 12U
Isp (s)	~70 s (experimental), >200 s (theoretical)
Thrust type/magnitude	0.5 - 2 mN (experimental), 0.5 – 8 (theoretical)
Delta-V (m/s)	
Propellant	High-test Peroxide
Power consumption (W)	~3W [5]
Flight heritage (if any)	None, Slingshot mission (2022, projected) [5]
Commercially available	No
Last updated	10/2021



Additional comments:

[Reference 2][August 2020][Thruster Development]
Direct thrust measurements were completed on a novel hydrogen peroxide (H_2O_2) vapor thruster utilizing a torsional thrust stand. Liquid H_2O_2 temperature, nozzle exit angle, and nozzle contact design were varied to determine the impact to performance. Specific impulse was calculated using the measured thrust and mass flow rate. Results were compared with an equivalent water vapor system and demonstrated a 60% improvement in Isp. Both H_2O_2 and water thrusters showed losses associated with boundary layer formation within the nozzle. Additional losses due to thermal contact with the manifold were witnessed in the H_2O_2 version. Modifications to the nozzle design and isolation are expected to lead to further performance improvements.

[Reference 3][August 2019][Thruster Development]
Three catalyst materials are evaluated: silver mesh, platinum mesh, and 0.5% platinum on alumina spheres. Silver mesh resulted in the highest catalyst chamber temperatures, specifically when 3 - 7 sheets were compacted into the chamber. Sheet numbers outside this range resulted in lower temperatures. Heat transfer proved to be the primary concern in the system, with substantial effects on catalyst temperature and overall system performance. Finite element modeling was used to identify heat paths in the design and make improvements to decrease catalyst chamber heat loss.

[Reference 4][February 2019][Thruster Development]
A novel thruster concept for CubeSats and other small satellites using hydrogen peroxide vapor as a propellant is presented and evaluated. This concept leads to the highest theoretical vacuum specific impulse of any hydrogen peroxide system (greater than 200 s) while retaining the advantages of small size and simple construction typical of liquid monopropellant systems. For a nominally sized thruster, the theoretical thrust can be varied from 0.5 to 8 mN simply by changing the temperature of the tank in which the liquid hydrogen peroxide is stored. Theoretical performance parameters of liquid and vapor thrusters are compared. A prototype system (tank, heater, platinum catalyst, and nozzle) is constructed and tested.

References:

[1] https://aerospace.org/events/space-policy-show-innovative-space-showcase
[2] Rhodes, Brandie L., et al. “Thrust Measurement of a Hydrogen Peroxide Vapor Thruster.” Thrust Measurement of a Hydrogen Peroxide Vapor Thruster | AIAA Propulsion and Energy Forum, Aug. 2020.
[3] Rhodes, Brandie L., et al. “Small-Scale Hydrogen Peroxide Vapor Propulsion System: Catalyst Performance and Heat Transfer.” *Small-Scale Hydrogen Peroxide Vapor Propulsion System: Catalyst Performance and Heat Transfer | AIAA Propulsion and Energy Forum*, Aug. 2019.
[4] Rhodes, Brandie L., et al. “Dynamics of a Small-Scale Hydrogen Peroxide Vapor Propulsion System.” Journal of Propulsion and Power, Feb. 2019.
[5] Rhodes, B., Piechowski, M., Hinkley, D., Ulrich, E., “HyPer – a green monopropellant for small satellite propulsion,” Small Satellite Conference 2021, SSC21-XI-02.

NO	5	
Comm. avail.	TRL	Aerospace-tested

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HyPer [2 of 2]

Additional comments:

[Reference 1][Oct 2021][Thruster testing]

HyPer has undergone various design changes in order to ensure its safety leading up to, and during launch on board Slingshot. The design of the thruster utilizes redundant o-ring seals at every interface, 5 psi and 100 psi pressure sensors, two solenoid valves in series, and incorporates vent relief valves in parallel to prevent any possibility of overpressurization. The unique Teflon™ PMD spans from the top of the tank (inlet into VRV pathways) to the bottom of the tank (inlet into manifold). The small 0.01 inch diameter holes allow only vapor or gas to enter into either pathway, ensuring that liquid would not become stuck in the manifold and forced out of the nozzle when the valves were opened.

Material compatibility has been tested for each component, along with the aluminum 1100 tank and manifold assemblies, to ensure maximum H_2O_2 compatibility and minimal decomposition. Thermal and structural analyses on the flight unit verified HyPer's ability to withstand the temperatures and vibrational profiles it would see on launch and onorbit. The G-10 standoff, thermally isolates HyPer from the bus panel, and the Delrin® PCB spacers, effectively isolate the electronics board from the heated tank.

HyPer has undergone various tests prior to integration including hydrostatic, leak, long term pressure rise, and performance. These tests increased confidence in the design and helped characterize HyPer's expected performance on-orbit. Structural and thermal modeling helped further understand the system and predict behavior.

Environmental testing requirements for thermal cycle and vibration were set by the bus provider, Blue Canyon Technologies. HyPer was tested both alone, and once integrated on the panel; passing both sets of tests.

After launch in early 2022, HyPer will begin its on-orbit campaign by testing out small pulses at propellant temperatures of 60°C, 70°C, and 80°C. After these initial check-out tests, various burn plans will be uploaded for HyPer to perform to fully characterize the thruster's capabilities. Position and velocity data taken from the 12U bus will be downlinked along with the thruster sensor data. Analysis of this data will allow for determination of thrust, specific impulse, and delta-V.

References:

[1] Rhodes, B., Piechowski, M., Hinkley, D., Ulrich, E., "HyPer – a green monopropellant for small satellite propulsion," Small Satellite Conference 2021, SSC21-XI-02.

NO	5	
Comm. avail.	TRL	Aerospace-tested

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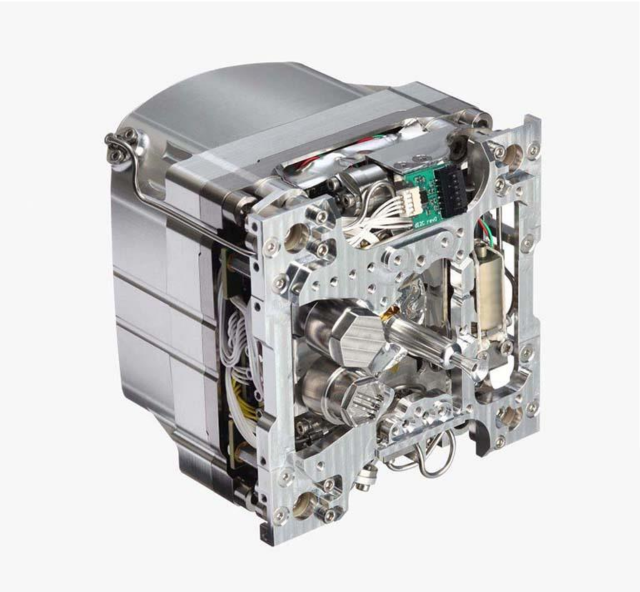
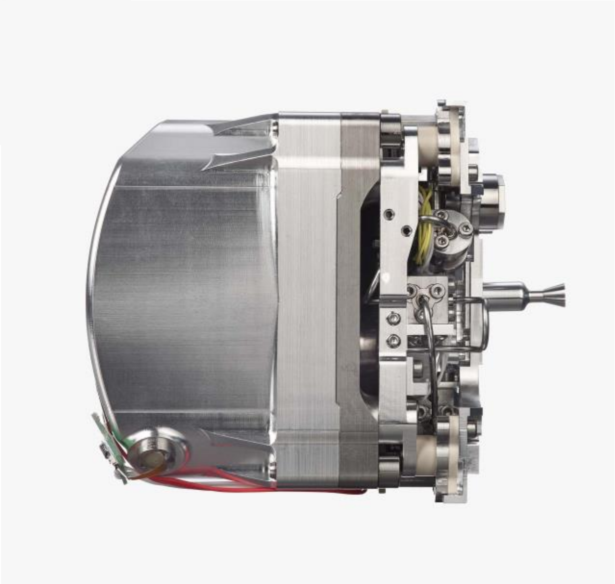
EPSS C1 configuration

Propulsion Technology	Green Monopropellant
Manufacturer/Country	NanoAvionics
TRL	4-5
Size (including PPU)	1.3U (also available in C2 and C3 configurations)
Design satellite size	3U+
Isp (s)	214s [1]
Thrust type/magnitude	1N BOL, 0.22 EOL [1]
Delta-V (m/s)	
Propellant	Ammonium Dinitramide blend [1]
Power consumption (W)	10W preheat, 1.7W firing [1]
Flight heritage (if any)	None
Commercially available	YES, lead time 12-14 months [1]
Last updated	05/2021



[1]



Additional comments:
[Reference 1][April 2021][Thruster information]
These specs refer to the C1 configuration. There are also C2 and C3 configurations.
NanoAvionics is the first aerospace company ready to offer a high-performance and environment-friendly CubeSat propulsion system, also suitable for small satellites. The system has the potential to unlock massive relaunch savings for satellite operators by an estimated 80%. The propulsion system is modular in design, permitting integration with multiple present and future small satellite platforms on the market. The system is designed to be easily scaled to optimize for the client mission by adjusting the volume of the tank to accommodate different propellant quantity needs. This system is fueled with ADN-based monopropellant which has up to 6% higher specific impulse and 24% higher energy density as compared to the hydrazine employed systems, permitting significant levels of thrust to be stored within a relatively small storage volume. In addition, EPSS allows high thrust-to-volume-to-weight ratio at very low power budget required making it very competitive and practically proven solution, even when compared with the electric (high Isp) propulsion. As ADN-based propellant is “green” its usage contributes to ESA’s and NASA’s clean space initiatives. Components such as valves, fuel tanks, propellant management system, and high-performance thrusters were designed, manufactured and supplied by NanoAvionics’ partners – globally trusted aerospace companies.

References:
[1] https://nanoavionics.com/cubesat-components/cubesat-propulsion-system-epss/

Comm. avail.	TRL	Aerospace-tested
	5	NO

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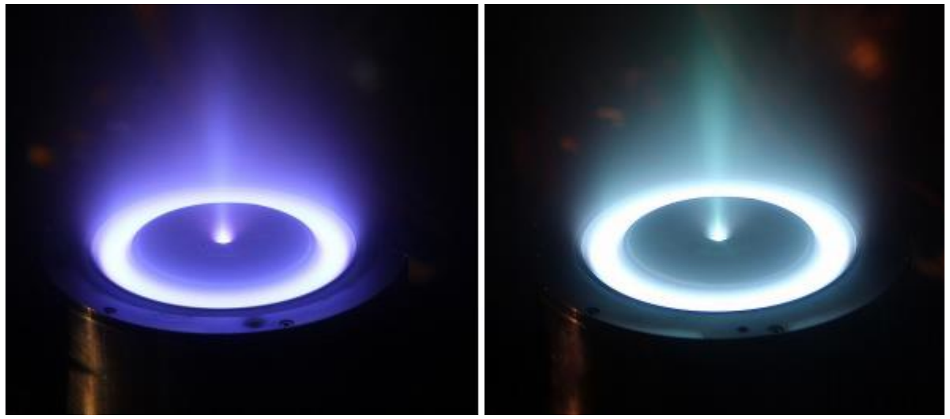
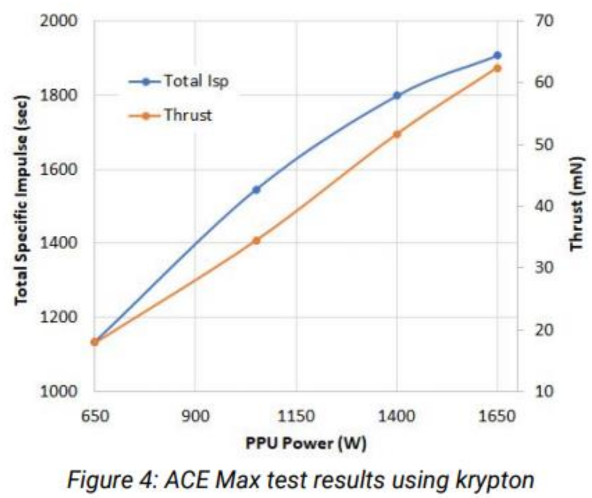
Astra Spacecraft Engine (ASE MAX) previously Apollo Constellation Engine Max (ACE Max), Apollo Fusion [1 of 2]

Propulsion Technology	Hall effect thruster
Manufacturer/Country	Apollo Fusion (USA), now ASTRA (USA)
TRL	4-5
Size (including PPU)	19.8 kg dry
Design satellite size	
Isp (s)	1760 s and 1.5 MN-s @ 1.4 kW (Xe) 1800 s and 1.5 MN-s @ 1.4 kW (Kr)
Thrust type/magnitude	60 mN @ 1.4 kW (Xe) 50 mN @ 1.4 kW (Kr)
Delta-V (m/s)	
Propellant	Xe/Kr (ACE Max is optimized for Kr operation)
Power consumption (W)	1.4 kW nominal (overall range 650 W to 1.8 kW)
Flight heritage (if any)	-
Commercially available	YES
Last updated	*11/2022*



ACE Max operating on Kr (left) and Xe (right) [2]

ACE Max thruster side profile [2]



ACE Max performance range on Kr [2]

Additional comments:

[Reference 1 - 3][March 2021][Overview]
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. ACE Max can be configured from 800W to 1.8kW but optimized for 1.4 kW operation on krypton. The HET also uses a instant-start, center mounted cathode.

The ACE Max is derived from the MaSMi thruster developed at NASA JPL. Specific performance details can be found in Ref. [3].

References:
[1] https://apollofusion.com/acemax.html
[2] https://apollofusion.com/datasheets/Apollo_ACE_Max_Datasheet-Jan_2021.pdf
[3] http://electricrocket.org/2019/283.pdf
[4]

5 NO

Comm. avail. TRL Aerospace-tested

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Astra Spacecraft Engine (ASE MAX) previously Apollo Constellation Engine Max (ACE Max), Apollo Fusion [2 of 2]

The ACE Max and ACE are technologically derived from the NASA JPL MaSMi thruster developed in 2011 [1 – 4]

[Reference 2][March 2021][Company news]
On May 7, 2019 Apollo Fusion, Inc. announced it has been awarded an exclusive, worldwide commercial license to NASA Jet Propulsion Laboratory's (JPL) MaSMi (Magnetically Shielded Miniature) Hall thruster, the world's first low-power (≤1.0 kW) magnetically shielded Hall thruster. MaSMi has demonstrated class-leading performance with a peak total efficiency of 54%, a peak total specific impulse of 1940 s, and an estimated throughput capability of >150 kg Xe. MaSMi is a key component of JPL's ASTRAEUS (Ascendant Sub-kW Transcelestial Electric Propulsion System), a low-power electric propulsion (EP) system optimized for use on smallsats. In support of ASTRAEUS, Apollo was awarded a contract to manufacture three engineering model MaSMi-EM thrusters for JPL this summer. Apollo is also designing a commercial version of this thruster called AXE (Apollo Xenon Engine) following an internal design-for-manufacturing process. The design-for-manufacturing improvements will enable AXE to be rapidly mass-manufactured for large constellation customers. Apollo CEO Mike Cassidy noted, "We're absolutely thrilled to be working with NASA JPL and with Dr. Ryan Conversano, the PI of ASTRAEUS and the inventor of MaSMi. The MaSMi thruster that we now have the exclusive license for can produce more than 2,000,000 Ns of total impulse and yet is about the size of a soda can. We've heard many times that our propulsion system's high performance coupled with our rapid, high-volume manufacturing is enabling new space missions and constellations. This new relationship with NASA JPL further demonstrates that Apollo can deliver for these new constellations."

In addition to the NASA JPL thruster that Apollo has licensed, the smaller Apollo Constellation Engine (ACE) provides outstanding performance at only 400 watts: 24 mN of thrust, 200,000 kN-s of total impulse, 4.5 kg of dry mass. This is about three times the total impulse per unit mass of any competitive propulsion system and about three times the total impulse per unit volume of any competitive propulsion system on the market today (for 50kg-500kg smallsats)

[Reference 2][March 2021][Company news]
December 16, 2020 – Saturn Satellite Networks Inc. has selected Apollo Fusion propulsion systems for Saturn's NationSat geostationary communications satellites. The Apollo 1.4 kW ACE Max propulsion system will be used for orbit transfer to geosynchronous orbit and on-orbit station keeping on 15 year missions. Saturn selected Apollo Fusion because Apollo's unique Electric Propulsion system supports the Saturn objectives to enable its NationSat small GEO sats to perform functions of much larger satellites, hence substantially reducing the barrier to spacecraft development and manufacturing

[Reference 6][June 2021][Company news]
Astra has announced the company's planned acquisition of Apollo Fusion in a transaction valued up to $145 million.
Under the agreement, Astra is acquiring Apollo Fusion for a purchase price of $50 million: $30 million in stock and $20 million in cash. Additionally, there is potential for earn-outs of up to $95 million: $10 million in employee incentive stock, $10 million in cash for reaching technical milestones, and $75 million ($60 million in stock, $15 million in cash) for reaching revenue milestones. PJT Partners is acting as financial advisor to Astra in connection with this series of transactions.

References:
[1] http://electricrocket.org/2019/283.pdf
[2] http://www.parabolicarc.com/2019/05/07/apollo-fusion-lands-nasa-jpl-license-manufacturing-contract/
[3] http://www.parabolicarc.com/tag/apollo-fusion/
[4] https://www.prnewswire.com/news-releases/apollo-fusion-inc-propulsion-systems-selected-by-saturn-satellite-networks-inc-301193712.html
[5] https://iopscience.iop.org/article/10.1088/1361-6595/ab47de/pdf
[6] https://smallsatnews.com/2021/06/12/launch-company-astra-announces-an-apollo-fusion-amalgam/

Comm. avail.	TRL	Aerospace-tested
	5	NO

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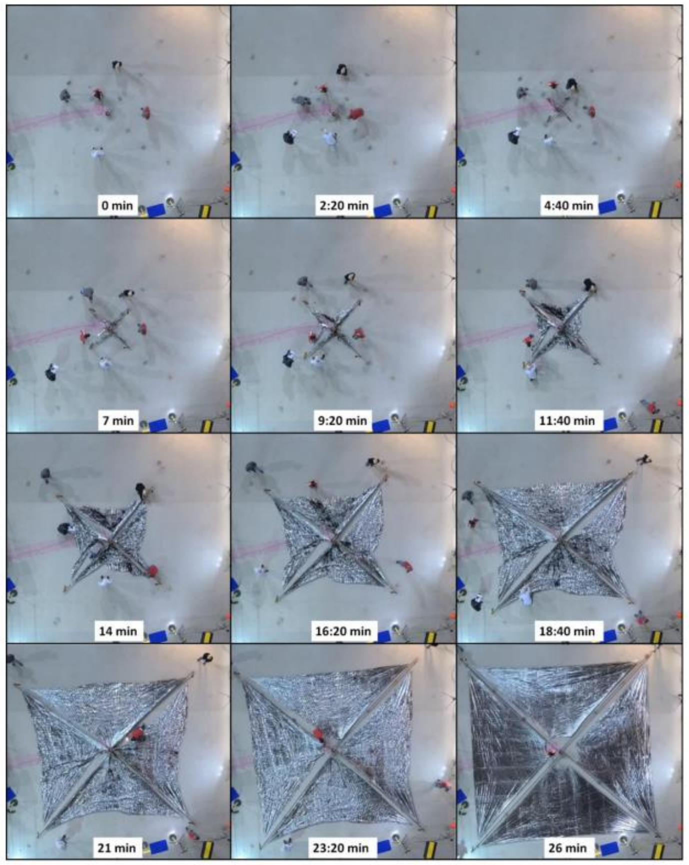
ACS3 Solar Sail

Propulsion Technology	Solar Sail
Manufacturer/Country	NASA (USA)
TRL	5-6
Size (including PPU)	
Design satellite size	ACS3 is 12U [1]
Isp (s)	n/a
Thrust type/magnitude	n/a
Delta-V (m/s)	n/a
Propellant	Propellantless
Power consumption (W)	
Flight heritage (if any)	None, to be flown on the ACS spacecraft, projected for mid to late 2022 [1]
Commercially available	NO
Last updated	12/2021



Deployment of the prototype unit [1]

Additional comments:

[Reference 1][Oct 2021][General information]

NASA's Space Technology Mission Directorate (STMD) is developing a new generation of compactly packageable composite booms designed specifically for small spacecraft applications where volumes for deployable structures are limited. NASA's Advanced Composite Solar Sail System (ACS3) will be the first spaceflight application of this boom technology. ACS3 will also be NASA's first practical solar sail. Objectives of the ACS3 project are to deploy an 80 m2 composite boom solar sail in low Earth orbit, and as an extended goal, demonstrate controlled solar sailing flight, including orbit raising and lowering. An overview of the ACS3 project and objectives, including descriptions of ACS3's solar sail structures and materials technology, 12U CubeSat spacecraft systems, and flight concept of operations, is provided here. Scalability of the ACS3 solar sail to future, near-term smallsat solar sailing mission requirements will also be discussed. Launch of ACS3 is currently anticipated for mid to late 2022.

[Reference 2][December 2021][Flight information]
Rocket lab USA, Inc. has been selected to launch NASA's ACS3, on their Electron launch vehicle, in mid-2022.

References:

[1] Wilkie, K., "The NASA Advanced Composite Solar Sail System (ACS3) Flight demonstration: a technology pathfinder for practical smallsat solar sailing," Small Satellite Conference 2021, SSC21-II-10.
[2] https://smallsatnews.com/2021/10/07/nasas-advanced-composite-solar-sail-system-to-be-deployed-via-a-rocket-lab-electron-launch-vehicle/

NO	5	NO
Comm. avail.	TRL	Aerospace-tested

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Plasma Processes AF-M315E Green Monoprop [1 of 2] PP3490-B/PP3490-D [3]

Propulsion Technology	Green Monoprop
Manufacturer/Country	Plasma Processes (Rubicon) (USA)
TRL	4-5
Size (including PPU)	<1U
Design satellite size	3U and larger
Isp (s)	195-208s [3]
Thrust type/magnitude	100 mN, 1N, 5N versions available [1]
Delta-V (m/s)	
Propellant	AF-M315E
Power consumption (W)	7.5 to 10W [3]
Flight heritage (if any)	Artemis-1 (see Lunar Flashlight) [3]
Commercially available	YES
Last updated	12/2023

[4]

Additional comments:

[Reference 1][Jun 2020][Company information]
Plasma Processes is located in Huntsville, Alabama and is a supplier of advanced materials solutions to commercial and government customers in the aerospace, defense, power generation, oil & gas, semi-conductor, and other key industries. They have expertise with high and ultra-high temperature materials, such as iridium, rhenium, tungsten, and molybdenum, and can apply coatings or create custom parts and powders using our advanced deposition processes.
In the area of liquid rocket engine subcomponents and coatings, they have experience with radiation cooled combustion chambers, non-toxic green propellant combustion chambers, regeneratively cooled combustion chambers, injector and faceplate coatings, catalyst beds and igniters, and nozzle extension coatings.
In the area of solid rocket motor subcomponents and coatings, they have experience with refractory metal subcomponents, ultra high temperature ceramic (UHTC) subcomponents, composite material subcomponents, and solid divert and attitude control system subcomponents.

[Reference 2][Jun 2020][Thruster and mission information]
The JPL-led Lunar Flashlight mission is manifested for Artemis-1, and will map the lunar south pole for volatiles. The mission will demonstrate several technological firsts, including being the first CubeSat to reach the Moon, the first planetary CubeSat mission to use green propulsion, and the first mission to use lasers to look for water ice. NASA-MSFC partnered with the Georgia Institute of Technology (GT) to build the Lunar Flashlight Propulsion System (LFPS), a self-contained unit that can deliver over 3000-Ns of total impulse for this mission. The LFPS is a pump-fed system that has four 100-mN ASCENT thrusters, built by Plasma Processes LLC., and a novel micro-pump built by Flight Works Inc. The LFPS system will undergo qualification testing in fall 2020.

References:
[1] https://plasmapros.com/markets/propulsion/
[2] NASA 2020 SOA for Small Satellites (POC Gabriel Benavides). https://www.nasa.gov/smallsat-institute/sst-soa-2020/in-space-propulsion
[3] Marshall, W., Cavender, D., Maynard, A., Zuttarelli, P., "State of the Art in Green Propulsion – 2020," JANNAF In-Space Chemical Propulsion TIM – September 2020, DISTRO A, Approved for public release.
[4] Email correspondence with plasma processes, POC Cheri McKechnie, April 2021

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Comm. avail.	TRL	Aerospace-tested

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Plasma Processes AF-M315E Green Monoprop [2 of 2]
PP3490-B/PP3490-D [3]

Additional comments:

[Reference 1][Dec 2023][5N thruster development]
Four 5N ASCENT thrusters entered hot fire acceptance testing in June 2023. Hot Fire Testing (HFT) verifies workmanship, performance characteristics, and conditions the thruster. HFT matrix was curated to only consume 10% of the thruster's rated life, preserving +90% (or 3kg) for the spacecraft's use. Data recorded during HFT to characterize thruster performance includes thrust, propellant flow rate, temperatures, pressures HD video and facility data. Specific impulse (Isp) was then calculated point-by-point from thrust and flow rate data.
The 5N LT Thrusters exhibited nominal thrust and flow rates at a nominal feed pressure of 20 bar. Continuous mode and pulsed mode testing was executed.
Rubicon is currently testing the 5N ASCENT thrusters in pump-fed operation on a flat-sat to support development of an Orbital Maneuvering Vehicle (OMV) as a part of a NASA Phase II SBIR with FLightWorks Inc. Two of the thrusters from the program have been delivered to NASA as part of a Green Propulsion STTR. The 5N thruster is planned to undergo a two-thruster qualification program with the goal of qualifying the design for 5 kg of ASCENT propellant.

References:
[1] Lentz, A., Cavender, D., Kilcoin, M., Daniel, N., "A review of the Rubicon space systems 5N low throughput ASCENT thruster development," SSC23-P2-16.

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Comm. avail.	TRL	Aerospace-tested

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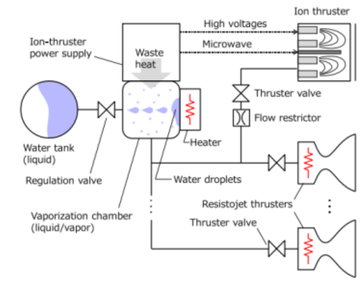
Water-based Resistojet + Ion Thruster System (KIR) [1 of 3]
Pale Blue Inc.

Propulsion Technology	Resistojet and Ion thruster
Manufacturer (Country)	Pale Blue Inc. (JAP) / Univ. of Tokyo
TRL	7 – 8 (resistojet) / 6 – 7 (ion thruster), complete system estimated at TRL 5-6
Size (including PPU)	1U (resistojet) / >1U (ion thruster), total volume 3U and ~3.7 kg dry + 1.25 kg water [3]
Design satellite size	Nano/Micro Sats (6U/10 kg)
Isp (s)	74 s (resistojet) / 500 s (ion thruster) [7]
Thrust type/magnitude	200 mN/kW (or about 1 mN per 4 nozzles for 4 mN total) (resistojet) and 140 µN (ion thruster) [7]
Delta-V (m/s)	450 – 360 m/s (ion thruster only, model results [3])
Propellant	Water
Power consumption (W)	5 – 20 W (resistojet) / 30 W (ion thruster) [7]
Flight heritage (if any)	Launched in 2019 ISS demo (AQUARIUS resistojet) / ion thruster has not flown Integrated into RAISE-3, demonstration JAXA satellite, launched 2023, but encountered a launch failure. [7, 8]
Commercially available	Yes
Last updated	*12/2023*



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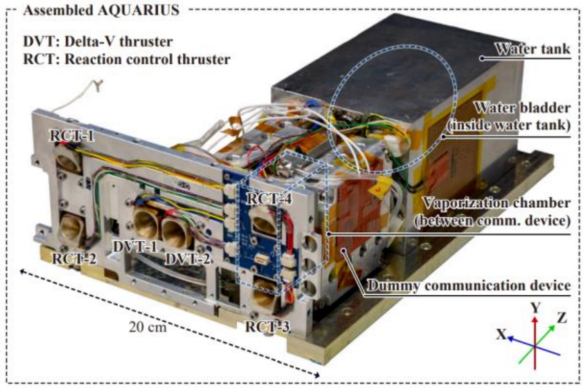

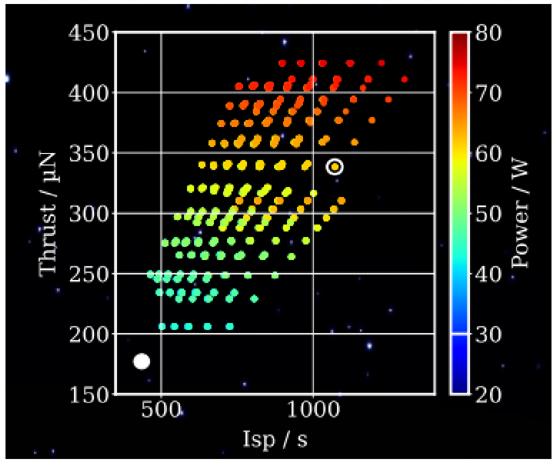

Ion thruster performance [8]

Additional comments:

References and notes on next chart….

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Water-based Resistojet + Ion Thruster System [2 of 3]
Pale Blue Inc.

Additional comments:

[Reference 2][Sep 2020][Overview]
Pale Blue Inc. is the commercial arm of University of Tokyo's water-based EP systems. University of Tokyo propose the use of a resistojet + ion thruster combined EP system to maximize the use of water as a propellant. Pale Blue is actively working on realizing this dual-device EP system. Water has been regarded as an attractive propellant in the view points of safety, availability, handling ability, low molecular mass, and future procurement in space. A multimode propulsion system is an attractive solution for the increasing demand for nano-/microsatellite missions. The proposal is to use microwave discharge water ion thrusters, tolerant for oxidization by water, and low-temperature water resistojet thrusters, enabling reuse of the waste heat. As a result of the assessment, it was expected that the propulsion system would have 3U size (10 × 10 × 30 cm3) and 3.70 kg mass, which realize in total a 6U and 10 kg satellite with 3U and 6 kg satellite bus system. The ion thruster would provide the maximum ΔV of 630 m/s by 47W system power and the resistojet thruster would have 3.80 mN thrust and 72 s specific impulse by 19.4 W. Additionally, reuse of the waste heat from ion-thruster power supplies would enable the simultaneous operations of the two thrusters even at 50 W, which is almost the same power as the single ion thruster operation
Reference [2] states the Pale Blue ion thruster prototype is designed off of a ion thruster with flight heritage from Univ of Tokyo (based on picture it is the I-COUPS). This could mean that the I-COUPS ion thruster is being commercialized via Pale Blue Inc for future smallsat missions.
Based on [4] the water based resistojet is based on the flown AQUARIUS resistojet. As of SmallSat 2020, only the resistojet had achieved flight heritage aboard an ISS tech demo mission and the integrated resistojet + ion thruster water system was being developed [2].

[Reference 6][March 2021][Company info]
Jun Asakawa is the CEO of Pale Blue. The company plans to hire several more specialists, each with expertise in a different field, to accelerate development with a 10-member team by the end of 2021.

References:
[1] https://pale-blue.co.jp/services.html
[2] https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=4859&context=smallsat
[3] https://arc.aiaa.org/doi/pdfplus/10.2514/1.A34407
[4] https://www.jstage.jst.go.jp/article/tjsass/63/4/63_T-19-61/_pdf/-char/ja
[5]https://reader.elsevier.com/reader/sd/pii/S0094576517317496?token=A0FF09BA07AEB72593598D504A37AAE825381EE163DC16 0F9A7CBE315A4E221CEF05B2B3B3B9CBEABC855C14A22B816C
[6] https://www.u-tokyo.ac.jp/focus/en/features/entrepreneurs04.html
[7] Nakagawa, Y., Yaginuma, K., Asakawa, J., Koizumi, H., "1U+ water ion and resistojet thruster module for on-orbit demonstration," IEPC-2022-276
[8] Ominetti, P., Tomita, D., Iwakawa, A., Nakagawa, Y., Yaginuma, K., Asakawa, J., "Development of water gridded ion thruster for small satellites: towards on-orbit demonstration," Small Satellite Conference, SSC23-P4-27.

5	NO
Comm. avail.	TRL	Aerospace-tested

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Water-based Resistojet + Ion Thruster System [3 of 3]
Pale Blue Inc.

Additional comments:

[Reference 1][July 2022][Thruster development and flight information]
KIR (Kakushin-3 Ion and Resistojet thruster) is a 1U+ (90 x 120 x 120 mm3) module for on-orbit demonstration of a water ion thruster and a water resistojet thruster. It is installed on RAISE-3, which is the demonstration satellite organized by JAXA. In RAISE-3, seven components for small satellites and CubeSats are installed, and KIR is one of them. These share the bus system and conduct each technological demonstration. RAISE-3 is to be launched by Epsilon rocket by Mar. 2023.
The development of KIR was completed, and it passed all the tests for shipping to JAXA. The water ion thruster is 150 µN of the thrust, 500 s of the specific impulse, and 28 W of the average power. Also, the resistojet thruster is 0.8 – 1.0 mN per nozzle of the thrust, ~ 40 s of the specific impulse, and 23 W of the averaged power when one nozzle generating the thrust.

[Reference 2][Dec 2023][Ground testing]
Despite the RAISE-3 launch failure, the thruster has fully passed random, sine, and shock tests, as well as TVAC, and has been performance characterized.

References:
[1] Nakagawa, Y., Yaginuma, K., Asakawa, J., Koizumi, H., “1U+ water ion and resistojet thruster module for on-orbit demonstration,” IEPC-2022-276
[2] Ominetti, P., Tomita, D., Iwakawa, A., Nakagawa, Y., Yaginuma, K., Asakawa, J., “Development of water gridded ion thruster for small satellites: towards on-orbit demonstration,” Small Satellite Conference, SSC23-P4-27.

Comm. avail.	TRL	Aerospace-tested
	5	NO

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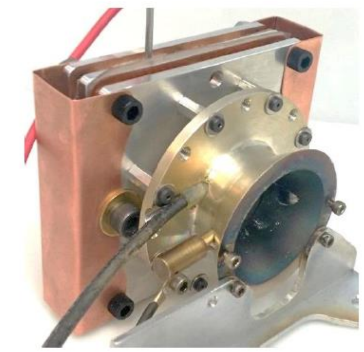
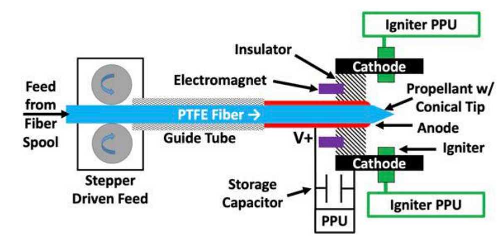
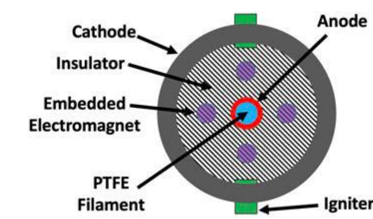
Fiber-fed pulsed plasma thruster (FPPT) [1 of 2]

Propulsion Technology	PPT
Manufacturer/Country	CU Aerospace (USA)
TRL	4-5
Size (including PPU)	1000 cm^3 (1U) [1], 1.7U tested [7]
Design satellite size	3U or larger DUPLEX is 6U [4]
Isp (s)	960-2400s [1, 6], 3500s at 0.6 mN [7]
Thrust type/magnitude	0.4 mN at 48W [6], 5500 N*s total impulse [1, 6] 0.6 mN at 78W, with 28,000 N*s total impulse [7]
Delta-V (m/s)	600 to 1000 m/s for a 5 kg CubeSat [1]
Propellant	PTFE [1]
Power consumption (W)	30 to 175W, 48W (nominal) [1], 78W tested [7]
Flight heritage (if any)	Slated for NASA Tipping Point “DUPLEX”, 2023 [4,5,7]
Commercially available	YES, Available as a 1.7U unit with <9 mth lead time [6]
Last updated	12/2023

Item	Estimated “Flight” FPPT Performance
Propulsion system dimensions	9.0 x 8.76 x 21.7 cm^3
Propulsion system volume	1,711 cm^3
Survival temperature range	– 35°C to + 80°C
Propellant	PTFE (Teflon), 2.2 g/cc storage density
Power to FPPT system when firing	48 W (1.5 Hz)
Capacitor Bank Energy	32 J
PPU efficiency	~0.75 (3 Hz, improves at lower rates)
Duty Cycle	TBD (est. 1 Hz continuous operation)
Propellant Mass	827 g
Dry Mass	1,975 g
Total propulsion wet mass	2,802 g
Nominal mass flow rate	0.010 mg/s
Total thrust time	2.6 years
Specific Impulse	3,500 s
Thrust @ 48 W	0.33 mN
Thrust/Power	7 μN/W
Thrust Vectoring	Est. ±10° pitch and yaw (roll capability TBD)
Total impulse	28,000 N-s
Volumetric total impulse	16,600 N-s/liter
Spacecraft ΔV, M(initial) = 10.5 kg	2,820 m/s







[7]

Additional comments:
[Reference 1, 2, 3][Oct 2019][Thruster information]
The FPPT feed system adapts the feed system from the Monofilament Vapor Propulsion system, and employs COTS 3D printer mechanical drive components well described and tested by Woodruff, et al. Spooled PTFE fiber is fed into the thrust chamber through a tubular anode, using a stepper motor to control feed rate. The capacitive ESU is charged and a current pulse is initiated by the pulsed igniter discharge. Fuel is vaporized and electromagnetically and electrothermally accelerated out of the cathode volume, which then returns to a vacuum state, and the cycle repeats.
[Reference 4,5][June 2020][Thruster development and flight]
They (CU Aerospace) will receive $1.7 million from NASA to build and test a six-unit CubeSat equipped with two different propulsion systems. “DUPLEX will test two of CU Aerospace’s thrusters in space to provide flight heritage for these new, innovative systems, significantly lowering risk for future customers while dramatically raising the Technology Readiness Level,” says David L. Carroll, CU Aerospace founder and current president. NearSpace Launch will be responsible for the CubeSat bus, power system, radios, and much of the electronics. The delivery of the DUPLEX spacecraft to NanoRacks is anticipated in February 2022 for future launch.
DUPLEX will fly the MVP and FPPT systems.

References:
[1] Woodruff, C., King, D., Burton, R., Bowman, J., Carroll, D., “Development of a fiber-fed pulsed plasma thruster for small satellites,” SSC19-WKVIII-06
[2] Woodruff, C., King, D., Burton, R., Carroll, D., “Fiber-fed pulsed plasma thruster (FPPT) for small satellites,” IEPC-2019-A899
[3] Woodruff, C., King, D., Burton, R., and Carroll, D., “Fiber-Fed Advanced Pulsed Plasma Thruster (FPPT),” U.S. Patent # 10,570,892, Feb. 25, 2020.
[4] https://aerospace.illinois.edu/news/nasa-funds-long-standing-partners-cubesat-development
[5] Small Sat 2020, public virtual forum
[6] https://cuaerospace.com/products-services/space-propulsion-systems/fiber-fed-pulsed-plasma-thruster-fppt
[7] Woodruff, C., Parta, M., King, D., Burton, R., Carroll, D., “Fiber-fed pulsed plasma thruster (FPPT) with multi-axis thrust vectoring,” IEPC-2022-558

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NO

Comm. avail. TRL Aerospace-tested

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Fiber-fed pulsed plasma thruster (FPPT) [2 of 2]

Additional comments:

[Reference 1][June 2020][Flight information]
In 2019, CU Aerospace was selected for a NASA STMD Tipping Point award to design, fabricate, integrate, and perform mission operations for the DUPLEX 6U CubeSat having two of CUA's micro-propulsion systems on board, one Monofilament Vaporization Propulsion (MVP) and one Fiber-Fed Pulsed Plasma Thruster (FPPT). The MVP is an electrothermal device that vaporizes and heats an inert solid polymer propellant fiber to 1100 K. The novel approach for propellant storage and delivery addresses common propellant safety concerns, which often limit the application of propulsion on low-cost CubeSats. In-orbit operations will include inclination change, orbit raising and lowering, drag makeup, and deorbit burns demonstrating multiple mission capabilities with approximately 20 hours of operation for MVP and >1,000 hours for FPPT. Launch is anticipated in mid-2022.

[Reference 2][Aug 2022][Thruster development and flight information]
A 1.7U FPPT with 28,000 N-s of total impulse is being fabricated and assembled for flight integration in CUA's NASA-funded Dual Propulsion Experiment (DUPLEX) CubeSat, presently manifested for launch in Q1 2023. This 1.7U FPPT system configuration has a 26 J energy storage unit (ESU) that can operate at 78 Watts (3 Hz) producing a mean thrust of 0.60 mN with a specific impulse of 3,500 s and an efficiency of 13%. The system will also include thrust vectoring electronics. This mission will provide flight heritage for FPPT, increase the system TRL to 8-9, and encourage customer acceptance of this new propulsion system.

References:

[1] NASA 2020 SOA for Small Satellites (POC Gabriel Benavides). https://www.nasa.gov/smallsat-institute/sst-soa-2020/in-space-propulsion

Comm. avail.	5	NO
	TRL	Aerospace-tested

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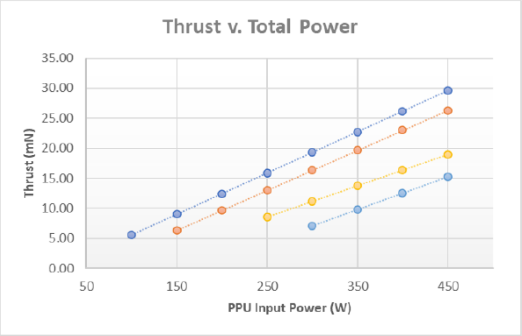
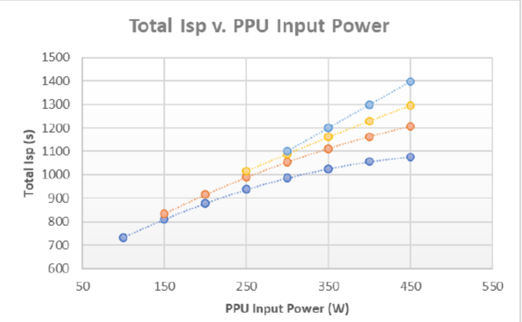
Exoterra Halo

Propulsion Technology	Hall Effect thruster
Manufacturer/Country	Exoterra (USA)
TRL	3-4
Size (including PPU)	0.75kg
Design satellite size	6U to ESPA
Isp (s)	730 to 1400s [1]
Thrust type/magnitude	4 to 30 mN [1]
Delta-V (m/s)	
Propellant	Xenon or Krypton
Power consumption (W)	125 to 450W [1]
Flight heritage (if any)	None Projected for first flight Q4 2022. [3]
Commercially available	YES
Last updated	08/2022





Requirement	Value	Requirement	Value
Discharge Power	~300 W, nominal	Operational Lifetime	4,000 h
Thrust	≥ 14 mN, goal of 20 mN	Total Impulse	300 kN-s
Specific Impulse	≥ 1,100 s	Cathode Start Cycles	10,000

[3]

Additional comments:
[Reference 1][Oct 2021][Thruster information]
Exoterra was founded in 2011.
Halo weighs 0.75 kg and fits within a 76 mm diameter by 50 mm long envelope, which is half the mass of competing Hall thrusters.
The Halo thruster and PPU have completed environmental testing to NASA GEVS load profiles. Life testing is ongoing with a projected lifetime of 4000 hrs. First flight is scheduled for 1W22, with follow-on flights in 2Q22 and 3Q22.
[Reference 2][Aug 2022][Thruster information and testing]
In this work a 400 W Hall-effect thruster was tested at a single setpoint for 1,000 hours. Periodic measurements of the ceramic discharge channel and pole cover parts were made over the course of the test. The method of measurement was 3D point cloud scans of a rubber injection mold of the same shape and form as the plasma-wetted volume of the discharge channel. Analysis of these channel and pole cover measurements indicate maximum erosion rates of 700 to 800 μm/kh on the outer and inner pole covers, respectively, and no erosion on the discharge channel. Further examination of the thicknesses of the pole covers revealed a life-limiting thickness on the inner pole. Assuming constant erosion rate at this location, the thruster lifetime is estimated to be at minimum 6,000 hours at the tested setpoint. Hall2De simulation results showing good agreement with the locations of erosion on the pole covers are also presented.
[Reference 3][Aug 2022][Thruster testing]
This electric propulsion system can provide 5-30 mN of thrust, up to 1,475 s of specific impulse and over 440 kN-s of total impulse. The Halo Electric Propulsion System has successfully completed a flight qualification program, flight hardware has been delivered and the first spaceflight of the system is slated for the fourth quarter of 2022.

References:
[1] https://exoterracorp.com/products/electric-propulsion-systems/
[2] Glascock, M., VanWoerkom, M., “Channel erosion measurements and predictions in a 400W hall thruster,” IEPC-2022-300.
[3] Glascock, M., Kiefer, E., VanWoerkom, M., “Performance and capability overview of the Halo electric propulsion system,” IEPC-2022-301.

Comm. avail.	5 TRL	NO Aerospace-tested

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mHET (MUSIC)

Propulsion Technology	Hall effect thruster
Manufacturer (Country)	Aliena (SGP)
TRL	4 to 5
Size (including PPU)	~3U
Design satellite size	CubeSats
Isp (s)	>1000 s [7]
Thrust type/magnitude	3 - 6 mN
Delta-V (m/s)	
Propellant	Krypton
Power consumption (W)	90W – 170W (discharge power only [2])
Flight heritage (if any)	MUSIC-Self-Ignition (MUSIC-SI) launched on NuX-1 mission (Jan 2022) [4, 5, 6, 7] Slated to be launched on demo mission 2023 and operational mission 2025 [7]
Commercially available	Yes
Last updated	*08/2022*

From [1]

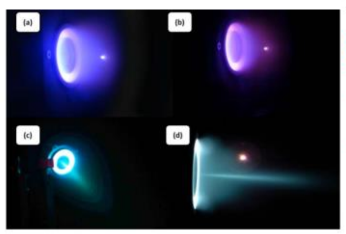
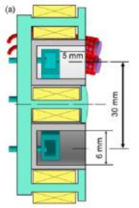
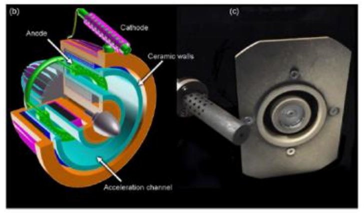


Fig. 3. Photographs of Hall thruster discharges with various propellants. (a) Krypton. (b) Argon. (c) Xenon, frontal view. (d) Xenon, side view.





From [2]

Additional comments:

[Reference 1][September 2020][Overview]
Aliena Pte Ltd is a Singapore-based EP startup which specializes in developing and manufacturing plasma-thruster systems for the small satellite market. On November 2019, Aliena raised $1.1 million USD in an investment round led by Cap Vista, the strategic venture investment arm of Singapore's Defence Science and Technology Agency. At the moment, they have website with company updates stating that they have established a Jet Propulsion Test Facility onsite in order to support EP product testing. On the website [1], they only have their mHET as product for sale. From company press release updates, it is clear that Aliena has an mHET prototype and have a video of a thruster firing.
I speculate that the mHET is actually based on the miniature krypton based HET from reference [2].
[Reference 2][September 2020][Performance]
Assuming thruster mHET is that of the small Kr-based HET in ref [2], the performance of the thruster is as follows: 3 – 6 mN, discharge voltages in the range of 165 V – 225 V, and discharge current in the range of 0.55 – 0.8 A.

References:
[1] https://www.aliena.sg/product
[2] Lim, J., Levchenko, I., Huang, S., Xu, L., Sim, R., Yee, J., Potrivitu, G., Sun, Y., Bazaka, K., Wen, X., Gao, J., Xu, S., "Plasma parameters and discharge characteristics of lab-based krypton-propelled miniaturized Hall Thruster," Plasma Sources Science and Technology, Vol, 28, 2019.
[3] https://momentus.space/wp-content/uploads/2020/06/Momentus-NuSpace-Aliena-Press-Release.pdf
[4] https://www.nanosats.eu/sat/nux-1
[5] https://space.skyrocket.de/doc_sdat/nux-1.htm
[6] https://smallsatnews.com/2022/01/19/hall-thruster-from-aliena-pte-ltd-empowers-nuspaces-nux-1-smallsat/
[7] Laterza, M., Potrivitu, G., Agarwal, D., Khoo, K., Pontianus, N., Lim, J., Eunseo, E., Supriyadi, S., Chenyi, L., Liau, L., Ramachandran, P., Teo, C., Ng, Z., Tsang, S., Teo, H., "Multi-stage ignition compact thruster concept and testing," IEPC-2022-294.

5 | NO
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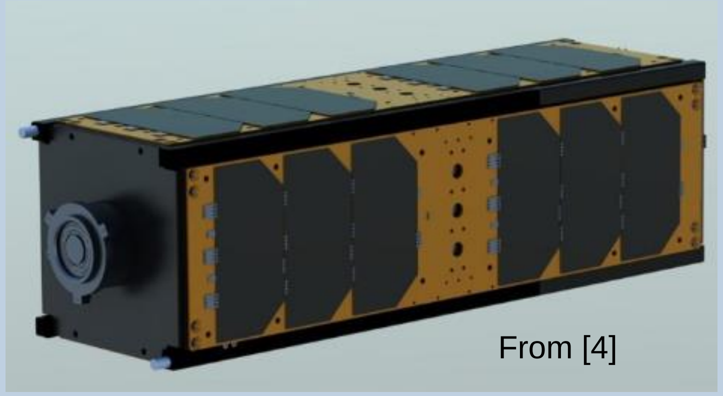
mHET (MUSIC)

Additional comments:

[Reference 1][September 2020][Press Release]

Aliena thruster to fly in space aboard NuX-1 cubesat in 2021 through Momentus.

Momentus, provider of in-space transportation services for satellites, today announced a launch service agreement with Singapore-based companies, NuSpace and Aliena. Momentus' Vigoride orbital transfer vehicle will carry the NuX-1 3U nanosatellite to its final orbit, after launching onboard a SpaceX Falcon 9 rocket from Vandenberg, California during the first quarter of 2021. NuX-1 is a demonstration satellite recently announced by NuSpace in partnership with Aliena. It will demonstrate autonomous orbit control maneuvers using **Aliena's ultra-low power miniature Hall-thruster** – a first for CubeSats of that size – as well as NuSpace's Attitude Determination & Control Systems (ADCS) that comes equipped with an autonomous orbit control system. The nanosatellite will also carry an Internet-of-Things (IoT) payload for NuSpace and constitute the pathfinder for NuSpace's planned IoT constellation.


From [4]

[Reference 2, 3][Feb 2022][Flight information]
The Hall thruster was integrated on a 3U smallsat — NuX-1 — made and owned by satellite IoT company NuSpace, and was brought to orbit by a SpaceX Falcon 9 via the Transporter-3 mission. The Hall thrusters that were developed for this mission are GEO-Hall thrusters that are sub-10 W class systems that were designed specifically to cater to meet the most demanding smallsat operations.
The GEO-Hall thrusters were designed to operate below the 10 W regime and have demonstrated capability to fit within extremely small form-factors, thereby heralding new potential opportunities for nanosatellites to consider the utilization of such systems for emerging missions and operations. Aliena has achieved a milestone reduction in power consumption for Hall thrusters through the utilization of a novel ignition and neutralization scheme developed internally. Additionally, this novel system allows for instant-ignition of the systems without requirement for the engines to be in a hot-standby mode or for warm-up cycles prior to firing, which are common drawbacks of systems that utilize active cathode neutralizers or solid fuel. This unique feature enables more agile operations to be executed through on-demand propulsion while not compromising on the form-factor and power budgets of the satellites, making it an extremely attractive option for small satellite operators through provision of more payload volume, and power budgets to be diverted for actual operations.

(No on-orbit data is available yet)

References:
[1] https://www.spacetechasia.com/singapore-startups-nux-1-cubesat-to-be-orbited-via-momentus-spacex/
[2] https://smallsatnews.com/2022/01/19/hall-thruster-from-aliena-pte-ltd-empowers-nuspaces-nux-1-smallsat/
[3] https://smallsatnews.com/2022/01/13/smallest-satellite-deployed-in-space-hosts-a-hall-thruster-provided-by-singapores-aliena/

5	NO
Comm. avail.	TRL	Aerospace-tested

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mHET (MUSIC)

Additional comments:

[Reference 1][Aug 2022][Thruster development]
The MUlti-Stage Ignition Compact thruster is a Hall derived propulsion system designed to allow a variety of neutralization options enabling it to operate between 10 W and 100 W of total power. The design philosophy centers around a quick pipeline to flight and rapid prototyping, where focus is placed on flight readiness first and performance optimization later. The first model to be flown was the Self Ignition, with an estimated thrust to power ratio of 10μN/W without the need of an external neutralizer. A Hot Mode version designed to operate at 100 W was tested delivering a total specific impulse above 1000 s, in line with expectations, but a lower thrust to power ratio than initially expected. The Hot Mode thruster will be launched on a technology demonstrator mission slated in Q1 2023 and on an operational mission scheduled for Q1 2025. A Carbon Nanotube Field-Emission Neutralizer is being developed for intermediate powers between 20 W and 50 W.

[Reference 2][Aug 2022][Thruster qual]
The thruster, an early version of the MUSIC-SI (MUlti-Stage Ignition Compact – Self-Ignition) Hall thruster, underwent a series of qualification campaigns that involved vibration tests for standalone structural verification and thermal vacuum cycling (TVAC) tests with a power processing unit (PPU). The thruster successfully passed the vibration and TVAC test campaigns and proved unchanged discharge characteristics during the post-vibration tests. Overall, the thruster accumulated close to 1000 hours of firing.

References:
[1] Laterza, M., Potrivitu, G., Agarwal, D., Khoo, K., Pontianus, N., Lim, J., Eunseo, E., Supriyadi, S., Chenyi, L., Liau, L., Ramachandran, P., Teo, C., Ng, Z., Tsang, S., Teo, H., "Multi-stage ignition compact thruster concept and testing," IEPC-2022-294.
[2] Khoo, K., Laterza, M., Potrivitu, G., Lim, J., "Novel cathodeless and very low-power hall thruster: qualification and integration on a 3U platform for an in-orbit demonstration mission," IEPC-2022-326.

	5	NO
Comm. avail.	TRL	Aerospace-tested

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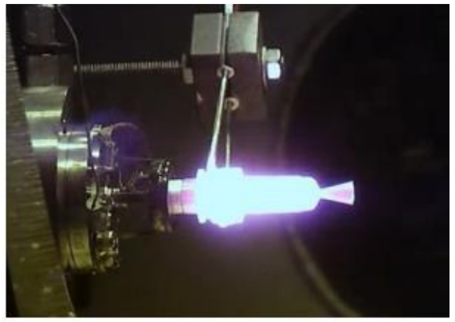
SPRITE 100-mN ASCENT thruster system

Propulsion Technology	Green monoprop (ASCENT)
Manufacturer/Country	Plasma Processes (Rubicon) (USA)
TRL	5
Size (including PPU)	1.5U, 2kg wet mass [1]
Design satellite size	Small Satellite
Isp (s)	235 s [1]
Thrust type/magnitude	100 mN [1]
Delta-V (m/s)	100 m/s to a 12U CubeSate [1]
Propellant	ASCENT (AFM-315E)
Power consumption (W)	7-9W [1]
Flight heritage (if any)	None (a heritage version flew on Lunar Flashlight, but this version incorporates significant design and process changes from Lunar Flashlight lessons learned)
Commercially available	Yes
Last updated	12/2023

Parameter	Requirement	Value
Thrust Range	> 90 mN	30-220 mN
Pulse Mode Thrust	> 90 mN	100 mN
Steady State Isp	> 190 sec	235 sec
Pulse Mode Isp	> 190 sec	214 sec
Min. Impulse Bits	< 5 mNs	3.6 mN
Response Time	< 150 ms	70 ms
Decay Time	< 300 ms	100 ms
Throughput	> 530 g	> 3 kg
Acc. Burn Time	> 3.5 hours	17+ hours
Longest Burn	N/A	101 mins
Heater Power	< 10 W	7-9 W

Figure 11: Clyde, the protoflight unit



Additional comments:

[References 1][Dec 2023][General information]
The 0.1N thruster was designed and developed under SBIR contracts with NASA. As it demonstrated a high level of technical maturity and thorough hot fire test performance, it was selected and used for the Lunar Flashlight mission (2022-2023). Twelve 0.1N thrusters were delivered as part of a SBIR Phase III award, and flight qualification was completed. Since then, the thruster has demonstrated over eight times its qualification throughput with ongoing test campaigns that further explore the thruster's capabilities. As of early 2023, one article has demonstrated over 17 hours of continuous firing and over 3 kg of total throughput.
To demonstrate and qualify the new module, four units of Sprite began development to pioneer assembly and integration processes, perform structural testing, demonstrate performance characteristics, and support a protoflight article. Taking inspiration from the original Pac-Man game, the four Sprite development units were named 'Inky', 'Blinky', 'Pinky', and 'Clyde' after the ghost sprites.

References:
[1] Kilcoin, M., Cavender, D., Daniel, N., Lentz, A., "Sprite, a modular template of in-space propulsion," Small satellite conference SSC23-VI-09.

5 NO

Comm. avail. TRL Aerospace-tested

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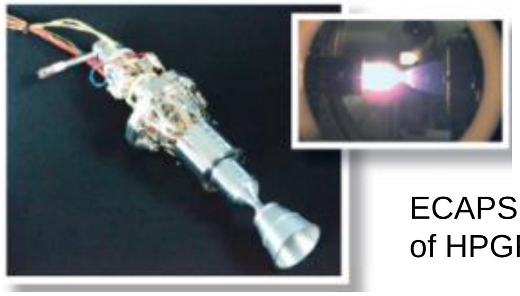
High Performance Green Propellant, 100 mN model (HPGP-100mN) [1 of 2]
ECAPS/Bradford Engineering/Orbital ATK

Propulsion Technology	ADN monopropellant, (hydrazine substitute)
Manufacturer/Country	ECAPS(Ecological Advanced Propulsion Systems)/Bradford Engineering (SWEDEN) and Orbital ATK/Northrop Grumman (US)
TRL	4-5 for 100 mN model
Size (including PPU)	<0.5U (55 mm excluding the flow control valve)
Design satellite size	Various sizes
Isp (s)	~209s [6]
Thrust type/magnitude	100 mN model: 30-100 mN (thrust range), 5 mN*s (impulse, minimum)
Delta-V (m/s)	~60 m/s to PRISMA (~200 kg) s/c, ~180 m/s to SkySat (~120 kg) s/c [these numbers from the 1N model]
Propellant	LMP-103S (ADN mixture)
Power consumption (W)	6.3 to 8W
Flight heritage (if any)	None to date
Commercially available	YES
Last updated	*03/2021*

- Coil Resistance (each coil)	Ω 40
Nominal Reactor Pre-heating Voltage	9 VDC
Regulated Reactor Ore-heating Power	6.3 - 8 W
Target Life - Qual. Level	
Pulses	2,000
Propellant Throughput	1 kg
Longest Continues Firing	18 minutes
Accumulated Firing Time	5 hours
Firing Sequences	150
Demonstrated Life	
Pulses	6,696
Propellant Throughput	0.4 kg
Longest Continues Firing Time	30 minutes
Accumulated Firing Time	2.3 hours
Firing Sequences	128

Thruster Type	HPGP
Propellant	LMP-103S
Thrust Class	100 mN
Primary Operational Mode	Δ v
Inlet Pressure Range	2.3 - 4.5 Bar
Thrust Range	30 - 100 mN
Nozzle Expansion Ratio	100:1
Steady State ISP (vacuum) Typical	192 - 2050 Ns/Kg (196 - 209 s)
Density Impulse (vacuum)	2387 - 2542 Ns/L
Minimum Impulse Bit	≤ 5 mNs
Overall Length	55 mm ec. FCV
Mass	0.040 kg ex. FCV
FCV Type	Solenoid
- No of Seats	Single Seat
- Pull-in Voltage	10 ± 2.5 VDC
- Holding Voltage	3.3 VDC

[6]



ECAPS offers several different sizes of HPGP thruster

Additional comments:

[References 1-5] [October 2018][General information about the 1N missions]

Manufacturer reports PRISMA successfully demonstrated 8% higher performance using HPGP than hydrazine on orbit.

ECAPS was selected to provide 19 complete 1N HPGP systems for Planet's constellation of SkySat Earth observation satellites. Five SkySat satellites with HPGP systems have been operational in orbit since 2016, and 6 additional SkySat satellites with HPGP systems launched in 2017. The 1N system is space qualified with 46 thrusters currently in-orbit. Eleven Earth imaging satellites with ECAPS High Performance Green Propulsion (HPGP) systems are being flown by Planet (previously Skybox Imaging and Terra Bella). SkySat- 3 was launched in June 2016 from the Satish Dhawan Space Centre on Antrix's PSLV, SkySat-4 through SkySat-7 were launched in September 2016 from the Guiana Space Centre on Arianespace's Vega, and SkySat-8 through 13 were launched in October 2017 from Vandenberg Air Force Base on Orbital ATK's Minotaur-C. Each spacecraft's HPGP system has been successfully commissioned and is operating nominally in orbit. Combined the HPGP systems have accumulated 12.8 years on-orbit, executed 118 maneuvers, and imparted 110 m/s of V. ECAPS is currently expanding its portfolio of thrusters to include 5N, 22N, and 220N thrusters. HPGP and HPGP thrusters are available through Orbital ATK in the US.

References:

[1] Dinardi, A., Anflo, K., Friedhodd, P., "On-Orbit Commissioning of High-Performance Green Propulsion (HPGP) in the SkySat Constellation," 31st Annual AIAA Conference on Small Satellites, SSC17-X-04.

[2] Friedhoff, P., Anflo, K., Persson, M., Thormahlen, P., "Growing Constellation of ADN based high performance green propulsion (HPGP) systems," AIAA JPC, 2018.

[3] Krejci, D., Lozano, P., "Space Propulsion Technology for Small Spacecraft," Proceedings of the IEEE, 2018.

[4] Friedhoff, P., Hawkins, A., Carrico, J., Dyer, J., "On-Orbit Operation and Performance of ADN based HPGP systems," AIAA JPC, 2017.

[5] http://ecaps.space/assets/pdf/Bradford_ECAPS_Folder_2017.pdf, http://ecaps.space/products-100mn.php, https://www.orbitalatk.com/defense-systems/missile-products/HPGP/Docs/HPGP%20Fact%20Sheet%20APPROVED%20OSR%2015-S-2043%20072115.pdf

[6] https://www.ecaps.space/products-100mn.php

4	NO
Comm. avail.	TRL	Aerospace-tested

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High Performance Green Propellant, 100 mN model (HPGP-100mN) [2 of 2]
ECAPS/Bradford Engineering/Orbital ATK

Additional comments:

[Reference 1] [December 2020][Mission information]

Integrated small satellite modules using the 100mN HPGP are also offered in conjunction with VACCO as part of their MiPS (Micro Propulsion System) within their CubeSat Propulsion line of products (www.cubesat-propulsion.com). The VACCO MiPS integrates arrays of 100mN HPGP and cold gas thrusters working in symphony to provide highly capable and highly modular microsatellite propulsion systems. VACCO MiPS and Bradford ECAPS 100mN HPGP are slated to be aboard an upcoming mission, ArgoMoon (www.cubesat-propulsion.com/argomoon-propulsion-system/) intended to be sent around the Moon to conduct scientific exploration.

References:
[1] https://www.ecaps.space/products-100mn.php

Comm. avail.	TRL	Aerospace-tested
	4	NO

DISTRO A: Approved for public release. OTR-2024-00338

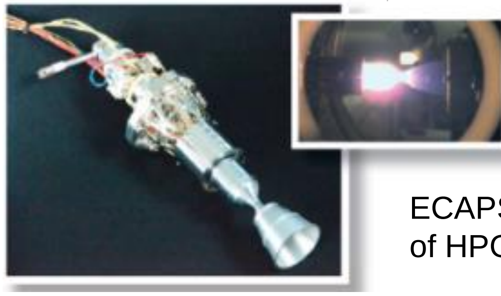
High Performance Green Propellant – 5N model (HPGP-5N) [1 of 2]
ECAPS/Bradford Engineering/Orbital ATK

Propulsion Technology	ADN monopropellant, (hydrazine substitute)
Manufacturer/Country	ECAPS(Ecological Advanced Propulsion Systems)/Bradford Engineering (SWEDEN) and Orbital ATK/Northrop Grumman (US)
TRL	4-5 for 5N model
Size (including PPU)	<1U (221 mm excluding the flow control valve)
Design satellite size	Various sizes
Isp (s)	253s [6]
Thrust type/magnitude	5N model: 1.5 to 5.5N, <0.1 N*s minimum impulse bit [6]
Delta-V (m/s)	~60 m/s to PRISMA (~200 kg) s/c, ~180 m/s to SkySat (~120 kg) s/c [these numbers from the 1N model]
Propellant	LMP-103S (ADN mixture)
Power consumption (W)	15 to 25W
Flight heritage (if any)	None to date
Commercially available	YES
Last updated	*03/2021*

Propellant	LMP-103S
Thrust Class	5 N
Primary Operational Mode	RCS + Δ v
Inlet Pressure Range	5.5 - 24 Bar
Thrust Range	1.5 - 5.5 N
Nozzle Expansion Ratio	150:1
Steady State ISP (vacuum) Typical	2345 - 2480 Ns/Kg (239 -253 s)
Density Impulse (vacuum)	2908 - 3075 Ns/L
Minimum Impulse Bit	≤0.1 Ns
Overall Length	221 mm
Mass	0.48 kg
FCV Type	Solenoid
- No of Seats	Dual Seat
- Pull-in Voltage	28 ± 4 VDC
- Holding Voltage	10 ± 1 VCD
- Coil Resistance (each coil)	72 Ω

Nominal Reactor Pre-heating Voltage	28 VDC
Regulated Reactor Ore-heating Power	15 - 25 W TBC
Target Life - Qual. Level	
Pulses	50,000
Propellant Throughput	100 kg
Longest Continues Firing	10 minutes
Accumulated Firing Time	20 hours
Firing Sequences	350
Demonstrated Life	
Pulses	10,000
Propellant Throughput	5 kg
Longest Continues Firing Time	60 seconds
Accumulated Firing Time	1 hour
Firing Sequences	115
Maturation Level	TRL 5

[6]



ECAPS offers several different sizes of HPGP thruster

Additional comments:

[References 1-5] [October 2018][General information about the 1N missions]

Manufacturer reports PRISMA successfully demonstrated 8% higher performance using HPGP than hydrazine on orbit.

ECAPS was selected to provide 19 complete 1N HPGP systems for Planet's constellation of SkySat Earth observation satellites. Five SkySat satellites with HPGP systems have been operational in orbit since 2016, and 6 additional SkySat satellites with HPGP systems launched in 2017. The 1N system is space qualified with 46 thrusters currently in-orbit. Eleven Earth imaging satellites with ECAPS High Performance Green Propulsion (HPGP) systems are being flown by Planet (previously Skybox Imaging and Terra Bella). SkySat- 3 was launched in June 2016 from the Satish Dhawan Space Centre on Antrix's PSLV, SkySat-4 through SkySat-7 were launched in September 2016 from the Guiana Space Centre on Arianespace's Vega, and SkySat-8 through 13 were launched in October 2017 from Vandenberg Air Force Base on Orbital ATK's Minotaur-C. Each spacecraft's HPGP system has been successfully commissioned and is operating nominally in orbit. Combined the HPGP systems have accumulated 12.8 years on-orbit, executed 118 maneuvers, and imparted 110 m/s of V. ECAPS is currently expanding its portfolio of thrusters to include 5N, 22N, and 220N thrusters. HPGP and HPGP thrusters are available through Orbital ATK in the US.

References:

[1] Dinardi, A., Anflo, K., Friedhodd, P., "On-Orbit Commissioning of High-Performance Green Propulsion (HPGP) in the SkySat Constellation," 31st Annual AIAA Conference on Small Satellites, SSC17-X-04.
[2] Friedhoff, P., Anflo, K., Persson, M., Thormahlen, P., "Growing Constellation of ADN based high performance green propulsion (HPGP) systems," AIAA JPC, 2018.
[3] Krejci, D., Lozano, P., "Space Propulsion Technology for Small Spacecraft," Proceedings of the IEEE, 2018.
[4] Friedhoff, P., Hawkins, A., Carrico, J., Dyer, J., "On-Orbit Operation and Performance of ADN based HPGP systems," AIAA JPC, 2017.
[5] http://ecaps.space/assets/pdf/Bradford_ECAPS_Folder_2017.pdf, http://ecaps.space/products-100mn.php, https://www.orbitalatk.com/defense-systems/missile-products/HPGP/Docs/HPGP%20Fact%20Sheet%20APPROVED%20OSR%2015-S-2043%20072115.pdf
[6] https://www.ecaps.space/products-5n.php

4

NO

Comm. avail. TRL Aerospace-tested

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High Performance Green Propellant – 5N model (HPGP-5N) [2 of 2]
ECAPS/Bradford Engineering/Orbital ATK

Additional comments:

[Reference 1] [December 2020][Thruster test information]

The 5N HPGP thruster is currently undergoing a test fire campaign with the NASA Goddard Space Flight Center, characterizing the performance of the thruster. The 5N HPGP is being examined for potential use for an interplanetary mission, where it will provide a key maneuver and orbit-insertion capability.

References:

[1] https://www.ecaps.space/products-5n.php

	4	NO
Comm. avail.	TRL	Aerospace-tested

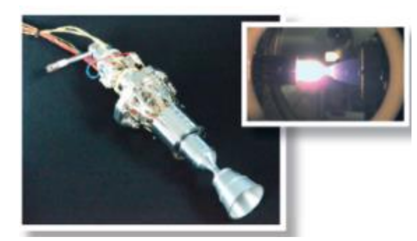
DISTRO A: Approved for public release. OTR-2024-00338

High Performance Green Propellant – 22N model (HPGP-22N) [1 of 2]
ECAPS/Bradford Engineering/Orbital ATK

Propulsion Technology	ADN monopropellant, (hydrazine substitute)
Manufacturer/Country	ECAPS(Ecological Advanced Propulsion Systems)/Bradford Engineering (SWEDEN) and Orbital ATK/Northrop Grumman (US)
TRL	4-5 for 22N model
Size (including PPU)	<1U (260 mm excluding the flow control valve)
Design satellite size	Various sizes
Isp (s)	255s [6]
Thrust type/magnitude	22N model: 5.5 to 22N, <0.44 N*s minimum impulse bit [6]
Delta-V (m/s)	~60 m/s to PRISMA (~200 kg) s/c, ~180 m/s to SkySat (~120 kg) s/c [these numbers from the 1N model]
Propellant	LMP-103S (ADN mixture)
Power consumption (W)	25 to 50W
Flight heritage (if any)	None to date
Commercially available	YES
Last updated	*03/2021*

Propellant	LMP-103S
Thrust Class	22 N
Primary Operational Mode	RCS + Δ v
Inlet Pressure Range	5.5 - 24 Bar
Thrust Range	5.5 - 22 N
Nozzle Expansion Ratio	150:1
Steady State ISP (vacuum) Typical	2385 - 2500 Ns/Kg (243 -255 s)
Density Impulse (vacuum)	2957 - 3100 Ns/L
Minimum Impulse Bit	≤0.44 Ns
Overall Length	260 mm
Mass	1.1 kg
FCV Type	Solenoid
- No of Seats	Dual Seat
- Pull-in Voltage	28 ± 4 VDC
- Holding Voltage	10 ± 1 VCD
- Coil Resistance (each coil)	64 Ω

Nominal Reactor Pre-heating Voltage	28 VDC
Regulated Reactor Ore-heating Power	25 - 50 W TBC
Target Life - Qual. Level	
Pulses	50,000
Propellant Throughput	150 kg
Longest Continues Firing	45 minutes
Accumulated Firing Time	7.6 hours
Firing Sequences	350
Demonstrated Life	
Pulses	26,481
Propellant Throughput	53 kg
Longest Continues Firing Time	38 minutes
Accumulated Firing Time	3 hours
Firing Sequences	282
Maturation Level	TRL 5/6



[6]

ECAPS offers several different sizes of HPGP thruster

Additional comments:

[References 1-5] [October 2018][General information about the 1N missions]

Manufacturer reports PRISMA successfully demonstrated 8% higher performance using HPGP than hydrazine on orbit.

ECAPS was selected to provide 19 complete 1N HPGP systems for Planet's constellation of SkySat Earth observation satellites. Five SkySat satellites with HPGP systems have been operational in orbit since 2016, and 6 additional SkySat satellites with HPGP systems launched in 2017. The 1N system is space qualified with 46 thrusters currently in-orbit. Eleven Earth imaging satellites with ECAPS High Performance Green Propulsion (HPGP) systems are being flown by Planet (previously Skybox Imaging and Terra Bella). SkySat- 3 was launched in June 2016 from the Satish Dhawan Space Centre on Antrix's PSLV, SkySat-4 through SkySat-7 were launched in September 2016 from the Guiana Space Centre on Arianespace's Vega, and SkySat-8 through 13 were launched in October 2017 from Vandenberg Air Force Base on Orbital ATK's Minotaur-C. Each spacecraft's HPGP system has been successfully commissioned and is operating nominally in orbit. Combined the HPGP systems have accumulated 12.8 years on-orbit, executed 118 maneuvers, and imparted 110 m/s of V. ECAPS is currently expanding its portfolio of thrusters to include 5N, 22N, and 220N thrusters. HPGP and HPGP thrusters are available through Orbital ATK in the US.

References:
[1] Dinardi, A., Anflo, K., Friedhodd, P., "On-Orbit Commissioning of High-Performance Green Propulsion (HPGP) in the SkySat Constellation," 31st Annual AIAA Conference on Small Satellites, SSC17-X-04.
[2] Friedhoff, P., Anflo, K., Persson, M., Thormahlen, P., "Growing Constellation of ADN based high performance green propulsion (HPGP) systems," AIAA JPC, 2018.
[3] Krejci, D., Lozano, P., "Space Propulsion Technology for Small Spacecraft," Proceedings of the IEEE, 2018.
[4] Friedhoff, P., Hawkins, A., Carrico, J., Dyer, J., "On-Orbit Operation and Performance of ADN based HPGP systems," AIAA JPC, 2017.
[5] http://ecaps.space/assets/pdf/Bradford_ECAPS_Folder_2017.pdf, http://ecaps.space/products-100mn.php, https://www.orbitalatk.com/defense-systems/missile-products/HPGP/Docs/HPGP%20Fact%20Sheet%20APPROVED%20OSR%2015-S-2043%20072115.pdf
[6] https://www.ecaps.space/products-22n.php

Comm. avail.	4 TRL	NO Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

High Performance Green Propellant – 22N model (HPGP-22N) [2 of 2]
ECAPS/Bradford Engineering/Orbital ATK

Additional comments:

[Reference 1] [December 2020][Thruster test information]

The 22N HPGP thruster is currently undergoing a test fire campaign with the NASA Goddard Space Flight Center, characterizing the performance of the thruster. This is intended to prepare the 22N HPGP thruster for use on future NASA missions, such as observatory or interplanetary science missions.

References:

[1] https://www.ecaps.space/products-22n.php

	4	NO
Comm. avail.	TRL	Aerospace-tested

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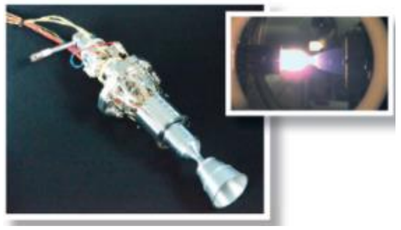
Green Propellant – 1N model (GP-1N) [1 of 2]
ECAPS/Bradford Engineering/Orbital ATK

Propulsion Technology	ADN monopropellant, (hydrazine substitute)
Manufacturer/Country	ECAPS(Ecological Advanced Propulsion Systems)/Bradford Engineering (SWEDEN) and Orbital ATK/Northrop Grumman (US)
TRL	4-5 for 1N model
Size (including PPU)	<1U (178 mm excluding the flow control valve)
Design satellite size	Various sizes
Isp (s)	227s [6]
Thrust type/magnitude	1N model: 0.25 to 1N, <0.07 N*s minimum impulse bit [6]
Delta-V (m/s)	~60 m/s to PRISMA (~200 kg) s/c, ~180 m/s to SkySat (~120 kg) s/c [these numbers from the 1N HPGP model]
Propellant	LMP-103S (ADN mixture) “LMP-103S/LT” [6]
Power consumption (W)	8 to 10W
Flight heritage (if any)	None to date
Commercially available	YES
Last updated	*03/2021*

Thruster Type	GP
Propellant	LMP-103S/LT
Thrust Class	1 N
Primary Operational Mode	Δ v
Inlet Pressure Range	4.5 - 22 Bar
Thrust Range	.25 - 1 N
Nozzle Expansion Ratio	100:1
Steady State ISP (vacuum) Typical	1900 - 2230 Ns/Kg (194 - 227 s)
Density Impulse (vacuum)	2318 - 2721 Ns/L
Minimum Impulse Bit	≤ 70 mNs
Overall Length	178 MM
Mass	0.38 KG
FCV Type	Solenoid
- No of Seats	Dual Seat

- Pull-in Voltage	28 ± 4 VDC
- Holding Voltage	10 ± 1 VCD
- Coil Resistance (each coil)	190 Ω
Nominal Reactor Pre-heating Voltage	28 VDC
Regulated Reactor Ore-heating Power	8 - 10 W
Target Life - Qual. Level	
Pulses	12,000
Propellant Throughput	5 - 8 kg
Longest Continues Firing	5 minutes
Accumulated Firing Time	5 hours
Firing Sequences	200
Demonstrated Life	
Pulses	4,272
Propellant Throughput	1.2 kg
Longest Continues Firing Time	5 minutes
Accumulated Firing Time	1.5 hours
Firing Sequences	55
Maturation Level	TRL 4/5

[6]



ECAPS offers several different sizes of HPGP thruster

Additional comments:

[References 1-5] [October 2018][General information about the 1N missions]

Manufacturer reports PRISMA successfully demonstrated 8% higher performance using HPGP than hydrazine on orbit.

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References:

[1] Dinardi, A., Anflo, K., Friedhodd, P., “On-Orbit Commissioning of High-Performance Green Propulsion (HPGP) in the SkySat Constellation,” 31st Annual AIAA Conference on Small Satellites, SSC17-X-04.
[2] Friedhoff, P., Anflo, K., Persson, M., Thormahlen, P., “Growing Constellation of ADN based high performance green propulsion (HPGP) systems,” AIAA JPC, 2018.
[3] Krejci, D., Lozano, P., “Space Propulsion Technology for Small Spacecraft,” Proceedings of the IEEE, 2018.
[4] Friedhoff, P., Hawkins, A., Carrico, J., Dyer, J., “On-Orbit Operation and Performance of ADN based HPGP systems,” AIAA JPC, 2017.
[5] http://ecaps.space/assets/pdf/Bradford_ECAPS_Folder_2017.pdf, http://ecaps.space/products-100mn.php, https://www.orbitalatk.com/defense-systems/missile-products/HPGP/Docs/HPGP%20Fact%20Sheet%20APPROVED%20OSR%2015-S-2043%20072115.pdf
[6] https://www.ecaps.space/products-1ngp.php

Comm. avail.	4 TRL	NO Aerospace-tested

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Green Propellant – 1N model (GP-1N) [2 of 2]
ECAPS/Bradford Engineering/Orbital ATK

Additional comments:

[Reference 1] [December 2020][General thruster information]
Bradford ECAPS's 1N GP Thruster is designed for attitude and orbit control of small-sized satellites. This in-development model is a variant of the 1N HPGP Thruster demonstrated aboard the PRISMA spacecraft and the SkySat series, for cost-critical missions where affordability takes priority over performance.

Non-toxic propellant makes for easier and less costly integration on secondary or 'piggy-back' missions.
Propellant loading is simple, fast and avoids the cost associated with loading hydrazine. Allows the operator to spend less time on ground operations and more time on space operations.
'Fuel at the factory' – be ready for launch vehicle integration upon arrival at the launch pad.
Allows for more secondary or 'piggy-back' launch opportunities, especially missions where there is concern about the hazards of hydrazine and its risks to the primary payload.
Allows for more capable missions than spacecraft without propulsion.
Allows for more agile mission profiles than electric propulsion. Spacecraft take significantly less time to execute maneuvers and orbit changes.
Although not as high as the 1N HPGP , the 1N GP still provides equivalent to greater performance and storage density over hydrazine.
Less costly thruster system (equivalent to hydrazine) allows for lower cost system build.
The 1N GP thrusters can be provided individually or as an integrated system. For instance, each SkySat propulsion system consisted of four 1N HPGP thrusters along with tanks, flow regulators and other avionics.

References:
[1] https://www.ecaps.space/products-1ngp.php

Comm. avail.	TRL	Aerospace-tested
	4	NO

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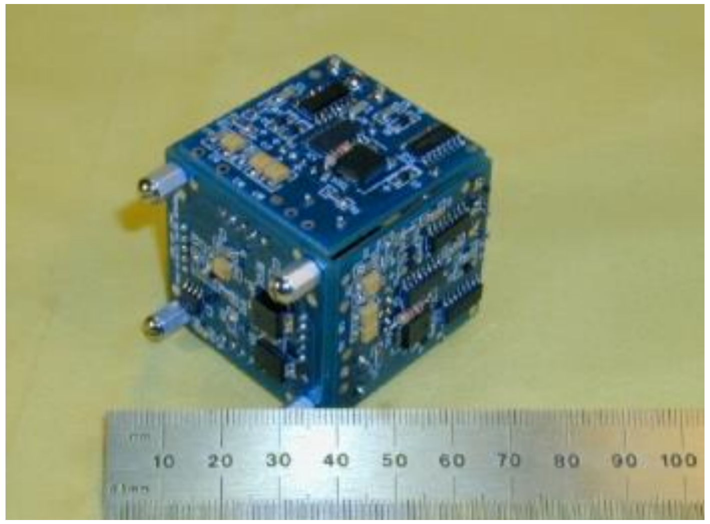
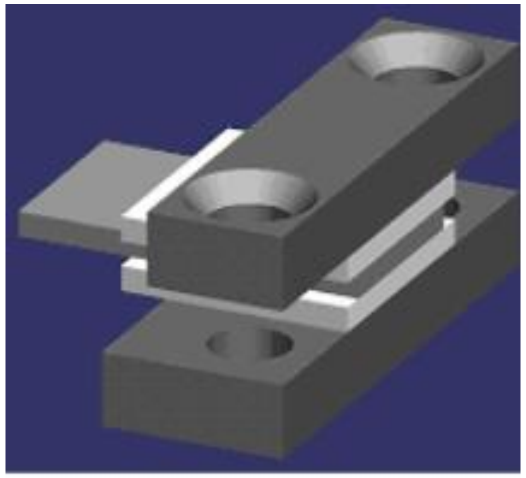
Micro Vacuum Arc Thruster (μVAT)
University of Illinois UC, Alameda Applied Science Corporation

Propulsion Technology	Vacuum Arc thruster
Manufacturer/Country	University of Illinois Urbana Champaign/ Alameda Applied Science Corporation (US)
TRL	4 Lab-tested with ground test data. Flown but no on-orbit data reported.
Size (including PPU)	<1U (<300g)
Design satellite size	2U
Isp (s)	~1000 s (up to 3000 s [4])
Thrust type/magnitude	Impulse, from 50 nN*s to 30 uN*s Up to 100 uN [4]
Delta-V (m/s)	Not reported
Propellant	Aluminum frame, spacecraft body
Power consumption (W)	4W
Flight heritage (if any)	Flown on 2U CubeSat in 2006 aboard the Illinois Observing NanoSatellite (ION)
Commercially available	Unknown
Last updated	*03/2021*


PPU designed for use aboard ION



Vacuum arc micro-thrusters (VAμT)
--Dark Gray Metal--
Main Frame (Cathode)
--White Ceramic--
Insolator
--Light Gray--
Arc Producing Metal (Anode)


VAT thruster, open view

Additional comments:

[References 1-4][Jan 2019][General info]
Thruster has been tested on the ground, and thrust vs. power curves have been generated. The ION NanoSatellite was constructed and tested by student engineers.

[Reference 5][Jan 2019][Mission info]
The ION (Illinois Observing Nanosatellite) has two primary technology missions. First, it is to test an experimental low thrust, electric propulsion system which was designed and built in a joint effort with Alameda Applied Sciences Corp (AASC). The second primary mission is to utilize a Photomultiplier Tube (PMT) to observe airglow phenomenon in the Earth's upper atmosphere. In addition to these two primary missions, ION will also conduct a number of secondary objectives. It will demonstrate the space use of a singleboard computer donated by Tether Applications, Inc. (TAI). Additionally, ION will perform a feasibility study investigating the use of an onboard complimentary metaloxide semiconductor (CMOS) imaging system for star tracking and earth photography. ION will also demonstrate the use of an active magnetic attitude system. Finally, ION will have the option of being used as a space based Bulletin Board System (BBS) or digipeater to be used by ham radio operators around the planet. The launch was not successful, as the Dnepr failed 86 sec after launch.

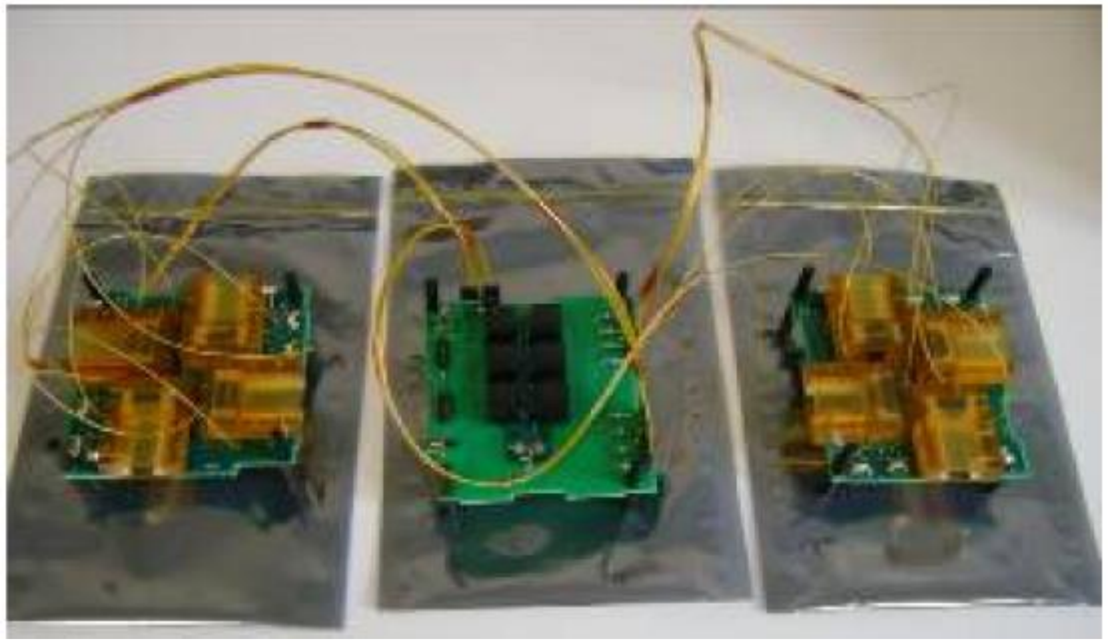
References:
[1] Schlein, J., Gerhan, A., Rysanek, F., et al. "Vacuum Arc Thruster for CubeSat Propulsion," IEPC.
[2] http://cubesat.ece.illinois.edu/Payload.html
[3] Krejci, D., Lozano, P., "Space Propulsion Technology for Small Spacecraft," Proceedings of IEEE, 2018.
[4] Spektor, R., Fathi, G., Brady, B., Moore, T., "2011 Review of Propulsion Options for The Aerospace CubeSat Project," Aerospace TOR-2011(8582)-6
[5] https://space.skyrocket.de/doc_sdat/ion.htm

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Pulsed Plasma Thruster (PPT)
Surrey Satellite Technologies (SSTL)

Propulsion Technology	PPT
Manufacturer/Country	Surrey Satellite Technologies (SSTL) (UK)
TRL	4 Lab tests with ground test data. Flown but no on-orbit data reported.
Size (including PPU)	~0.25U
Design satellite size	3U
Isp (s)	1340s
Thrust type/magnitude	0.9 uN (impulse, average of impulse bits firing at 0.25 Hz)
Delta-V (m/s)	76 m/s
Propellant	Electrodes (tin-coated copper)
Power consumption (W)	1.5W
Flight heritage (if any)	Launched Feb 2013 aboard STRaND-1 from India on the PSLV C-20 (Polar Satellite Launch Vehicle)
Commercially available	Unknown
Last updated	*03/2021*



PPT bank flight modules

Additional comments:

[Reference 1-2][Jan 2019][Flight info]
Launched on same flight as the warm butane resistojet. Entire satellite was designed on a very low budget, in employee's spare time. System was successfully launched but vehicle failed to respond in orbit.

References:
[1] Mission information: http://space.skyrocket.de/doc_sdat/strand-1.htm
[2] Kenyon, S., Bridges, D., et al. "STRAND-1: Use of a $500 Smartphone as the Central Avionics of a Nanosatellite," 62nd international Astronautical Congress, Cape Town, SA, 2011.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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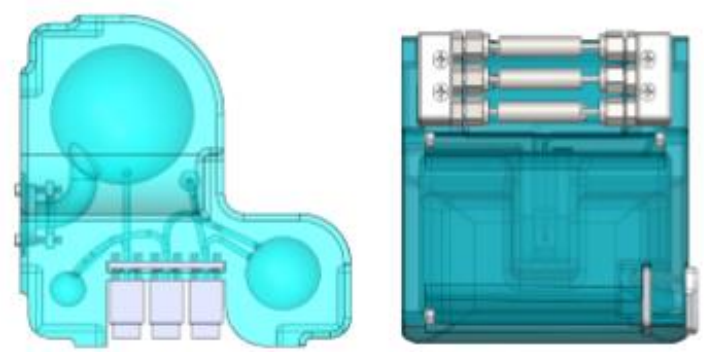
Bevo-2 Cold Gas Propulsion System
University of Texas Austin

Propulsion Technology	Cold gas
Manufacturer/Country	University of Texas at Austin (USA)
TRL	4
Size (including PPU)	1/2U
Design satellite size	3U
Isp (s)	64 to 80 s
Thrust type/magnitude	100 to 150 mN (continuous) 60 to 70 N*s (impulse, total) 1.1 mN*s (impulse bit, min)
Delta-V (m/s)	10 m/s for Bevo-2 (3U satellite)
Propellant	Refrigerant Dupont 236-fa
Power consumption (W)	1.5W
Flight heritage (if any)	Bevo-2 (2016), INSPIRE (TBD)
Commercially available	Likely but unclear
Last updated	*03/2021*

CAD model and final integrated hardware



Bevo-2 3U spacecraft

Additional comments:

[Reference 1-4][Jan 2019][General and flight info]

This research focuses on the design of a capable, simple, and inexpensive cold-gas propulsion system that can be applied to many small satellite platforms. Such a thruster system has been designed for a 3U CubeSat platform. However, the design can easily be scaled up or down to accommodate other small satellite applications. The basis of the design is from the original idea proposed by David Hinkley at The Aerospace Corporation (Hinkley, 2008). The concept is to have the intricacies of a cold-gas propulsion system built into a single module using the rapid prototyping or 3D printing process. Specifically, the thruster is manufactured by means of the stereolithography (SLA) process. Effectively, the entire thruster, including the main tank, all secondary tanks, internal piping, and converging-diverging nozzle, is encased in one block of plastic. Such a design has obvious benefits. First, the time it takes to manufacture the thruster is relatively short. It takes one week or less to go from computer-aided design (CAD) to completed module. Second, the module is inexpensive compared to its traditional counterparts. Third, the design is inherently modular. For example, the nozzle location can be placed practically anywhere, presumably as close to the center of mass of the satellite as possible. Lastly, many different propellants can be used without a design change, including non-toxic green propellants. For Bevo2, the main requirement on the propulsion system was to provide a total change in velocity, or delta-v, of at least 10 .

Bevo 2 is a picosat mission of the University of Texas, and was part of NASA Johnson Space Center's LONESTAR-2 (Low-Earth Orbiting Navigation Experiment for Spacecraft Testing Autonomous Rendezvous and Docking) project. The goal of this mission was to launch two satellites together that will separate in orbit and perform proximity operations, including taking pictures of each other. UT-Austin's satellite was known as Bevo-2. Bevo-2 was a 3-unit CubeSat that was to be deployed from the Texas A&M AggieSat-4 satellite, a ~50 kg nanosatellite. AggieSat-4, containing Bevo-2, was deployed on 29 January 2016 via the Space Station Integrated Kinetic Launcher for Orbital Payload Systems (SSIKLOPS). Aggiesat-4 was to eject Bevo-2 later for joint operations, but it was ejected prematurely shortly after deployment from the ISS and was apparently not activated.

This system was also slated for NASA's INSPIRE mission, but launch date is TBD.

References:

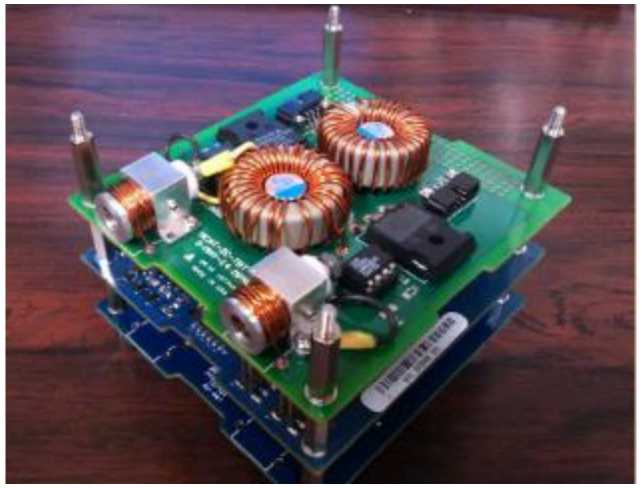
[1] Arestie, S., Lightsey, E., Hudson, B., "Development of a Modular, Cold Gas Propulsion System for Small Satellite Applications," Journal of Small Satellites, 2012.
[2] http://space.skyrocket.de/doc_sdat/bevo-2.htm
[3] https://space.skyrocket.de/doc_sdat/inspire.htm
[4] https://www.jpl.nasa.gov/cubesat/missions/inspire.php

Comm. avail.	TRL	Aerospace-tested
NO	4	NO

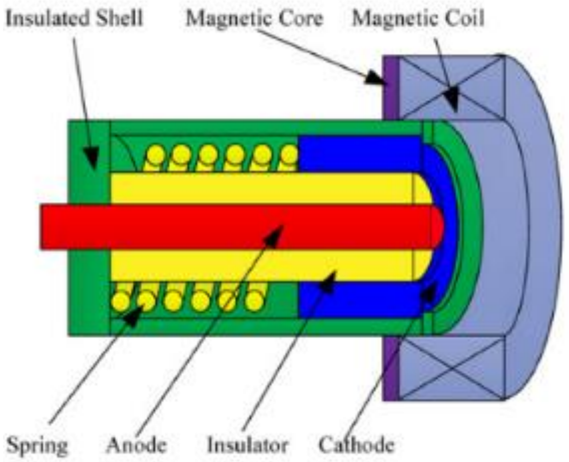
DISTRO A: Approved for public release. OTR-2024-00338

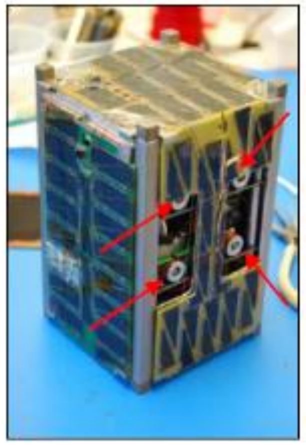
u-CAT (Micro-CAT) [1 of 2]
George Washington University/USNA

Propulsion Technology	Pulsed Plasma Thruster
Manufacturer/Country	George Washington University (USA)/ US Naval Academy, POC: M. Keidar
TRL	4
Size (including PPU)	<0.5U
Design satellite size	1U, 1.5U, 3U
Isp (s)	2000-3000s
Thrust type/magnitude	1 mN*s (impulse bit) 9.5 mN at 50 Hz [6], 1.7 mN at 50W (50% efficiency) [7]
Delta-V (m/s)	300 m/s (speculated)
Propellant	Titanium metal
Power consumption (W)	<0.1W per pulse 50W operating power [7]
Flight heritage (if any)	BRICSat-P (2015), Projected flight GWsAT (2018)
Commercially available	Unclear
Last updated	*08/2022*



Thruster with electronics





Thrusters, incorporated into BRICSat-P, a 1.5U CubeSat with 4X GWU micro-CAT thrusters

Additional comments:

[Reference 1-5][Jan 2019][General info, flight info]

Thruster heads: The thruster heads consist of a coaxial anode and cathode with a ceramic insulator in between to prevent contact between the elements; an aluminum housing has been designed to encase the thruster components. The thruster creates an arc between an anode and cathode, similar to a spark plug. The cathode acts as the propellant. According to experiments done by the MpNL, the use of titanium increases the ion current by 3.25%, as opposed to nickel which only increases the ion current by 3%.1 Each of the four thrust heads has a nickel anode and titanium cathode, also known as a bi-modal micro-cathode arc thruster.

The micro-CAT propulsion system was initially space-qualified on the BRICSat-P (Ballistically Reinforced Communication Satellite). This satellite, a 1.5U CubeSat, was launched in May 2015. BRICSat-P's primary mission was to test the use of the thrusters on orbit. Results show the thrusters did indeed fire and work successfully, but detailed quantitative data from orbit has not been found as of Sept 2018. The thrusters are slated to fly on BRICSAT-D, which should have launched 2017, but no data can be found on the mission as of June 2018. BRICSAT-D is part of the Autonomous Mobile On-Orbit Diagnostic System (AMODS), funded by the US Naval Academy.

References:

[1] Hurley, S., Teel, G., Lukas, J., et al., "Thruster subsystem for the US Naval Academy's (USNA) BRICSat-P," IEPC-2015-37.
[2] Keidar, M., Zhuang, T., Shashurin, A., Teel, G., Chiu, D., Lukas, J., Haque, S., Brieda, L., "Electric Propulsion for Small Satellites," Plasma Phys. Control. Fusion, Vol 57, 2015.
[3] Kolbeck, J., Lukas, J., Teel, G., Keidar, M., Hanlon, E., Pittman, J., Lange, M., Kang, J., "u-CAT Micro-Propulsion Solution for Autonomous Mobile On-Orbit Diagnostic System," 30th AIAA Annual Small Satellite Conference, SSC16-V-7.
[4] Wenberg, D., Hanlon, E., Keegan, B., Lange, M., Kang, J., Kolbeck, J., Teel, G., Keidar, M., "BRICSat-D Flight Experiment: Demonstrating the Feasibility of Low-Cost Diagnostic Missions," AIAA 2017-0616
[5] https://digitalcommons.usu.edu/smallsat/2014/Workshop/14/
[6] Kolbeck, J., Anders, A., Beilis, I., Keidar, "Micro-propulsion based on vacuum arcs," Journal of Applied Physics, Vol 125, 2019.
[7] Zolotukhin, D., Bandaru, S., Daniels, K., Keidar, M., "A two-stage uCAT-MPD thruster: towards millinewton thrust," IEPC-2022-561.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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u-CAT (Micro-CAT) [2 of 2]
George Washington University/USNA

Additional comments:

[Reference 1][Aug 2022][Thruster design improvements, ground testing]
We discuss our efforts aimed at simultaneous improvement of the levels of thrust, thrust-to-power ratio (TPR) and efficiency of the two-stage micro-cathode arc thruster with magneto-plasma-dynamical second stage (μCAT-MPD). Such attempts include planar construction of the first stage (μCAT) with tightly-pressed ring anode and central disc cathode, refractory (Mo) second-stage electrode, higher and stabilized second-stage voltage, and improved thermal isolation of the permanent magnet from the discharge area. Aforementioned features allowed achieve the average thrust of milli-newton range – up to 1.7±0.3 mN, together with high TPR of 37 μN/W and efficiency of 50 %, remaining low mass (~100 g) and low consuming power (~50 W) of the thruster.

References:
[1] Zolotukhin, D., Bandaru, S., Daniels, K., Keidar, M., “A two-stage uCAT-MPD thruster: towards millinewton thrust,” IEPC-2022-561.

Comm. avail.	TRL	Aerospace-tested
NO	4	NO

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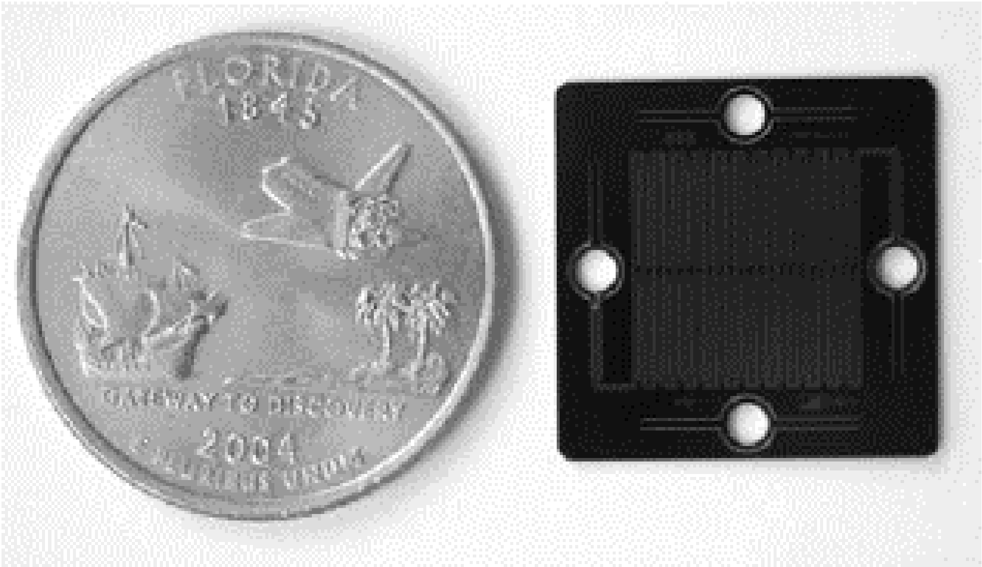
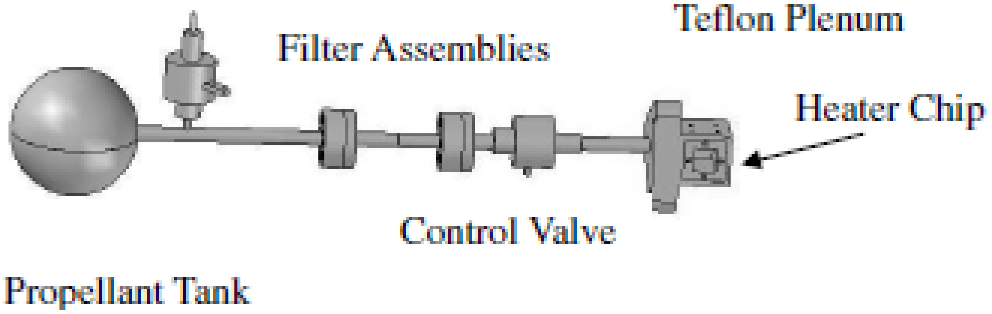
Free-Molecule Microresistojet (FMMR)

Propulsion Technology	Resistojet
Manufacturer/Country	AFRL/USC (USA)
TRL	4
Size (including PPU)	Not reported, but ~1U from images.
Design satellite size	10 to 25 kg
Isp (s)	80s
Thrust type/magnitude	129 uN
Delta-V (m/s)	
Propellant	Water
Power consumption (W)	<10W, 1-2 W typical
Flight heritage (if any)	3CS (Three-Corner-Satellite) (2004, failed to reach orbit)
Commercially available	No
Last updated	*03/2021*





Additional comments:

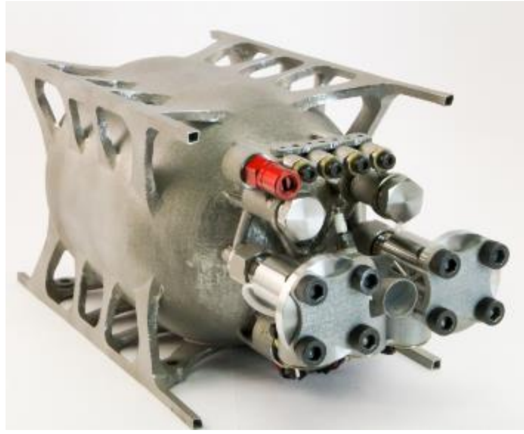
[Reference 1][Jan 2019][General info]
The FMMR consists of three main parts: the heater chip, the flow control, and the propellant storage. The propellant gas arrives in the plenum after passing through a set of phase-separating filters and an actuating valve. The FMMR generates thrust by expelling the propellant gas in the plenum through a series of the expansion slots in the MEMS-fabricated heater chip. The technology demonstrator was analyzed and tested in this study to determine its performance characteristics when operating with water propellant. Experimental data show that the free-molecule microresistojet, with a heated wall temperature of 580 K, can attain a specific impulse of 79.2 s with a thrust level of 129 uN. For a given mass flow, higher thrust levels can be achieved by increasing the temperature of the free-molecule-microresistojet heater chip. The experimental results agree favorably with predicted values from kinetic theory. Applying the measured performance of the technology demonstrator to an optimized setup, the free-molecule-microresistojet system could provide a 45-deg slew of a typical nanosatellite in 60 s, which is acceptable for many nanosatellite applications.
[Reference 2][Jan 2019][Flight info]
The 3CS stack was originally slated for launch aboard the Space Shuttle in 2003, but after Shuttle Columbia tragedy, mission organizers switched to Boeing Delta IV Heavy rocket (it was its first launch). Due to a problem with the rocket during launch, 3CS failed to achieve orbit. Satellites were to have been dropped off at a low 180 km × 240 km, but they entered orbit at a height of only 105 km, which led to a rapid decay.

References:
[1] Lee, R., Bauer, A., Killingsworth, M., Lilly, T., Duncan, J., Ketsdever, A., “Free-molecule-microresistojet performance using water propellant for nanosatellite applications,” Journal of Spacecraft and Rockets, Vol 45, 2008.
[2] https://en.wikipedia.org/wiki/3_Corner_Satellite

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

PM400 [1 of 2]
Dawn Aerospace/Hyperion Technologies/Berlin Space Technologies/HEAD

Propulsion Technology	Biprop (Nitrous + Propene)
Manufacturer/Country	Dawn Aerospace (previously Hyperion Technologies) (NETHERLANDS/NEW ZEALAND). Partners: Berlin Space Technologies (Germany) and China HEAD Aerospace Technology Co. (China). Dawn Aerospace (component: thruster nozzle) (NETHERLANDS)
TRL	3-4
Size (including PPU)	2U
Design satellite size	3U and larger (ideally 3U to 12U)
Isp (s)	>285s
Thrust type/magnitude	1N (continuous, nom.), 75 mN*s (impulse bit, min), 11 N*s (impulse bit, max), >1750 N*s (impulse, total)
Delta-V (m/s)	230 m/s for 6U (8 kg) CubeSat
Propellant	Nitrous oxide (oxidizer) and propene (fuel)
Power consumption (W)	6W (firing), <0.1W (sleep/idle), 5V supply
Flight heritage (if any)	None known
Commercially available	NO
Last updated	*03/2021*



Additional comments:

[Reference 1-2][Jan 2019][General info]
Storability reported at >5 years, and can be ready to fire seconds after wake-up. It has an integrated thruster management system. Operating temperature -5 to 35 C. Propellant is stored at 45 bar (oxidizer) and 7.5 bar (fuel) – self-pressurized. Dry mass is 1400g, with propellant mass 625g. The module can be delivered compatible with all major CubeSat structure standards as well as customized mechanical interface. The manufacturer reports no measured thruster degradation. The PM400 is a bi-propellant propulsion module for 6-12U CubeSats. It allows maneuvers of up to 230 m/s to be performed utilizing the non-toxic propellants nitrous oxide and propane in a self-pressurizing configuration.
Low system complexity and zero propellant toxicity allow for simple and robust operations, both on the ground and when in orbit. The medium tank pressure and high storage density of liquid propellants enables high safety factor tanks to be used with little mass penalty. The standard configuration with a 2U propulsion module can be configured to suit any CubeSat structure and features an I²C or RS422/RS485 compliant interface.
Through the use of additive manufacturing, the system is highly customizable. Design parameters such as total system delta-v, interface style and thrust direction can be changed on request and adapted to an existing CubeSat architecture. The PM400 can be seamlessly integrated with the iADCS400 to provide a fully integrated GNC and ADCS solution.
The standard 2U configuration of the PM400 propulsion module can deliver in excess of 230 m/s of velocity increment to a 6U CubeSat of 8 kg. The system utilizes a single 1 N thruster. This relatively high thrust allows maneuvers to be completed in a timely manner as well as enabling the use of Hohmann transfer orbits. The smallest deliverable impulse bit of 75 mN*s results in a velocity increment of 0.01 m/s of a 6U CubeSat. A velocity increment of up to 1.37 m/s can be imparted before cooldown is required. Impulse repeatability can be achieved to +/- 9 mN*s (3 σ). The system makes use of 5 pressure and temperature sensors to monitor system health and provide real-time thruster performance data.

[Reference 1][March 2021][Commercial availability]
As of March 2021, the PM400 appears to have been removed from the company website and is no longer commercially available.

References:
[1] https://hyperiontechnologies.nl/
[2] http://www.dawnaerospace.com/

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

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PM400 [2 of 2]
Dawn Aerospace/Hyperion Technologies/Berlin Space Technologies/HEAD

Additional comments:

[Reference 1][Nov 2022][General info]
Sidus Space, Inc. (NASDAQ:SIDU) has signed an agreement with Dawn Aerospace ("Dawn") to implement the latter's green, chemical propulsion technology into the company's LizzieSat™ smallsat.

References:
[1] https://smallsatnews.com/2022/11/02/sidus-space-notches-an-agreement-with-dawn-aerospace-for-smallsat-propulsion-tech/

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

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"CubeSat Propulsion Module" PM200
Dawn Aerospace/Hyperion Technologies/Berlin Space Technologies/HEAD [1 of 2]

Propulsion Technology	Biprop (Nitrous + Propene)
Manufacturer/Country	Dawn Aerospace (prev. Hyperion Technologies) (NETHERLANDS/NEW ZEALAND), Partners: Berlin Space Technologies (Germany) and China HEAD Aerospace Technology Co.(China), Dawn Aerospace (thruster nozzle) (NETHERLANDS)
TRL	~4 to 5
Size (including PPU)	0.7U and 1U standard sizes available
Design satellite size	3U and larger (ideally 3U to 6U)
Isp (s)	>285s
Thrust type/magnitude	0.33 to 1 N (throttled), 0.5N (nominal), 35 mN*s (impulse bit, min.), 7500 mN*s (impulse bit, max), >850 N*s (impulse, total)
Delta-V (m/s)	230 m/s for 3U (4 kg) CubeSat
Propellant	Nitrous oxide (oxidizer) and propene (fuel), Operating temperature 0 to +30 C
Power consumption (W)	12W (firing), <0.1W (sleep/idle), 5V supply
Flight heritage (if any)	D-Orbit ION satellite (Vega launch vehicle, launched September 2020) [3] D-Orbit ION satellite (Transporter-1 SpaceX, launched Jan 2021) [7] Hiber 4 (launched Jan 2021) [5] Projected for Hiber 3 (2020) [4, 6]
Commercially available	Yes. Website quotes $42,000 for base model, 6 month lead time. [3]
Last updated	*05/2021*

[Reference 2]

Standard sizes
0.7U and 1U

Nominal thrust
0.5N

Specific impulse
>285 s

Propellants
Nitrous oxide (N2O) and propene (C3H6)

Thrust, range
0.33 N at 0°C
0.55 N at 15°C
1 N at 30°C

Minimum impulse bit
35 mN.s
< 20 mN.s cold gas N2O
< 2 mN.s cold gas C3H6

Maximum impulse bit
7,500 mN.s

Firing power
12.5 W

Regulatory
REACH compliant and ITAR free

Health monitoring
2 pressure sensors
1 temperature sensor

Operational temperature
0°C to 30°C

Cold-start capable
Yes

Electronics
Integrated control

Electronics connector
PC104

Data interface
RS-485 full-duplex

Radiation tolerance
50 k rads

Proof pressure
Oxidiser 110 bar
Fuel 40 bar

Burst pressure
Oxidiser > 150 bar
Fuel > 55 bar

Flow rate
Oxidiser 170 mg/s
Fuel 18 mg/s

Droplet formation in plume and backflow
None

0.7U Module

Total impulse
>425 N.s

Mass (dry / wet)
1000 g / 1170 g

Propellant mass
170 g

Dimensions
70.0 x 95.4 x 95.4 mm

1U Module

Total impulse
>850 N.s

Mass (dry / wet)
1100 g / 1410 g

Propellant mass
310 g

Dimensions
97.7 x 95.4 x 95.4 mm

Additional comments:

[Reference 1][Jan 2019][General info]

Storability reported at >5 years, and can be ready to fire seconds after wake-up. It has an integrated thruster management system. Operating temperature -5 to 35 C. Propellant is stored at 45 bar (oxidizer) and 9 bar (fuel) – self-pressurized. Dry mass is 1100g, with propellant mass 310g.

The PM200 is a bi-propellant propulsion module intended for use in 3-6U CubeSats. It allows maneuvers of up to 230 m/s to be performed utilizing non-toxic propellants (nitrous oxide and propene) in a self-pressurizing configuration. Low system complexity and zero propellant toxicity allow for simple and robust operations, both on the ground and when in orbit. The medium tank pressure and high storage density of liquid propellants enables high safety factor tanks to be used with little mass penalty. The standard configuration with a 1U propulsion module can be configured to suit any CubeSat structure and features an I²C or RS422/RS485 compliant interface. Through the use of additive manufacturing, the system is highly customizable. Design parameters such as total system delta-v, interface style and thrust direction can be changed on request and adapted to an existing CubeSat architecture.

The PM200 can be seamlessly integrated with Hyperion Technologies' line of integrated attitude determination and control systems to provide a fully integrated GNC and ADCS solution. The standard 1U configuration of the PM200 propulsion module can deliver in excess of 230 m/s of velocity increment to a 3U CubeSat of 4 kg. The system utilizes a single 0.5 N thruster. This relatively high thrust allows maneuvers to be completed in a timely manner as well as enabling the use of Hohmann transfer orbits. Integrated thrust vector control ensure that inherent thruster disturbance torques are actively compensated. The smallest deliverable impulse bit of 35 mN*s results in a velocity increment of 0.01 m/s of a 3U CubeSat. A velocity increment of up to 1.37 m/s can be imparted before cooldown is required. The system makes use of pressure and temperature sensors to monitor system health and provide real-time thruster performance data.

References:

[1] https://hyperiontechnologies.nl/
[2] Publicly distributed flier at SmallSat 2019
[3] https://www.dawnaerospace.com/products/p/cubesat-propulsion-module
[4] https://www.dawnaerospace.com/blog/dawn-signs-hiber
[5] https://smallsatnews.com/2021/01/25/hibers-green-propulsion-smallsat-hiber-four-launched-via-the-spacex-transporter-1-mission/
[6] https://space.skyrocket.de/doc_sdat/hiber-1.htm
[7] https://smallsatnews.com/2021/05/04/dawn-aerospaces-smallsat-green-propellant-thruster-proves-itself-on-orbit-with-d-orbits-ion-space-tug/

DISTRO A: Approved for public release. OTR-2024-00338

4

NO

Comm. avail. | TRL | Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

"CubeSat Propulsion Module" PM200
Hyperion Technologies/Berlin Space Technologies/HEAD [2 of 2]

Additional comments:]

[Reference 1][Aug 2018][General info]
We talked to them at SmallSat 2018 and they were displaying their hardware and 3-D printed frame (basically the unit shown in the picture). The igniter is a small spark plug. They said that they had ground test data, but we have not seen it published. They were also interested in ground-testing. The PM200 would fit the niche for high-thrust, high-delta-v missions that require propellant storability of a few years and short warm-up times.

[Reference 2][Aug 2019][General info]
This unit can be scaled. The lead time is estimated at 4-6 months (for a model close to their standard PM200), and 6-9 months for a customized model (for example, for a customized tank). The tank and plumbing can all be easily customized because it is a 3D printed system. The unit comes with software. It has been pressure-tested up to 100 bar pressure, and has gone through launch safety with ESA. They are actively looking for flight missions.

[Reference 3][Dec 2020][Launch news]
Today [September 3, 2020] saw the first D-Orbit ION mission launched upon Arianespace's Vega SSMS PoC Flight VV16.
The free-flying CubeSat dispenser is home to a 1U CubeSat Propulsion Module Dawn produced together with Hyperion Technologies. It also hitched a ride to space alongside a few Planet Earth observation satellites. The launch marks a significant milestone in compliance for the world of 3D printed space hardware. The 1U CubeSat propulsion module was the first-ever ECSS compliant 3D printed bi-propellant propulsion system to be allowed to be launched to space, fully pressurized. All safety and compliance procedures were satisfied per European Space Agency standards by CNES.

[Reference 4][Dec 2020][Scheduled missions]
Green bi-propellant propulsion developer Dawn Aerospace and IoT provider Hiber have announced a contract for the Hiber-3 and Hiber-4 satellites. Both satellites are scheduled for launch in early 2020. Dubbed the 'HiberDrive', Hiber have contracted a brand-new Attitude and Orbit Control System (AOCS), miniaturized to 1U. The deal was backed by the European Space Agency (ESA) and the Netherlands Space Office via the ARTES program. Hiber launched their first two satellites, Hiber-1 and Hiber-2 at the end of 2018, which are currently in the demonstration and validation phase. The company plans to grow the constellation to serve growing demand of the Hiberband, with all future satellites boasting the HiberDrive.

[Reference 5][Feb 2021][Flight info]
IoT solutions provider Hiber has successfully launched their 3U cubesat, Hiber Four, onboard SpaceX's dedicated rideshare mission: Transporter-1. The satellite was equipped with a new-to-market green propulsion system from Dawn Aerospace and Hyperion Technologies. Supported by the European Space Agency and Netherlands Space Office via the ARTES program, Hiber teamed up with Dawn and Hyperion to find a better solution. Using this new system, the Hiber Four will swiftly move from its deployed 500 km SSO out to its final 600 km orbit.

[Reference 6][May 2021][Flight info]
Dawn Aerospace has confirmed the company's novel satellite thruster has been proven in space —six thrusters were onboard D-Orbit's ION Satellite Carrier — the companies have been working together since early 2019.
Since launching on SpaceX's Transporter-1 mission in January of 2021, D-Orbit's ION space-tug for satellites has performed hundreds of in-space firings of each Dawn Aerospace B20 thruster.

References:
[1] Public conversations at SmallSat 2018
[2] Public conversations at SmallSat 2019 (POCs Jeroen Wink – CEO, James Powell, Rob Hermsen)
[3] https://www.dawnaerospace.com/blog/ionscvlucas
[4] https://www.dawnaerospace.com/blog/dawn-signs-hiber
[5] https://smallsatnews.com/2021/01/25/hibers-green-propulsion-smallsat-hiber-four-launched-via-the-spacex-transporter-1-mission/
[6] https://smallsatnews.com/2021/05/04/dawn-aerospaces-smallsat-green-propellant-thruster-proves-itself-on-orbit-with-d-orbits-ion-space-tug/

Comm. avail.	TRL	Aerospace-tested
	4	NO

DISTRO A: Approved for public release. OTR-2024-00338

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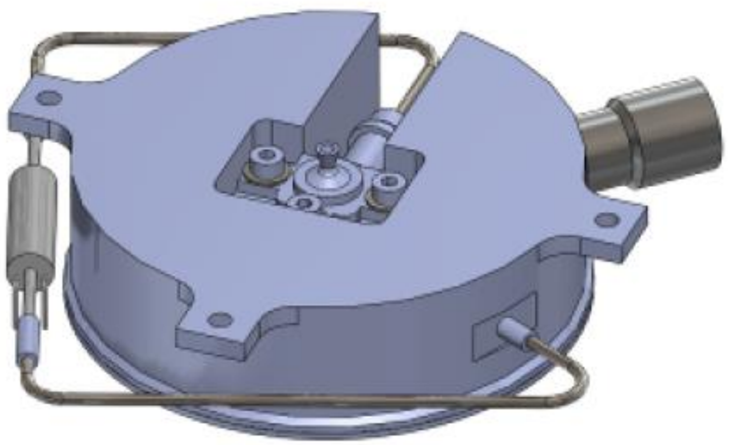
Water-alcohol Resistojet Propulsion De-orbit Re-entry Velocity Experiment (WARP-DRiVE) Surrey Satellite Technologies (SSTL)

Propulsion Technology	Water-alcohol resistojet, also adapted to warm butane resistojet
Manufacturer/Country	Surrey Satellite Technologies (SSTL) (UK)
TRL	4
Size (including PPU)	~0.25
Design satellite size	3U
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	2 m/s (3U CubeSat, STRaND-1, 2013)
Propellant	Butane + water/alcohol?, 0.4 kg
Power consumption (W)	7 W
Flight heritage (if any)	Launched Feb 2013 aboard STRaND-1 from India on the PSLV C-20 (Polar Satellite Launch Vehicle)
Commercially available	Unknown
Last updated	*03/2021*



Resistojet embedded in a custom propellant tank

Additional comments:

[References 1-3][Jan 2019][General info]
No test data has been found in literature. Propulsion unit has been flown, but no on-orbit data has been found. Limited information on propulsion system.
Space researchers at the University of Surrey's Surrey Space Centre and SSTL engineers developed STRaND-1, a 3U CubeSat weighing 3.5kg containing a smartphone payload that was launched into orbit in 2013. STRaND-1 was built in engineer's free time using advanced commercial off-the-shelf components.
The propulsion module on STRaND is split into two parts; the SSTL butane resistojet (based on the heritage SSTL resistojet) and the SSC Pulsed Plasma Thruster (PPT). The STRaND-1 CubeSat is baselined to have a warm gas butane propulsion system on board to enable orbital manoeuvres. The system builds on the extensive SSTL heritage with the design and operation of butane propulsion systems, while testing out new processes and hardware to reduce the system size and cost. These two points are critical to enable the system to be viable for a CubeSat. The propulsion system must fit in a space smaller than 75x75x21mm, and had to be completed on a stringent budget. Typical space-rated components were ruled out for these reasons. The system is designed to provide 2ms-1 ΔV to the STRaND-1 CubeSat. A Lee solenoid valve is employed as a flow control valve in the system. The small size again made it ideal. All internal materials are compatible with the propellant and test gases. The resistojet itself is manufactured by SSTL. It is a simple design consisting of a resistive wire wound round a mandrel. The gas is forced to spiral down the resistojet to increase the travel path and thus the heat transfer. The resistojet acts as a vaporiser to ensure no liquid propellant is expelled, as well as increasing the specific impulse of the system.
System was successfully launched but vehicle failed to respond in orbit.

References:
[1] Mission information: http://space.skyrocket.de/doc_sdat/strand-1.htm
[2] Kenyon, S., Bridges, D., et al. "STRAND-1: Use of a $500 Smartphone as the Central Avionics of a Nanosatellite," 62nd international Astronautical Congress, Cape Town, SA, 2011.
[3] http://www.sstl.co.uk/Missions/STRaND-1--Launched-2013/STRaND-1/STRaND-1-FAQs

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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Green Rocket – Hybrid [1 of 2]
Utah State University

Propulsion Technology	Hybrid, 3D printed
Manufacturer/Country	Utah State University (USA)
TRL	4
Size (including PPU)	Scalable
Design satellite size	Scalable
Isp (s)	>230s
Thrust type/magnitude	22N (thrust, continuous)
Delta-V (m/s)	
Propellant	ABS plastic/GOX ABS plastic/HTP [5]
Power consumption (W)	
Flight heritage (if any)	NASA sounding rocket (2018)
Commercially available	NO
Last updated	*12/2023*

Thruster ground tests

Additional comments:

[Reference 1-4][Jan 2019][General info]

This is an ABS 3-D printed hybrid rocket. The ABS is melted and then deposited through Fused Deposition Modeling (FDM), where the plastic filament is unwound from a coil and supplies material to an extrusion nozzle. “The nozzle is heated to melt the material and can move in both horizontal and vertical directions by a computer-controlled mechanism. The FDM-processed ABS possesses unique electrical breakdown properties that can be exploited to allow for rapid on-demand system ignition. Even though the ABS material possesses a very high electrical resistivity and dielectric strength and is not normally considered to be an electrical conductor, as FDM-processed ABS is subjected to a moderate electrostatic potential field, the layered material structure concentrates minute electrical charges that produce localized arcing between material layers. Joule heating from the resulting arc produces a small but highly-conductive melt layer. This melt layer allows for very strong surface arcing to occur at moderate input voltage levels (200-300V). Additional joule heating from the arcing causes sufficient amount of fuel material to be vaporized to seed combustion when simultaneously combined with an oxidizing flow.”

NASA chose their payload (amongst others) to fly on their NASA's Undergraduate Student Instrument Project, a 43-foot-tall sounding rocket launched in 2018.

Initially, high-pressure gaseous oxygen (GOX) was to be used as the oxidizer, however after safety considerations by NASA Wallops High Pressure Safety Management Team, it was concluded the oxidizer needed to contain 60% nitrogen, only 40% oxygen. On March 25th 2018, the system was successfully tested aboard a sounding rocket launched from NASA WFF in a hard space vacuum and the motor was successfully re-fired 5 times in space. The payload spent more than 200 seconds above the Von-Karman line in a hard-vacuum environment. During the tests, 8 N thrust level and 215 specific impulse were achieved as predicted.

References:

[1] Whitmore, S., Merkley, S., Spurrier, Z., Walker, S., “Development of a power efficient, re-startable, “green” propellant thruster for small spacecraft and satellites,” Small Sat Conference, 2015. SSC15-P-34.
[2] Bulcher, A., Whitmore, S., “A green hybrid thruster using moderately enriched compressed air as the oxidizer,” AIAA JPC, 2018.
[3] https://phys.org/news/2018-03-nasa-usu-student-built-space.html
[4] http://rgs.usu.edu/techtransfer/wp-content/uploads/sites/50/2018/02/Green-Rockets-020918.pdf
[5] Thibaudeau, R., Whitmore, S., “Development of a KMNO4 catalyst-infused fuel grain for H2O2 hybrid thruster ignition enhancement,” Small Satellite Conference, SSC23-WVIII-07, 2023.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

Green Rocket – Hybrid [2 of 2]
Utah State University

Additional comments:

[Reference 1][Oct 2022][General info]
The Space Dynamics Lab is developing a prototype "green" hybrid prototype propulsion system for SmallSats. The system is based on Utah State's patented High Performance Green Hybrid Propulsion (HPGHP) technology. HPGHP leverages unique dielectric breakdown properties of 3D-printed acrylonitrile butadiene styrene (ABS), allowing restart, stop, and re-ignition. HPGHP works most reliably using gaseous oxygen (GOX) as the oxidizer, but has experienced ignition reliability and latency issues when replaced by high test hydrogen peroxide (HTP). This deficiency results from HTP's high decomposition energy barrier. Tests show that noble metal catalysts like platinum on alumina are effective at decomposing 90% HTP in monopropellant form, but the decomposition releases insufficient energy to reliably ignite a hybrid rocket. This study reports on a non-catalytic, thermal-ignition method for hybrid rockets. Combustion is initiated using a gaseous oxygen pre-lead, with HTP being introduced to the hot combustion chamber once full GOX-ignition occurs. Residual energy from the GOX/ABS combustion thermally decomposes the HTP flow, with the freed-oxygen allowing full HTP-hybrid combustion. Design options and test results are presented for prototype systems at 0.5, 1.0, and 5 N thrust levels using 90% HTP with acrylonitrile butadiene styrene (ABS) and polymethylmethacrylate (PMMA) as fuels.

[Reference 2][Dec 2023][Advancements to incorporate HTP]
Utah State University's patented High Performance Green Hybrid Propulsion (HPGHP) technology leverages unique dielectric breakdown properties of 3D-printed acrylonitrile butadiene styrene (ABS), allowing re-start, stop, and reignition. HPGHP works most reliably using gaseous oxygen (GOX) as the oxidizer but has experienced ignition reliability and latency issues when replaced high test hydrogen peroxide (HTP), which has a significantly higher storage density. This deficiency results from HTP's high decomposition energy barrier. Traditionally, inline external catalyst beds or GOX pre-lead burns are used to overcome this energy barrier to achieve ignition; however, the extra hardware required for these systems have inhibited their adoption into flight units for small satellite propulsion modules. The presented research replaces the external catalyst by diffusion-blending ABS with 1-2% potassium permanganate (KMNO4), and then 3-D printing fuel grains using the augmented feed-stock. The embedded catalyst allows for near-instantaneous decomposition as HTP enters the combustion chamber, releasing gaseous oxygen that, when combined with the arc-ignition energy, provides quick and reliable ignition. No preheat is required, and the infused fuel does not reduce the overall system performance. "Drop-in" design options and test results are presented for a prototype system at a1 N thrust level using 90% HTP.

References:
[1] Smith, T., Lewis, Z., Olsen, K., Thibaudeau, R., Whitmore, S., "A miniaturized hydrogen peroxide/ABS based hybrid propulsion systems for Cubesats," SSC22-X-02.
[2] Thibaudeau, R., Whitmore, S., "Development of a KMNO4 catalyst-infused fuel grain for H2O2 hybrid thruster ignition enhancement," Small Satellite Conference, SSC23-WVIII-07, 2023.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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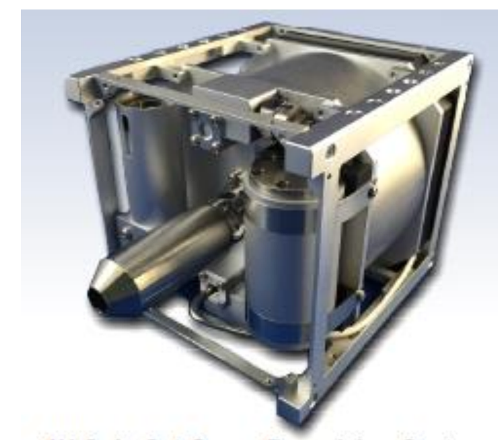
Busek Green Monopropellant Thrusters, BGT-X5
Busek [1 of 2]

Propulsion Technology	Green Monopropellant
Manufacturer/Country	Busek (USA)
TRL	4-5 (BGT-X5 model)
Size (including PPU)	1U
Design satellite size	3U and larger
Isp (s)	220 – 225 s
Thrust type/magnitude	500 mN (BGT-X5 model, continuous, nominal, max) Thrust is throttleable for each model 50 mN*s (BGT-X5 model, impulse, min) 565 N*s (BGT-X5 model, impulse, total)
Delta-V (m/s)	146 m/s for 4 kg CubeSat
Propellant	AF-M315E
Power consumption (W)	20W (catalyst preheat, BGT-X5 model)
Flight heritage (if any)	None known
Commercially available	YES
Last updated	*04/2022*

Various models of green monopropellant thrusters



1U CubeSat Green Propulsion System

Additional comments:

[Reference 1][Jan 2019][General info]
Various models of this thrusters exist. There is only a manufacturer datasheet for the BGT-X5 (probably the highest TRL of the different models). Busek's BGT-X5 green monopropellant thruster system produces 0.5N thrust and features a highly stable "green" propellant alternative to hydrazine. The thruster features a patented long-life catalyst reactor, high temperature thruster body, and low power piezo microvalve (flight heritage). The novel propellant tank and patent-pending Post-Launch Pressurization System (PLPS) enable a compact high-thrust propulsion solution for Cubesats and Smallsats. The BGT-X5 system has 1U volume and easily scales by increasing the size of the propellant tank to support higher total impulse applications. Alternately, multiple systems can be easily integrated onto a single spacecraft for modular attitude control and translational thrust. The thruster delivers 500 mN thrust at 220-225 seconds specific impulse at approximately 400 psi feed pressure. As a 1U system, it delivers 146 m/s delta-v to a 4 kg CubeSat and is capable of multiple start-stops for precision firing and short impulse bits on the order of 0.05 N-s. The rugged flight electronics includes an integrated DCIU with communication via RS-422.

References:
[1] http://www.busek.com/technologies__greenmonoprop.htm

4 NO
Comm. avail. TRL Aerospace-tested

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Busek Green Monopropellant Thrusters, BGT-X5
Busek [2 of 2]

Additional comments:

[Reference 1][Aug 2019][System development and integration]
An Engineering Model (EM) 1U CubeSat propulsion system utilizing the non-toxic, “green” monopropellant AF-M315E was developed. This technology demonstrator program, also known as Advanced Monopropellant Application for CubeSats (AMAC), produced a self-contained, 1.5kg-wet system that is expected to provide 0.1-0.5N variable thrust and up to 565N-sec total impulse. This propulsive capability translates to a maximum of 146m/s delta-V for a 3U/4kg CubeSat. The system’s only input requirements are 20W of power at the spacecraft bus voltage and an RS-422 port for communication. In addition to Busek’s 0.5N micro thruster BGT-X5, the cornerstone of the AMAC technology, other notable subsystem components include 1) an ultra-low power piezoelectric microvalve, 2) a material-compatible bellows tank for propellant storage and feed, and 3) a patent-pending Post-Launch Pressurization System (PLPS) that can generate inert pressurant gas in space and re-pressurize the tank on demand. To date, AMAC’s mechanical components have been integrated and successfully hot-fire tested on a systems level. The results obtained from this hot-fire demonstration are the focus of this publication. With significant system hardware and CONOPS risks retired, the AMAC program is now progressing toward flight electronics development, with the goal of producing a fully-integrated protoflight unit in early 2018.

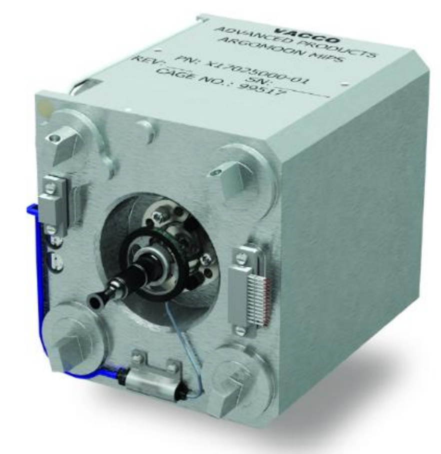
References:
[1] Tsay, M., Feng, C., Zwahlen, J., “System-level demonstration of Busek’s 1U CubeSat Green Propulsion Module “AMAC”,” AIAA JPC, 2017

Comm. avail.	TRL	Aerospace-tested
	4	NO

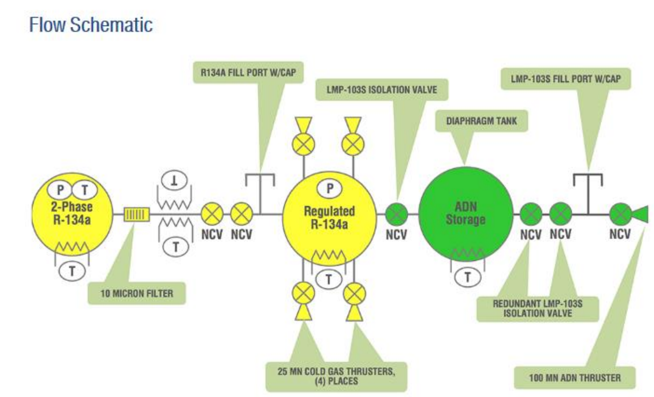
DISTRO A: Approved for public release. OTR-2024-00338

ArgoMoon Propulsion System, Hybrid Micro-Propulsion System
VACCO

Propulsion Technology	Hybrid: Combines green monopropellant + cold gas
Manufacturer/Country	VACCO (USA)
TRL	4-5
Size (including PPU)	~1.5U
Design satellite size	3U and larger
Isp (s)	~220 to 240 s (estimated from comparable thrusters)
Thrust type/magnitude	200 mN total = 100 mN (central) + 4X(25 mN) from cold gas thrusters 800 N*s (impulse, total)
Delta-V (m/s)	56 m/s for 14 kg CubeSat
Propellant	ADN green propellant (LMP-103S), or Air Force green (AF-M315E) + refrigerant (R134A)
Power consumption (W)	4.3W (operational), 20W (warmup), 1W (standby)
Flight heritage (if any)	None to date, projected to fly on ArgoMoon aboard Artemis-1 (now slated for 2021, originally 2019) Launched Nov 2022 aboard Artemis [4] Projected to be launched aboard LUMIO [5]
Commercially available	Unknown
Last updated	*05/2023*



Vacco's ArgoMoon Propulsion System



Additional comments:

[Reference 1-2][Dec 2019][General info]

VACCO's hybrid Micro Propulsion System (MiPS) combines green mono-propellant and cold gas propulsion in a single system to provide attitude control and orbital maneuvering. Argotec's ArgoMoon program utilizes VACCO's hybrid propulsion system to achieve high levels of total impulse in a limited volume to accomplish the mission requirements. The VACCO ArgoMoon MiPS is approximately 1.3U plus the tuna can volume and uses one 100 mN green thruster to develop 783 N-sec of total impulse that provides 56 m/s of delta-v for a 14 kg CubeSat. The four 25 mN cold gas thrusters develop 72 N-sec of total impulse. Each thruster independently operates to perform both delta-v and ACS maneuvers through an integrated microprocessor controller. ArgoMoon is a small lunar mission designed by the Italian company Argotec, which is building the ArgoMoon CubeSat under the Italian Space Agency (ASI) internal review and approval process.

[Reference 3][Dec 2019][General info]

ArgoMoon is a nanosatellite that will fly on NASA's Artemis 1 mission into a heliocentric orbit in cislunar space on the maiden flight of the Space Launch System and the Orion spacecraft, in 2021. The satellite has the dimensions of a shoe box (12 cm x 24 cm x 36 cm) in CubeSat terms, it is a 6U.

The objective of the ArgoMoon mission is to provide NASA information about the correct launch vehicle operations through photography. At the time the second stage will release the CubeSats, it will not be able to communicate with the ground anymore. Flying ArgoMoon in the Artemis-1 mission will also be the opportunity to test nanotechnology in the hostile environment of deep space. ArgoMoon will complete its operations using a proprietary software for autonomous navigation.

References:

[1] http://space.skyrocket.de/doc_sdat/argomoon.htm
[2] http://www.cubesat-propulsion.com/argomoon-propulsion-system/
[3] https://en.wikipedia.org/wiki/ArgoMoon
[4] https://blogs.nasa.gov/blog/tag/argomoon/
[5] DiTana, V., Reverberi, G., Fazzoletto, E., Balossino, A., "Exploring the solar system with Cubesats: new missions from Argotec," Conference proceedings, Interstellar SmallSat Conference, May 2023.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

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BET-100 (100 uN-class Electrospray)
Busek

Propulsion Technology	Electrospray/Colloid
Manufacturer/Country	Busek (USA)
TRL	4-5 Some components have flown and have higher TRLs.
Size (including PPU)	~0.5U
Design satellite size	1U, 3U
Isp (s)	1000 to 1800 s
Thrust type/magnitude	5 to 100 uN thrust(throttleable) 175 N*s (impulse, total)
Delta-V (m/s)	45 m/s for 4 kg spacecraft
Propellant	EMI-IM (speculated), propellant tank is expandable
Power consumption (W)	5.5W
Flight heritage (if any)	None known, but technology was demonstrated on LISA Pathfinder (NASA ST-7). Candidate for NASA Pathfinder (2018)
Commercially available	NO
Last updated	*03/2021*

Busek's 100 uN electrospray based on heritage hardware

Additional comments:

[Reference 1][Jan 2019][General info]
This is another thruster in the family of Busek's electrospray thrusters. Although this thruster has not had direct flight history, its technology was flown on Lisa Pathfinder. Since 1998, Busek has been a recognized leader in the field of electrospray physics, which led to the Jet Propulsion Laboratory's award to Busek to develop the first electrospray thruster system. This system included custom power management, digital control interface and propellant storage and management systems. The extreme precision (equivalent to the weight of a mosquito antenna) required the development of new miniature valves capable of withstanding the performance requirements, in addition to a propellant-less carbon nanotube cathode. Since delivering the flight hardware to JPL in 2008, Busek has been continuing its effort to result in a new class of miniature, high performance electrospray propulsion.
NATICK, MA - MARCH 2, 2016 - Busek today announced that its BET-100 miniature cubesat propulsion system has been selected for a $1.6 million NASA award. The contract is sponsored by the Small Spacecraft Technology Program within NASA's Space Technology Mission Directorate (STMD), and carries a total value up to $2.3 million. NASA's Commercialization Readiness Program identifies and advances the highest value technologies for spaceflight, the BET-100 now being a candidate for a Pathfinder Technology Demonstrator space mission. NASA's Ames Research Center in California's Silicon Valley will lead the project in collaboration with NASA's Glenn Research Center in Cleveland, Ohio. The Busek micro-propulsion system will enable unprecedented in-space maneuverability for CubeSats and small satellites.

[Reference 1][March 2021][Commercial availability]
As of March 2021, this product appears to have been removed from the manufacturer's website and is no longer commercially available.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

References:
[1] http://www.busek.com/index_htm_files/Busek%20Wins%20NASA%20Cubesat%20Propulsion%20Award%2002MAR2016.pdf

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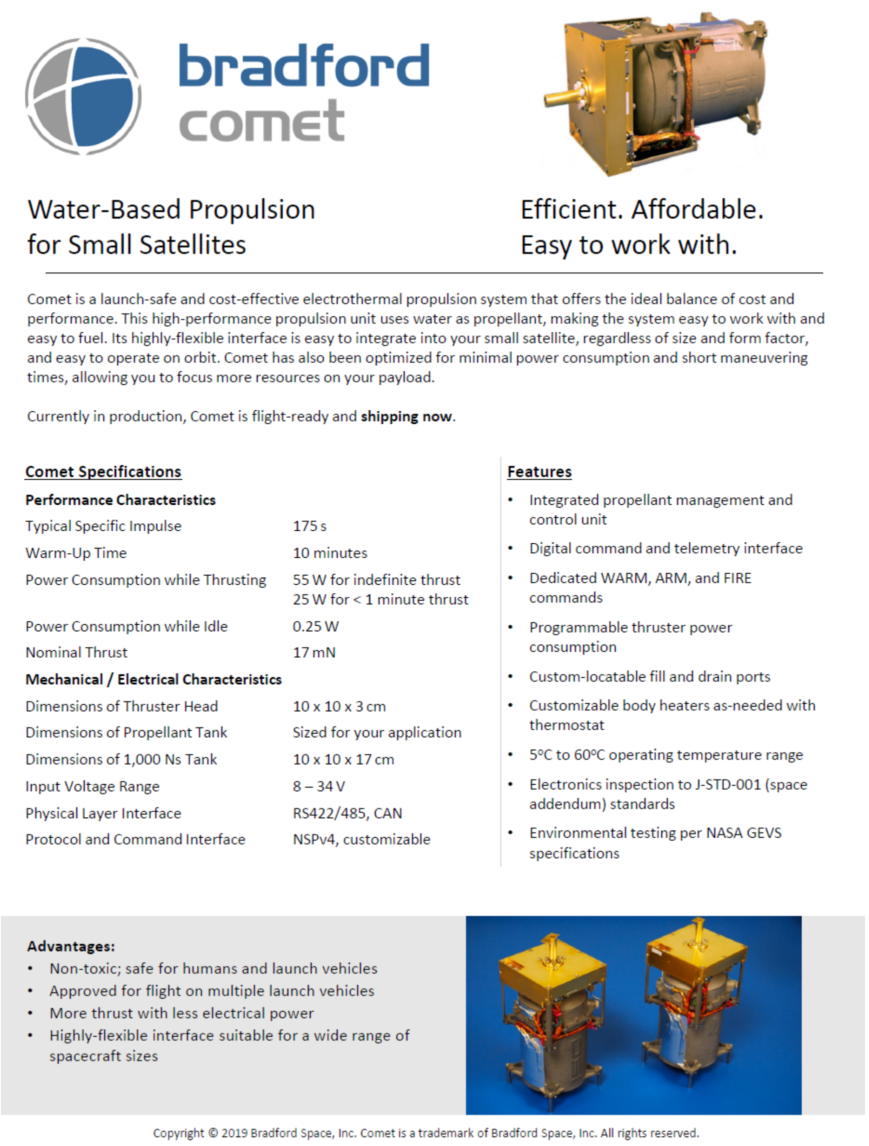
COMET [1of 3]
Deep Space Industries (DSI)/Bradford Space Inc. (BSI)

Propulsion Technology	Electrothermal resisto-jet
Manufacturer/Country	Deep Space Industries (DSI) (USA)/Bradford Space(USA) (with facilities in Netherlands and Sweden) Rebranded Jan 2019 as Bradford Space Inc. (BSI) under ECAPS
TRL	4
Size (including PPU)	~1 to 2U (sized for application)
Design satellite size	3U and larger
Isp (s)	182s (website) 175s [6]
Thrust type/magnitude	18 mN (continuous, nominal) 17 mN [6]
Delta-V (m/s)	96 m/s for 13kg spacecraft (Hawkeye)
Propellant	Water
Power consumption (W)	40W (indefinite thrust), 25W for <1 minute thrust, 0.25W while idle. Warm up time 5-10 minutes.
Flight heritage (if any)	Hawkeye 360 Pathfinder (A, B, C) (Dec 2018) Capella Space (2018) [7, 8] BlackSky Constellation (Joint venture between LeoStella, Spaceflight Industries, and Thales Alenia Space) 20 satellites, launching beginning 2020) 10 units on orbit as of March 2021. [9]
Commercially available	YES, single unit price $200,000 on website. Lead time 3 months from order to delivery
Last updated	*03/2021*


bradford comet

Water-Based Propulsion for Small Satellites

Efficient. Affordable. Easy to work with.

Comet is a launch-safe and cost-effective electrothermal propulsion system that offers the ideal balance of cost and performance. This high-performance propulsion unit uses water as propellant, making the system easy to work with and easy to fuel. Its highly-flexible interface is easy to integrate into your small satellite, regardless of size and form factor, and easy to operate on orbit. Comet has also been optimized for minimal power consumption and short maneuvering times, allowing you to focus more resources on your payload.

Currently in production, Comet is flight-ready and **shipping now**.

Comet Specifications

Performance Characteristics	
Typical Specific Impulse	175 s
Warm-Up Time	10 minutes
Power Consumption while Thrusting	55 W for indefinite thrust 25 W for < 1 minute thrust
Power Consumption while Idle	0.25 W
Nominal Thrust	17 mN
Mechanical / Electrical Characteristics	
Dimensions of Thruster Head	10 x 10 x 3 cm
Dimensions of Propellant Tank	Sized for your application
Dimensions of 1,000 Ns Tank	10 x 10 x 17 cm
Input Voltage Range	8 – 34 V
Physical Layer Interface	RS422/485, CAN
Protocol and Command Interface	NSPv4, customizable

Features

- Integrated propellant management and control unit
- Digital command and telemetry interface
- Dedicated WARM, ARM, and FIRE commands
- Programmable thruster power consumption
- Custom-locatable fill and drain ports
- Customizable body heaters as-needed with thermostat
- 5°C to 60°C operating temperature range
- Electronics inspection to J-STD-001 (space addendum) standards
- Environmental testing per NASA GEVS specifications

Advantages:
- Non-toxic; safe for humans and launch vehicles
- Approved for flight on multiple launch vehicles
- More thrust with less electrical power
- Highly-flexible interface suitable for a wide range of spacecraft sizes

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Additional comments:

[Reference 1-6][Feb 2019][General info]
The dimensions of a 1000 N*s tank are 10x10x7 cm, and can be sized for a particular application and mission. The dimensions of the thruster head are 10x10x3 cm. Operating temperature range is 5 to 60C (includes body heaters as needed with thermostat). Environmental testing per NASA GEVS specifications has been done.

References:
[1] Sarda, K., Roth, N., Zee, R., CaJacob, D., Orr, N., "Making the Invisible Visible: Precision RF-Emitter Geolocation from Space by the HawkEye 360 Pathfinder Mission," SSC18-II-06, SmallSat Conference, 2018.
[2] Bonin, G., Tarantini, V., Orr, N., Armitage, S., "Comet: A Launch-Safe, Low-Cost Water-Based Propulsion System for Nano- and Microsatellites," Poster session, Small Satellite Conference, 2018.
[3] Orr, N., Tarantini, V., Foulds, C., Armitage, S., Bonin, G., "Development of a Launch Safe CubeSat and Microsatellite Water Propulsion System," Poster Session, Small Satellite Conference, 2017.
[4] http://deepspaceindustries.com/wp-content/uploads/2018/03/Comet-Spec-Sheet.pdf
[5] https://spacenews.com/deep-space-industries-acquired-by-bradford-spoce/
[6] Communications with manufacturer and manufacturer's spec sheet handed out at SmallSat Symposium 2019, and also emailed from Ian Fichtenbaum to Mark Mueller.
[7] https://www.geekwire.com/2019/bradford-buys-deep-space-industries-shifting-focus-asteroid-mining-green-propulsion/
[8] https://spacenews.com/water-propulsion-technologies-picking-up-steam/
[9] public company newsletter

Comm. avail. | 4 TRL | NO Aerospace-tested

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COMET [2 of 3]
Deep Space Industries (DSI)/Bradford Space Inc. (BSI)

Additional comments:

[References 1-4]

In April 2018, California-based Deep Space Industries announced that it has signed a contract to provide water-spraying thrusters for the BlackSky Earth observation satellites that are due to be built in Seattle. The contract covers an initial block of 20 Comet water-based satellite propulsion systems. The systems expel superheated water vapor as propellant to adjust the attitude of small spacecraft in orbit. Twenty satellites are scheduled to go into orbit by 2020 in the first phase of an Earth observation effort managed by BlackSky, a subsidiary of Seattle-based Spaceflight Industries.

To be launched in Q4 2018, the HawkEye 360 (HE360) Pathfinder mission will validate key enabling technologies and operational methods necessary to provide unprecedented analysis of wireless signals for commercial and government applications using small satellites. Applications range from logistics monitoring and tracking of aircraft, ships, and ground transportation, to emergency response and other data analytics and services. The mission will nominally consist of three Pathfinder satellites, operated in formation, to demonstrate and validate an initial operational capability. Following the Pathfinder demonstration a constellation with more than 18 satellites will be deployed. HE360 has contracted Deep Space Industries (DSI) and major subcontractor Space Flight Laboratory (SFL) to design and manufacture the spacecraft platform for the Pathfinder demonstration mission. In addition to being a world leader in low-cost high-performance small spacecraft, SFL is a pioneer in low-cost precision spacecraft formation flight, a key enabling technology for HE360 mission. DSI, a world leader in state-of-the-art launch safe propulsion systems, is providing the CometTM water-fueled resisto-jet propulsion system for the mission.

[Reference 5][Jan 2019]

As of Jan 2019, Deep Space Industries has been acquired by Bradford Space, a U.S.-owned company with facilities in the Netherlands and Sweden. Ian Fichtenbaum, a director of Bradford Space, confirmed in a Jan. 1 email that the deal had closed, but that terms of the acquisition could not be disclosed. Fichtenbaum said that Bradford sees Comet as a complementary product to its existing ECAPS thrusters. DSI, which will be rebranded as Bradford Space Inc., or BSI, will continue to work on a satellite bus called Xplorer that is intended for use on missions beyond Earth orbit.

[Reference 7][Feb 2019]

The On Orbit Hawkeye360 Pathfinder Smallsats Are Nearing Completion of Checkout and Testing

[Reference 8][Jun 2020][Flight info]

Capella Space's first radar satellite and HawkEye 360's first cluster of three radio-frequency mapping satellites move in orbit by firing Bradford Space's water-based Comet electrothermal propulsion system.

References:

[1] Sarda, K., Roth, N., Zee, R., CaJacob, D., Orr, N., "Making the Invisible Visible: Precision RF-Emitter Geolocation from Space by the HawkEye 360 Pathfinder Mission," SSC18-II-06, SmallSat Conference, 2018.
[2] Bonin, G., Tarantini, V., Orr, N., Armitage, S., "Comet: A Launch-Safe, Low-Cost Water-Based Propulsion System for Nano- and Microsatellites," Poster session, Small Satellite Conference, 2018.
[3] Orr, N., Tarantini, V., Foulds, C., Armitage, S., Bonin, G., "Development of a Launch Safe CubeSat and Microsatellite Water Propulsion System," Poster Session, Small Satellite Conference, 2017.
[4] http://deepspaceindustries.com/wp-content/uploads/2018/03/Comet-Spec-Sheet.pdf
[5] https://spacenews.com/deep-space-industries-acquired-by-bradford-space/
[6] Communications with manufacturer and manufacturer's spec sheet handed out at SmallSat Symposium 2019, and also emailed from Ian Fichtenbaum to Mark Mueller.
[7] http://satnews.com/story.php?number=1268258787
[9] https://spacenews.com/water-propulsion-technologies-picking-up-steam/

	4	NO
Comm. avail.	TRL	Aerospace-tested

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DISTRO A: Approved for public release. OTR-2024-00338

COMET [3 of 3]
Deep Space Industries (DSI)/Bradford Space Inc. (BSI)

Additional comments:

[Reference 1][June 2020][Hawkeye vehicle info]
The HE360 Pathfinder mission employs the versatile flight proven NEMO platform of UTIAS/SFL. This state-of-the-art microsatellite bus has been employed by a wide range of commercial and government users, and depended upon in applications and business models which would only allow for a high-performance high-reliability yet affordable platform. The HE360 Pathfinder platform is essentially a 20 x 20 x 44 cm form factor with an additional ~7 cm high 'mezzanine', with a launch wet mass of 13.4 kg. Similar to spacecraft designed to the CubeSat standard, four launch rails interface with the separation system and guide the spacecraft during ejection from SFL's XPOD separation system.
Propulsion system: DSI (Deep Space Industries) is providing a novel electro-thermal propulsion system that uses liquid water as the working fluid, significantly reducing integration and launch risks relative to other market options of similar performance. The unit has a qualified specific impulse (Isp) of 182 seconds, giving it exceptional performance with comparison to a typical cold-gas system. Conversely, while it has a lower Isp than newly available low-power electric propulsion systems, the higher thrust means that DSI's system can be used quasi-impulsively. This reduces the time required for maneuvers. Electric propulsion systems also typically utilize high voltage power supplies or RF-amplifiers that produce wide-band RF noise, which is detrimental to the RF payload. The propulsion system on Pathfinder has a ΔV of 96 m/s, though, the system features an easily expandable propellant tank, allowing for simple propellant volume tailoring. The water propellant needs to stay liquid at all times. The thermal design of the spacecraft passively maintains the propellant in a liquid state, but auxiliary heaters are positioned to augment this in an emergency.

References:
[1] https://directory.eoportal.org/web/eoportal/satellite-missions/h/hawkeye

	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

Hybrid ADN Delta-V / RCS system
Hybrid ADN MiPS - 13067003-01

Propulsion Technology	Hybrid rocket (ADN/cold gas)
Manufacturer/Country	VACCO (USA)/ECAPS (SWEDEN)
TRL	4
Size (including PPU)	1U
Design satellite size	3U
Isp (s)	200 to 250s
Thrust type/magnitude	440 mN total (5 thrusters) => 1X 100 mN ADN + 4X 10 mN cold gas ACS 1040 N*s (impulse, total, main thruster) 70 N*s (impulse, total, ACS cold-gas thrusters, each) <0.1 mN*s (impulse, minimum)
Delta-V (m/s)	200 m/s for 5 kg satellite
Propellant	ADN propellant (central thruster) + R134A refrigerant (4X cold-gas ACS thrusters)
Power consumption (W)	15W (operational), <0.1W (standby)
Flight heritage (if any)	None known
Commercially available	YES
Last updated	*03/2021*

VACCO/ECAPS hybrid rocket utilizing ammonium dinitramide "green" propellant

Operating Parameters

Max Operating Pressure	244 psia	Cycle Life	900,000 firings
Proof Pressure	366 psia	Total Delta-V Impulse	1,036 N-sec
Burst Pressure	610 psia	Total RCS Impulse	69 N-sec
Delta-V Thrust	100 mN	RCS Minimum Impulse Bit	<0.1 mN/sec
ACS Thrust	10mN	Operating Voltage	9 to 12.6 vdc
Internal Leakage	3.0 scc/hr	Dry Mass	1,093 grams
External Leakage	1.0×10^{-6} scch	ADN Propellant Mass	528 grams
Operating Temperature	0°C to +50°C	ACS Propellant Mass	176 grams
Non-Operating Temperature	-10°C to +60°C	Total Mass	1,797 grams
Vibration	23 Grms		

Additional comments:

[Reference 1-2][Jan 2019][

The VACCO / ECAPS CubeSat Hybrid ADN Delta-V / Reaction Control System is a high performance micro propulsion system (MiPS) specifically designed for CubeSats. The Hybrid ADN MiPS is a self-contained subsystem that can be scaled from 0.5U to >1U.

A single axial high-thrust, central high specific impulse (Isp) ADN thruster delivers up to 1,036 N-sec of total impulse using only integral propellant. Four additional ACS cold-gas thrusters produce 10 mN each. Manufacturer reports cycle life of 900,000 firings.

References:

[1] http://www.vacco.com/images/uploads/pdfs/HybridMiPS-ReactionControlSystem-0714.pdf
[2] https://www.cubesat-propulsion.com/wp-content/uploads/2015/10/Hybrid-adn-delta-5.pdf

4

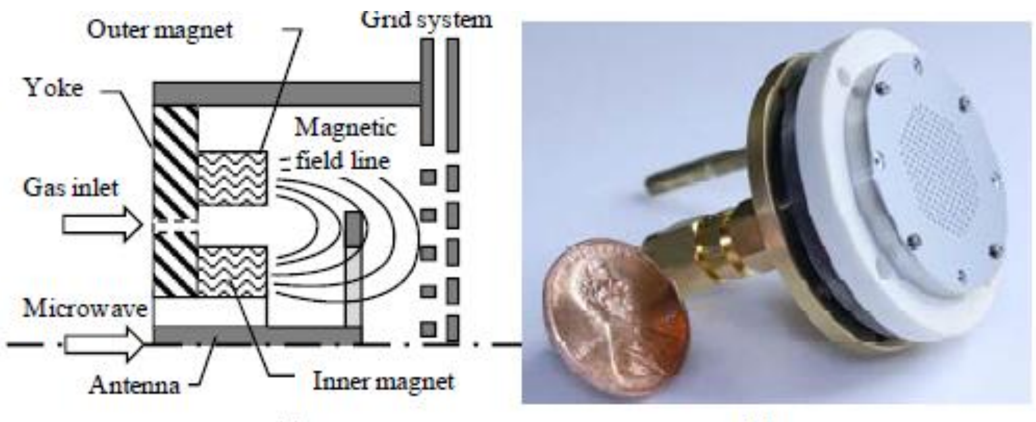
NO

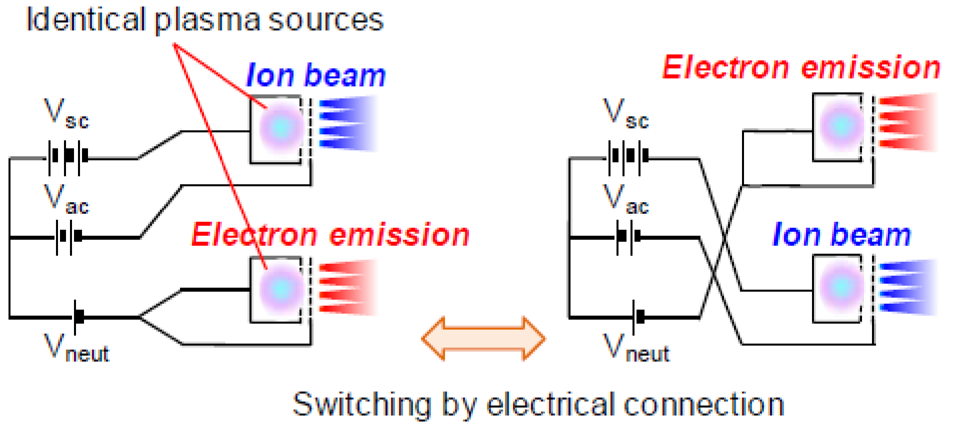
Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Miniature microwave discharge ion engine, μ-1 (micro-1/ "mu-one")

Propulsion Technology	Microwave ion engine
Manufacturer/Country	Shizuoka University/JAXA (Japan)
TRL	4-5
Size (including PPU)	Not reported, but very small.
Design satellite size	~10 to 50 kg
Isp (s)	500 to 1100 s [1 to 4] 665s, ground test result [5]
Thrust type/magnitude	150 to 400 uN [1 to 4] 165 uN, ground test results [5]
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	10-30W
Flight heritage (if any)	None known, although "mu-10" has flown on Hayabusa2 (2014)
Commercially available	No
Last updated	*03/2021*





Additional comments:

[Reference 1][Jan 2019][General info]
We developed a miniature ECR discharge ion engine driven by 1.0 W microwave power and 6.0 W ion acceleration power.18) This miniature ion engine is named as μ1 ("mu-one"), due to the 1-cm-class beam diameter and 1-W-class microwave power. It is the smallest ion engine in the "μ" series of ion engines developed in ISAS of JAXA.19-21) The μ1 has the 250 W/A ion production cost and 37 % mass utilization efficiency for 1.0 W microwave input power and 0.15 sccm xenon mass flow. We measured the fundamental characteristics of electron emission from this ion engine. This was performed by installing a single-aperture orifice plate with the μ1 instead of the grid system and by applying the positive voltage to the collector plate placed outside. This experiment gave us important conclusions: 1) there was a minimum threshold for diameter and 2) the best position was above the ring-antenna. Based on this result, a new grid system dedicated for the switching operation was designed. This grid system has two different types of apertures for ions and electrons respectively. The grid system had sufficient performances to extract ion beam for thrust and to emit electrons for the neutralization. Finally successful demonstration of the switching operation was shown by using two μ1 ion engines. The plasma source consumes 1.0 W microwave power and 0.15 sccm mass flow rate under the typical condition. The thruster can provide 3.3 mA ion beam in ion engine mode and neutralize the same amount of ion beam by the contact voltage below 40 V in neutralizer mode.
This thruster is capable of operating without a neutralizer by utilizing a pair of thrusters and alternating operating.

[Reference 2][Jan 2019][Flight info]
The "mu-10" thruster is well known, and has been tested extensively and flown successfully on the Hayabusa2 asteroid mission (launched 2014).

[Reference 5][March 2021][Thruster ground testing]
The highest thrust was 164 ± 13.4 μN, and the highest specific impulse was 665 ± 59 s while neglecting the neutralizer.

References:
[1] Koizumi, H., Kuninaka, H., "Ion beam extraction and electron emission from the miniature microwave discharge ion engine u-1," IEPC-2009-178.
[2] Nishiyama, K., Hosoda, S., Ueno, K., Tsukizaki, R., Kuninaka, H., "Development and testing of the Hayabusa2 ion engine system," IEPC-2015-333.
[3] Spektor, R., Fathi, G., Brady, B., Moore, T., "2011 Review of Propulsion Options for the Aerospace CubeSat Project," Aerospace report TOR-2011(8582)-6
[4] Koizumi, H., Kuninaka, H., "Performance Evaluation of a Miniature Ion Thruster u1 (mu-one) with a unipolar and bipolar operation," IEPC-2011-297.
[5] Nakagawa, Y., Koizumi, H., Kawahara, H., Komurasaki, K., "Performance characterization of a miniature microwave discharge ion thruster operated with water," Acta Astronautica, Vol. 157, 2019.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

SPT-20 Hall-type thruster

Propulsion Technology	Hall thruster
Manufacturer/Country	LPMI (Laboratoire de Physique des Millieux Ionises)/National Aerospace University “KhAI” (France/Ukraine)
TRL	3-4
Size (including PPU)	Small
Design satellite size	3U and larger
Isp (s)	500 to 1000 s [1]
Thrust type/magnitude	2 to 5 mN [1]
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	20W
Flight heritage (if any)	None known
Commercially available	Unknown
Last updated	*03/2021*

Plasma plume for the SPT-20 thruster

Additional comments:

[Reference 1][Jan 2019][General info]
A laboratory model of the SPT-20 was tested. It is a small power, small size Hall-type thruster with an annular quartz channel. The external channel diameter is 20 mm and the inner diameter is 10 mm. The xenon inlet is located on the side of the main discharge channel using a lateral tube. At LPMI, the primary electron emitter is a tungsten filament located outside of the thruster channel. The discharge voltage, typically 200V, is applied between the anode and the external cathode (filament). This SPT-20 thruster has also been studied at RCC Kurchatov Institute (Russia, E-1 facility), using a hollow cathode instead of a filament.

[Reference 2][Jan 2019][Diagnostics/thruster testing]
Optical emission spectroscopy measurements were performed on the SPT-20 and used to calculate the erosion rate of ceramics. This optical emission spectroscopy research to characterize the rate erosion of the ceramics is partially supported by the French Research Group, GDR CNRS/CNES/SNECMA/Universités n°2759 " Propulsion Spatiale à Plasma" and STCU grant #1936 and France-Ukraine programme DNIPRO-2007 (P.A.I.).

References:

[1] Guerrini, G., Michaut, C., Dudeck, M., Bacal, M., “Parameter analysis of three small ion thrusters (SPT-20, SPT-50, A3),” Proceedings of the 2nd European Spacecraft Propulsion Conference, 1997.

[2] Pagnon, D., Pellerin, S., Dudeck, M., et al., “Ukrainian SPT-20 Hall effect thruster: analysis of the plume by optical emission spectroscopy,” IEPC-2007-361.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

HT400 Hall Effect Thruster
Alta-Space/SITAEL

Propulsion Technology	Hall Effect Thruster (HET)
Manufacturer/Country	Alta-Space, now (SITAEL) (ITALY)
TRL	3-4
Size (including PPU)	900g [4]
Design satellite size	<500 kg
Isp (s)	Up to 1800s [4]
Thrust type/magnitude	20 to 50 mN [4]
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	400W
Flight heritage (if any)	None known
Commercially available	NO
Last updated	*03/2021*

HT400	
Nominal Power	400 W
Thrust Range	20 - 50 mN
Max. I_{sp}	1800 s
TRL	5
Estimated lifetime 5000 hrs Power can go up to 800W with no thermal problems; intended for satellites up to 500kg	

SITAEL's HT400 thruster

SPECIFICATIONS	
Thruster Technology	Hall Effect Thruster
Propellant	Xenon 99,996% (tested also with Argon)
Power	250 – 800 W (tested up to 1000 W)
Thrust	20 - 50 mN
Isp	Up to 1850 s
Efficiency	Up to 50%
Thruster unit mass	~900 g
Thruster feed pressure	25 mbar
PPU power input	Unregulated 28 V; 2,5 A peak current
Thruster Unit Power input (PPU output)	150 - 400 V; 0,4 - 1,5 A
Thruster envelope	Ø 100x63 mm (I/F and cathode excluded)
Physical I/F	No.3 M5 screwed rod on a Ø 52 mm circle
Technology Readiness Level (TRL)	5
Qualification status	EQM Coupling test with SITAEL 1 kW PPU breadboard done

SITAEL

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Small Satellites, Advanced Propulsion, Instruments and Avionics, Services and Applications.

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[4]

Additional comments:
Alta and Alma space merged into SITAEL in 2015.

[Reference 1][Jan 2019][General info]
Estimated lifetime is 5000 hrs (unclear whether this is supported by test data). Power can go up to 800W with no thermal problems, and the system is intended for satellites up to 500 kg.

[Reference 2][Jan 2019][Testing results]
Manufacturer reports 600 hrs of cumulated firing time.

[Reference 3][Dec 2019][General info]
The HT 400 Hall Effect Thruster (HET) has been designed to perform orbit and attitude control tasks on micro and mini satellites. Its design, based on permanent magnets, is conceived to be installed onboard of Telecommunication and Earth observation platforms. In particular, it is in the forefront of Low Power Hall Effect Thrusters (LP-HET), thruster class especially suitable for small satellites where power and mass budgets are strongly limited.

References:

[1] Misuri, T., "Low power electric propulsion at Sitael," International workshop on ion propulsion and accelerator industrial applications, Presentation, 2017.
[2] Misuri, T., "Sitael low power electric propulsion systems for small satellites," EPIC workshop, Presentation, 2018.
[3] http://www.sitael.com/space/advanced-propulsion/electric-propulsion/hall-effect-thrusters/
[4] https://satcatalog.com/datasheet/SITAEL%20-%20HT%20400.pdf

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

XR-150-050

Propulsion Technology	Resistojet
Manufacturer/Country	Alta-Space, now (SITAEL) (ITALY)
TRL	3-4
Size (including PPU)	<1U, 220 g
Design satellite size	
Isp (s)	At 50W power: 50 s with Xe, 57 s with Kr [3] Cold operation: 30s with Xe, 38s with Kr [3]
Thrust type/magnitude	111 mN at 4 bar feed pressure [3]
Delta-V (m/s)	
Propellant	Xe, Kr, Ar, any non-oxidizing propellant
Power consumption (W)	<50W, using 28V bus [2]
Flight heritage (if any)	None known
Commercially available	YES
Last updated	*03/2021*

Thruster	XR150-050		XR150-100	
Weight [g]	220 (without piping)			
Size [mm]	Ø 27 x 80			
Propellant	Xe	Kr	Xe	Kr
Nominal Thrust range [mN]	50 ÷ 150			
Power bus [Vdc]	28*			
Max power @ 28Vdc [W]	≤ 50		≤ 100	
Specific impulse [s]	≥ 49	≥ 60	≥ 56	≥ 69
Thruster inlet pressure	≤ 5.5 bar	≤ 4.5 bar	≤ 7.5 bar	≤ 6.5 bar
Lifetime** [hrs]	≥ 250			
Total Impulse** [Ns]	≥135k	≥110k	≥200k	≥160k

(*) other bus voltages compatibility available on request
(**) the lifetime and the total impulse are limited only by propellant shortage concerns.

Additional comments:

[Reference 2][Jan 2019][Company info/thruster info]
SITAEL resistojet thrusters (XR-50, -100 and -150) have been developed since 2003 adapting to different size, mass and performance requirements.Design of the thruster has been ruggedized by substituting the original tungsten filament heater with an industrial COTS component for very harsh environments. Their flexible design allows for additional optimization depending on specific mission profile or custom specifications. SITAEL XR-series thrusters, even if optimized considering Xenon as propellant, may be operated with any non-oxidizing gas or liquid droplets. Each thruster configuration presents an embedded miniature conical nozzle and may be also operated in “cold-gas” mode with reduced performance and lower thermal regimes, thus ensuring an intrinsic redundancy of the system. Lifetime is reported as >200 hrs.

[Reference 3][Jan 2019][Testing results]
Two XR150 models were built and tested with Xe and Kr. The XR150-100 and XR150-050 allow direct coupling with spacecrafts with a 28V unregulated power bus voltage. The XR150 resistojet thruster can be operated either in hot and cold gas mode. When the heater is switched-off, the thruster behavior is the same as a standard cold gas thruster, with typical performances that depend on the inlet pressure and the propellant characteristics. As all resistojet thrusters, the XR150 is designed to be started both in hot and cold gas conditions. In the hot start mode, the heater is switched-on before the propellant flow (pre-heating), and it allows to reach the desired specific impulse just at the beginning of the thruster operation. The pre-heating time varies according to the initial temperature of the thruster. In the cold start mode, the heater and the propellant flow are switched-on at the same time and the thermal steady state condition is achieved after few minutes from the beginning of the operation (depending on the initial temperature of the thruster unit). Accordingly, the specific impulse increases from the value corresponding to the cold gas mode up to the one corresponding to the hot gas mode (for Xe, from 30 to 50-56 s). This case leads to an increase of the amount of propellant required for the envisaged maneuver, but can be used in case of unexpected events that require quick thrust impulses. With the aim to identify a suitable architecture for an integrated propulsion system for full electric platforms, Sitael performed dedicated analysis using its XR150 resistojet thruster. The company developed and manufactured two XR150 engineering models with power consumption of 50W and 100 W (the XR150-100 and the XR150-050). A specific experimental test campaign was performed with Xe and Kr to investigate its ability to operate with such kind of propellants as a valid alternative to traditional cold gas thrusters. The test campaign confirmed the results of the computational analyses and demonstrate the effectiveness of these thrusters as auxiliary propulsion system.

References:
[1] Misuri, T., “Sitael low power electric propulsion systems for small satellites,” EPIC workshop, Presentation, 2018.
[2] www.sitael-hellas.com/wp-content/uploads/2015/10/XR-family.pdf
[3] Cifali, G., Gregucci, S., Andreussi, T., Andrenucci, M., “Resistojet thrusters for auxiliary propulsion of full electric platforms,” IEPC-2017-371

	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

XR-150-100

Propulsion Technology	Resistojet
Manufacturer/Country	Alta-Space, now (SITAEL) (ITALY)
TRL	3-4
Size (including PPU)	<1U, 220 g
Design satellite size	
Isp (s)	At 100W power: 57 s with Xe, 70 s with Kr [3] Cold operation: 30s with Xe, 38s with Kr [3]
Thrust type/magnitude	111 mN at 4 bar feed pressure [3]
Delta-V (m/s)	
Propellant	Xe, Kr, Ar, any non-oxidizing propellant
Power consumption (W)	<100W, using 28V bus [2]
Flight heritage (if any)	None known
Commercially available	YES
Last updated	*03/2021*

Thruster	XR150-050		XR150-100	
Weight [g]	220 (without piping)			
Size [mm]	Ø 27 x 80			
Propellant	Xe	Kr	Xe	Kr
Nominal Thrust range [mN]	50 ÷ 150			
Power bus [Vdc]	28*			
Max power @ 28Vdc [W]	≤ 50		≤ 100	
Specific impulse [s]	≥ 49	≥ 60	≥ 56	≥ 69
Thruster inlet pressure	≤ 5.5 bar	≤ 4.5 bar	≤ 7.5 bar	≤ 6.5 bar
Lifetime** [hrs]	≥ 250			
Total Impulse** [Ns]	≥135k	≥110k	≥200k	≥160k

(*) other bus voltages compatibility available on request
(**) the lifetime and the total impulse are limited only by propellant shortage concerns.

Additional comments:

[Reference 2][Jan 2019][General info]
SITAEL resistojet thrusters (XR-50, -100 and -150) have been developed since 2003 adapting to different size, mass and performance requirements.Design of the thruster has been ruggedized by substituting the original tungsten filament heater with an industrial COTS component for very harsh environments. Their flexible design allows for additional optimization depending on specific mission profile or custom specifications. SITAEL XR-series thrusters, even if optimized considering Xenon as propellant, may be operated with any non-oxidizing gas or liquid droplets. Each thruster configuration presents an embedded miniature conical nozzle and may be also operated in “cold-gas” mode with reduced performance and lower thermal regimes, thus ensuring an intrinsic redundancy of the system. Lifetime is reported as >200 hrs.
[Reference 3][Jan 2019][Thruster info/testing results]
Two XR150 models were built and tested with Xe and Kr. The XR150-100 and XR150-050 allow direct coupling with spacecrafts with a 28V unregulated power bus voltage. The XR150 resistojet thruster can be operated either in hot and cold gas mode. When the heater is switched-off, the thruster behavior is the same as a standard cold gas thruster, with typical performances that depend on the inlet pressure and the propellant characteristics. As all resistojet thrusters, the XR150 is designed to be started both in hot and cold gas conditions. In the hot start mode, the heater is switched-on before the propellant flow (pre-heating), and it allows to reach the desired specific impulse just at the beginning of the thruster operation. The pre-heating time varies according to the initial temperature of the thruster. In the cold start mode, the heater and the propellant flow are switched-on at the same time and the thermal steady state condition is achieved after few minutes from the beginning of the operation (depending on the initial temperature of the thruster unit). Accordingly, the specific impulse increases from the value corresponding to the cold gas mode up to the one corresponding to the hot gas mode (for Xe, from 30 to 50-56 s). This case leads to an increase of the amount of propellant required for the envisaged maneuver, but can be used in case of unexpected events that require quick thrust impulses. With the aim to identify a suitable architecture for an integrated propulsion system for full electric platforms, Sitael performed dedicated analysis using its XR150 resistojet thruster. The company developed and manufactured two XR150 engineering models with power consumption of 50W and 100 W (the XR150-100 and the XR150-050). A specific experimental test campaign was performed with Xe and Kr to investigate its ability to operate with such kind of propellants as a valid alternative to traditional cold gas thrusters. The test campaign confirmed the results of the computational analyses and demonstrate the effectiveness of these thrusters as auxiliary propulsion system.

References:
[1] Misuri, T., “Sitael low power electric propulsion systems for small satellites,” EPIC workshop, Presentation, 2018.
[2] www.sitael-hellas.com/wp-content/uploads/2015/10/XR-family.pdf
[3] Cifali, G., Gregucci, S., Andreussi, T., Andrenucci, M., “Resistojet thrusters for auxiliary propulsion of full electric platforms,” IEPC-2017-371

	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

MultiFEEP

Propulsion Technology	FEEP
Manufacturer/Country	TU Dresden (Germany), now commercialized by Morpheus Space
TRL	3-4
Size (including PPU)	Dry mass 280g, wet mass up to 400g, Total system size = 90x45x45 mm. 2 MultiFEEP systems (4 thrusters in total) can be integrated into 1U [1]
Design satellite size	1U or larger
Isp (s)	2600 to 8500s [1]
Thrust type/magnitude	Dynamic thrust range 1 to 120 uN, maximum 140 uN, total impulse max 13000 N*s [1]
Delta-V (m/s)	
Propellant	Gallium metal
Power consumption (W)	0.4 to 19W [3]
Flight heritage (if any)	None. UWE-4 (launched Dec 2018, carrying NanoFEEP technology – a similar system)
Commercially available	YES
Last updated	*03/2021*

Additional comments:

[Reference 1][Aug 2019][General thruster info]
This is a larger, more powerful version of the NanoFEEP. See NanoFEEP for more Morpheus company information. UWE-4 flew NanoFEEP which is a similar system to MultiFEEP. The MultiFEEP system consists of 2 thrusters, 2 neutralizers, and the control electronics board.

References:
[1] http://www.morpheus-space.com/documents/M-Space%20Products.pdf

4 NO
Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Stellar Bi-Propellant
Stellar Exploration

Propulsion Technology	Bi-propellant (hydrazine + N2O4), joint development with MSSS [1]
Manufacturer/Country	Stellar Exploration (USA)
TRL	3-4
Size (including PPU)	~4U (design)
Design satellite size	12U and larger, up to ESPA-class
Isp (s)	285s [1]
Thrust type/magnitude	4X 3N thrusters = 12N [1]
Delta-V (m/s)	2000 m/s for 12U CubeSat [1]
Propellant	Hydrazine + NTO
Power consumption (W)	Unknown
Flight heritage (if any)	Secondary payload on Psyche (2022, projected). 7 dual-mode units to be delivered by end of 2023 to Millenium [4].
Commercially available	Yes
Last updated	*03/2023*

[Reference 1]

Additional comments:

[Reference 1-3][Aug 2019][General info]
From the SpaceNews article, "Stellar Exploration developed the new thruster with funding from NASA's Small Innovative Missions for Planetary Exploration program, which supports the formulation and development of small spacecraft science missions. The company is proposing to fly it for the first time on a cubesat that would ride to Mars along with NASA's Psyche asteroid exploration mission in 2022. Psyche is slated to perform a Mars fly-by, which means a cubesat riding along will need its own powerful propulsion to enter Martian orbit."
The system has low-pressure tanks to ease range safety concerns.
It is not clear that this system is available for sale although the website suggests that it is available. The website has no ground test data, hardware drawings, or specifications.
In 2009, the company's CEO, Thomas Svitek, published a paper in SmallSat on a high-performance hydrazine monopropellant micropropulsion system (cited below), but this system does not seem to be available either on the website. He also published several others in the 1990's, also at SmallSat, on Mars relay spacecraft and micro landers.
"Range safety (do not harm) is the critical requirement. The design is fully compliant with AFSCM 91-710 V4. Propellant tanks are unpressurized for launch. System is fully welded and sealed. Triple safety inhibit requirement is met. Fueling and integrating to the system into the deployer occurs off-site. If an anomaly occurs, the entire deployer assembly is removed as a unit and remediated off-site without impacting the primary payload… Safe propellant handling procedures rely on existing long-standing knowledge base and experience in order to achieve OSHA/NIOSH compliance at affordable cost."

References:
[1] https://www.stellar-exploration.com/
[2] https://spacenews.com/new-thruster-aims-to-help-microsats-bust-out-of-the-kiddy-pool/
[3] Biddy, C., Svitek, T., "Monopropellant Micropropulsion System for CubeSats," SSC-09-II-2, Small Satellite Conference, 2009.
[4] Email correspondence with Tomas Svitek [March 2023]

4 | NO
Comm. avail. | TRL | Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Stellar SR-5B Biprop

Propulsion Technology	Bi-propellant
Manufacturer/Country	Stellar (USA)
TRL	4-5
Size (including PPU)	
Design satellite size	3U up to ESPA
Isp (s)	288 s
Thrust type/magnitude	5N (nominal)
Delta-V (m/s)	
Propellant	Hydrazine, NTO (MON-3)
Power consumption (W)	
Flight heritage (if any)	None known
Commercially available	YES
Last updated	02/2022

SR-5B Biprop Thruster	
Fuel	Hydrazine (HPH)
Oxidizer	NTO (MON-3)
Injector	Single unlike doublet Grade 5 Titanium
Chamber	Radiatively cooled Niobium C103 with R512E coating
Thrust (F)	5 N (nominal)
Nozzle Expansion Ratio (ε)	140:1
Steady-State I_{sp}	288 sec
Pulsed I_{sp}	230-260 sec
Mixture Ratio	1.1-1.2
Nozzle Outer Diameter	23 mm

Additional comments:

[Ref 1][Feb 2022][Thruster development]
Further improvements to thruster design have been implemented. Testing is planned at White Sands in 2022.
The flightworks propellant pump has been testing and characterized, compatible with both hydrazine and MON-3.

References:
[1] Public test results, email correspondence with T. Svitek Jan 2022 (more information in report, “Recent flight results design summary”

4 NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Busek Green Monopropellant Thrusters, BGT-X1
Busek

Propulsion Technology	Green Monopropellant
Manufacturer/Country	Busek (USA)
TRL	3-4
Size (including PPU)	0.5 to 1U
Design satellite size	3U and larger
Isp (s)	214s
Thrust type/magnitude	100 mN (continuous, nominal, max) Throttleable from 20 to 180 mN <14 mN*s (impulse bit, min)
Delta-V (m/s)	
Propellant	AF-M315E
Power consumption (W)	4.5W (catalyst preheat, BGT-X1 model)
Flight heritage (if any)	None known
Commercially available	YES
Last updated	*03/2021*

Various models of green monopropellant thrusters

1U CubeSat Green Propulsion System

Additional comments:

[Reference 1][Dec 2019][General info]
Various models of this thrusters exist. There is only a manufacturer datasheet for the BGT-X5 (probably the highest TRL of the different models). Busek's BGT-X5 green monopropellant thruster system produces 0.5N thrust and features a highly stable "green" propellant alternative to hydrazine. The thruster features a patented long-life catalyst reactor, high temperature thruster body, and low power piezo microvalve (flight heritage). The novel propellant tank and patent-pending Post-Launch Pressurization System (PLPS) enable a compact high-thrust propulsion solution for Cubesats and Smallsats. The BGT-X5 system has 1U volume and easily scales by increasing the size of the propellant tank to support higher total impulse applications. Alternately, multiple systems can be easily integrated onto a single spacecraft for modular attitude control and translational thrust. The thruster delivers 500 mN thrust at 220-225 seconds specific impulse at approximately 400 psi feed pressure. As a 1U system, it delivers 146 m/s delta-v to a 4 kg CubeSat and is capable of multiple start-stops for precision firing and short impulse bits on the order of 0.05 N-s. The rugged flight electronics includes an integrated DCIU with communication via RS-422.

References:
[1] http://www.busek.com/technologies__greenmonoprop.htm

Comm. avail.	TRL	Aerospace-tested
	4	NO

DISTRO A: Approved for public release. OTR-2024-00338

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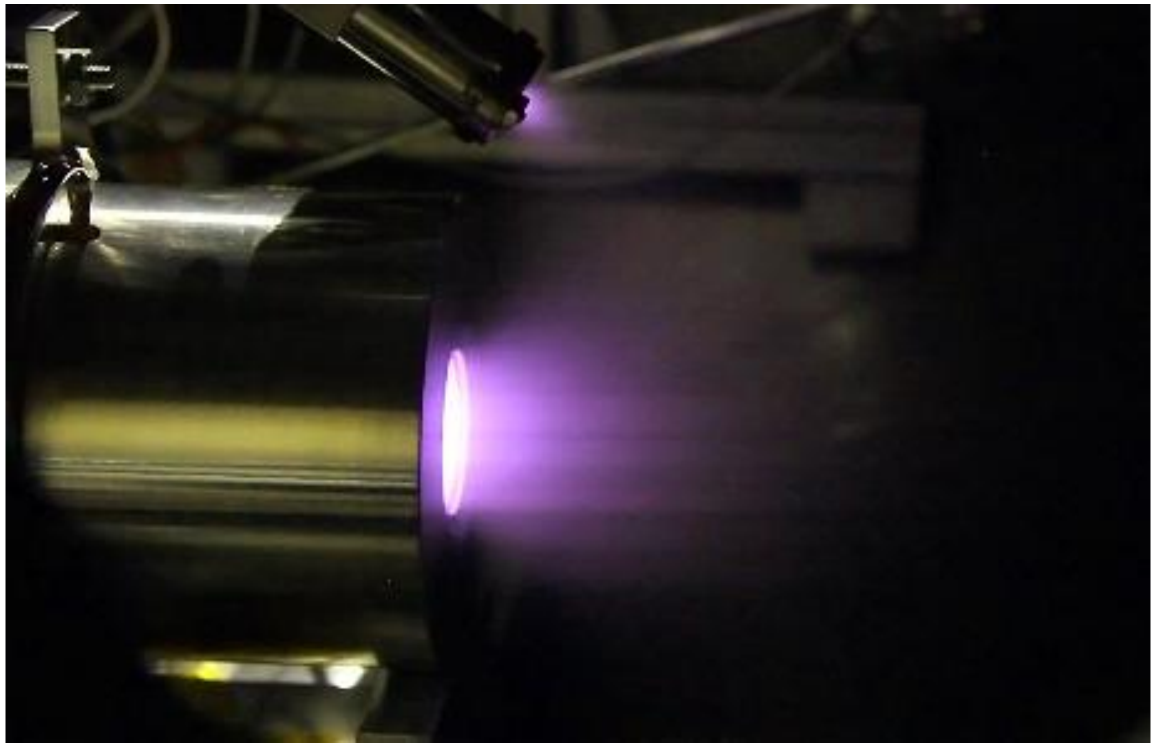
Cylindrical Hall Thruster
University of Toronto SFL/Canadian Advanced Nanosatellite Propulsion System (CNAPS)

Propulsion Technology	Hall Thruster
Manufacturer/Country	University of Toronto Space Flight Laboratory (SFL) (CANADA)
TRL	3-4
Size (including PPU)	Diameter is 26 mm
Design satellite size	150 kg
Isp (s)	>200s
Thrust type/magnitude	1-10 mN
Delta-V (m/s)	100 m/s
Propellant	Xenon
Power consumption (W)	<200W
Flight heritage (if any)	None known
Commercially available	Unknown
Last updated	*03/2021*



Cylindrical Hall Thruster, 2015

Additional comments:

[References 1-2][Jan 2019][Thruster info]
Thruster builds on previous SFL experience with cold gas thrusters. They have ongoing collaborations with COM DEV, MDA, Magellan Aerospace. Funded by the Canadian Space Agency.

SFL at the University of Toronto is developing a low power cylindrical Hall thruster that operates below 200 W and has a diameter of 26 mm for the ionization chamber. The cylindrical geometry of the ionization chamber was chosen in order to overcome the challenges of the annular chamber of traditional Hall thrusters. With this configuration, better efficiencies can be achieved while maintaining a sufficient thrust magnitude between 2.5-12 mN. Annular ionization chambers are mechanically simpler and produce high thrust to power ratios that are beneficial for small spacecraft applications. However, the efficiency still gets reduced when this chamber gets redesigned to optimize low power operation.
Excluding the cathode, the weight of the first prototype was 1.6 kg. This device went under magnetic characterization and performance tests in vacuum. It uses xenon as a baseline propellant due to its improved performance over other gases such as argon. Current status is unknown.

References:
[1] Pigeon, C., Orr, N., Larouche, B., Tarantini, V., Bonin, G., Zee, T., "A low power cylindrical hall thruster for next generator microsatellites," Small Satellite Conference 2015. SSC15-P36.
[2] https://www.utias-sfl.net/?page_id=1274

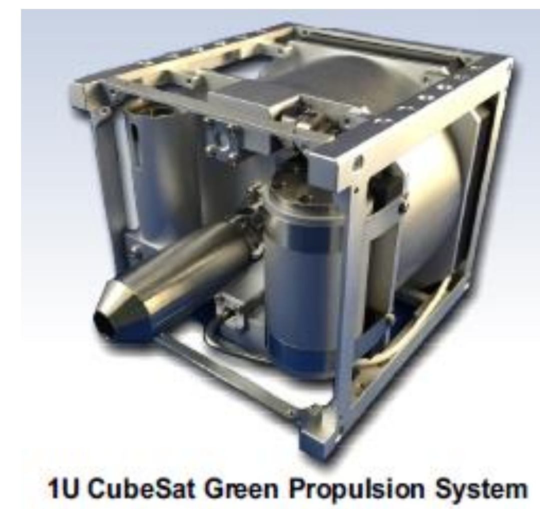
NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Busek Green Monopropellant Thrusters, BGT-5
Busek

Propulsion Technology	Green Monopropellant
Manufacturer/Country	Busek (USA)
TRL	4-5
Size (including PPU)	BGT-5 size unclear
Design satellite size	3U and larger
Isp (s)	>230s
Thrust type/magnitude	5000 mN (continuous, nominal, max) Throttleable from 1 to 6 Newtons Minimum impulse bit TBD
Delta-V (m/s)	
Propellant	AF-M315E
Power consumption (W)	50W (catalyst preheat, BGT-5 model)
Flight heritage (if any)	None known
Commercially available	YES
Last updated	*03/2021*

Various models of green monopropellant thrusters



Additional comments:

[Reference 1][Dec 2019][Thruster info]
Various models of this thrusters exist. There is only a manufacturer datasheet for the BGT-X5 (probably the highest TRL of the different models). Busek's BGT-X5 green monopropellant thruster system produces 0.5N thrust and features a highly stable "green" propellant alternative to hydrazine. The thruster features a patented long-life catalyst reactor, high temperature thruster body, and low power piezo microvalve (flight heritage). The novel propellant tank and patent-pending Post-Launch Pressurization System (PLPS) enable a compact high-thrust propulsion solution for Cubesats and Smallsats. The BGT-X5 system has 1U volume and easily scales by increasing the size of the propellant tank to support higher total impulse applications. Alternately, multiple systems can be easily integrated onto a single spacecraft for modular attitude control and translational thrust. The thruster delivers 500 mN thrust at 220-225 seconds specific impulse at approximately 400 psi feed pressure. As a 1U system, it delivers 146 m/s delta-v to a 4 kg CubeSat and is capable of multiple start-stops for precision firing and short impulse bits on the order of 0.05 N-s. The rugged flight electronics includes an integrated DCIU with communication via RS-422.

References:
[1] http://www.busek.com/technologies__greenmonoprop.htm

Comm. avail.	TRL	Aerospace-tested
	4	NO

Halcyon [1 of 3]

Propulsion Technology	Green monopropellant
Manufacturer/Country	Benchmark (USA)
TRL	4 – awaiting flight data
Size (including PPU)	Configureable
Design satellite size	6U to ESPA
Isp (s)	150 to 170s for the Halcyon [5] 290 to 310s for the Halcyon Avant [5]
Thrust type/magnitude	250 mN, 1N, 5N, 10N for Halcyon [5] 2N, 10N, 22N for Halcyon Avant [5]
Delta-V (m/s)	
Propellant	HTP or HTP+Butane
Power consumption (W)	10W pressurization, 3W operation
Flight heritage (if any)	Launched aboard SXRS-6 (Transporter-3) in Jan 2022. Projected for Mission Possible in 2024 [4]
Commercially available	YES 6 month lead time, $135K (1000 N*s, single thruster system with ODPS) [1]
Last updated	02/2023

BENCHMARK space systems

PRODUCT, CONFIGURATION, AND PRICING INQUIRIES
Sales@Benchmark-Space.com

HALCYON

Integrated Non-Toxic Chemical Propulsion Systems

FIRST FLIGHT HERITAGE - 2021

PRODUCT HIGHLIGHTS

Halcyon is a non-toxic ('green'), high thrust propulsion product line developed for 3U through ESPA satellite operations. Our systems are designed to remove common customer pain points by combining intelligent control electronics with a modular system architecture that utilizes readily available materials and propellants to deliver **highly configurable, cost-effective solutions with best-in-class lead times.**

APPLICATIONS

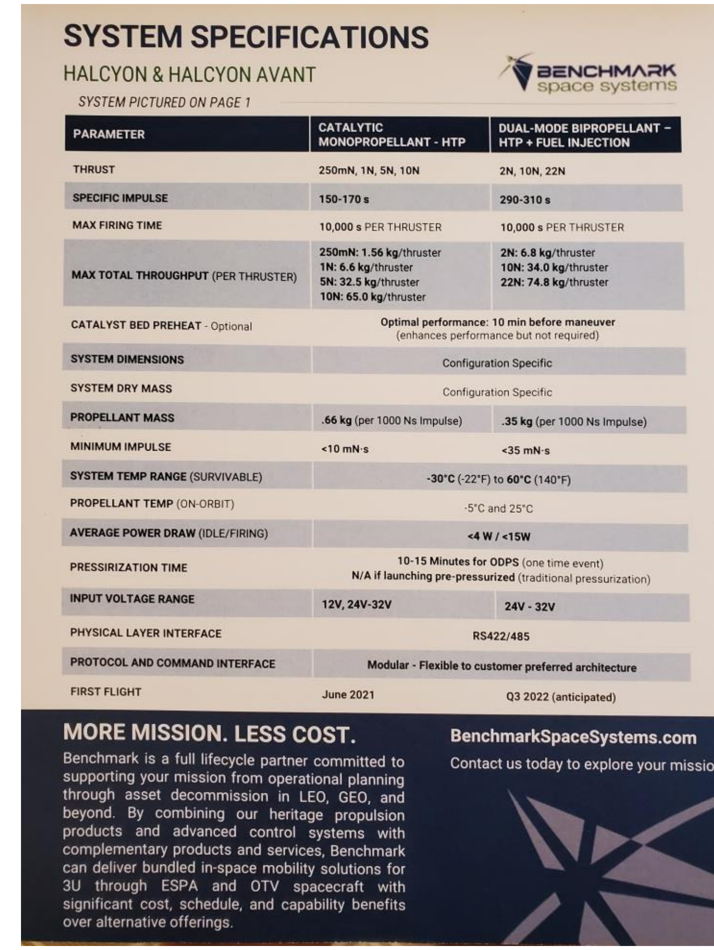
Orbit Insertion, Collision Avoidance, Orbit Transfer, Station Keeping, Precision Pointing, Momentum Management, RPO and Servicing, Controlled Deorbit

MISSION-OPTIMIZED TECHNOLOGY

Based on mission-proven methods for catalytic combustion of HTP, our Halcyon product family has a range of monopropellant or dual-mode (monoprop and biprop operability) thrusters, propellant tanks sizes, and system architectures, resulting in a well-equipped toolbox for mission-optimized mobility packages. From rapid maneuver operations to full missions, the Halcyon product line can be tailored for ease of integration and enhanced on-orbit performance for any mission.

Total Impulse: 1,000 – 500,000+ Ns
Thruster Quantity: 1, 4, 5, 8, Custom
Optional: ODPS™ on-demand pressurization
RAFTI™ refueling port

BenchmarkSpaceSystems.com



SYSTEM SPECIFICATIONS

HALCYON & HALCYON AVANT

BENCHMARK space systems

SYSTEM PICTURED ON PAGE 1

PARAMETER	CATALYTIC MONOPROPELLANT - HTP	DUAL-MODE BIPROPELLANT – HTP + FUEL INJECTION
THRUST	250mN, 1N, 5N, 10N	2N, 10N, 22N
SPECIFIC IMPULSE	150-170 s	290-310 s
MAX FIRING TIME	10,000 s PER THRUSTER	10,000 s PER THRUSTER
MAX TOTAL THROUGHPUT (PER THRUSTER)	250mN: 1.56 kg/thruster 1N: 6.6 kg/thruster 5N: 32.5 kg/thruster 10N: 65.0 kg/thruster	2N: 6.8 kg/thruster 10N: 34.0 kg/thruster 22N: 74.8 kg/thruster
CATALYST BED PREHEAT - Optional	Optimal performance: 10 min before maneuver (enhances performance but not required)	
SYSTEM DIMENSIONS	Configuration Specific	
SYSTEM DRY MASS	Configuration Specific	
PROPELLANT MASS	.66 kg (per 1000 Ns Impulse)	.35 kg (per 1000 Ns Impulse)
MINIMUM IMPULSE	<10 mN·s	<35 mN·s
SYSTEM TEMP RANGE (SURVIVABLE)	-30°C (-22°F) to 60°C (140°F)	
PROPELLANT TEMP (ON-ORBIT)	-5°C and 25°C	
AVERAGE POWER DRAW (IDLE/FIRING)	<4 W / <15W	
PRESSIRIZATION TIME	10-15 Minutes for ODPS (one time event) N/A if launching pre-pressurized (traditional pressurization)	
INPUT VOLTAGE RANGE	12V, 24V-32V	24V - 32V
PHYSICAL LAYER INTERFACE	RS422/485	
PROTOCOL AND COMMAND INTERFACE	Modular - Flexible to customer preferred architecture	
FIRST FLIGHT	June 2021	Q3 2022 (anticipated)

MORE MISSION. LESS COST.

Benchmark is a full lifecycle partner committed to supporting your mission from operational planning through asset decommission in LEO, GEO, and beyond. By combining our heritage propulsion products and advanced control systems with complementary products and services, Benchmark can deliver bundled in-space mobility solutions for 3U through ESPA and OTV spacecraft with significant cost, schedule, and capability benefits over alternative offerings.

BenchmarkSpaceSystems.com

Contact us today to explore your mission!

Additional comments:

References and notes on next chart…

Comm. avail.	4 TRL	NO Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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Halcyon [2 of 3]

Additional comments:

[Reference 1][March 2021][Thruster information]
The most versatile system in our integrated products line-up combines an HTP thruster developed by legacy Tesseract with Benchmark's fluid handling and flight controller subsystems in a turn-key system offering. The Halcyon takes advantage of readily available catalyst materials in its monopropellant configuration resulting in a reliable non-toxic chemical-class solution with moderate specific impulse and excellent pulse-mode performance for precision operations. For more demanding missions with large movements and demanding mobility requirements, the Halcyon is available in a 'dual mode' configuration, which takes advantage of post-catalyzed gas-gas injection that can double the specific impulse of the unit. This system is suitable for most smallsat missions, enabling the widest range of on-orbit mobility operations of any small satellite propulsion solution on the market. The Halcyon is scheduled to make it's on-orbit debut in H1 2021.
[Reference 2][June 2021][Flight information]
Starfish Space, a satellite servicing company and Benchmark Space Systems are now engaged in a strategic collaboration to advance precision, on-orbit refueling and docking capabilities, starting with demonstrations during Orbit Fab's Tanker 1 mission, launching next month aboard a SpaceX Falcon 9 rocket. Starfish is integrating and testing its CEPHALOPOD rendezvous, proximity operations and docking (RPOD) software with Benchmark's non-toxic, hydrogen peroxide-fueled, Halcyon thruster, the primary propulsion system for Orbit Fab's Gas Stations in Space™ tanker, to optimize spacecraft control accuracy in preparation for the first-ever tanker maneuvers in space during simulated docking demonstrations. Both Benchmark's green chemical Halcyon propulsion system, set to power four separate spacecraft missions bound for launch in 2021, and Starfish's autonomous CEPHALOPOD RPOD software, will accomplish flight heritage during the inaugural Orbit Fab mission aboard a tanker built by Astro Digital.

References:
[1] https://www.benchmarkspacesystems.com/products/propulsion
[2] https://smallsatnews.com/2021/05/18/precision-on-orbit-servicing-is-the-focus-of-starfish-space-benchmark-space-systems-strategic-collaboration/
[4] https://smallsatnews.com/2022/10/18/the-exploration-company-selects-benchmark-space-systems-propulsion-system-to-power-their-mission-possible-demonstrator-flight/
[5] Flyer distributed at SmallSat Symposium, Feb 2023

Comm. avail.	TRL	Aerospace-tested
	4	NO

DISTRO A: Approved for public release. OTR-2024-00338

Halcyon [3 of 3]

Additional comments:

[Reference 1][Feb 2022][Flight information]
With milestone hot fire engine tests of its Halcyon Avant non-toxic chemical propulsion system completed at its Pleasanton, California, facility, Benchmark Space Systems‘ highly-anticipated system has been integrated into Spaceflight Inc.’s first Sherpa-LTC orbital transfer vehicle (OTV). The propulsive OTV is set for launch on the SpaceX Transporter 3 mission that is scheduled for liftoff on January 13th from Cape Canaveral. Spaceflight’s historic SXRS-6 mission is set to deliver 13 payloads on the company’s first multi-destination rideshare mission. Spaceflight is the first to use Benchmark’s Halcyon Avant green, bipropellant system, which boasts a 25% increase in fuel efficiency over state-of-the-art green monopropellants, using low-cost and readily available propellants. Spaceflight designed Sherpa-LTC to offer rideshare customers a fast on-orbit transportation option. Benchmark’s Halcyon Avant green bipropellant system enables satellites to reach their desired orbits quickly.

[Reference 2][Nov 2022][Company information]
Under a collaborative agreement, Benchmark and The Exploration Company will work together to develop an innovative propulsion system that will use non-toxic, high-test, peroxide propellant, in line with The Exploration Company’s long-term commitment towards reusability and sustainability. The system will be based on Benchmark’s flight-proven Halcyon Avant propulsion system, featuring Benchmark’s 22N “Ocelot” bi-propellant (HTP + IPA) thrusters.
Benchmark will be responsible for the design, manufacturing, verification and delivery of the propulsion equipment and assemblies, such as the thruster assembly and the propellant tanks. The Exploration Company will be responsible for the design, verification and qualification of the overall propulsion system, including the coordination of the interface between the demonstration capsule ‘Nyx’ and the propulsion system.
The Exploration Company scheduled its launch of the demonstration Mission Possible in 2024 with the main objective to perform a safe re-entry of the capsule that will host payloads from first customers. Moreover, the target is to perform a safe splash-down in the ocean, including recovery.

[Reference 3][Nov 2022][Company information]
With its Halcyon propulsion systems playing pivotal roles in key military and commercial space missions this year, Benchmark Space Systems announced it has tripled its team from 30 to 83 and boosted its 5-year production capacity to one-thousand engines — all in the last twelve months to meet rapidly rising demand for its mission-proven thrusters.
Benchmark has booked more than 250 engine orders, with the majority of those systems being built and tested at the company’s headquarters facility in Burlington, Vermont, where the firm’s wave of recent hires includes new key executives, Wesley Grove, Senior Operations Manager and Matt Bradley, Vice President of Finance. Benchmark also appointed Kent Frankovich as Vice President of Electric Propulsion, who will be based at Benchmark’s pre-delivery system test center in Pleasanton, California.

References:
[1] https://smallsatnews.com/2022/01/10/benchmarks-non-toxic-chemical-propulsion-system-integrated-into-spaceflights-sherpa-ltc-otv-ready-for-transporter-3-mission/
[2] https://smallsatnews.com/2022/10/18/the-exploration-company-selects-benchmark-space-systems-propulsion-system-to-power-their-mission-possible-demonstrator-flight/
[3] https://smallsatnews.com/2022/11/16/benchmark-space-systems-grows-nearly-tripling-their-team-and-expanding-production-to-meet-propulsion-system-demand/

Comm. avail.	TRL	Aerospace-tested
	4	NO

DISTRO A: Approved for public release. OTR-2024-00338

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Peregrine

Propulsion Technology	Bipropellant
Manufacturer/Country	Benchmark (USA)
TRL	3-4
Size (including PPU)	Configureable
Design satellite size	6U to ESPA
Isp (s)	270s
Thrust type/magnitude	100 mN to 22 N
Delta-V (m/s)	
Propellant	HTTP+NHMF
Power consumption (W)	10W pressurization, 3W operation
Flight heritage (if any)	None
Commercially available	YES 6 month lead time, $160K (2000 N*s, single thruster system with ODPS) [1]
Last updated	03/2021

Additional comments:

[Reference 1][March 2021][Thruster information]
Benchmark's innovative green bi-propellant system was developed around our patented micromixing technique to enable hypergolic combustion at much smaller scale than traditional thrusters. By eliminating high-cost and supply-limited catalyst materials and delivering over 270s of specific impulse, the Peregrine product line delivers unmatched cost-of-performance for rapid movement and longer burn operations. Missions that require maximum thrust performance, while avoiding toxic propellants, launch manifest, or other cost challenges with alternative chemical propulsion offerings will benefit from this innovative solution, available with optional ODPS™ technology. The Peregrine is scheduled for full qualification testing at AFRL in 2021.

References:
[1] https://www.benchmarkspacesystems.com/products/propulsion

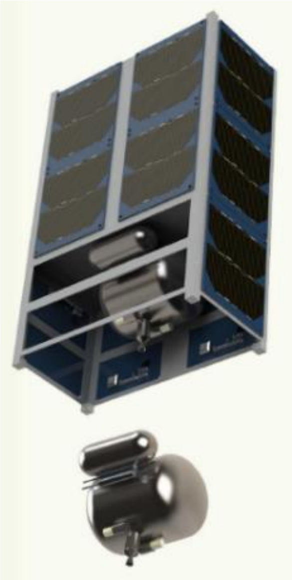
4 NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

B125 Propulsion System
Benchmark Space Systems

Propulsion Technology	Biprop
Manufacturer/Country	Benchmark Space Systems (USA)
TRL	3-4
Size (including PPU)	1U, scalable
Design satellite size	3U or larger, scaleable from 6U to ESPA-size
Isp (s)	285s
Thrust type/magnitude	1.25N (continuous, nominal) Scalable from 100 mN to 22N, 1100N*s (impulse, total), < 0.5 mN*s (impulse bit, minimum)
Delta-V (m/s)	160 m/s
Propellant	“Green”, HTP (high-test peroxide, i.e. high concentration peroxide) + alcohol
Power consumption (W)	5W peak
Flight heritage (if any)	None known (projected Q4 2020)
Commercially available	YES, website says 6 months lead time
Last updated	*03/2021*



Thruster nozzle size	100 mN - 22 N
Thruster quantity	1 - 8
Propellant	'Green', HTP + Alcohol
Specific Impulse	270 s
Minimum Impulse Bit	≤ 0.05 mN·s
Power (pressurization)	5 W
Power (standby)	≤ 0.1 W
Power (thrust valve, ea.)	≤ 3 W

The B125 takes up 1-2U inside of a standard 6U CubeSat

[1]

Additional comments:

[Reference 1][Aug 2018][General info]
The B125 is designed to offer a distinguished high thrust, high Delta-v solution for small satellites. The proprietary micro mixing, homogenously-catalyzed bipropellant system that does not require a catalyst bed or pre-heat offers distinct advantages over alternative propulsion techniques. The result is a low-power, low-cost system that offers higher specific impulse than hydrazine or ionic monopropellants. The B125 propulsion systems comes complete with an integrated thruster, fuel and oxidizer storage tanks, and control hardware in a compact package. This system can be customized to fit mission requirements.
[Reference 2][Jun 2020][Development info]
Company news:
In the past few months we have crossed crucial checkpoints for our B125 Green Bi-Propellant system (scalable for 6U through ESPA satellites).
We successfully tested our signature On Demand Pressurization System (ODPS), the key differentiator in offering safe and unpressurized launches as well as the remainder of subsystem tests. System integration of our 4-thruster B125 was another major milestone hit, as part of Benchmark’s AFWERX Phase II contract and demonstrates our team’s ability to collaborate and execute development tasks despite a broadly challenging distributed work environment during our current global pandemic. The 4-thruster system is currently being prepared for qualification testing at Edwards AFB (now planned for Q3), being administered by the USAF Small Sat Portfolio organization. Benchmark Space plans to send our first liquid propellant system into space in Q4 2020.

As of March 2021, this system is no longer found on the website and has been changed to not commercially available.

References:
[1] https://www.benchmarkspacesystems.com/
[2] Public Benchmark newsletter

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

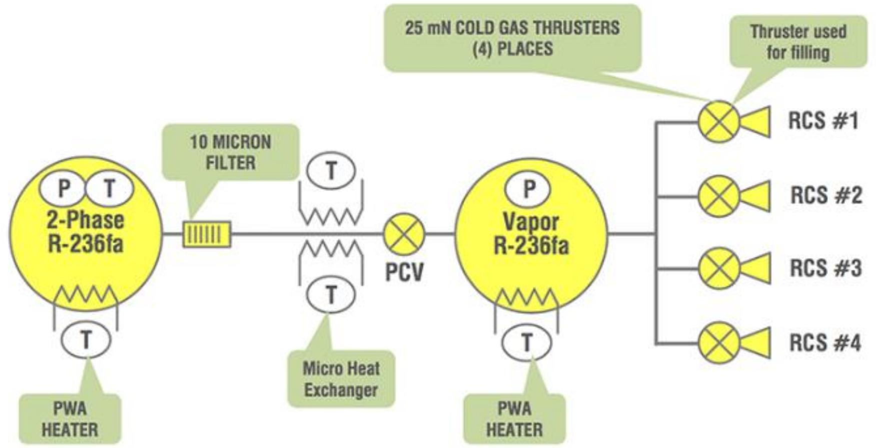
DISTRO A: Approved for public release. OTR-2024-00338

CuSP Propulsion System
VACCO

Propulsion Technology	Cold gas
Manufacturer/Country	VACCO (USA)
TRL	4
Size (including PPU)	0.3U
Design satellite size	3U, 6U
Isp (s)	~40s (estimated from similar thusters)
Thrust type/magnitude	100 mN total (4X 25 mN cold gas thrusters) 70 N*s (impulse, total)
Delta-V (m/s)	9 m/s for an 8 kg CubeSat
Propellant	Refrigerant R-236FA
Power consumption (W)	1W (standby), 12W (warmup), 11W (operating)
Flight heritage (if any)	None to date, projected to fly on CuSP (2019, now 2021 – on Artemis-1)
Commercially available	Unknown
Last updated	*03/2021*

Performance density: 231 N-sec/L

Vacco's CuSP Propulsion System



Additional comments:

[Reference 1][Jan 2019][General info]
VACCO's cold gas Micro Propulsion System (MiPS) provides attitude control and orbital maneuvering. SWRI's CuSP program utilizes VACCO's cold gas system to achieve highly reliable propulsion while serving as a space weather station. The VACCO CuSP MiPS is approximately 0.3U in volume and uses four 25 mN cold gas thrusters to develop 69 N-sec of total impulse that provides 8.8 m/s of delta-v for an 8 kg CubeSat. Each thruster independently operates to perform both delta-v and ACS maneuvers through an integrated microprocessor controller.
CuSP (CubeSat mission to study Solar Particles), formerly CuSPP+ (CubeSat mission to study Solar Particles over the Earth's Poles), is a 6U CubeSat space weather mission on an interplanetary trajectory designed an built by the Southwest Research Institute (SwRI). It is an increment to the originally planned CuSPP low earth orbit mission

References:
[1] http://www.cubesat-propulsion.com/cusp-propulsion-system/

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

MPS-120 CubeSat High-Impulse Adaptable Modular Propulsion System CHAMPS Aerojet Rocketdyne

Propulsion Technology	Hydrazine or AF-M315E Monopropellant, 3-D printed propulsion system
Manufacturer/Country	AeroJet Rocketdyne (USA)
TRL	3-4 (hydrazine system assumed higher TRL)
Size (including PPU)	1U
Design satellite size	3U, 6U, and larger
Isp (s)	230s (estimated from other AF-M315E thrusters)
Thrust type/magnitude	2.8N (high thrust mode, nominal, continuous) 0.26N (low thrust mode, nominal, minimum) 6000 N*s (impulse, total) 0.0004 N*s (impulse bit, minimum) 0.25 to 1.25N (thrust, total)
Delta-V (m/s)	210 m/s for 4kg spacecraft, 80 m/s for 10 kg spacecraft
Propellant	Hydrazine, AF-M315E Monopropellant
Power consumption (W)	<4W (start-up), <1W (operation)
Flight heritage (if any)	None known
Commercially available	Unclear
Last updated	*04/2021*

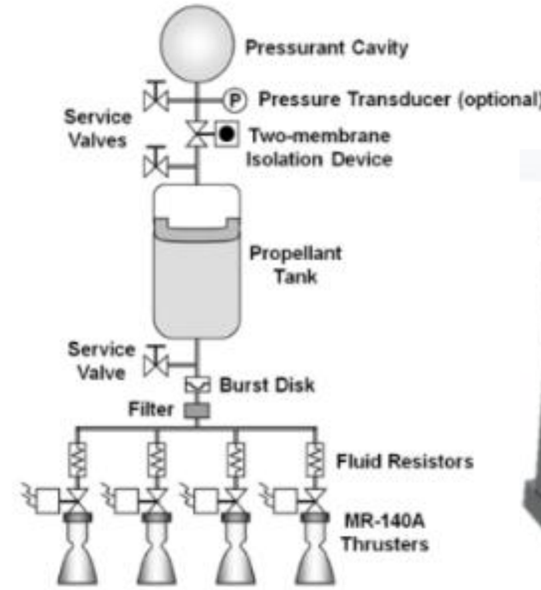
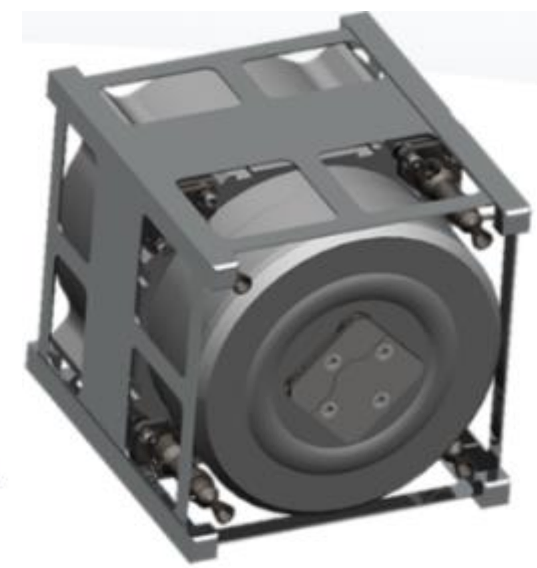


Figure 5: CHAMPS Functional Schematic



Solid model of CHAMPS thruster

Additional comments:

[References 1-6][Jan 2019][General info]

No information available on manufacturer's website, and no photographs of hardware. Development status is "**In Development**" as of 2018.

Thruster unit consists of 4 thrusters for attitude control. Each thruster can provide 780 N*s (for the 1U model) and 2000 N*s (for the 2U model). Literature articles cite the thruster should be qualified "soon". Some reports of ground testing has been found, as cited from Aerojet's website:

"SACRAMENTO, Calif., Dec. 15, 2014 (GLOBE NEWSWIRE) -- Aerojet Rocketdyne, a GenCorp (NYSE:GY) company, has successfully completed a hot-fire test of its MPS-120™ CubeSat High-Impulse Adaptable Modular Propulsion System™ (CHAMPS™). The MPS-120 is the first 3D-printed hydrazine integrated propulsion system and is designed to provide propulsion for CubeSats, enabling missions not previously available to these tiny satellites. The project was funded out of the NASA Office of Chief Technologist's Game Changing Opportunities in Technology Development and awarded out of NASA's Armstrong Flight Research Center. The test was conducted in Redmond, Washington."

However, no detailed test data has been found and no flight has been scheduled.

Surrey Satellite Technologies mentions on their website that they have developed a new platform called "Surrey GMP-A" (Geostationary Minisatellite Platform), which will feature Aerojet Rocketdyne Hall thruster and MPS-120 propulsion systems. But no launch information is available.

References:

[1] Schmuland, D., Masse, R., Sota, C., "Hydrazine Propulsion Module for CubeSats," 25th Annual AIAA Conference on Small Satellites, SSC11-X-4.
[2] Schmuland, D., Carpenter, C., Masse, R., Overly, J., "New insights into additive manufacturing processes: enabling low-cost, high-impulse propulsion systems," Small Satellite Conference talk, 2013.
[3] https://www.rocket.com/sites/default/files/documents/CubeSat/MPS-120%20data%20sheet-single%20sheet.pdf
[4] https://www.rocket.com/sites/default/files/documents/CubeSat%20Mod%20Prop-2sided.pdf
[5] http://mstl.atl.calpoly.edu/~bklofas/Presentations/SummerWorkshop2014/SSC14-WK-36_Carpenter.pdf
[6] http://www.sst-us.com/downloads/brochure_surreygmp-a_lowres.pdf
[7] Carpenter, C., Schmuland, D., Overly, J., Masse, R., "CubeSat modular propulsion systems product line development status and mission applications," Aerojet report (year?) https://www.rocket.com/sites/default/files/documents/CubeSat/AIAA-2013-3760.pdf

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Roll Out Composite FCC Approved Life Limit Deorbit Device (ROC FALL)

Propulsion Technology	Passive de-orbit
Manufacturer/Country	ROCCOR (USA)
TRL	4
Size (including PPU)	<1U
Design satellite size	3U, 6U
Isp (s)	n/a
Thrust type/magnitude	Propellant-less
Delta-V (m/s)	n/a
Propellant	n/a
Power consumption (W)	
Flight heritage (if any)	STP-2 (2019)
Commercially available	YES
Last updated	03/2021


ROCCOR

ROC™ FALL Deorbit Device

Roll Out Composite FCC Approved Life Limit Deorbit Device

Deployable drag device that ensures predictable, reliable and timely deorbit from LEO to meet space debris regulations

Integrated into 140kg Spacecraft, Launching in Q3 '18

FEATURES

- FCC Approved
- Easily Scalable Design
- Rapid lead-time
- Simple Integration
- Deorbit Analysis Included
- 3-5 Year On-Orbit Hibernation
- Low Power Actuation
- Self-Driven Deployment

Deployed Area:

	2m²	4m²	8m²
Mass	< 1 kg	< 2 kg	< 4 kg
Volume	10 x 10 x 45cm	10 x 10 x 65cm	15 x 15 x 90cm

For Business Inquires:
Chris.Pearson@roccor.com

Based in Longmont, Colorado

Additional comments:

[Reference 1][Mar 2019][Device information]
The de-orbit device is FCC approved, has an easily scalable design, rapid lead time, and simple integration. It offers 3-5 year on-orbit hibernation, low power actuation, and self-driven deployment. The manufacturer's website states that it is integrated into a 140 kg spacecraft, to be launched in 2018.

[Reference 2][Dec 2019][Flight info]
Roccor, based in Longmont, Colorado, has developed a simple roll-out drag sail design to meet the Inter-Agency Space Debris Coordination Committee (IADC) 25-year deorbit lifetime guideline. Recently, a large defense contractor developing a 150kg class small satellite for launch on the U.S. Air Force's Space Test Program-2 (STP2) mission came to Roccor to provide a baseline strategy to ensure deorbit within 25 years after the spacecraft's end of life. The booster for STP2 is a SpaceX Falcon Heavy to be loaded with a cluster of military and scientific research satellites. Despite being given minimal payload volume, mass, development time, and budget with which to work, Roccor was able to develop a simple roll-out drag sail design to meet the requirements. The result was Roccor's ROC™ FALL concept, a cost-effective solution with regulatory approval for end-of-life management.

[Reference 3][Dec 2019][Flight info]
At 2:30 a.m. on Tuesday, June 25, SpaceX launched the STP-2 mission from Launch Complex 39A (LC-39A) at NASA's Kennedy Space Center in Florida. Deployments began approximately 12 minutes after liftoff and ended approximately 3 hours and 32 minutes after liftoff.

References:
[1] https://roccor.com/wp-content/uploads/2018/05/ROC-FALL-Data-Sheet-2018-04-04.pdf
[2] https://www.leonarddavid.com/new-deorbit-device-roc-fall/
[3] https://www.spacex.com/news/2019/06/26/stp-2-mission

Comm. avail.	4	NO
	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

FG-34

Propulsion Technology	Hall thruster
Manufacturer/Country	Fakel (Russia)
TRL	3-4
Size (including PPU)	1U (0.97kg)
Design satellite size	
Isp (s)	Up to 1360 s
Thrust type/magnitude	Up to 18 mN
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	130 to 390 W
Flight heritage (if any)	None known
Commercially available	NO
Last updated	*03/2021*

FG-34 thruster after manufacturing

Performances	Value
Diascharge volatge, V	160…300
Discharge current, A	0.8…1.3
Discharge power, W	130…390
Thrust, mN	up to 18
Specific impulse, s	up to1360
Efficiency, %	up to 35
Power-to-thrust ratio, W/mN	18…21
Mass, kg	0.97
Overall dimensions, mm	100x92x85

Additional comments:

[Reference 1][Dec 2019][General information]

Creation of high-pulse electric propulsion with the thrust specific impulse higher than 2500 s was made at EDB Fakel (Kaliningrad) in 1999-2000. Back at that time in frames of contractual works with Atlantic Research Corporation (ARC, USA) a high-voltage thruster experimental model was developed based on the separate modified elements and assembly units of the PPS 1350R and based on the anode new design scheme, and this model was conventionally named as SPT-1. The proposed design scheme of the SPT-1 thruster high-voltage experimental model, according to the authors, is a new type of Hall-effect thrusters. It is stipulated by the fact that this thruster discharge chamber (DCh) is combined: DCh exit part is formed by dielectric rings and its bottom part is made metallic by means of the walls of the adjoining hollow anode-gas distributor. On the basis of the research tests results of the hollow magnet anode plasma thruster laboratory models at EDB Fakel, a parametric family of the PlaS-type of thrusters conceptual models with the power from 100 W to 6 kW was developed, namely: PlaS-34, PlaS-40, PlaS-55 and PlaS-120CM.

The magnet system optimization, made for PlaS thrusters, allowed us to improve the magnet contour efficiency in some way and decrease magnet flow losses in the contour. However, the introduced design changes do not allow us to achieve a significant increase in the system functional efficiency. As it is known, the thruster magnet field lines have an oval shape. Therefore, this shape determines the shape of the magnet contour itself, namely, exclusion of the rectangular-shape joints of the thruster magnet system elements. It resulted in an idea to make a magnet system with a shape that is close to the natural shape of the magnet field lines. This idea is currently being evaluated based on the low-power PlaS-34 thruster design. This design is called the FG-34 thruster. In the FG-34 thruster, the magnet contour is designed oval. In this design the joints between the elements are made with smooth transitions along the radii, namely, steep rectangular-shaped transitions are excluded in the places where the magnet inductance losses are maximum. The length of such a contour is minimum and, consequently, the magnet resistance is the lowest,what leads to the decrease of the magnet flow losses. Thruster FG-34 has passed test in the range of discharge power from 130 to 390 W with discharge voltage from 160 to 300 V and discharge current from 0.8 to 1.3 A. Investigations in the wide range of discharge voltages and discharge currents is planned to be performed on FG-34 thruster. Based on test results, optimization of the thruster magnetic system and discharge system including improvement of its mechanical and thermal interfaces will be carried out.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

References:

[1] Bernikova, M., Gopanchuk, V., “Parametric family of the PlaS-type thrusters: development status and future activities,” IEPC-2017-39.

DISTRO A: Approved for public release. OTR-2024-00338

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“MicroJoe”/Micro-Joe [1 of 2]

Propulsion Technology	Hybrid rocket
Manufacturer/Country	Utah State University USU (USA)/Space Dynamics Laboratory (SDL)
TRL	4
Size (including PPU)	3cm diameter by 7 cm long
Design satellite size	>= 12U
Isp (s)	212s (280s in vacuum) [1]
Thrust type/magnitude	25N (30N in vacuum) [1]
Delta-V (m/s)	
Propellant	GOX/ABS plastic [1], Nytrox/ABS [4]
Power consumption (W)	
Flight heritage (if any)	None. Suborbital NASA Terrier Improved Malemute demonstrated March 2018.
Commercially available	NO
Last updated	04/2022

Figure 1. Static Hot-fire Test of Prototype 25-N Thruster Unit.

[Reference 3]

Additional comments:
[References 1-3][Aug 2019][General information]
“MicroJoe,” has a diameter of 3.168 cm and length of 6.850 cm. Under ambient conditions with an optimized expansion ratio nozzle, MicroJoe achieves Isp values of 212 s and near 25 N of thrust. Tests completed on the same configuration but under vacuum conditions with a high expansion ratio nozzle at NASA Marshall Space Flight Center showed that the system delivers nearly 30 N of thrust with an Isp of at least 280 s. 21,22 This performance is comparable to many liquid and solid propulsion systems. Its typical operating chamber pressure range is between 100 and 200 psia. Combustion efficiency was estimated at approximately 95%, and the regression rate constants were estimated as {a=6.75*1e−4 (m/s, kg/m2-s), n=0.22}. A longer motor with otherwise the same configuration produced regression constants of {a=3.5*1e−4 (m/s, kg/m2-s), n=0.22}.

[Reference 4][Dec 2019][General info]
Researchers at USU have developed a novel on-demand ignition system, which can be reliably controlled. The system consists of a 3-D printed acrylonitrile butadiene styrene (ABS) matrix combined with an oxidizer of either gaseous oxygen (GOX) or an enriched air mixture (Nitrox). In the system, unique electrical breakdown properties of the ABS matrix are exploited so that spontaneous combustion occurs at desirable local oxygen partial pressures. USU researchers have also developed a method of reducing the required volume of high-pressure Nitrox by more than 30% through the addition of certain elements to the ABS matrix.

References:
[1] Chamberlain, B., “Additively-manufactured hybrid rocket consumable structure for Cubesat propulsion,” MS Thesis, Utah State University, 2018.
[2] Whitmore, S., A. and Merkley, S. L., "Vacuum Test Measurements of a Novel Green-Propellant Thruster for Small Spacecraft," Compendium of the Marshall Space Flight Center Faculty Fellowship Program, NASA/TM-2017- 218234, March 2017, pp. 162-198.
[3] Whitmore, S. A., and Bulcher, M. A., "Vacuum Test of a Novel Green-Propellant Thruster for Small Spacecraft," 53st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Atlanta GA, 9- 12 July, 2017, Paper Reference No. 27036334, July 2017.
[4] https://research.usu.edu/techtransfer/hybrid-green-rocket-system/

Comm. avail.	TRL	Aerospace-tested
NO	4	NO

DISTRO A: Approved for public release. OTR-2024-00338

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"MicroJoe"/Micro-Joe [2 of 2]

Additional comments:

[Reference 1][Feb 2021][Flight info]
During the mission the USU Thruster was successfully fired 5 times in a hard vacuum environment above the Von-Karman line. Low-resolution telemetry data was successfully downlinked and delivered to USU for analysis. This data was demodulated, time-tagged, and converted to engineering units. A preliminary analysis of the motor performance has been performed. Based on these results, it is concluded that the first three burns did not reach the expected peak operating chamber pressure. The expected thrust level dropped as a result to approximately 5 N, even though each motor was receiving the planned 2.6 grams per second of EAN40 oxidizer, as it had during multiple ground tests. From the observed 120+ psi in each motor along with the observed pressure spike in motor 1 during the fourth burn, it was determined that a low energy, smoldering type burn was achieved. The large indicated chamber pressure indicates that ABS fuel was being vaporized, because all preliminary cold flow ground tests never exceeded 60 psia. This also indicates that the ignition sequence was fully functional and the spark path of each fuel grain was operational across all 5 motor ignitions.

The Terrier Malemute was mated to the launch rails on Wednesday, March 21st. Originally, the plan was for a 24 hour wait period before launch on Thursday, March 22nd. However, adverse weather conditions delayed the actual launch until Sunday, March 25. The integrated vehicle remained on the launch rail for 4+ days while waiting for clear weather. The test team has concluded that the highly-porous 3-D printed ABS fuel grains had partial water condensation throughout due to the 4+ days sitting on the rail and exposed to the violent weather of a late season "nor-easter" storm. The day of launch dawned cold and clear with temperatures in the low 20's F. It is very likely that any entrapped moisture in the fuel grains was frozen solid. Currently, a series of ground-experiments have been completed that indicate this assumption to be true. These follow-on experiments involved briefly dipping the grains into water and then placing them in a freezer. Initial tests mimicked the USIP test with identical 3-second pulse series, showed very similar results to those obtained. The primary difference was the fact that it only required 2 burns to clear away the entrapped water that was halting successful ignition. Successful ignition and steady state burn was achieved on the frozen fuel grains during the third burn, as opposed to the fourth burn on the USIP sub-orbital flight test.
During the flight, it took 3+ burns in order for the ignition pyrolysis to clear away the entrapped water and allow for full combustion. Full combustion was finally achieved at approximately 16 seconds into the experiment. This event is noted by the sharp rise in chamber pressure and thrust time history traces for the starboard thruster. At this point the thruster achieved the design 8 N thrust level and 215 second specific impulse predicted by the flight test analysis. Obviously, sitting on the launch rail for 5+ days during a violent late winter mid-Atlantic storm represents less than ideal launch conditions. The fact that the non-ruggedized system worked at all is a testament to the robustness of the overall design.

References:
[1] Bulcher, A., Whitmore, S., "A green hybrid thruster using moderately enriched compressed air as the oxidizer," AIAA Propulsion and Energy Conference, JPC, 2018.

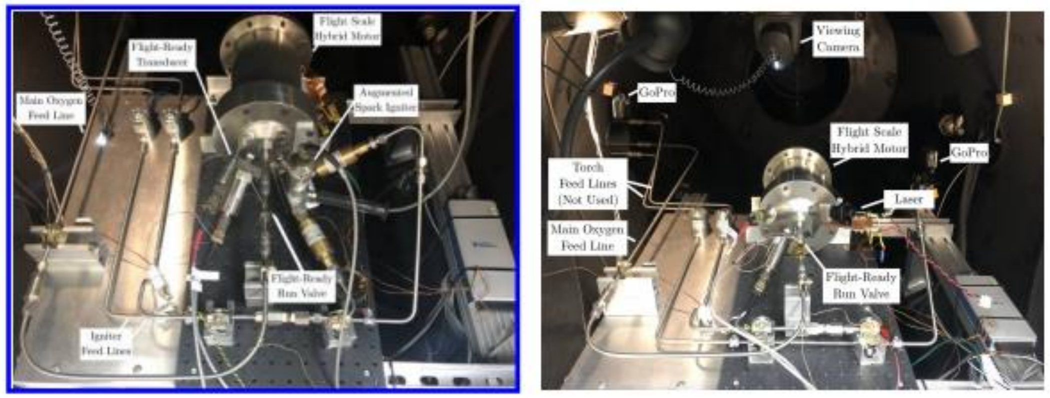
NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

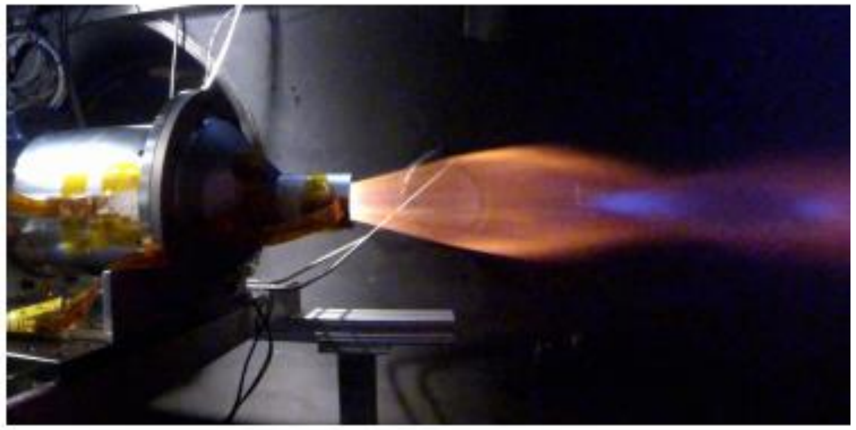
DISTRO A: Approved for public release. OTR-2024-00338

JPL Hybrid

Propulsion Technology	Hybrid
Manufacturer/Country	JPL
TRL	4
Size (including PPU)	A few U
Design satellite size	12U to ESPA class
Isp (s)	>300s
Thrust type/magnitude	~50N [1]
Delta-V (m/s)	800 m/s to a 25kg spacecraft
Propellant	PMMA/Gox
Power consumption (W)	n/a
Flight heritage (if any)	None
Commercially available	NO
Last updated	03/2021



Vacuum chamber set-up with hybrid motor installed and torch ignitor (left) and laser igniter (right)



Additional comments:

[Reference 1][Dec 2019][Testing results/thruster development]
A hybrid propulsion system using PMMA and gaseous oxygen has been designed to deliver orbit insertion ΔV to spacecraft ranging in scale from a 12U CubeSat to an ESPA-class SmallSat. The notional mission profile for this system required 8 to 12 ignitions of the hybrid motor. Thus, a reliable igniter capable of re-lighting the hybrid in the vacuum of space had to be identified and demonstrated. Pyrotechnic igniters, used extensively on hybrid motors, are typically single-use and thus are not suitable for this application. Two candidate ignition systems, a laser igniter and an augmented spark igniter, were identified for testing in a low pressure environment. The goal of this testing was to demonstrate 2 times the required number of mission ignitions, in this case 24 successful ignitions, in a low pressure environment less than 30 mTorr, and thereby increase the TRL of the system.
The first set of tests used an augmented spark bi-propellant torch as the ignition system. Gaseous methane is mixed with gaseous oxygen and ignited via a spark plug.
The hybrid motor laser igniter was designed by researchers at Stanford University and transported to JPL for testing. The laser igniter is comprised of two components: the laser system and a compatible fuel target. The laser system gets attached to the front end of the motor. This system combines a 16 W, 1064 nm near-IR diode laser with a focusing lens assembly and a pressure-sealed window, all mounted on a copper platform which doubles as a heat sink.

References:
[1] Jens, E., Karp, A., Williams, K., Nakazono, B., Rabinovitch, J., Dyrda, D., Mechentel, F., "Low Pressure Ignition Testing of a Hybrid SmallSat Motor," AIAA Propulsion and Energy Forum, 2019.
[2] Jens, E. T., Karp, A. C., Rabinovitch, J., , Nakazono, B., Conte, A., and Vaughan, D., "Design of Interplanetary Hybrid CubeSat and SmallSat Propulsion Systems," 54th AIAA/SAE/ASEE Joint Propulsion Conference & Exhibit, American Institute of Aeronautics and Astronautics, 2018.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

AQUAJET ECR

Propulsion Technology	Electron Cyclotron Resonance (ECR)
Manufacturer/Country	Surrey Space Center, University of Surrey (UK), in collaboration with AVS UK Ltd., STFC, SSTL (UK)
TRL	3-4
Size (including PPU)	Unclear, ~1U
Design satellite size	3U and larger
Isp (s)	736s (at 171W)
Thrust type/magnitude	0.72 mN (at 171W), ~0.3W at 90W
Delta-V (m/s)	
Propellant	Xenon, Argon, Water
Power consumption (W)	17 to 171W
Flight heritage (if any)	None
Commercially available	NO
Last updated	03/2021

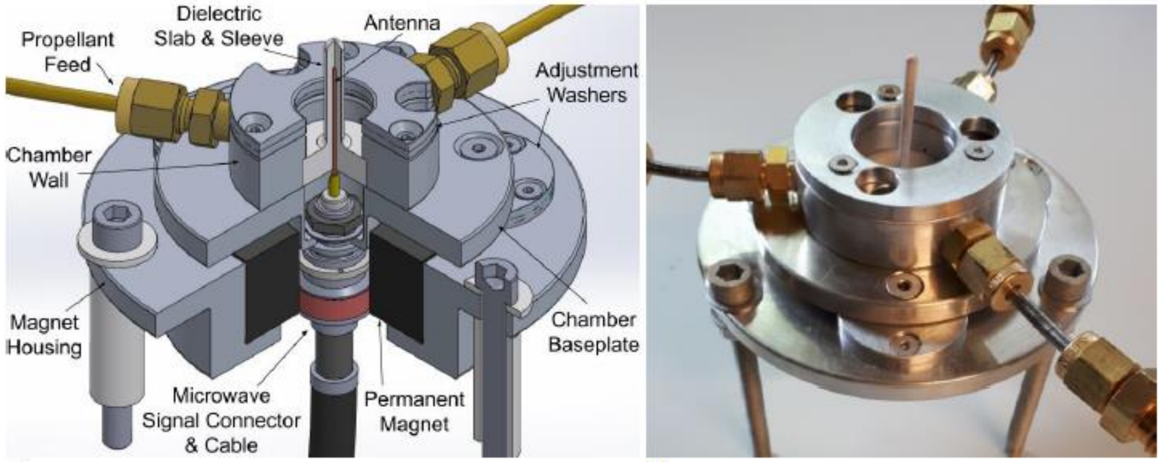
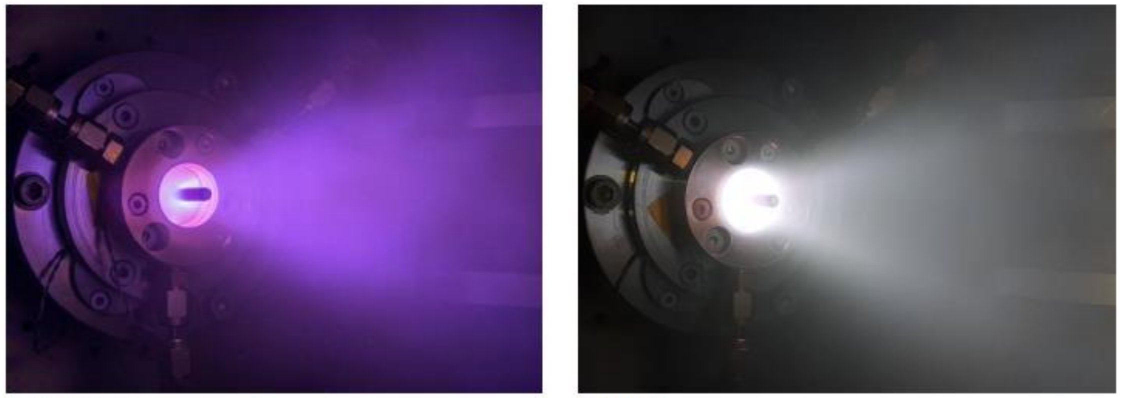


Figure 1. a) Cutaway view of the AQUAJET thruster 3D model, highlighting the main thruster components. b) Photograph of the AQUAJET thruster assembly.



a) Argon b) Water

Additional comments:

[Reference 1][Oct 2019][Thruster information]

This gap in the market [between high power Hall thrusters and Gridded Ion Engines and a need for small satellite propulsion] has led to a collaboration between SSC (at the University of Surrey), AVS UK Ltd., STFC, and SSTL, which is funded by the UK Space Agency, on the development and investigation of a new electrodeless, water-propelled Electron Cyclotron Resonance (ECR) thruster: AQUAJET. The AQUAJET thruster is a potentially scalable, cathodeless ambipolar plasma source utilizing ECR at 2.45 GHz with a simple permanent magnet configuration to provide thrust at low power. Its modular design provides a test-bed for multiple geometric thruster configurations, giving flexibility of thruster optimization for operation with different propellants. This new technology is designed as a low-cost solution to address the problems with lifetime limitations, scalability, and compatibility with unconventional propellants, that are prominent among the established technologies in use today.

The AQUAJET thruster has a modular design that allows for testing of multiple geometric configurations, including three chamber radii (8, 10, and 12 mm) and a variety of discharge chamber lengths (6, 8, 10, and 12 mm for the radius 8, and 10 mm chambers, and 8, 10, 12, and 14 mm for the radius 12 mm chamber), with an adjustable ECR zone position. A microwave signal of 2.45 GHz is supplied to an axial copper antenna via a series of coaxial cables, and a DC block to isolate (in DC) the thruster from the generator obtaining a floating configuration. The antenna is supported by an aluminium baseplate and is located at the centre of a cylindrical aluminium discharge chamber; it is insulated from the plasma by a dielectric slab and sleeve made from boron nitride. Three brass inlets feed propellant directly into the discharge chamber via small holes in the chamber walls. A set of aluminium washers provide additional lengths to the discharge chamber and allow for the adjustment of the ECR zone position by increasing the distance between the magnet and the discharge chamber. The ECR heating mechanism, induced by the application of a microwave frequency to a suitable magnetic field, allows for significantly higher electron temperatures to be achieved compared to those attainable with RF discharge sources.

[Reference 2][March 2021][General info]

The UK Space Agency has awarded a consortium that includes ISIS Neutron and Muon Source (ISIS) a £560,000 grant to develop an innovative new spacecraft propulsion system that runs on the ultimate 'green' propellant: water. The Aquajet thruster, which uses technology found in the ISIS machine, opens up the possibility of low-cost, long-mission spacecraft that could refuel using water found on asteroids. With the next phase of development funded, the team expect to achieve 'dramatic improvements at all power levels' before AVS bring the thruster to the market, which they hope to do by 2021.

References:

[1] Moloney, R., Karadag, B., Fabris, A., Staab, D., Frey, A., Garbayo, A., Shadbolt, L., Azevedo, E., Faircloth, D., Lawrie, S., Tarvainen, O., "Experimental validation and performance measurements of an ECR thruster operating on multiple propellants," IEPC-2019-199.
[2] https://stfc.ukri.org/news-events-and-publications/features/aquajet-the-space-thruster-that-runs-on-water/

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

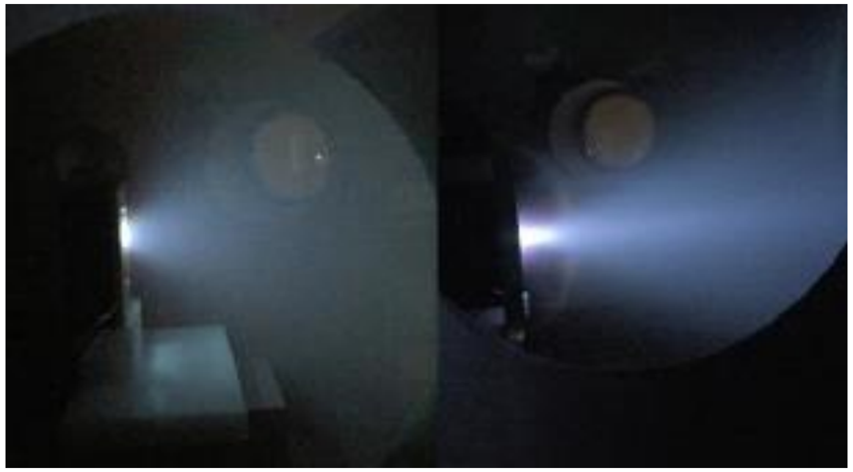
BBM6 Plasma Jet Pack (PJP)

Propulsion Technology	Vacuum arc thruster
Manufacturer/Country	Comat Propulsion (France)
TRL	4
Size (including PPU)	1U
Design satellite size	3U and above
Isp (s)	400-3200s (2400 s with copper cathode) [1]
Thrust type/magnitude	270 uN (copper cathode), 196 N*s (impulse, total)
Delta-V (m/s)	
Propellant	Copper
Power consumption (W)	Up to 30W
Flight heritage (if any)	None
Commercially available	NO
Last updated	03/2021

Power	0 - 30	W
Overall Volume	1	U
Overall Mass	1	Kg
Thrust to power *	2 - 14	µN/W
Specific Impulse *	400 - 3200	s
Total impulse	196	Ns
Electronic efficiency	90	%

** depending of the metal propellant*

BBM6 Performance (above), firing (below) [Ref 1]



Additional comments:
[Reference 1][Oct 2019][Thruster and company information]
COMAT1 designs, manufactures, qualifies and commercializes equipment for space industry since 1977. This company initially developed its activity in the microgravity field, designing and building science equipment for manned flight. Some years ago, COMAT expanded its expertise to satellite markets and particularly to space equipment such as mechanism and propulsion. COMAT is an integrated company with the ability to deliver a global offer for space equipment. Since 2015, Comat develops several tools and collaborates with different research centers in order to improve the understanding of the vacuum arc physics. Comat engaged an experimental strategy based on iterative Bread Board Models (BBMs) characterization. The final objective is to commercialize two types of propulsion modules: 1)Plasma Jet Pack 0-30W for nanosatellites in 2021, and 2)Plasma Jet Pack 0-150W for small satellites in 2022.
In four years the PJP Technology Readiness Level (TRL) increased from 0 to 5. The first BBM was tested in 2015 at TRL 1, and the BBM6 was tested at the end of 2018 at TRL 4-5. The development is now focused on life duration (total impulse) and robustness of the system. The BBM6 is a propulsion module ready to make an IOD/IOV mission with total impulse up to 200Ns. The final product will be available in 2021/2022 after the characterization of the last BBM (BBM7-2020) and the qualification process scheduled in 2021.

[Reference 2][March 2021][General info]
An official website has been found, and the 1st Technical Meeting of the PJP Project was held in Toulouse (France) and hosted by the Project Coordinator (COMAT) on January 16, 2020.

References:
[1] Blanchet, A., Herrero, L., Voisin, L., Pilloy, B., Courteville, D., “Plasma jet pack technology for nano-microsatellites,”IEPC-2019-271
[2] https://plasmajetpack.com/

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

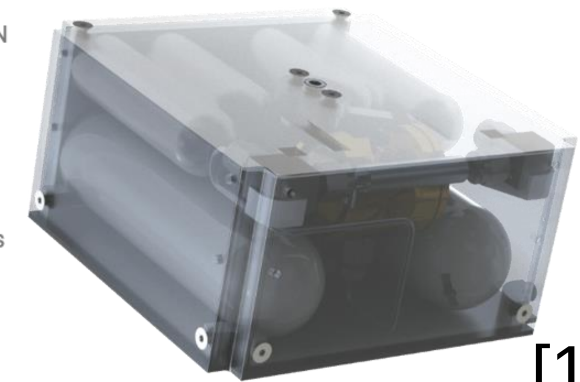
DISTRO A: Approved for public release. OTR-2024-00338

“Starling” DFAST Propulsion System [1 of 2]
Benchmark Space Systems

Propulsion Technology	Re-ignitable Solid (proprietary), Warm gas thruster
Manufacturer/Country	Benchmark Space Systems (USA)
TRL	3 to 4
Size (including PPU)	1U, wet mass 1.5kg
Design satellite size	3U or larger, scaleable from 3U to 24U spacecraft
Isp (s)	70s (cold), 155s (warm gas)
Thrust type/magnitude	1N (continuous, nominal), scaleable from 10 mN to 1 Newtons 200 N*s (impulse, total), 0.05 N*s (impulse, minimum)
Delta-V (m/s)	26 m/s for an 6U (kg) spacecraft
Propellant	Inert, non-toxic, solid (proprietary)
Power consumption (W)	50W peak, <0.1W idle <1W for cold operation, 15W for warm operation
Flight heritage (if any)	None known. BSS1 (Benchmark Space Systems 1) launched aboard Firefly-Alpha rocket September 2021 but vehicle failed to reach orbit [4]
Commercially available	YES, lead time on website is 4 months Lead time on website is 4 months, $50K for 70 N*s, single-thruster system with ODPS [1]
Last updated	*10/2021*

Thruster nozzle size	10 mN - 1 N
Thruster quantity	1 - 4
Non-toxic Propellant	Inert, solid
Specific Impulse (cold)	70 s
Specific Impulse (hot)	105 - 150 s
Minimum Impulse	≤ 0.05 mN·s
Power (pressurization)	10 W
Power (standby)	≤ 0.1 W
Power (thrust valve)	≤ 3 W
Power (resistojet)	15 - 50 W

[2]



[1]

The DFAST takes up 1-2U inside of a standard 6U CubeSat

[1]

Additional comments:
[Reference 1][Aug 2018][General info]
Benchmark Space Systems’ DFAST chemical thruster is designed to provide the benefits of a reliable, high-precision propulsion system with unprecedented safety and affordability to CubeSat developers and operators. This proprietary system uses an inert, non-toxic chemical that is stored and launches in a solid state, and is pressurized on orbit. This allows the system to be handled, transported, stored, launched, and deployed safely. The integrated DFAST system incorporates the thruster, propellant storage, and control hardware into a standardized, compact package. It can be scaled to fit the mission requirements.

References:
[1] https://www.benchmarkspacesystems.com/
[2] Public newsletter from Benchmark
[3] https://spacewatch.global/2020/08/benchmark-space-systems-secures-transformational-agreement-with-tesseract-space-to-provide-green-in-space-propulsion/
[4] https://space.skyrocket.de/doc_sdat/bss-1.htm

Comm. avail.	TRL	Aerospace-tested
	4	NO

"Starling" DFAST Propulsion System [2 of 2]
Benchmark Space Systems

Additional comments:

[Reference 1][Jun 2020][Launch information and thruster development]
Our DFAST warm-gas thruster (scalable for 1U-12U spacecraft) has completed the subsystem qualification test campaign and has been integrated into our on-orbit demonstration satellite BSS1. Range safety was smooth sailing for our 'unpressurized, inert' launch mode. In the same week the FCC regulatory policy vote took place, our team was notified that our experimental license was granted, and we're ready for launch! Our latest update from Firefly following their test anomaly and accelerated re-group, is that the inaugural Alpha launch is scheduled to deliver BSS1 to orbit in summer 2020!

[Reference 2][Dec 2020][Company information]
Benchmark Space Systems, a leading provider of in-space propulsion systems for small satellites, announced a permanent licensing partnership to integrate Tesseract Space intellectual property, assets, and staff to elevate Benchmark's major expansion in the development, deployment, and support of its exclusively non-toxic chemical propulsion solutions for global rideshare markets.

References:
[1] Public newsletter from Benchmark
[2] https://spacewatch.global/2020/08/benchmark-space-systems-secures-transformational-agreement-with-tesseract-space-to-provide-green-in-space-propulsion/

	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

B1 Thruster, 1N

Propulsion Technology	Biprop
Manufacturer/Country	Dawn Aerospace (Netherlands/New Zealand)
TRL	4-5
Size (including PPU)	260g dry mass
Design satellite size	3U and above
Isp (s)	>285s
Thrust type/magnitude	0.4 to 0.4N
Delta-V (m/s)	
Propellant	N2O + C3H6
Power consumption (W)	9W max for igniter, for 50 ms
Flight heritage (if any)	Unclear
Commercially available	YES
Last updated	03/2022

B1 THRUSTER

The B1 Thruster assembly includes the thruster body, valves, and control electronics. The thruster body is additively manufactured as a single structure using Inconel 718 and includes the injector, combustion chamber, and nozzle. Health monitoring instrumentation includes an integrated and isolated thermocouple and chamber pressure sensor. With standard data and power interfaces, thrusters are easy to command and operate.

Available in a variety of form factors, the B1 Thruster is currently used in the following arrangements within Dawn systems:

- One thruster in the center of Dawn's single-thruster CubeSat Propulsion Modules
- Four thrusters, mounting in each corner of Dawn's four-thruster CubeSat Propulsion Modules.
- Eight thrusters on a single system positioned to allow for full 6-axis spacecraft control.
- A modular building block for customized propulsion systems, with absolute freedom on positioning and mounting.

Download PDF and STEP files

Physical

Propellants
N2O and C3H6

*Domestically available propellants: no lead time

Pressurization
Self-pressurizing

*No PMD or complex regulation required

Thruster dimensions
3.70 x 2.68 x 1.85 in
94 x 68 x 47 mm

Nozzle expansion ratio
100:1

Dry mass
0.57 lbm
260 g

Valves
Solenoid

*Two valves per thruster

Environmental

Operational temperature
14°F to 86°F
-10°C to 30°C

Survival temperature
-22°F to 149°F
-30°C to 65°C

Regulatory
ITAR free, REACH compliant

Interfaces

Data
CAN bus, RS-485 or RS-422

Fluid connection
1/4 in (Swagelok)

Valve power
Hit: 12 W max for 50 ms
Hold: 0.8 W

Igniter
9 W Max for 50 ms

Mounting
Customer and application dependant

Performance

Inlet pressure, range
Ox 402 to 1044 psi
27.7 to 72.0 bar
Fu 72.5 to 213 psi
5.0 to 14.7 bar

Flow rate, range
Ox 0.0003 to 0.0011 lbm/s
120 to 500 mg/s
Fu 0.00003 to 0.00013 lbm/s
15 to 60 mg/s

Chamber pressure, range
29 to 87 psi
2 to 6 bar

Thrust, range
0.09 to 0.31 lbf
0.39 to 1.37 N

*Throttle enabled through closed-loop control of bulk propellant temperature

Isp, vac
285 s

*Constant Isp due to stable mass flow rates and pressure

Cold-start capable
Yes

*Spark-based ignition allows for rapid and highly repeatable (12,000+) cold-starts

Minimum impulse bit (Bi-prop mode)
0.013 lbf.s
0.059 N.s

Maximum impulse bit (Bi-prop mode)
1.69 lbf.s
7.5 N.s

Minimum impulse bit (Cold-gas mode)
0.0005 lbf.s
0.002 N.s

*Cold-gas mode can utilize either N20 or C3H6

Maximum impulse bit (Cold-gas mode)
22.5 lbf.s
100 N.s

Additional comments:
[Reference 1][Feb 2022][General information]
The B1 Thruster assembly includes the thruster body, valves, and control electronics. The thruster body is additively manufactured as a single structure using Inconel 718 and includes the injector, combustion chamber, and nozzle. Health monitoring instrumentation includes an integrated and isolated thermocouple and chamber pressure sensor. With standard data and power interfaces, thrusters are easy to command and operate.
Available in a variety of form factors, the B1 Thruster is currently used in the following arrangements within Dawn systems:
One thruster in the center of Dawn's single-thruster CubeSat Propulsion Modules
Four thrusters, mounting in each corner of Dawn's four-thruster CubeSat Propulsion Modules.
Eight thrusters on a single system positioned to allow for full 6-axis spacecraft control.
A modular building block for customized propulsion systems, with absolute freedom on positioning and mounting.

[Reference 2][Feb 2022][General information]
Dawn Aerospace is providing satellite propulsion to hyperspectral imaging company Pixxel, who is building a health monitor for the planet through a constellation of hyperspectral imaging small satellites. In the last 12 months, Dawn has had several propulsion systems launched to space, with a total of 21 thrusters, powering a variety of satellites, including cubesats and OTV's. At the end of 2021, the company announced it had over one hundred of its 1N and 20N "green" thrusters in production, with this projected to triple over the next twelve months.

References:
[1] https://www.dawnaerospace.com/products/satdrive#b1
[2] https://smallsatnews.com/2022/02/08/dawn-aerospace-propulsion-to-empower-pixxels-hyperspectral-imaging-smallsats/

	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

Parabilis Rombus

Propulsion Technology	Hybrid
Manufacturer/Country	Parabilis (USA)
TRL	3-4
Size (including PPU)	34 kg (dry mass), 22” diameter x 18” height [2]
Design satellite size	Microsat
Isp (s)	260s [2]
Thrust type/magnitude	222 N (50 lbf), total impulse 45 kN*s [2]
Delta-V (m/s)	
Propellant	Poly(methyl methacrylate) PMMA, Nitrous Oxide N2O [2]
Power consumption (W)	28V
Flight heritage (if any)	None
Commercially available	YES
Last updated	03/2021


PARABILIS SPACE TECHNOLOGIES

ROMBUS
Rapid Orbital Mobility Bus

Affordable, Impulsive ΔV for Small Satellites

Parabilis’ ROMBUS Propulsion Module provides high-impulse thrust for satellite translational maneuvers which can be used for initial orbit insertion, rapid orbit rephasing, threat/collision avoidance, and targeted re-entry at the satellite’s mission end of life.

The design consists of a hybrid propulsion system utilizing Poly(methyl methacrylate) (PMMA) for the fuel and nitrous oxide (N_2O) for the oxidizer. The basic configuration is a single, centrally located motor nested within the oxidizer tanks. Two cold gas thruster triads use the N_2O as propellant to provide low-thrust maneuvers and attitude control to augment reaction wheels or to dump momentum from reaction wheels.

Features

- Compact module for high-thrust impulsive maneuvering
- Non-toxic, non-hazardous propellants
- Long-term storability, both ground and on-orbit
- Multiple re-start capability for multi-burn maneuvers
- Nitrous oxide propellant used in symbiotic RCS/ACS pods
- Self-pressurizing nitrous oxide, no pumps or press. system
- Simple, proven, and reliable design
- Significantly lower cost than competing solutions
- Adaptable configuration for custom missions and features

Design Heritage from Maneuvering and Orbital Transfer Vehicle (MOTV)

Parameter	Specification
Fuel	Poly(methyl methacrylate) (PMMA)
Oxidizer	Nitrous Oxide (N_2O)
Isp, Vacuum	260s, Primary Hybrid Motor 65s, ACS/RCS Thrusters
Thrust	222 N (50 lbf), throttleable
Total Impulse	44.6 kN-s
Dry Mass	33.7 kg
RCS & Residual	3.5 kg
Propellant Mass	15.2 kg
Volume	<21.5” dia x 18” height (without Lightband™ height)
Power	Input 28V ±4

Small-Scale Hybrid Motor Demonstration Test

1195 LINDA VISTA DRIVE, SUITE F | SAN MARCOS, CA 92078 | 855-727-2245 | PARABILIS-SPACE.COM

[2]

Additional comments:

[Reference 1-2][Jun 2020][Company, thruster, and vehicle information]
Parabilis Space Technologies, Inc. is an SBA-certified, HUBZone small business with offices located in San Marcos, California. Parabilis’ areas of expertise include propulsion systems and vehicles, small satellite systems and buses, and systems integration. Parabilis operates a propulsion test facility in Lakeside, CA permitted for numerous fuels and oxidizers. Parabilis is one of the few companies in the world that has both propulsion and satellite capabilities under one roof.

References:
[1] https://parabilis-space.com/
[2] Public release brochure provided to Aerospace in March 2020

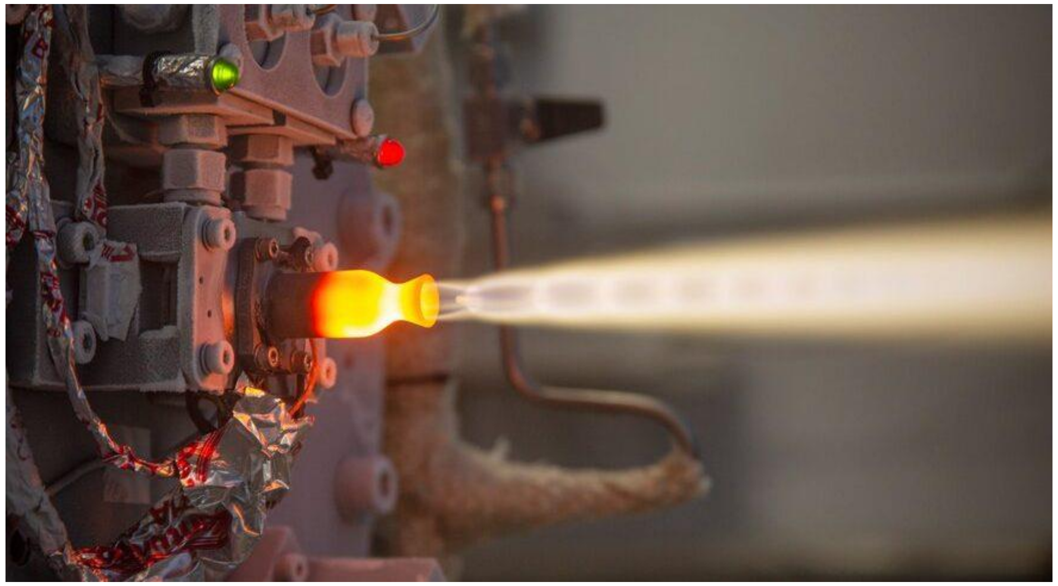
Comm. avail.	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

TALOS ACS Propulsion system

Propulsion Technology	Bi-prop
Manufacturer/Country	Frontier Aerospace (USA)
TRL	4
Size (including PPU)	?
Design satellite size	Peregrine is >500 kg
Isp (s)	>300s
Thrust type/magnitude	10 lbf (45N) and 150 lbf [3]
Delta-V (m/s)	
Propellant	MON/MMH
Power consumption (W)	
Flight heritage (if any)	None yet. Peregrine mission (2021, projected)
Commercially available	NO
Last updated	12/2020



[3]

Additional comments:
[Reference 2][December 2020][Thruster news]
NASA's Thruster for the Advancement of Low-temperature Operation in Space (TALOS) project is developing small thrusters to reduce overall spacecraft mass and power, which will reduce mission costs. The thrusters can make alterations in a spacecraft's flight path or altitude and can be used to enter orbit and descend to the surface of another world. They can also serve as main propulsion thrusters for landers. The TALOS thrusters burn mixed oxides of nitrogen and monomethyl hydrazine propellants (MON-25/MMH), which are capable of operating at low temperatures for an extended period without freezing. Although MON-25 has been tested since the 1980s, no spacecraft currently uses the propellant, or fuel. TALOS is capable of operating at a wide temperature range, between -40- and 80-degrees Fahrenheit. That's compared to state-of-the-art thrusters of the same size that generally use similar propellants, which operate between 45- and 70-degrees Fahrenheit.
January 2020 – NASA and Frontier Aerospace performed roughly 60 hot-fire tests on the main propulsion thruster prototypes over approximately three weeks. The tests were the first round of development testing on the TALOS axial thruster.
March 2020 – NASA and Frontier Aerospace performed roughly 60 hot-fire tests on two main propulsion thrusters over 10 days. The tests took place in a vacuum chamber that simulates the environment of space at Moog-ISP in Niagara Falls, New York. Engineers collected multiple data streams, including the combustion chamber's pressure and stability and the feed system's pressure and temperature, which delivers propellant from tanks to the thruster.

[Reference 4, 1][December 2020][Thruster news]
Frontier revealed on Monday it is making progress to qualify engines designed to produce 150 and 10 pounds of thrust for Peregrine, a lunar lander developed by Astrobotic Technologies. NASA awarded Frontier Aerospace $1.9M in 2018 for the design and testing of thrusters for the Peregrine mission. Peregrine would transport payloads to the moon's surface and orbit. Astrobotic plans to send the lander to space next year. Frontier's thrusters will use trans-lunar injection to boost Peregrine in conjunction with a Dynetics-made propulsion system.
Frontier has completed its CDR for NASA Marshall Space Flight Center in support of Artemis mission.

References:
[1] https://www.frontier.us/projects
[2] http://www.parabolicarc.com/2020/08/22/nasas-talos-thrusters-designed-to-lower-cost-of-landing-on-moon/
[3] https://spacenews.com/frontier-aerospace-talos/
[4] https://blog.executivebiz.com/2020/11/frontier-aerospace-designs-tests-thrusters-for-peregrine-lunar-lander/

Comm. avail.	TRL	Aerospace-tested
NO	4	NO

DISTRO A: Approved for public release. OTR-2024-00338

R-800/R-800EPS/R-800HT

Propulsion Technology	Hall effect thruster
Manufacturer/Country	Rafael (Israel)
TRL	3-4
Size (including PPU)	
Design satellite size	Small Sat
Isp (s)	1000-1500s
Thrust type/magnitude	25-48 mN
Delta-V (m/s)	
Propellant	Xenon, Krypton
Power consumption (W)	450-900W
Flight heritage (if any)	None, improved derivative of the R-400EPS, in orbit on VENUS satellite
Commercially available	NO
Last updated	08/2022

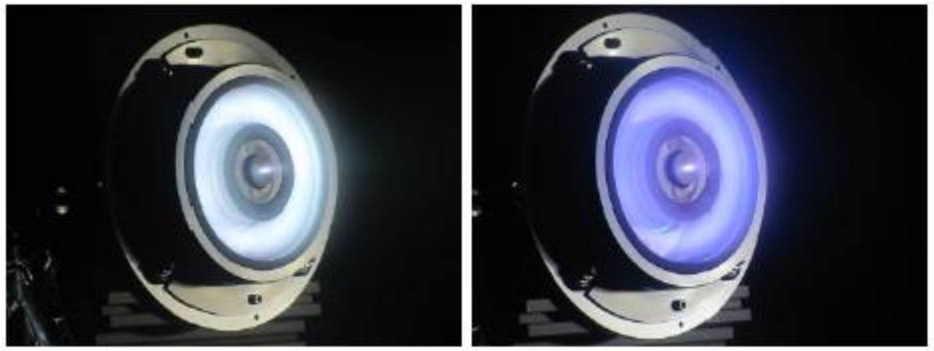


Figure 4. Pictures of Rafael's R-800-DM Hall thruster operating on xenon (left) and Krypton (right).

[1]

Property	Value
Power	450-900
Thrust (Xe)	25-48 mN
Isp (Xe)	1000-1500 sec
Propellant	Xe, Kr
Total Impulse (Xe)	> 560 kNs

Figure 5. Picture of Rafael's R-800 Heaterless Cathode (ARC-2A)

Additional comments:

[Reference 1][Jan 2021][Thruster development/flight]
For over a year, Rafael has been developing the R-800EPS, a full Hall thruster based electric propulsion in the 450-900W power range. The R-800EPS is an improved derivative of the R-400EPS (in orbit onboard the VENUS satellite) and consists of a low power thruster unit, base on hall thruster and hallow cathode, power processing unit, and a propellant management assembly. The R-800EPS is designated to operate with either xenon or krypton. The thruster has a conventional hall thruster configuration with the gas distributer serving also as the anode. At the same time, the thruster consists of a unique set of materials and structure that makes it relatively light weight. The R-800HT consists of permanent magnets and a center cathode, making it energy efficient with low volume signature.
Several Development Models (DM) of the R-800 thruster were produced in order to assess thruster performance and test its design features. During this initial development phase an appropriate magnetic field topology and magnitude were selected for performance optimization at different discharge power levels. In addition, new simplified designs of the gas distributer, and thruster body were examined with the purpose of reducing the thruster mass, coast, and ease of integration. The design verification activities culminated with a 500 hour thruster operation test, with xenon, after which the thruster lifetime was extrapolated. The estimated thruster lifetime is greater than 560 kNs. To validate the lifetime estimation, based on the 500 hr experiment, a numerical simulation was conducted that accounts for the thruster's geometry, channel materials, mass flow rate, discharge voltage, and magnetic field topology. To assure simulation validity, it was outsourced to an external acclaimed independent EP laboratory. Simulation results show that the estimated thruster lifetime is approximately 560 kNs. This result is in line with the minimum total impulse calculated by simple extrapolation.
An EM of the thruster is currently manufactured and is scheduled to start characterization in the upcoming months.

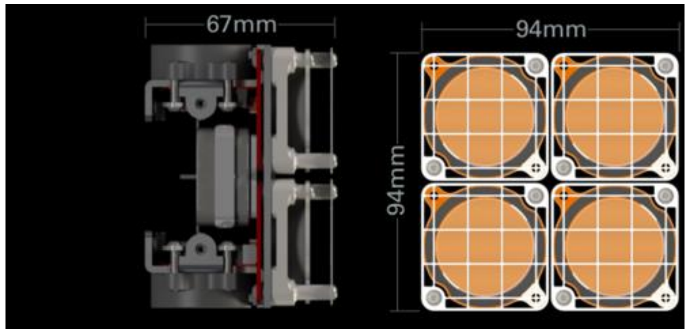
References:
[1] Lev, D., Zimmerman, R., Shoor, B., Appel, L., Ben-Ephraim, M., Herscovitz, J., Epstein, O., "Electric propulsion activities at Rafael in 2019," IEPC-2019-600.
[2] Appel, L., Medvinsky, G., Shoor, B., Sirota, A., Zimmerman, R., lev, D., Epstein, O., "Integration test of the R-800 low power hall thruster electric propulsion system," IEPC-2022-358.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

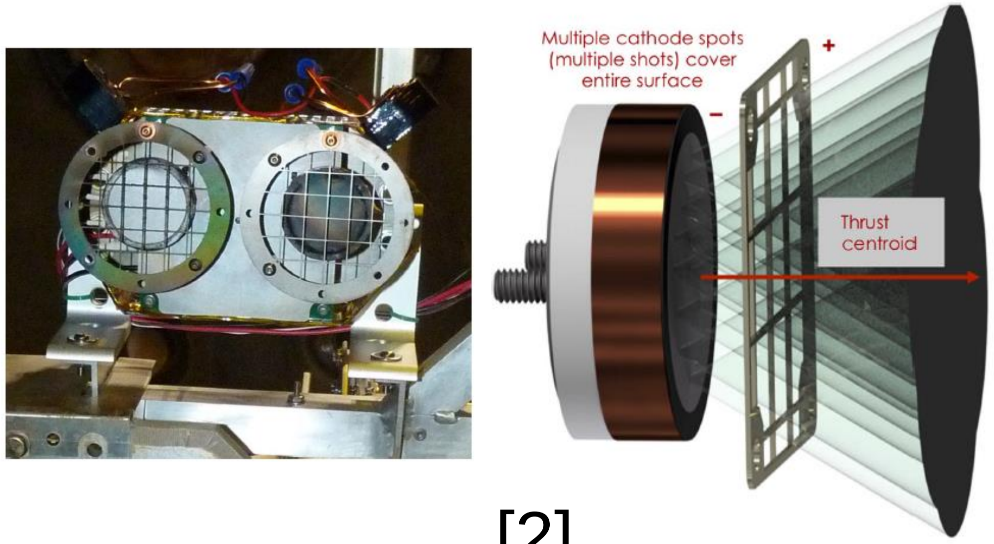
DISTRO A: Approved for public release. OTR-2024-00338

15-PUCK Metal Plasma Thruster (MPT) [1 of 2]

Propulsion Technology	Metal Plasma Thruster
Manufacturer/Country	Alameda AASC Space (USA), a version is offered through Benchmark Systems (see their Metal Plasma Thruster)
TRL	4
Size (including PPU)	2.5U including power control unit [1]
Design satellite size	12U or larger (ASTRA RROCI will be 12U)
Isp (s)	710s (Gold propellant), 2000s (Magnesium propellant) [1]
Thrust type/magnitude	6 mN (nominal, at 33W), 15000 N*s (total impulse) [1]
Delta-V (m/s)	400 m/s for a 40 kg satellite [1]
Propellant	Various metals including Molybdenum, Gold, Magnesium, Aluminum, palladium, niobium, and also carbon [2, 3]. Mass 360 g [1]
Power consumption (W)	Not provided on website, but speculate few hundred watts (~300-400W)
Flight heritage (if any)	None Projected for ASTRA RROCI mission (to be launched early 2022) [1]
Commercially available	YES
Last updated	02/2023



[1]



[2]

Additional comments:
[Reference 2][Feb 2021][Thruster information]
The metal plasma thruster (MPT) is a pulsed, electric propulsion device that burns solid metal propellant, converting approximately 30 ug/pulse of metal into hot plasma (3 eV temperature) that expands hydrodynamically into vacuum to generate impulse/thrust. The MPT consists of a cathode of the metal propellant, facing a semitransparent anode that is made of a refractory metal such as tungsten (W). A short (~1 us) voltage spike (approximately a few hundred volts) is applied to the copper trigger sleeve that generates plasma to bridge the vacuum gap between the cathode and anode grid. This seed plasma triggers formation of cathode spots on the cathode face, each of which carries t ypically 20-50 A and ejects an ionized plasma of the cathode metal towards the anode grid at high velocity (~10-30 km/s). Each cathode spot lasts for <1 us and, when extinguished, stimulates creation of a new spot nearby. The cathode face is fully covered by spots over multiple firings, and the erosion creates an average thrust vector that is normal to the cathode face and aligned with its axis.
[Reference 3][Feb 2021][Ground testing]
A torsional thrust stand, calibrated for impulse bits in the range of 0.1–0.5 mN·s, was used to measure impulse bits from a metal plasma thruster. Impulse data were obtained on roughly 1400 shots, with metal plasma thruster targets of molybdenum, niobium, palladium, aluminum, and carbon. Model predictions (based on a simple circuit model and published plasma parameters) were validated by data from the calibrated torsional thrust stand. Over a typical 50-shot firing sequence, the impulse bits measured showed a coefficient of variation of approximately 5%. This implies that individual impulse bits of about 0.4 mN·s can be imparted to a satellite with ±5% variation about the mean in a total impulse burst of 20 mN·s. For a 20 kg satellite, this would result in a velocity increment ΔV of just 1 mm/s, enabling very precise attitude control and fine positioning control of nano- and microsatellites. The metal plasma thruster uses solid metal propellant and hence requires no liquids, gases, flow valves, or flow controls and has no moving parts. Total impulse approximately 5000 (N·s)/liter and provides orbit raising and drag compensation capability.

References:
[1] https://www.aasc.space/
[2] Krishnan, M., Velas, K., Leemans, S., “Metal Plasma Thruster for Small Satellites,” Journal of Propulsion and Power, Vol 36, 2020.
[3] Krishnan, M., Frankovich, K., Mackey, J., “Impulse bit measurements from metal plasma thruster,” Journal of Propulsion and Power, 2021.

Comm. avail.	4	NO
	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

15-PUCK Metal Plasma Thruster (MPT) [2 of 2]

Additional comments:

[Reference 1][Feb 2021][Flight info]
AASC is please to announce that in August 2020, AASC was selected by ASTRA LLC to deliver a flight-ready version of our Metal Plasma Thruster (MPT) for ASTRA's EWS Rapid Revisit Optical Cloud Imager (RROCI) Mission, scheduled for launch in early 2022. The US Space Force's Space and Missile Systems Center has selected ASTRA, LLC to develop and demonstrate and Electro-Optical/Infrared (EO/IR) LEO-based cloud characterization solution (RROCI) that supports US warfighter operations. RROCI is currently funded through launch readiness.
AASC is proud to support this project as a provider of a compact, reliable electric propulsion thruster with no moving parts, using solid metal propellant and a low voltage power processing unit. The scalable MPT configurations are described in www.aasc.space. A flight ready unit will be delivered to Pumpkin Labs, who will build and integrate the 12U spacecraft bus. The AASC MPT will raise the 12U spacecraft from its injection orbit up to its operational orbit in the early mission phase, provide attitude adjustments throughout the mission, and finally maneuver the craft down to a lower orbit for burn-up at the end of the mission.
AASC has matured the MPT thruster with recent support from NASA via an SBIR contract. Direct thrust measurements made at NASA on a sensitive pendulum thrust stand confirm the predictions based on plasma parameters in the thruster.

References:

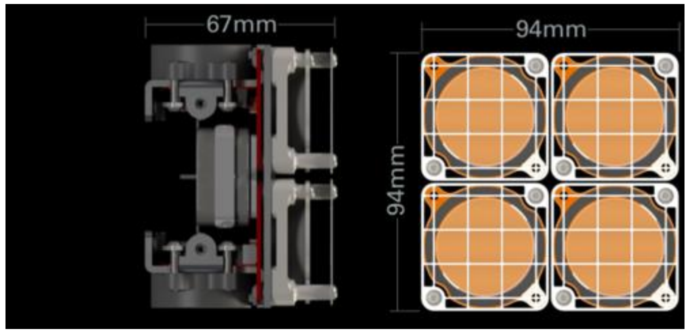
[1] https://www.aasc.space/

	4	NO
Comm. avail.	TRL	Aerospace-tested

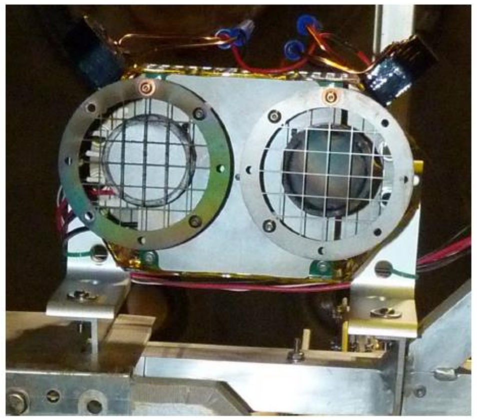
DISTRO A: Approved for public release. OTR-2024-00338

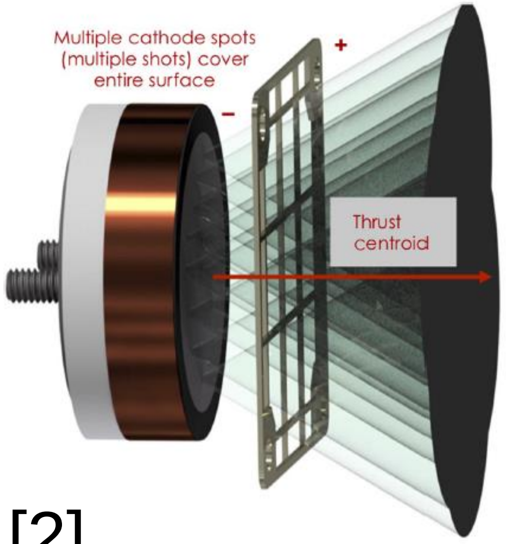
4-PUCK Metal Plasma Thruster (MPT) [1 of 2]

Propulsion Technology	Metal Plasma Thruster
Manufacturer/Country	Alameda AASC Space (USA), a version is offered through Benchmark Systems (see their Metal Plasma Thruster)
TRL	4
Size (including PPU)	~0.67U including power control unit [1]
Design satellite size	3U or larger (ASTRA RROCI will be 12U)
Isp (s)	710s (Gold propellant), 2000s (Magnesium propellant) [1]
Thrust type/magnitude	1.6 mN (nominal, at 33W), 4000 N*s (total impulse) [1]
Delta-V (m/s)	720 m/s for a 6 kg satellite [1]
Propellant	Various metals including Molybdenum, Gold, Magnesium, Aluminum, palladium, niobium, and also carbon [2, 3]. Mass 360 g [1]
Power consumption (W)	133W [1]
Flight heritage (if any)	None Projected for ASTRA RROCI mission (to be launched early 2022) [1]
Commercially available	YES
Last updated	08/2022



[1]





[2]

Additional comments:
[Reference 2][Feb 2021][Thruster information]
The metal plasma thruster (MPT) is a pulsed, electric propulsion device that burns solid metal propellant, converting approximately 30 ug/pulse of metal into hot plasma (3 eV temperature) that expands hydrodynamically into vacuum to generate impulse/thrust. The MPT consists of a cathode of the metal propellant, facing a semitransparent anode that is made of a refractory metal such as tungsten (W). A short (~1 us) voltage spike (approximately a few hundred volts) is applied to the copper trigger sleeve that generates plasma to bridge the vacuum gap between the cathode and anode grid. This seed plasma triggers formation of cathode spots on the cathode face, each of which carries t ypically 20-50 A and ejects an ionized plasma of the cathode metal towards the anode grid at high velocity (~10-30 km/s). Each cathode spot lasts for <1 us and, when extinguished, stimulates creation of a new spot nearby. The cathode face is fully covered by spots over multiple firings, and the erosion creates an average thrust vector that is normal to the cathode face and aligned with its axis.
[Reference 3][Feb 2021][Ground testing]
A torsional thrust stand, calibrated for impulse bits in the range of 0.1–0.5 mN·s, was used to measure impulse bits from a metal plasma thruster. Impulse data were obtained on roughly 1400 shots, with metal plasma thruster targets of molybdenum, niobium, palladium, aluminum, and carbon. Model predictions (based on a simple circuit model and published plasma parameters) were validated by data from the calibrated torsional thrust stand. Over a typical 50-shot firing sequence, the impulse bits measured showed a coefficient of variation of approximately 5%. This implies that individual impulse bits of about 0.4 mN·s can be imparted to a satellite with ±5% variation about the mean in a total impulse burst of 20 mN·s. For a 20 kg satellite, this would result in a velocity increment ΔV of just 1 mm/s, enabling very precise attitude control and fine positioning control of nano- and microsatellites. The metal plasma thruster uses solid metal propellant and hence requires no liquids, gases, flow valves, or flow controls and has no moving parts. Total impulse approximately 5000 (N·s)/liter and provides orbit raising and drag compensation capability.

References:
[1] https://www.aasc.space/
[2] Krishnan, M., Velas, K., Leemans, S., “Metal Plasma Thruster for Small Satellites,” Journal of Propulsion and Power, Vol 36, 2020.
[3] Krishnan, M., Frankovich, K., Mackey, J., “Impulse bit measurements from metal plasma thruster,” Journal of Propulsion and Power, 2021.

🛒	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

4-PUCK Metal Plasma Thruster (MPT) [2 of 2]

Additional comments:

[Reference 1][Feb 2021][Flight info]
AASC is please to announce that in August 2020, AASC was selected by ASTRA LLC to deliver a flight-ready version of our Metal Plasma Thruster (MPT) for ASTRA's EWS Rapid Revisit Optical Cloud Imager (RROCI) Mission, scheduled for launch in early 2022. The US Space Force's Space and Missile Systems Center has selected ASTRA, LLC to develop and demonstrate and Electro-Optical/Infrared (EO/IR) LEO-based cloud characterization solution (RROCI) that supports US warfighter operations. RROCI is currently funded through launch readiness.
AASC is proud to support this project as a provider of a compact, reliable electric propulsion thruster with no moving parts, using solid metal propellant and a low voltage power processing unit. The scalable MPT configurations are described in www.aasc.space. A flight ready unit will be delivered to Pumpkin Labs, who will build and integrate the 12U spacecraft bus. The AASC MPT will raise the 12U spacecraft from its injection orbit up to its operational orbit in the early mission phase, provide attitude adjustments throughout the mission, and finally maneuver the craft down to a lower orbit for burn-up at the end of the mission.
AASC has matured the MPT thruster with recent support from NASA via an SBIR contract. Direct thrust measurements made at NASA on a sensitive pendulum thrust stand confirm the predictions based on plasma parameters in the thruster.

References:
[1] https://www.aasc.space/

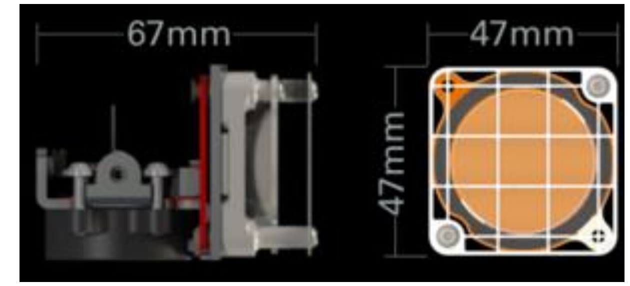
4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

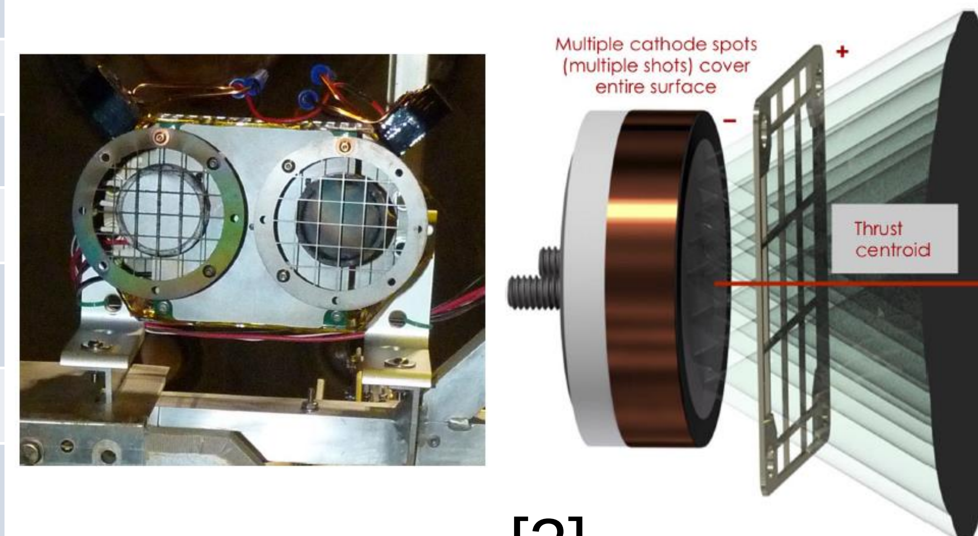
DISTRO A: Approved for public release. OTR-2024-00338

1-PUCK Metal Plasma Thruster (MPT) [1 of 2]

Propulsion Technology	Metal Plasma Thruster
Manufacturer/Country	Alameda AASC Space (USA), a version is offered through Benchmark Systems (see their Metal Plasma Thruster)
TRL	4
Size (including PPU)	~0.5U including power control unit, 0.15U not including power control unit) [1] Total mass 0.75kg [1]
Design satellite size	3U or larger (ASTRA RROCI will be 12U)
Isp (s)	710s (Gold propellant), 2000s (Magnesium propellant) [1]
Thrust type/magnitude	0.4 mN (nominal, at 33W), 1000 N*s (total impulse) [1]
Delta-V (m/s)	
Propellant	Various metals including Molybdenum, Gold, Magnesium, Aluminum, palladium, niobium, and also carbon [2, 3]. Mass 90 g [1]
Power consumption (W)	33W [1]
Flight heritage (if any)	None Projected for ASTRA RROCI mission (to be launched early 2022) [1]
Commercially available	YES
Last updated	08/2022



[1]



[2]

Additional comments:

[Reference 2][Feb 2021][Thruster information]

The metal plasma thruster (MPT) is a pulsed, electric propulsion device that burns solid metal propellant, converting approximately 30 ug/pulse of metal into hot plasma (3 eV temperature) that expands hydrodynamically into vacuum to generate impulse/thrust. The MPT consists of a cathode of the metal propellant, facing a semitransparent anode that is made of a refractory metal such as tungsten (W). A short (~1 us) voltage spike (approximately a few hundred volts) is applied to the copper trigger sleeve that generates plasma to bridge the vacuum gap between the cathode and anode grid. This seed plasma triggers formation of cathode spots on the cathode face, each of which carries t ypically 20-50 A and ejects an ionized plasma of the cathode metal towards the anode grid at high velocity (~10-30 km/s). Each cathode spot lasts for <1 us and, when extinguished, stimulates creation of a new spot nearby. The cathode face is fully covered by spots over multiple firings, and the erosion creates an average thrust vector that is normal to the cathode face and aligned with its axis.

[Reference 3][Feb 2021][Ground testing]

A torsional thrust stand, calibrated for impulse bits in the range of 0.1–0.5 mN·s, was used to measure impulse bits from a metal plasma thruster. Impulse data were obtained on roughly 1400 shots, with metal plasma thruster targets of molybdenum, niobium, palladium, aluminum, and carbon. Model predictions (based on a simple circuit model and published plasma parameters) were validated by data from the calibrated torsional thrust stand. Over a typical 50-shot firing sequence, the impulse bits measured showed a coefficient of variation of approximately 5%. This implies that individual impulse bits of about 0.4 mN·s can be imparted to a satellite with ±5% variation about the mean in a total impulse burst of 20 mN·s. For a 20 kg satellite, this would result in a velocity increment ΔV of just 1 mm/s, enabling very precise attitude control and fine positioning control of nano- and microsatellites. The metal plasma thruster uses solid metal propellant and hence requires no liquids, gases, flow valves, or flow controls and has no moving parts. Total impulse approximately 5000 (N·s)/liter and provides orbit raising and drag compensation capability.

References:

[1] https://www.aasc.space/
[2] Krishnan, M., Velas, K., Leemans, S., “Metal Plasma Thruster for Small Satellites,” Journal of Propulsion and Power, Vol 36, 2020.
[3] Krishnan, M., Frankovich, K., Mackey, J., “Impulse bit measurements from metal plasma thruster,” Journal of Propulsion and Power, 2021.

Comm. avail.	TRL	Aerospace-tested
	4	NO

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

1-PUCK Metal Plasma Thruster (MPT) [2 of 2]

Additional comments:

[Reference 1][Feb 2021][Flight info]
AASC is please to announce that in August 2020, AASC was selected by ASTRA LLC to deliver a flight-ready version of our Metal Plasma Thruster (MPT) for ASTRA's EWS Rapid Revisit Optical Cloud Imager (RROCI) Mission, scheduled for launch in early 2022. The US Space Force's Space and Missile Systems Center has selected ASTRA, LLC to develop and demonstrate and Electro-Optical/Infrared (EO/IR) LEO-based cloud characterization solution (RROCI) that supports US warfighter operations. RROCI is currently funded through launch readiness.
AASC is proud to support this project as a provider of a compact, reliable electric propulsion thruster with no moving parts, using solid metal propellant and a low voltage power processing unit. The scalable MPT configurations are described in www.aasc.space. A flight ready unit will be delivered to Pumpkin Labs, who will build and integrate the 12U spacecraft bus. The AASC MPT will raise the 12U spacecraft from its injection orbit up to its operational orbit in the early mission phase, provide attitude adjustments throughout the mission, and finally maneuver the craft down to a lower orbit for burn-up at the end of the mission.
AASC has matured the MPT thruster with recent support from NASA via an SBIR contract. Direct thrust measurements made at NASA on a sensitive pendulum thrust stand confirm the predictions based on plasma parameters in the thruster.

References:
[1] https://www.aasc.space/

🛒	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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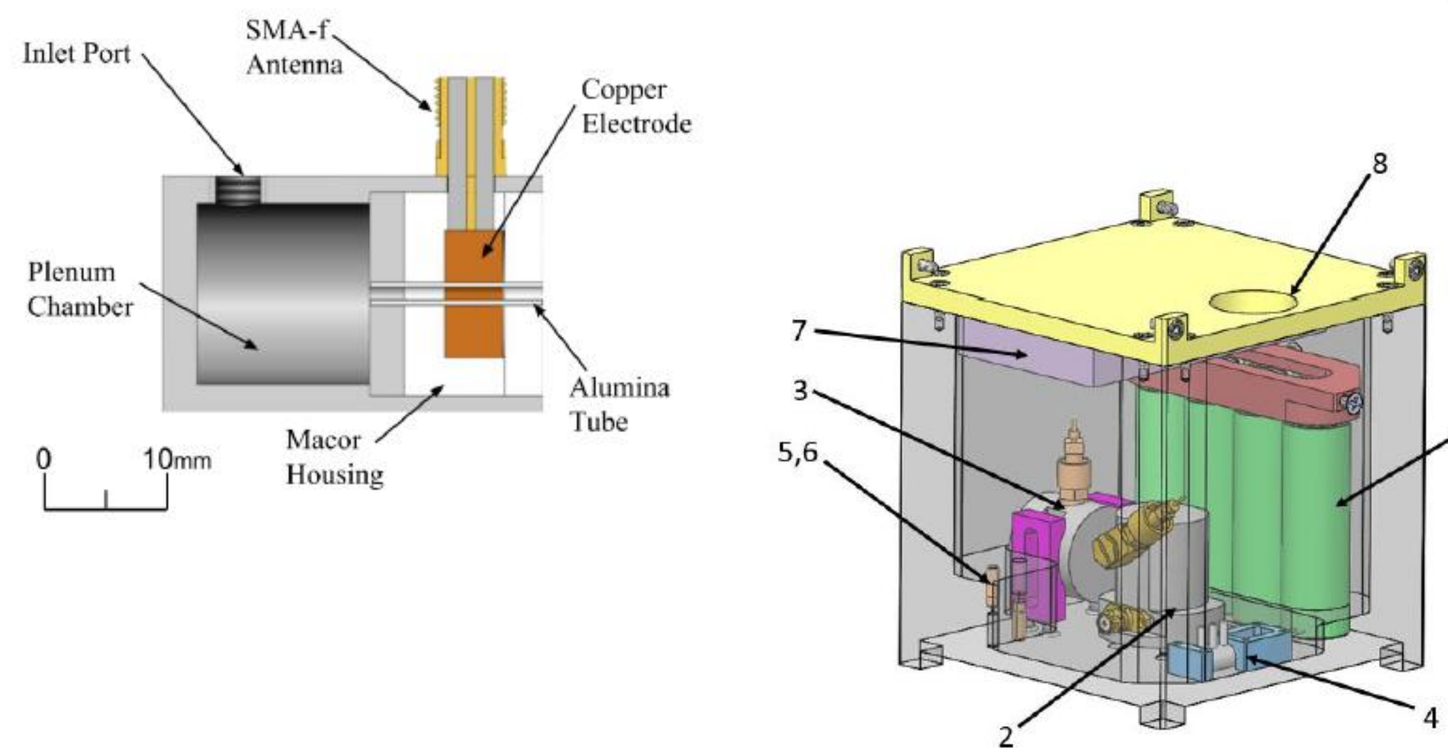
Pocket Rocket

Propulsion Technology	Weakly ionized RF plasma
Manufacturer/Country	California Polytechnic State University, Cal Poly CubeSat Lab (USA)
TRL	3-4
Size (including PPU)	60g (35 mm long, radius 25 mm) [1]
Design satellite size	3U or larger
Isp (s)	100s [1]
Thrust type/magnitude	2.4 mN [2]
Delta-V (m/s)	Up to 50 m/s for 3U spacecraft [1] 20 m/s with xenon, 10 m/s with argon [2]
Propellant	Inert gas (usually argon)
Power consumption (W)	10W RF power [1]
Flight heritage (if any)	None
Commercially available	NO
Last updated	04/2021



Fully integrated Pocket Rocket thruster fits into a 1U Cube

Additional comments:

[Reference 1][Aug 2019][Thruster info]
The Pocket Rocket thruster was first conceived of and investigated by the Australian National University. Radiofrequency (RF) power of a few Watts ionizes a fraction of an inert neutral propellant creating a weakly ionized plasma. Charge exchange collisions in the plasma heat the remaining neutral propellant, increasing thrust and specific impulse produced compared to a cold gas thruster of similar size. The Pocket Rocket thruster is embedded into the structure, with batteries, power processing unit (PPU), and propellant regulation and delivery system *contained within the pressure vessel*. Containing electronic components inside the pressure vessel assists with radiation and thermal protection systems. When used as part of a generic 3U CubeSat mission, the pressurized 1U form factor is capable of producing between 5 and 50 m/s of Δv.

[Reference 2][April 2021][Thruster info]
The research presented provides an overview of a 1U+ form factor propulsion system design developed for the Cal Poly CubeSat Laboratory (CPCL). This design utilizes a Radiofrequency Electrothermal Thruster (RFET) called Pocket Rocket that can generate 9.30 m/s of delta-V with argon, and 20.2 ± 3 m/s of delta-V with xenon. Due to the demand for advanced mission capabilities in the CubeSat form factor, a need for micro-propulsion systems that can generate between 1 – 1500 m/s of delta-V are necessary. By 2019, Pocket Rocket had been developed to a Technology Readiness Level (TRL) of 5 and ground tested in a 1U CubeSat form factor that incorporated propellant storage, pressure regulation, RF power and thruster control, as well as two Pocket Rocket thrusters under vacuum, and showcased a thrust of 2.4 mN at a required 10 Wdc of power with Argon propellant. The design focused on ground testing of the thruster and did not incorporate all necessary components for operation of the thruster. Therefore in 2020, a 1U+ Propulsion Module that incorporates Pocket Rocket, the RF amplification PCB, a propellant tank, propellant regulation and delivery, as well as a DC-RF conversion with a PIB, that are all attached to a 2U customer CubeSat for a 3U+ overall form factor. This design was created to increase the TRL level of Pocket Rocket from 5 to 8 by demonstrating drag compensation in a 400 km orbit with a delta-V of 20 ± 3 m/s in the flight configuration. The 1U+ Propulsion Module design included interface and requirements definition, assembly instructions, Concept of Operations (ConOps), as well as structural and thermal analysis of the system. The 1U+ design enhances the capabilities of Pocket Rocket in a 1U+ form factor propulsion system and increases future mission capabilities as well as propulsion system heritage for the CPCL.

References:
[1] Van Ness, P., Ramirez, G., Gnagy, S., Diamantopoulous, S., Grieg, A., "Pressurized 1U CubeSat Propulsion Unit," SSC19-WKVIII-05
[2] Harper, James. Thesis: Pocket Rocket: A 1U+ propulsion system design to enhance cubesat capabilities, CalPoly, June 2020.

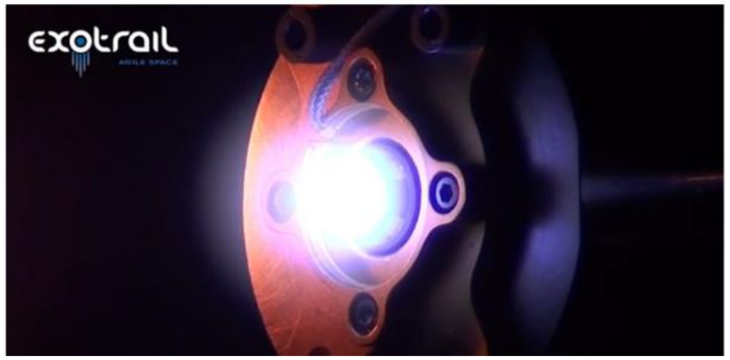
NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

ExoMG-micro [1 of 2]
Exotrail

Propulsion Technology	Hall Effect Thruster
Manufacturer/Country	Exotrail (FRANCE)
TRL	3-4
Size (including PPU)	2U to 4U, < 4.4 kg for wet EP string (cluster configuration available)
Design satellite size	SmallSats (30 – 250 kg)
Isp (s)	1000 s [2]
Thrust type/magnitude	3 to 50 kN*s (total impulse) 5 mN (thrust, continuous, nominal) 7 mN @ 150 W
Delta-V (m/s)	Up to 1000 m/s for 400 kg payload [4]
Propellant	Xenon
Power consumption (W)	150W, nominal
Flight heritage (if any)	None Projected to be on SpaceVan (2024) [4] Slated for Starfish Space's Otter Pup satellite (launched projected for summer 2023) – unclear exactly which hall thruster model [5]
Commercially available	YES
Last updated	*04/2023*

Clusterization of the ExoMG-micro HETs [3]



Clusterization of the ExoMG-micro HETs

Additional comments:

[Reference 1,2][Jan 2019][General info]

In Jan 2018, the company website reported:

"Our team successfully proceeded to multiple ignitions of our Hall Effect Thruster (HET) at Plateforme d'Intégrations et Tests (OVSQ/CNRS) in December 2017. This is a major milestone for Exotrail, after 18 months of technical development. We have worked with the LAPLACE/GREPHE laboratory based in Toulouse – world expert in plasma physics applied to space propulsion – for the design of our thruster in order to optimize its performances. This thruster is the smallest Hall Effect Thruster ever designed and successfully ignited in the world.

The rest of the technical development is also going according to plan. Exotrail is aiming at developing a fully integrated thruster with all the necessary components (cathode, fluidics, electronics). We have successfully tested all the key sub-systems and are on our track to have a first version of our integrated system in mid-2018, only two years after the beginning of our development. This is the result of a great team work but also of the help of our partners – SATT Paris-Saclay, who has been funding our technical development since mid-2016, the Centre National de la Recherche Scientifique (CNRS), the Synchrotron Soleil and the Université Versailles Saint-Quentin en Yvelines. Exotrail is developing a range of electric propulsion systems for small satellites (10-100kg). Thanks to the use of Hall Effect technology, our thruster boasts a superior thrust-to-power ratio than competing systems. A high thrust means that you can access your operational orbit quicker than with other technologies (3 to 6 times quicker than FEEP, VAT or GIT electric thrusters) or double the power available for your main payload (vs. the same competing technologies). We provide the best balance between the high fuel efficiency brought by electric technologies and the highest thrust-to-power ratio. We will start official pre-orders in 2019, but you can contact us right now for more info."

See additional info on company in ExoMG-nano.

References:

[1] https://exotrail.com/news/2018-01-15/32-we-successfully-ignited-the-smallest-het-ever-designed/
[2] https://exotrail.com/product/
[3] http://www.parabolicarc.com/2020/07/18/exotrail-signs-contract-with-cnes-to-develop-cluster-of-thrusters/
[4] https://smallsatnews.com/2022/04/12/exotrail-signs-a-launch-service-agreement-with-spacex-to-launch-their-spacevan-otv-mission/
[5] https://smallsatnews.com/2023/02/07/starfish-space-to-perform-leo-satellite-docking-using-electric-propulsion/

Comm. avail.	TRL	Aerospace-tested
	4	NO

DISTRO A: Approved for public release. OTR-2024-00338

ExoMG-micro [2 of 2]
Exotrail

Additional comments:

[Reference 1][April 2021][Thruster]
The ExoMGTM - micro is the higher power model of the two offered by Exotrail. The ExoMGTM - micro model caters to satellites in the 30 kg – 250 kg mass range and is designed to be used as a standalone or in a clustered configuration [1]. However, the cluster configuration, called the ExoMGTM - cluster, is being designed, investigated, and developed in partnership with the French Space Agency, CNES (Centre National d'Etudes Spatiales) to enable the clusterization of several HETs. The motivation for the ExoMGTM - cluster is to address the needs of satellites in the 50 kg – 250 kg mass range. Hardware and prototype demonstration are scheduled for 2022.

[Reference 2 and 3][April 2021][News]
Exotrail signed a contract with ESA to accelerate the qualification and flight demonstration of the ExoMGTM - micro.

[Reference 4][April 2022][Flight info]
Exotrail has officially released the firm's new, in-space, mobility service which is delivered by their SpaceVan™, a unique Orbital Transfer Vehicle (OTV).
The debut SpaceVan™ mission will launch onboard a Falcon 9 rideshare mission in October 2023 following a launch service agreement signed between Exotrail and SpaceX.
At least three subsequent missions are planned throughout 2024 onboard multiple different launchers. Deploying constellations over several planes, altitudes and inclinations often means using dedicated launch vehicles which dramatically increase launch costs.
With the SpaceVan™ mobility service, satellite operators can now quickly and efficiently deploy their constellations over several different planes, altitudes, and inclinations, while still taking advantage of significantly cheaper rideshare vehicles. Exotrail has leveraged its capabilities in flight dynamics, system design and electric propulsion to create an in-space mobility service.The SpaceVan™ uses Exotrail's space proven ExoMG™ propulsion system which is a key differentiator from its chemical propulsion OTVs counterparts and offers up to 1 km/s of deltaV for a payload capacity of up to 400 kg.

[Reference 5][April 2022][Company news]
The French Space Agency, CNES, has selected Exotrail to complete a research and technology study to optimize the operations of mega constellations. The study will focus on MEO and LEO, where thousands of satellites are soon expected to be operational and propelled by electric propulsion. The study will determine the best operational procedures to implement in mega constellation's flight dynamic system, including station keeping and collision avoidance – two critical operations.

[Reference 6][July 2022][Thruster testing]
Unsure if this is the correct thruster, but suspected to be as it is referencing a 100W thruster test and it was authored by Exotrail.
The cluster was composed of the ISCT100v2-ICARE-0X – X refering to the number of the anode block used. The ISCT100v2-ICARE-0X, standing for ICARE Small Customizable Thruster, is a 100 W-class Hall thruster, with performances comparable to the Busek BHT-100.
Testing of 2 side-by-side mounted 100W HETs, including plasma plume content, using xenon.

[Reference 7][Aug 2022][Thruster testing]
The ExoMGTM - micro propulsion system has been cycled with a total xenon flow rate range of [8, 10] sccm. The full propulsion system achieved 529 ignition cycles, performing 257 hours of firing. After this, the THD (thruster head) has been operated to reach 727 total ignition cycles and 831 hours of operation for studying erosion mechanisms.

References:
[1] https://exotrail.com/product/
[2] https://spacenews.com/exotrail-wins-esa-contracts-%e2%80%a2-smartsky-suing-atg-equipment-contractor-%e2%80%a2-eutelsat-executive-steps-down/
[3] https://exotrail.com/news/2020-09-11/92-esa-selected-exotrail-and-signed-2-contracts-for-the-delivery-of-electric-propulsion-solutions/
[4] https://smallsatnews.com/2022/04/12/exotrail-signs-a-launch-service-agreement-with-spacex-to-launch-their-spacevan-otv-mission/
[5] https://smallsatnews.com/2022/03/23/cnes-mega-constellation-optimization-study-contracted-to-exotrail/
[6] Hallouin, T., Guglielmi, A., Gurciullo, A., Moriconi, B., Mazouffre, S., "Far-field plume properties of a cluster of 100W-class permanent magnets Hall thrusters," IEPC-2022-292
[7] Moriconi, B., Hallouin, T., Gurciullo, A., "Hall thruster ExoMG-micro, ExoMG-nano and low current cathode development at Exotrail: cyclic life testing results," IEPC-2022-291

	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

China: Vacuum Arc Thruster

Propulsion Technology	VAT
Manufacturer/Country	China: LIP (Lanzhou Institute of Physics)
TRL	4
Size (including PPU)	<1 U
Design satellite size	~3U (<10 kg) [1]
Isp (s)	>1000 s [1]
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Metal
Power consumption (W)	
Flight heritage (if any)	None, projected for the XX-1 microsatellite, launch date unknown [1]
Commercially available	NO
Last updated	09/2021

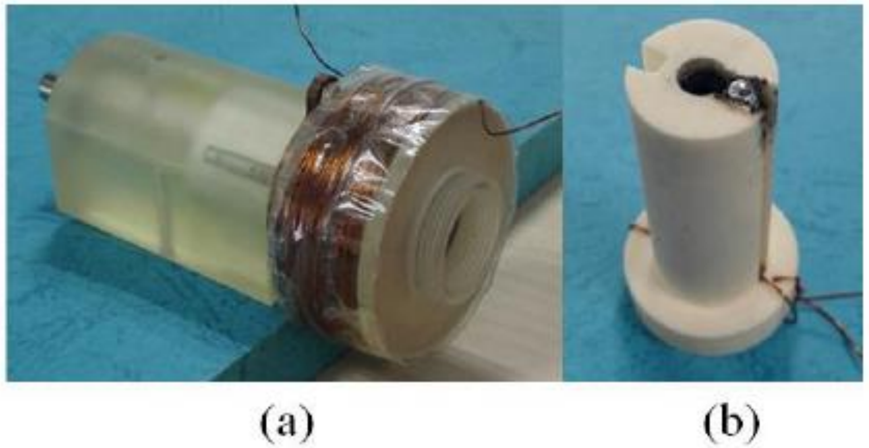


Figure 3. The photo of VAT(a: co-axial type, b: ring-geometry)

VAT photo, developed by LIP [1]

Additional comments:

[Reference 1][September 2021][Thruster information]

The VAT (vacuum arc thruster) is a form of low power electric propulsion that is operated by arcing between the cathode and anode, and is driven by pulsed current. The breakdown between the electrodes forms a microscopic sites on the cathode surface called a cathode spot. The material in the spot is vaporized, and ionized, and the thrust is produced by the material jetting.
Co-axial and ring-geometry VATs have been developed at LIP. The propellant is solid, usually metals, making storage easy. The ignition voltage for these systems is <1 kV, and the VAT system is simple and relatively low mass, making the VAT system a good choice for low mass satellites (<10kg).
The system at LIP has been tested to over 1 million shots, and typical arc pulse waveforms are shown. The data indicate that the Isp is >1000 s, and efficiency is approximately 13%.
The VAT electric system will perform station keeping for the XX-1 microsatellite that have been developed by the academy of TIAYI in China.

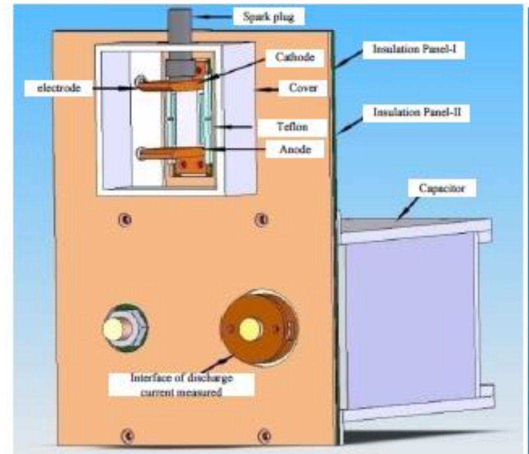
References:
[1] Yanhui, J., Tianping, Z., Chenchen, W., Yujun, K., Xianming, W., Shangmin, W., Ning, G., “The latest development of low power electric propulsion for small spacecraft,” IEPC-2017-78**.**

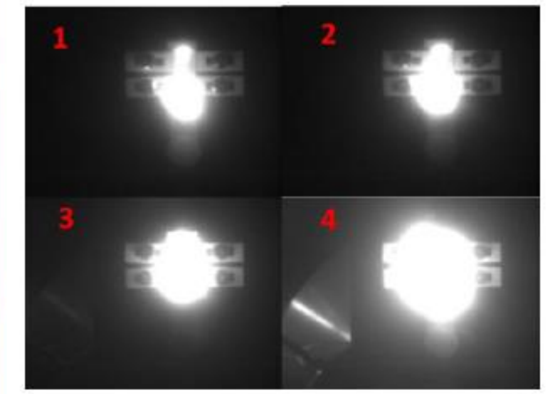
NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

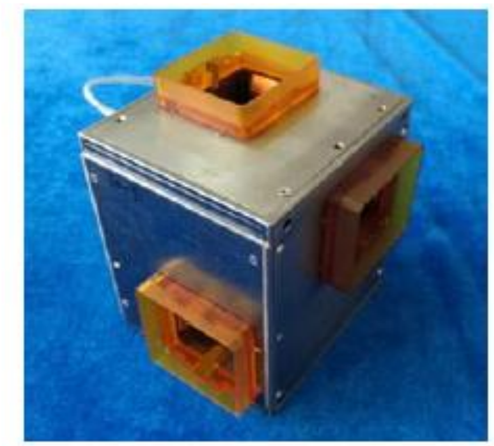
China: Micro-PPT

Propulsion Technology	PPT
Manufacturer/Country	China: LIP (Lanzhou Institute of Physics)
TRL	4
Size (including PPU)	1U
Design satellite size	3U
Isp (s)	>700 s at 1 Hz [1]
Thrust type/magnitude	>40 uN [1]
Delta-V (m/s)	
Propellant	Teflon [1]
Power consumption (W)	<5 W [1]
Flight heritage (if any)	None
Commercially available	NO
Last updated	09/2021





Photographs of the micro-PPT system [1]



Additional comments:

[Reference 1][September 2021][Thruster information]
The PPT system developed at LIP has been tested in vacuum. Data shows that the discharge time is approximately 13 us, with a discharge current peak of 22.5 kA. The thruster was tested to 220 million cycles, showing good stability and repeatability. The performance was computer by the experimental paraters as 40 uN*s impulse bit, Isp > 700s at 1 Hz frequency, and a discharge voltage of 1600V.
The PPT system will be used on a cube sat design by Northwestern Polytechnic University. The system mass is less than 2 kg, input power is less than 5W, mean thrust larger than 40 uN, and Isp is larger than 700s.

References:
[1] Yanhui, J., Tianping, Z., Chenchen, W., Yujun, K., Xianming, W., Shangmin, W., Ning, G., “The latest development of low power electric propulsion for small spacecraft,” IEPC-2017-78.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

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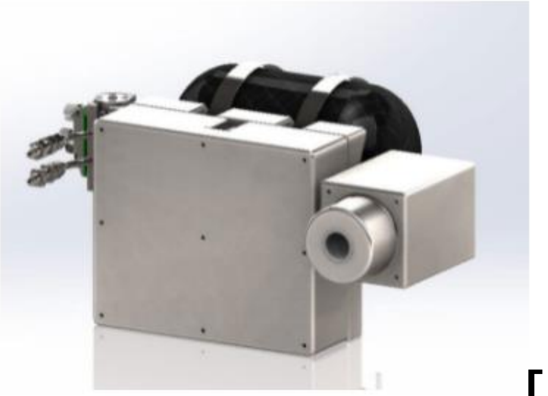
Maxwell Block 2

Propulsion Technology	RF thruster
Manufacturer/Country	Phase Four (USA)
TRL	4
Size (including PPU)	5 kg (excluding tank), 20 cm x10 cm x25 cm
Design satellite size	SmallSat
Isp (s)	Up to 600s
Thrust type/magnitude	Up to 10 mN
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	350 to 500W
Flight heritage (if any)	None
Commercially available	Yes, first target deliveries in H1 2022, website gives price at $340,000
Last updated	04/2022



MAXWELL BLOCK 2

H1 2022

[1]

Additional comments:
[Reference 1][April 2022][Thruster information]

Maxwell Block 2 takes the thruster, electronics, and fluid systems from Block 1 and arranges them in a panel-integrated fashion. This allows the system to mate to a variety of propellant tanks for different mission total impulse requirements while still using the same production line and production schedule. Block 2 is under development and is scheduled for first deliveries in H1 2022.

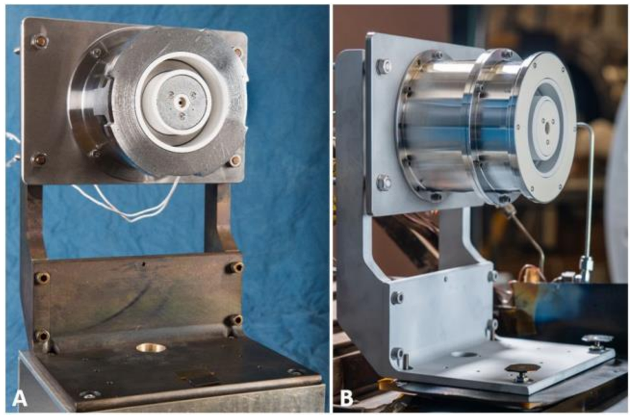
References:
[1] https://phasefour.io/maxwell/

Comm. avail.	TRL	Aerospace-tested
	4	NO

DISTRO A: Approved for public release. OTR-2024-00338

NASA SSEP H71M-PM/H71M-EM

Propulsion Technology	Hall thruster (integrated propulsion system)
Manufacturer/Country	NASA (USA)
TRL	3-4
Size (including PPU)	
Design satellite size	~180 kg (small sat), few hundred kg [1]
Isp (s)	>1700 s, ~50% efficiency [1]
Thrust type/magnitude	50 mN [1]
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	200 to 1000 W [1]
Flight heritage (if any)	None, although previous version H64M-LM reached TRL6 (was qualified but did not fly) [1]
Commercially available	NO
Last updated	07/2022



NASA H64M-LM HET and NASA H71-PM HET mounted on thrust stand adapter brackets prior to their first operational tests in a vacuum environment [1]

Parameter	Units	H64M	H71M
Total Propellant Throughput	kg	> 90	> 140
Total Impulse	MN-s	> 1	> 2.5
Lifetime	hours	> 10,000	> 14,000
On / Off	Cycles	> 5,000	> 8,000
Thruster Power Range	W	200 - 600	200 – 1,000
Thruster Voltage Range	V	200 - 300	200 - 400
Thrust Capability	mN	> 32	> 50
Specific Impulse Capability	s	> 1500	> 1700
Thruster Efficiency Capability	%	> 50	> 50
Thruster Mass	kg	< 2.5	< 3.5
PPU Input Voltage	V	24 – 34	24 - 34

Additional comments:

[Reference 1][July 2022][Thruster development]
The National Aeronautics and Space Administration (NASA) is maturing high-propellant throughput sub-kilowatt electric propulsion technologies to enable small spacecraft deep space science and exploration missions with high delta-v requirements. The pathfinder model (PM) propulsion system consists of the H71M-PM Hall-effect thruster, a breadboard 1-kW power processing unit (PPU), and a propellant flow control system. The propulsion system requirements balance the needs of various high delta-v NASA and commercial industry mission concepts to achieve a design that both enables a variety of NASA small spacecraft deep space missions, while remaining viable for select commercial applications. The H71M-PM thruster has completed performance characterization and three 500-h short duration wear tests (SDWT). The propulsion system provides stable thrust generation over a wide range of operating conditions from 200 W to 1 kW, and 200 V to 400 V. The thruster has demonstrated a thrust as high as 68 mN at 300 V and 1 kW. The thruster has similarly demonstrated a specific impulse of 1850 s at 400 V and 1 kW. Key surfaces were machined between each SDWT to simulate accelerated discharge channel and pole cover erosion. Profilometry scans across masked pole cover surfaces were conducted to determine erosion rates. SDWT results indicate that a target thruster lifetime of 14 kh with 50% margin is feasible, although further verification is needed. Component testing has demonstrated propellant azimuthal flow uniformity better than ± 2 percent of the nominal value, azimuthal magnetic field uniformity better than ± 0.5 percent of the nominal value, and cathode heater cycle testing to greater than 30,000 cycles. A second-generation breadboard PPU has been fabricated and is currently under test. Propulsion system integrated system testing is planned to use the H71M-PM and the breadboard 1-kW PPU. Pathfinder model test results are now supporting the design of the H71M-EM engineering model thruster. NASA has made these technologies available to U.S. industry through a no cost, nonexclusive licensing agreement.

References:
[1] Benavides, G., Kamhawi, H., Sarver-Verhey, T., Rhodes, C., Baird, M., Mackey, J., “High-propellant throughput sub-kw electric propulsion system for deep space science and exploration,” IEPC-2022-343.

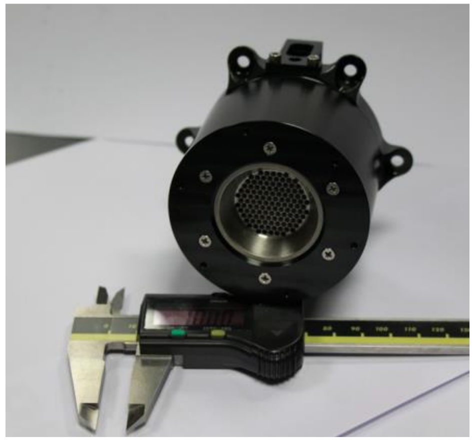
NO	4	NO
Comm. avail.	TRL	Aerospace-tested

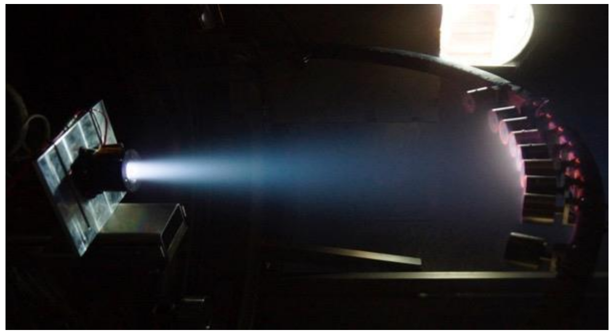
DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

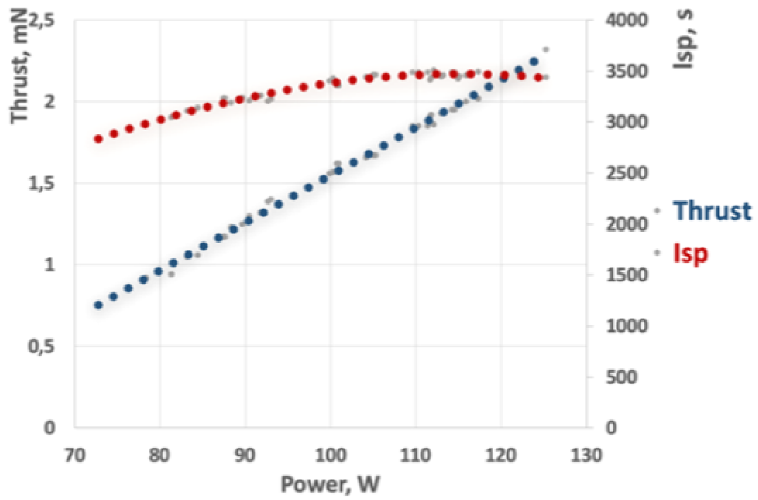
RIT 3.5

Propulsion Technology	RF ion
Manufacturer/Country	Mars Space Limited (UK)
TRL	Thruster is at TRL5, but system is likely at TRL ~3-4
Size (including PPU)	
Design satellite size	For CubeSats and smaller small sats
Isp (s)	~3500 s [1]
Thrust type/magnitude	1.5 mN at 100 W [1]
Delta-V (m/s)	
Propellant	Xenon, Krypton [1]
Power consumption (W)	10 to 120 W
Flight heritage (if any)	None
Commercially available	Unknown
Last updated	July 2022





RIT 3.5 EM miniaturized RF ion thruster and its operation in ESA ESTEC EPL facility, and operating envelope of the RIT 3.5 for the M-ARGO mission [1]



Additional comments:

[Reference 1][July 2022][Thruster information]
Mars Space Ltd (MSL) has recently acquired the design rights to the RIT3.5 engine, which is a miniaturized radio-frequency ion thruster that was originally developed at TransMIT GmbH up to TRL 5 through the development of an engineering model that was capable of operating in the thrust range of 50 µN to 2.5 mN at quantization of 0.2 µN. Thanks to the excellent performances, the RIT3.5 is ideally placed to support cubesat applications, as well as more complex and demanding scientific missions, such as NGGM. Thermal and mechanical models were both developed by Thales Alenia Space in Turin.
As mentioned above, MSL has recently acquired the rights to the design of the RIT3.5 and is currently leading an activity funded by ESA, for the development and qualification of a miniaturized ion thruster sub-assembly. The ultimate aim of this development contract is to reach TRL6 for the entire RIT3.5 sub-assembly (i.e. thruster and neutralizer, harness and pipework). In order to achieve TRL6 at sub-assembly level it will be necessary to reach at least TRL6 at unit level, and in addition to perform adequate testing and verification at sub-assembly level. To help support these activities, Mars Space are collaborating with the expertise from TransMIT, in particular for the thruster elements and interface with other EP subsystem elements, such as the RFG and PPU.

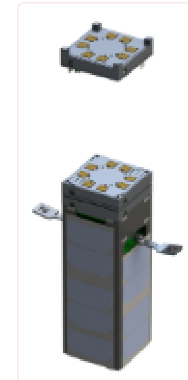
References:
[1] Guarducci, F., Marangone, D., Clark, S., Lewis, R., Gabriel, S., Smirnova, M., Mingo, A., “Development and industrialization of the RIT 3.5,” IEPC-2022-272.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

STEP-1 (Staged Electrospray Pathfinder-1)

Propulsion Technology	Electrospray
Manufacturer/Country	MIT (USA)
TRL	4
Size (including PPU)	~0.25U or smaller each panel
Design satellite size	CubeSat
Isp (s)	600s
Thrust type/magnitude	12 uN (each individual thruster head)
Delta-V (m/s)	
Propellant	EMI-CF3BF3 ionic liquid
Power consumption (W)	0.120W (each individual thruster head)
Flight heritage (if any)	None Projected to fly on STEP-1, tentative launch date 2023 [2]
Commercially available	No
Last updated	08/2022



Name	STEP-1 (Staged Electrospray Pathfinder 1)
Type	CubeSat
Units or mass	3U
Status	not launched, expected in 2023
Organisation	Massachusetts Institute of Technology
Institution	University
Entity	Academic / Education
Nation	US
Oneliner	Technology demonstration mission for the staged electrospray propulsion system.

[2]

Additional comments:

[Reference 1][Aug 2022][Thruster information]
Comparing the two propellants tested in detail, EMI-BF4 and EMI-CF3BF3, the results are very promising. The performance characterisation show that there is little difference between the selection in the tested configuration, where if anything the new option of EMI-CF3BF3 performs better. Simultaneously we show that this propellant does not absorb water, whereas EMI-BF4 takes on water at a troublesome rate. Therefore, STEP-1 (Staged Electrospray Pathfinder 1) is likely to proceed with EMI-CF3BF3.
The thrusters tested here produce around 12 micronewtons of thrust at a specific impulse of around 600 seconds, while only consuming 120 milliwatts of power

References:
[1] Pettersson, G., Bruno, A., Corrado, M., Medina, B., Krejci, D., Lozano, P., “Performance measurements and propellant testing for the STEP-1 CubeSat electrospray thrusters,” IEPC-2022-216.
[2] https://www.nanosats.eu/sat/step-1-mit

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Mission Extension Pod (MEP) Hall thruster

Propulsion Technology	Hall thruster
Manufacturer/Country	Northrop Grumman (USA) Tactical Space Systems Division (TSSD)
TRL	3
Size (including PPU)	
Design satellite size	Small Sat
Isp (s)	1600s [1]
Thrust type/magnitude	58 mN at 1000W [1]
Delta-V (m/s)	3000 m/s [1]
Propellant	Xenon
Power consumption (W)	1000W [1]
Flight heritage (if any)	None, projected to launched in 2024 onboard NGC's Mission Expension Pod.
Commercially available	No
Last updated	08/2022

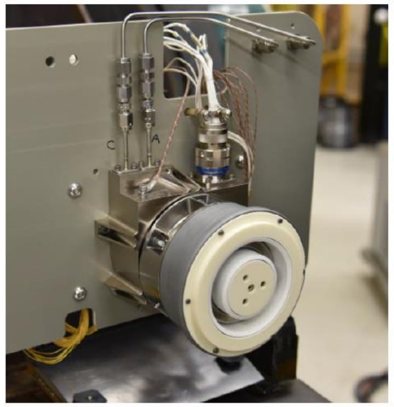


Figure 2. Engineering Model NGHT-1X.

Figure 3. NGHT-1X firing in NASA's VF-8 facility.

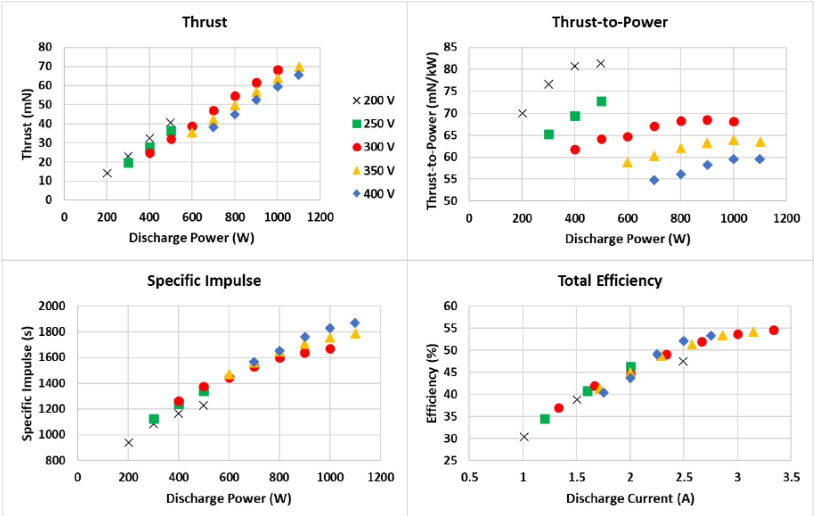


Figure 8. NGHT-1X performance, measured in NASA's VF-8 facility after a 500-hour wear test.

[1]

Additional comments:

[Reference 1][Aug 2022][Thruster information]
The qualification phase is on track to start toward the end of 2022 in support of first flight hardware delivery by the middle of 2023 and first flight of the MEP by the middle of 2024. Preliminary characterization of Northrop Grumman's NGHT-1X low power Hall thruster and associated hardware shows best-in-class performance and has demonstrated robust operation over a wide range of throttle points and environmental conditions. Once environmental qualification is complete in 2023, the NGHT-1X will define the state-of-the-art in flight-ready, commercially available Hall thrusters in the sub-kW power class, suitable for applications ranging from satellite servicing to deep space SmallSat missions. The first mission application of the NGHT-1X system will be onboard Northrop Grumman's Mission Extension Pod, which is slated for first launch in 2024, and several other applications are already under consideration in addition to the MEP.

References:
[1]Nikrant, A., Glogowski, M., Cochran, D., Moquin, T., Choi, Y., Benavides, G., Kamhawi, H., Sarver-Verhey, T., Baird, M., Rhodes, C., Mackey, J., "Overview and performance characterization of Northrop Grumman's 1 kW Hall thruster string," IEPC-2022-303.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

200W ECRA

Propulsion Technology	Microwave ECR
Manufacturer/Country	ONERA (FRA), Justus Liebig University (DEU)
TRL	4
Size (including PPU)	
Design satellite size	Small sat
Isp (s)	1820 at 220W [1] (multiple operating modes are possible)
Thrust type/magnitude	7 mN at 220W [1] (multiple operating modes are possible)
Delta-V (m/s)	
Propellant	Xenon [1]
Power consumption (W)	200W [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	08/2022

Fig. 1 (left) ECRA thruster geometry, (center) picture of a 30 W ECRA thruster, (right) operating ERCA thruster

[1]

Operation set point	Q_m [sccm]	Power [W]	Thrust [mN]	I_{sp} [s]	TTPR [mN/kW]	Thruster efficiency (%)
High thrust	4.1	221	**7.15**	1821	32.4	28.9
High Isp	2.5	245	6.93	**2879**	28.3	40.0
High TTPR	2	38	2.47	1289	**65.6**	41.5
High efficiency	2	85	4.19	2190	49.6	**53.3**
Intermediate	2.5	146	**5.56**	**2310**	**38.1**	**43.2**

Additional comments:
[Reference 1][Aug 2022][Thruster information]
The ECRA thruster is a magnetic nozzle electron cyclotron resonance thruster developed at ONERA. Microwave (MW) at 2.45 GHz are injected using a coaxial line that terminates in an opened coaxial cavity. The propellant is injected in this cavity and is ionized by the MW power. This cavity is limited radially by the outer conductor which is 27.5 mm diameter in the 30 W ECRA case and 70 mm in the 200 W ECRA case. To terminate the cavity a backplate transparent to MW is positioned at the back of the source. The magnetic nozzle is generated by an annular permanent magnet located at the back of the cavity. The permanent magnet is positioned such that the electron cyclotron resonance (ECR) at 2.45 GHz is located inside the cavity. During this study, only Xenon has been used as propellant gas but other gas such Krypton, Argon, Iodine, Oxygen, Air, Nitrogen, etc… could be used as no component of the thruster is sensitive to oxidation.
During the H2020 MINITOR project the ECRA thruster developed at ONERA have been optimized in order to increase its performances. A second thruster working at 200 W has been developed from the first prototype operating at 30 W. The optimization of the thrusters allowed to improve considerably the thruster performances while measured in similar test conditions, and obtain total thrust efficiencies as high as 50 %. The effect of going from the B61 chamber to the Jumbo chamber is critical. It can be explained partially by the better background pressure but not completely. Experiments where the background pressure is artificially increased in Jumbo to meet the B61 conditions demonstrated that there is a chamber dependent effect. It is believed that the size of the vacuum chamber plays a role but it has not been demonstrated. Further work may focus on performing experiments in another high pumping rate facility and try to distinguish pumping speed to other facility effects. Lastly, the erosion and stability test demonstrates that the thruster lifetime of the 200 W thruster can be estimated to be over 1,000 hours. The thruster showed very stable operation during 100 hours.

References:
[1] Desangles, V., Packan, D., Jarrige, J., Peterschmit, S., Dietz, P., Scharmann, S., Holste, K., Klar, P., “ECRA thruster advances, 30W and 200W prototypes latest performances,” IEPC-2022-513.

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

30W ECRA

Propulsion Technology	Microwave ECR
Manufacturer/Country	ONERA (FRA), Justus Liebig University (DEU)
TRL	4
Size (including PPU)	
Design satellite size	Small sat
Isp (s)	1580s at 25W [1] (multiple operating modes are possible)
Thrust type/magnitude	1.5mN at 25W [1] (multiple operating modes are possible)
Delta-V (m/s)	
Propellant	Xenon [1]
Power consumption (W)	30W [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	08/2022

[1]

Fig. 1 (left) ECRA thruster geometry, (center) picture of a 30 W ECRA thruster, (right) operating ERCA thruster

Operation set point	Q_m [sccm]	Power [W]	Thrust [mN]	I_{sp} [s]	TTPR [mN/kW]	Thruster efficiency (%)
Initial Performances	1.0	24	**0.8**	**840**	**33**	**13**
Final Performances	1.0	25	**1.5**	**1580**	**60**	**44**
High thrust	1.2	50	**2.0**	1800	40	35
High Isp	0.6	45	1.4	**2500**	31	40
High TTPR	1.0	17.5	1.1	1200	**65**	40
High efficiency	0.8	35	1.6	2200	46	**50**

Additional comments:
[Reference 1][Aug 2022][Thruster information]
The ECRA thruster is a magnetic nozzle electron cyclotron resonance thruster developed at ONERA. Microwave (MW) at 2.45 GHz are injected using a coaxial line that terminates in an opened coaxial cavity. The propellant is injected in this cavity and is ionized by the MW power. This cavity is limited radially by the outer conductor which is 27.5 mm diameter in the 30 W ECRA case and 70 mm in the 200 W ECRA case. To terminate the cavity a backplate transparent to MW is positioned at the back of the source. The magnetic nozzle is generated by an annular permanent magnet located at the back of the cavity. The permanent magnet is positioned such that the electron cyclotron resonance (ECR) at 2.45 GHz is located inside the cavity. During this study, only Xenon has been used as propellant gas but other gas such Krypton, Argon, Iodine, Oxygen, Air, Nitrogen, etc… could be used as no component of the thruster is sensitive to oxidation.
During the H2020 MINITOR project the ECRA thruster developed at ONERA have been optimized in order to increase its performances. A second thruster working at 200 W has been developed from the first prototype operating at 30 W. The optimization of the thrusters allowed to improve considerably the thruster performances while measured in similar test conditions, and obtain total thrust efficiencies as high as 50 %. The effect of going from the B61 chamber to the Jumbo chamber is critical. It can be explained partially by the better background pressure but not completely. Experiments where the background pressure is artificially increased in Jumbo to meet the B61 conditions demonstrated that there is a chamber dependent effect. It is believed that the size of the vacuum chamber plays a role but it has not been demonstrated. Further work may focus on performing experiments in another high pumping rate facility and try to distinguish pumping speed to other facility effects. Lastly, the erosion and stability test demonstrates that the thruster lifetime of the 200 W thruster can be estimated to be over 1,000 hours. The thruster showed very stable operation during 100 hours.

References:
[1] Desangles, V., Packan, D., Jarrige, J., Peterschmit, S., Dietz, P., Scharmann, S., Holste, K., Klar, P., “ECRA thruster advances, 30W and 200W prototypes latest performances,” IEPC-2022-513.

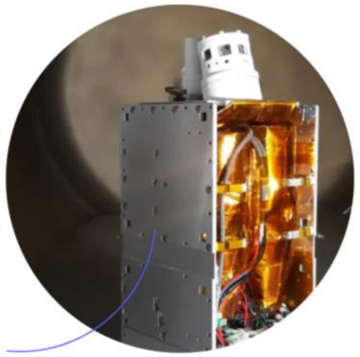
NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Spaceware-mini (previously ExoMG-mini)

Propulsion Technology	Hall thruster
Manufacturer/Country	Exotrail (France)
TRL	4-5 (estimated similar to –micro model)
Size (including PPU)	
Design satellite size	Small satellite
Isp (s)	Not specified but estimated at 1200s, similar to micro
Thrust type/magnitude	Xenon 15 to 30 mN, 23 mN nominal [1] Krypton 12 to 24 mN, 18 mN nominal [1] Total impulse up to 300 kN*s [1]
Delta-V (m/s)	
Propellant	Xenon, Krypton, Iodine (although no performance specifications are given for iodine) [1]
Power consumption (W)	400W, nominal
Flight heritage (if any)	None Slated for Starfish Space's Otter Pup satellite (launched projected for summer 2023) – unclear exactly which hall thruster model [2]
Commercially available	Yes
Last updated	04/2023

	spaceware™ *mini*	spaceware™ *mini cluster²*
Power Nominal - (range)	400W (300-600 W)	800 W (300-1200 W)
Thrust Nominal - (range)	18 mN (Kr) - (12 - 24mN) 23mN (Xe) - (15 - 30mN)	36 mN (Kr) - (12 – 48mN) 46mN (Xe) - (15 - 60mN)
Total impulse	Up to 300 kN.s	Up to 600 kN.s
Propellant Compatibility	Krypton / Xenon / Iodine	Krypton / Xenon / Iodine



[1]

Additional comments:
[Reference 1][Oct 2022][Thruster information]
See other models (-nano, -micro) for thruster technical information.
Airbus and Exotrail have signed an agreement for the integration of spaceware™ – mini thruster (formerly known as ExoMG™ – mini), Exotrail's new 300 to 600W class electric propulsion system, as part of Airbus' Earth Observation (EO) satellite platform portfolio. The agreement contemplates the purchase and delivery of the 300W thruster version at completion of qualification activities in 2024 following a fast-paced new product development. spaceware™ – mini will significantly enlarge Exotrail's spaceware TM electric propulsion systems portfolio in the commercial and institutional markets for mid-size satellites. Exotrail will ensure the compatibility of its 300W class thruster with Airbus' platforms, providing then Airbus with a new European source for Hall Effect propulsion thruster.

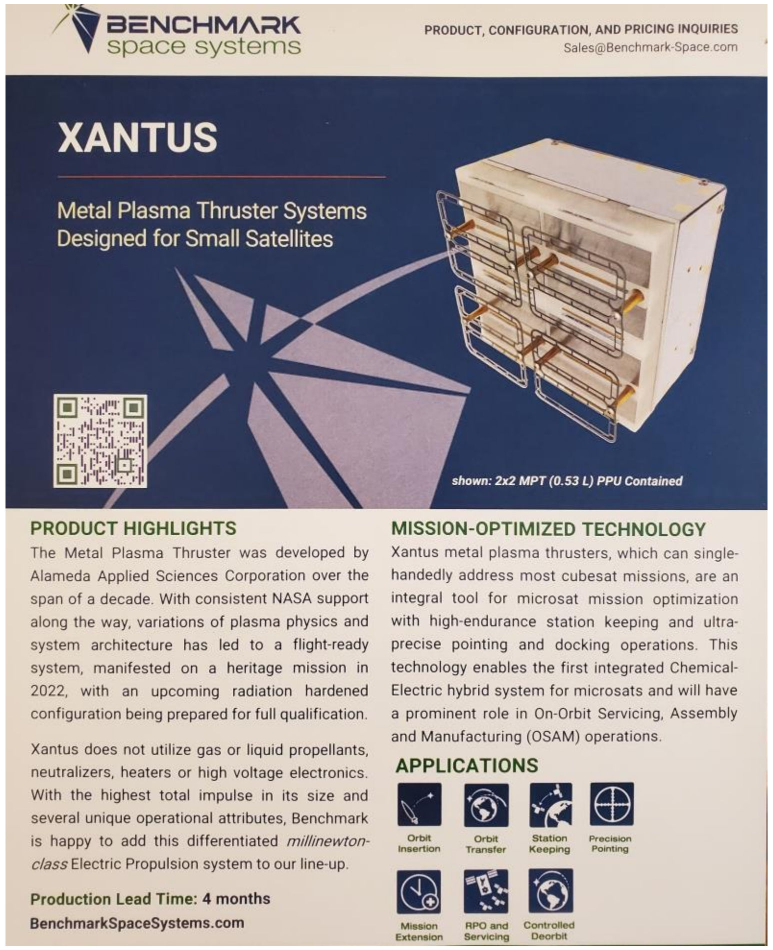
References:
[1] https://smallsatnews.com/2022/09/22/exotrail-airbus-partner-together-on-the-implementation-of-propulsion-for-eo-smallsats/
[2] https://smallsatnews.com/2023/02/07/starfish-space-to-perform-leo-satellite-docking-using-electric-propulsion/

Comm. avail.	4	NO
	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Xantus metal plasma thruster

Propulsion Technology	Metal PPT
Manufacturer/Country	Benchmark (USA) in collaboration with Alameda Applied Sciences Corporation (USA)
TRL	4
Size (including PPU)	<1U
Design satellite size	3U and
Isp (s)	1800s [1]
Thrust type/magnitude	Total impulse 5000 N*s, no values provided by average thrust
Delta-V (m/s)	
Propellant	Molybdenum
Power consumption (W)	0W standby power, 1 to 100W operational power
Flight heritage (if any)	None Launched on Jan 2023 USSF RROCI Demo missions, was not deployed. [2] Manifested on 2024 USSF EWS mission. [2]
Commercially available	Yes Manufacturer quotes 4 month lead time [1]
Last updated	12/2023


BENCHMARK space systems

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XANTUS

Metal Plasma Thruster Systems Designed for Small Satellites

shown: 2x2 MPT (0.53 L) PPU Contained

PRODUCT HIGHLIGHTS

The Metal Plasma Thruster was developed by Alameda Applied Sciences Corporation over the span of a decade. With consistent NASA support along the way, variations of plasma physics and system architecture has led to a flight-ready system, manifested on a heritage mission in 2022, with an upcoming radiation hardened configuration being prepared for full qualification.

Xantus does not utilize gas or liquid propellants, neutralizers, heaters or high voltage electronics. With the highest total impulse in its size and several unique operational attributes, Benchmark is happy to add this differentiated *millinewton-class* Electric Propulsion system to our line-up.

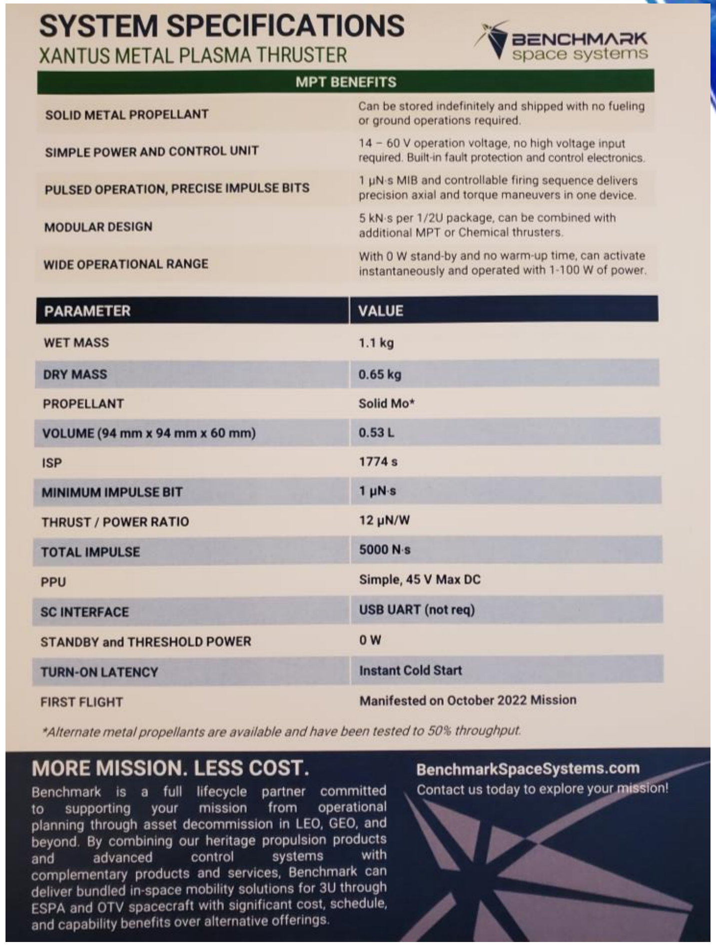
Production Lead Time: 4 months
BenchmarkSpaceSystems.com

MISSION-OPTIMIZED TECHNOLOGY

Xantus metal plasma thrusters, which can single-handedly address most cubesat missions, are an integral tool for microsat mission optimization with high-endurance station keeping and ultra-precise pointing and docking operations. This technology enables the first integrated Chemical-Electric hybrid system for microsats and will have a prominent role in On-Orbit Servicing, Assembly and Manufacturing (OSAM) operations.

APPLICATIONS

Orbit Insertion · Orbit Transfer · Station Keeping · Precision Pointing · Mission Extension · RPO and Servicing · Controlled Deorbit


SYSTEM SPECIFICATIONS
XANTUS METAL PLASMA THRUSTER

BENCHMARK space systems

MPT BENEFITS	
SOLID METAL PROPELLANT	Can be stored indefinitely and shipped with no fueling or ground operations required.
SIMPLE POWER AND CONTROL UNIT	14 – 60 V operation voltage, no high voltage input required. Built-in fault protection and control electronics.
PULSED OPERATION, PRECISE IMPULSE BITS	1 μN·s MIB and controllable firing sequence delivers precision axial and torque maneuvers in one device.
MODULAR DESIGN	5 kN·s per 1/2U package, can be combined with additional MPT or Chemical thrusters.
WIDE OPERATIONAL RANGE	With 0 W stand-by and no warm-up time, can activate instantaneously and operated with 1-100 W of power.

PARAMETER	VALUE
WET MASS	1.1 kg
DRY MASS	0.65 kg
PROPELLANT	Solid Mo*
VOLUME (94 mm x 94 mm x 60 mm)	0.53 L
ISP	1774 s
MINIMUM IMPULSE BIT	1 μN·s
THRUST / POWER RATIO	12 μN/W
TOTAL IMPULSE	5000 N·s
PPU	Simple, 45 V Max DC
SC INTERFACE	USB UART (not req)
STANDBY and THRESHOLD POWER	0 W
TURN-ON LATENCY	Instant Cold Start
FIRST FLIGHT	Manifested on October 2022 Mission

Alternate metal propellants are available and have been tested to 50% throughput.

MORE MISSION. LESS COST.

Benchmark is a full lifecycle partner committed to supporting your mission from operational planning through asset decommission in LEO, GEO, and beyond. By combining our heritage propulsion products and advanced control systems with complementary products and services, Benchmark can deliver bundled in-space mobility solutions for 3U through ESPA and OTV spacecraft with significant cost, schedule, and capability benefits over alternative offerings.

BenchmarkSpaceSystems.com
Contact us today to explore your mission!

[1]

Additional comments:

[Reference 1][Feb 2023][General information]
The metal plasma thruster was developed by Alameda Applied Sciences Corporation over the span of a decade with NASA support.

References:
[1] Flyer distributed at SmallSat Symposium Feb 2023
[2] Flyer distributed at SmallSat Logan Aug 2023.

	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Neumann Drive ND-50 (Gen2)

Propulsion Technology	Metal PPT
Manufacturer/Country	Neumann Space Australia (AUS)
TRL	4
Size (including PPU)	~1U
Design satellite size	3U+
Isp (s)	Molybdenum ~1800s [4]
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Molybdenum
Power consumption (W)	
Flight heritage (if any)	
Commercially available	Yes
Last updated	04/2023

[3]

Additional comments:
[References 1-3][April 2023][General information]
Neumann Space is working with partners at CisLunar Industries to demonstrate that debris can be economically recycled on-orbit, turned into propellant for our thrusters, and then used to move debris around – either by putting it into a space disposal orbit where it rapidly and safely falls to an altitude where it can safely burn up during re-entry, or delivering the debris to an orbital recycling centre for further processing.
The Neumann Drive uses our patented Centre-Triggered Pulsed Cathodic Arc Thruster (CTPCAT) technology to convert a solid conductive fuel rod into plasma and produce thrust. The system can use a range of conductive fuels giving unprecedented control over propulsion performance.
This marks the first time the Neumann Drive®, whose unique propulsion technology uses solid metallic propellant, has been integrated onto a satellite. The satellite is now undergoing final testing before being shipped to the U.S. for a scheduled launch in mid-2023.

References:
[1] https://neumannspace.com/
[2] https://smallsatnews.com/2023/03/14/neumann-drive-propulsion-system-now-integrated-onto-australias-skykraft-satellite-2/
[3] https://smallsatnews.com/2023/03/02/australian-space-companies-achieve-critical-propulsion-technology-commercialization-milestone/

	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Subliming solid microthruster

Propulsion Technology	Cold gas (sublimating solid propellant)
Manufacturer/Country	JPL (USA)
TRL	4-5
Size (including PPU)	Very small (~1 inch x 1 inch x 1 inch) [1]
Design satellite size	Small satellite or CubeSat
Isp (s)	~60 s [1]
Thrust type/magnitude	~ 1 mN [1]
Delta-V (m/s)	
Propellant	Ammonium hydrosulfide [1]
Power consumption (W)	Extremely low power (likely less than 1 W)
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023

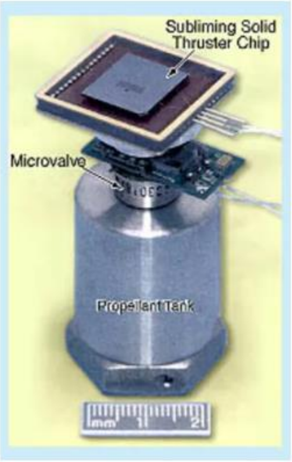
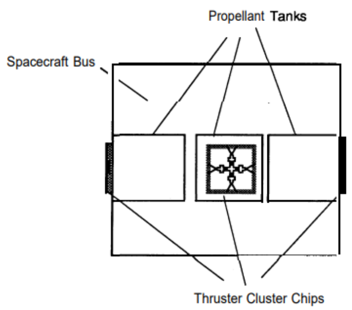


Figure 2. Microthruster Model shows the level of miniaturization that can replace bulkier units.



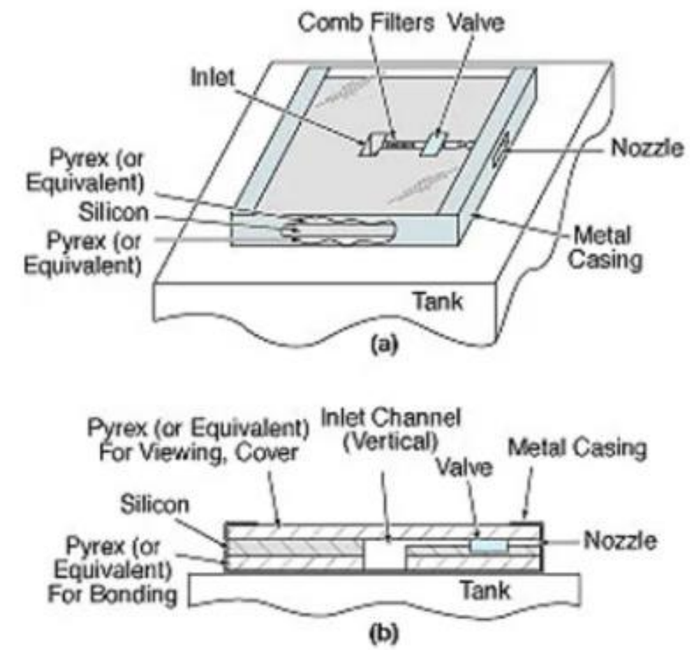


Figure 1. The Concept of the Subliming Solid Microthruster is illustrated in oblique view (a) and side view (b).

Additional comments:

[References 1 and 2][December 2023][General information]
The propellant in a subliming thruster would be contained in an aluminum tank (see Figure 1) with an outlet connected to the subliming solid microthruster chip. This chip, micromachined from silicon, contains a nozzle and an integrated filter. Ultimately, a thruster valve will also be integrated into this chip. A wire electric heater could be wrapped around the tank, or else a film electric heater could be deposited on the tank. The propellant material (e.g., ammonium hydrosulfide) would be sublimed on command by activating the heater. Opening a valve placed into a flowpath between the nozzle and tank will allow the vapor to flow to whichever nozzle faced in the direction opposite the required direction of thrust. The wall of the tank could be as thin as 0.020 in. (0.5 mm) because the vapor pressure that it would have to withstand would be very small; thus, the tank could be very light in weight.

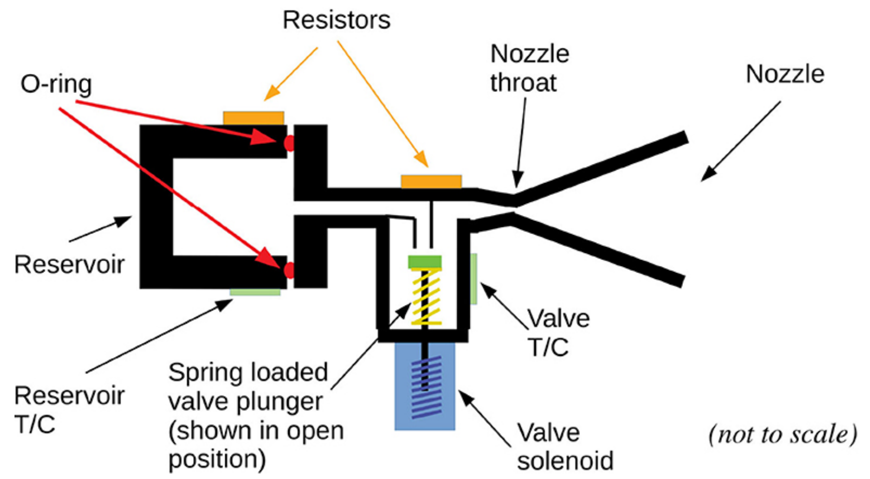
References:
[1] George, T., Mueller, J., Muller, L., "Subliming solid microthruster," NASA Technical Support Package, 1998. https://www.techbriefs.com/component/content/article/32042-npo19926
[2] Frisbee, R., "Advanced space propulsion for the 21st century," Journal of Propulsion and power, 2003. https://users.encs.concordia.ca/~hoing/Teaching/MECH6251/advanced.pdf

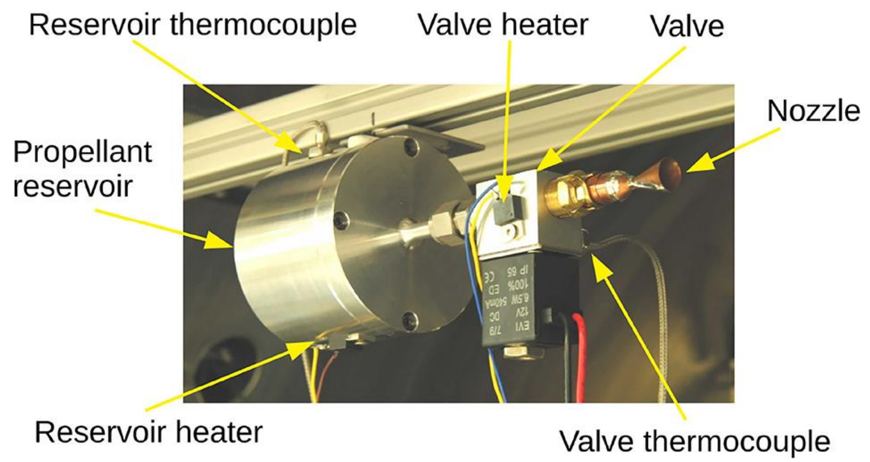
NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Napthalene subliming solid microthruster

Propulsion Technology	Cold gas (sublimating solid propellant)
Manufacturer/Country	Australian National University (Australia)
TRL	4
Size (including PPU)	Approximately 1U, although could be optimized further
Design satellite size	Small satellite/CubeSat
Isp (s)	25s [1]
Thrust type/magnitude	~800 uN [1]
Delta-V (m/s)	
Propellant	Napthalene
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023





Additional comments:

[References 1 and 2][Dec 2023][General information]
Thrust was measured with very nice square-wave like structures and a max of ~800 uN. 10 g of propellant were contained in the reservoir. Performance measured at several different reservoir temperatures between 50C and 70C. Isp was measured/calculated at ~25s.
The authors recognized that optimization of the system would be necessary moving forward, especially to optimize the heat transfer to the reservoir.

References:
[1] Tsifakis, D., Charles, C., Boswell, R., "Napthalene as a cubesat cold gas thruster propellant," Frontiers in physics, 2020. https://www.frontiersin.org/articles/10.3389/fphy.2020.00389/full
[2] https://www.abc.net.au/news/2021-12-09/moth-ball-technology-propels-satellites-into-space/100683662

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Sublimating-solid micro-propulsion system

Propulsion Technology	Cold gas (sublimating solid propellant)
Manufacturer/Country	NASA (USA)
TRL	4
Size (including PPU)	~1U (not optimized)
Design satellite size	Small satellite or CubeSat
Isp (s)	83 s [1]
Thrust type/magnitude	300 mN [1]
Delta-V (m/s)	
Propellant	Ammonium hydrogen sulfide (NH4HS) [1]
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023

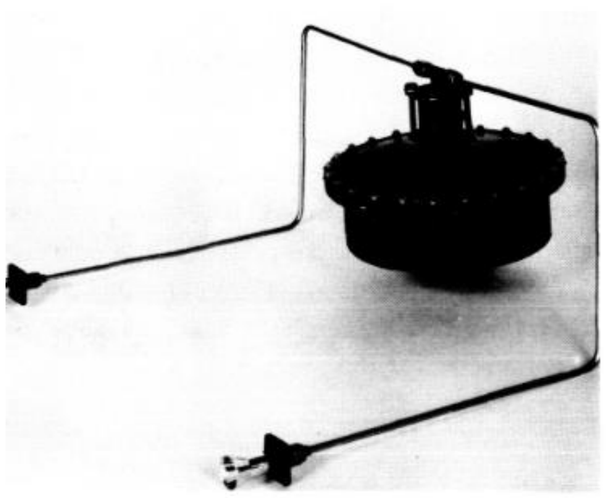


Figure 1—Assembled sublimating-solid micropropulsion system.

Table 1

System Specifications.

Parameter	Specification
Total Thrust (2 nozzles)	5 x 10^{-2} lbf (nominal)
Specific Impulse	83 lbf-sec/lbm (theoretical)
Inlet Nozzle Pressure	1.80 psia (nominal)
Tank Pressure	6.35 psia (nominal)
Total Mass Flow	6.04 x 10^{-2} lbm/sec (nominal)
Thrust Coefficient	1.80 (theoretical)
Throat Area	7.85 x 10^{-3} in^2
Area Ratio	40

Additional comments:

[References 1][Dec 2023][General information]
NH4HS has a vapor pressure of ~390 torr at room temperature
Hardware design: (This was strictly a lab-model and was not packaged for flight)

An integrating micro-thrust balance was utilized to evaluate the impulse and thrust performance characteristics of a rocket system which employs a new concept for propulsion; that is, it effects a controlled thrust from the sublimation of a solid propellant. The propulsion package tested was designed to provide thrust in a control system of a spin stabilized satellite.

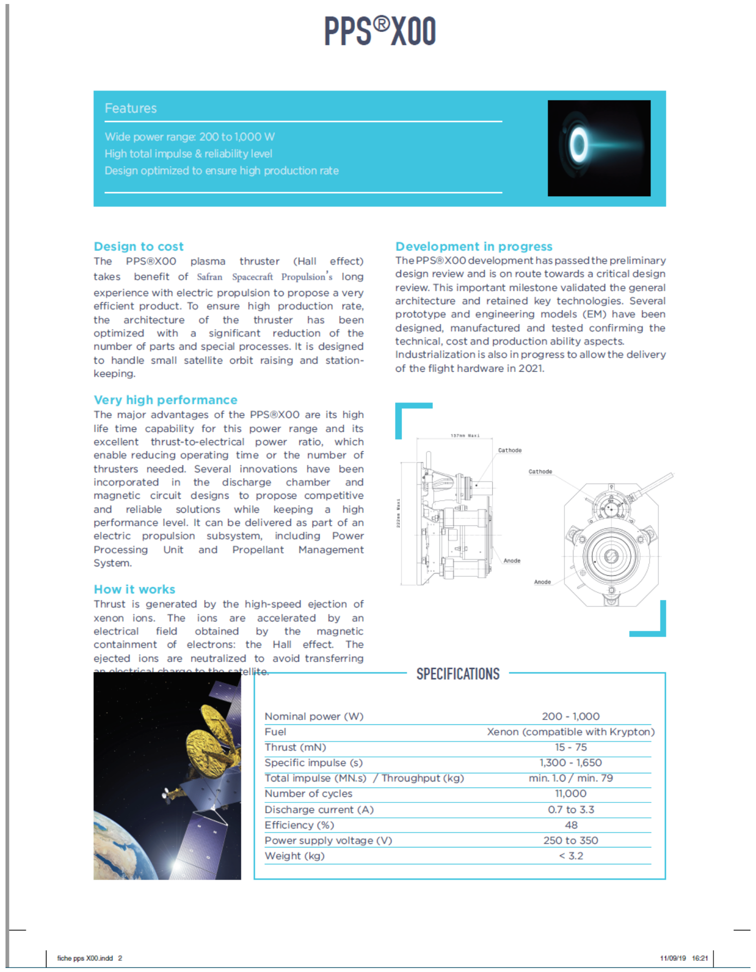
References:
[1] Forsythe, R., "Impulse and thrust test of a sublimating-solid micropropulsion system," NASA report, 1966. https://core.ac.uk/reader/80674900

NO	4	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

PPS-X00 (PPSX00, PPS X00)

Propulsion Technology	Hall thruster
Manufacturer/Country	Safran (France)
TRL	4
Size (including PPU)	<3.2 kg [1]
Design satellite size	Small Sat
Isp (s)	1300 to 1650 s [1]
Thrust type/magnitude	15 to 75 mN [1]
Delta-V (m/s)	
Propellant	Xenon and Krypton
Power consumption (W)	200 to 1000W [1]
Flight heritage (if any)	None known
Commercially available	Yes
Last updated	12/2023


PPS®X00

Features

Wide power range: 200 to 1,000 W
High total impulse & reliability level
Design optimized to ensure high production rate

Design to cost

The PPS®X00 plasma thruster (Hall effect) takes benefit of Safran Spacecraft Propulsion's long experience with electric propulsion to propose a very efficient product. To ensure high production rate, the architecture of the thruster has been optimized with a significant reduction of the number of parts and special processes. It is designed to handle small satellite orbit raising and station-keeping.

Very high performance

The major advantages of the PPS®X00 are its high life time capability for this power range and its excellent thrust-to-electrical power ratio, which enable reducing operating time or the number of thrusters needed. Several innovations have been incorporated in the discharge chamber and magnetic circuit designs to propose competitive and reliable solutions while keeping a high performance level. It can be delivered as part of an electric propulsion subsystem, including Power Processing Unit and Propellant Management System.

How it works

Thrust is generated by the high-speed ejection of xenon ions. The ions are accelerated by an electrical field obtained by the magnetic containment of electrons: the Hall effect. The ejected ions are neutralized to avoid transferring an electrical charge to the satellite.

Development in progress

The PPS®X00 development has passed the preliminary design review and is on route towards a critical design review. This important milestone validated the general architecture and retained key technologies. Several prototype and engineering models (EM) have been designed, manufactured and tested confirming the technical, cost and production ability aspects. Industrialization is also in progress to allow the delivery of the flight hardware in 2021.

SPECIFICATIONS

Nominal power (W)	200 - 1,000
Fuel	Xenon (compatible with Krypton)
Thrust (mN)	15 - 75
Specific impulse (s)	1,300 - 1,650
Total impulse (MN.s) / Throughput (kg)	min. 1.0 / min. 79
Number of cycles	11,000
Discharge current (A)	0.7 to 3.3
Efficiency (%)	48
Power supply voltage (V)	250 to 350
Weight (kg)	< 3.2

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Additional comments:

[References 1][Dec 2023][General information]
The PPS®X00 development has passed the preliminary design review and is on route towards a critical design review. This important milestone validated the general architecture and retained key technologies. Several prototype and engineering models (EM) have been designed, manufactured and tested confirming the technical, cost and production ability aspects. Industrialization is also in progress to allow the delivery of the flight hardware in 2021.

References:

[1] https://www.safran-group.com/products-services/ppsrx00-stationary-plasma-thruster

4

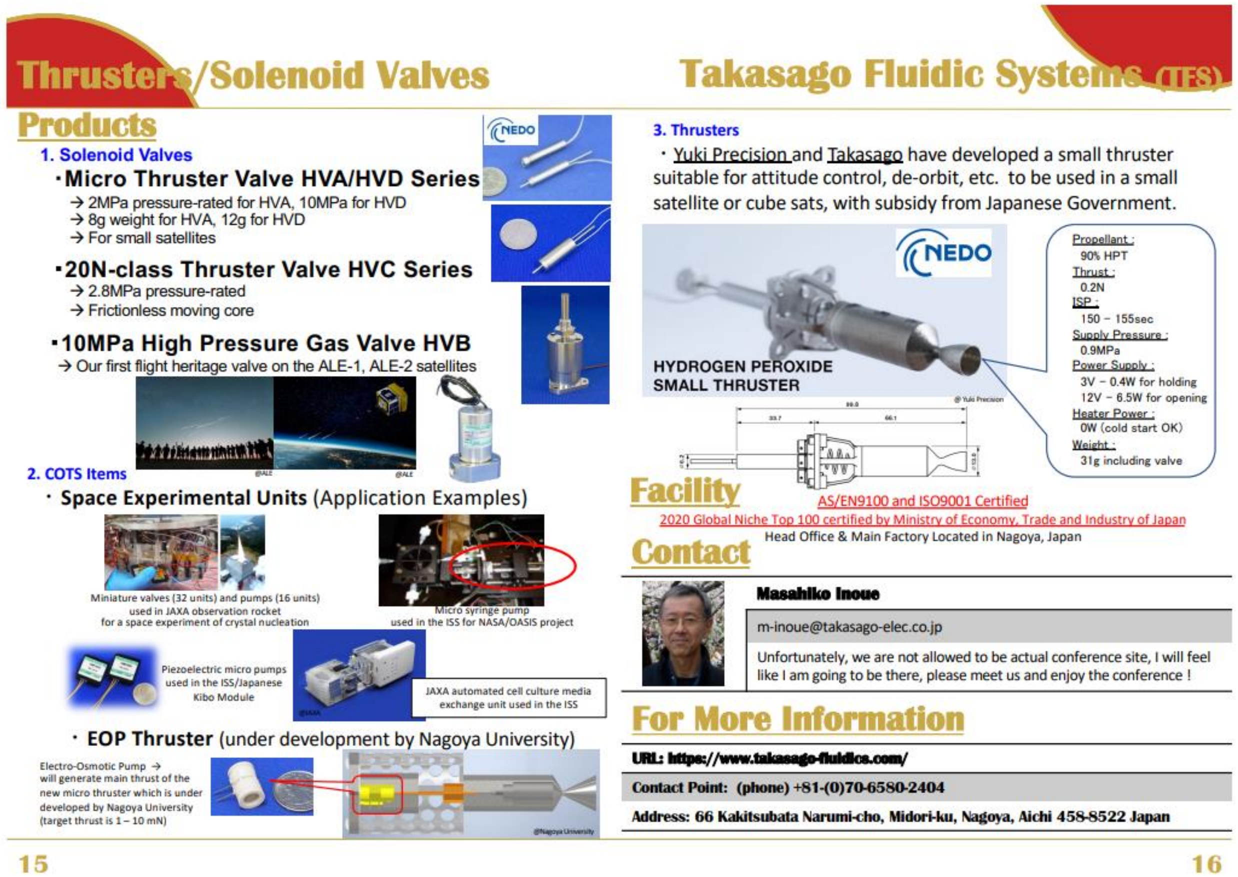
NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Yuki Peroxide monoprop thruster

Propulsion Technology	Monopropellant (H2O2)
Manufacturer/Country	Yuki Precision/Takasago (JAPAN)
TRL	4
Size (including PPU)	31 g including valve [1]
Design satellite size	Small satellites (down to CubeSats)
Isp (s)	155 s [1]
Thrust type/magnitude	0.2N (can be scaled up to 1N) [1]
Delta-V (m/s)	
Propellant	H2O2 (90% HTP)
Power consumption (W)	0.4W (standby), 6.5W (operating) Cold starts are ok (0W possible) [1]
Flight heritage (if any)	None
Commercially available	Yes
Last updated	12/2023



Additional comments:

[References 1][Dec 2023][General information]
Yuki Precision and Takasago have developed a small thruster suitable for attitude control, de-orbit, etc. to be used in a small satellite or cube sats, with subsidy from Japanese Government.
Contact Masahiko Inoue (m-inoue@takasago-elec.co.jp) or Yukiko Matsumoto (Yukiko.Matsumoto@yukiseimitsu.co.jp)

References:
[1] https://www.jspacesystems.or.jp/ICD/SmallSat/Leaflet20210617.pdf
[2] https://www.yukiseimitsu.co.jp/information/news/14518/

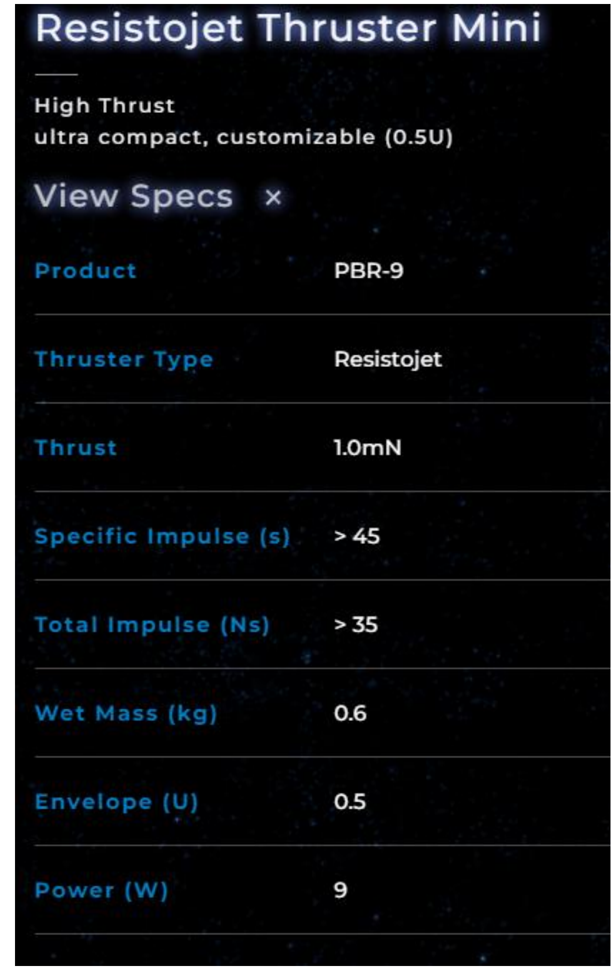
4

NO

Comm. avail. TRL Aerospace-tested

Pale Blue Water Resistojet (Mini)

Propulsion Technology	Water resistojet
Manufacturer/Country	Pale Blue (JPN)
TRL	~3
Size (including PPU)	0.5U
Design satellite size	1U and above
Isp (s)	>45
Thrust type/magnitude	1 mN
Delta-V (m/s)	
Propellant	water
Power consumption (W)	9W
Flight heritage (if any)	None
Commercially available	YES
Last updated	09/2023



[1]

Additional comments:

[Reference 2][September 2023][General information]
Pale Blue was founded in 2020. According to their website:
“Our thrusters are powered by water plasma that is generated via Electron Cyclotron Resonance (ECR) and is the culmination of decades of research by JAXA and the University of Tokyo. Pale Blue has successfully miniturized this plasma-generation method so that it can flexibly meet the propulsion needs of a wide range of satellites, even cubesats. Spacecraft manufacturers and operators can now capture all of the benefits of water without the steep performance tradeoffs that historically made water-based propulsion unviable for space propulsion.”

[Reference 3][September 2023][General information]
Pale Blue has been awarded a new contract with Yonsei University in South Korea to provide the Resistojet (0.5U sized water vapor) propulsion system for a pair of 6U satellites. The propulsion system will be used to do formation flying for a laser crosslink system between the two smallsats in LEO as well as conduct optical communications. The laser crosslink payload employs a deployable, optical telescope to compensate for the compact bus capability of a typical CubeSat platform. With this novel design, a stable communication link can be achieved at a distance of up to 1000 km. The proposed data rate is at least 1 Gbps., which is a challenging objective given the efficient and low cost nature of the systems.

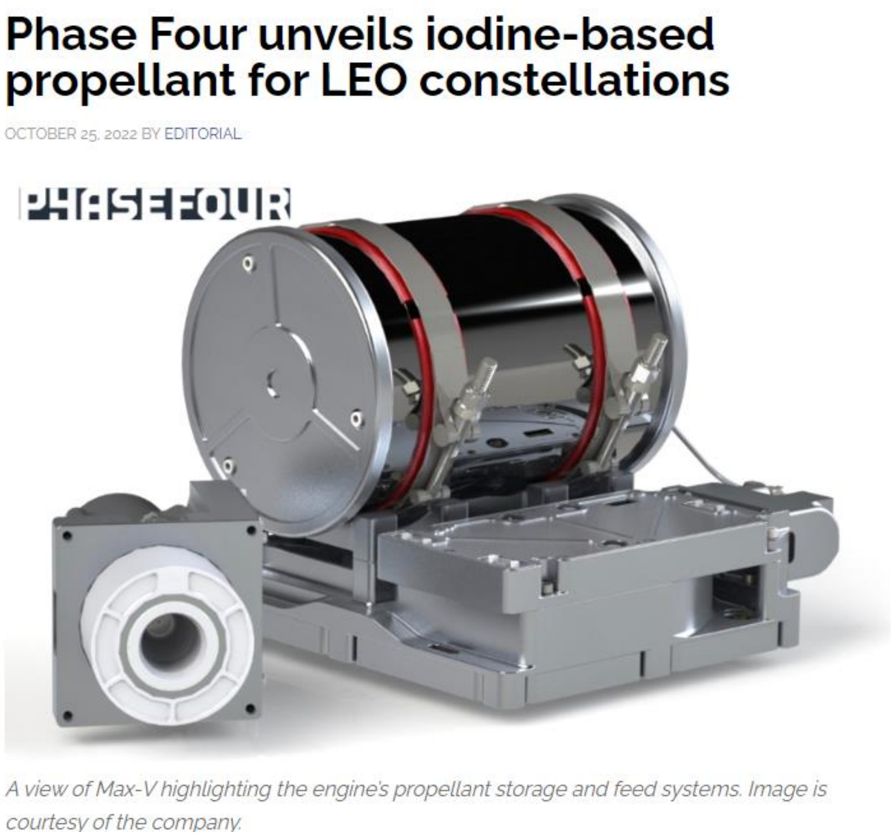
References:
[1] https://pale-blue.co.jp/product/
[3] https://smallsatnews.com/2023/08/07/pale-blue-to-supply-water-based-propulsion-systems/

Comm. avail.	TRL	Aerospace-tested
	3	NO

DISTRO A: Approved for public release. OTR-2024-00338

Max-V

Propulsion Technology	RF thruster
Manufacturer/Country	Phase Four (USA)
TRL	3
Size (including PPU)	
Design satellite size	Small Satellite
Isp (s)	1200 s [1]
Thrust type/magnitude	50 mN thrust, >100 kN*s total impulse [1]
Delta-V (m/s)	
Propellant	Iodine
Power consumption (W)	200 W to 1.5 kW [1]
Flight heritage (if any)	None
Commercially available	Not yet, available to order second half of 2023 [1]
Last updated	11/2022



[1]

Additional comments:

[Reference 1][Nov 2022][Thruster information]
Phase Four, the creator of the radio-frequency thruster for satellite propulsion, will expand its Maxwell turn-key, plasma propulsion line and offer satellite manufacturers a high performance engine using an inexpensive, domestically sourced iodine-based propellant — Max-V leverages the Maxwell Block 2 engine's architecture and builds on the radio-frequency thruster's propellant agnostic capabilities.

References:
[1] https://smallsatnews.com/2022/10/25/phase-four-unveils-iodine-based-propellant-for-leo-constellations/

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

SPT-30 Hall thruster

Propulsion Technology	Hall effect thruster
Manufacturer/Country	Research Institute of Applied Mechanics and Electrodynamics of Moscow Aviation Institute (RIAME)
TRL	3-4
Size (including PPU)	
Design satellite size	
Isp (s)	1170s
Thrust type/magnitude	11 mN
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	200W
Flight heritage (if any)	None known
Commercially available	NO
Last updated	03/2021

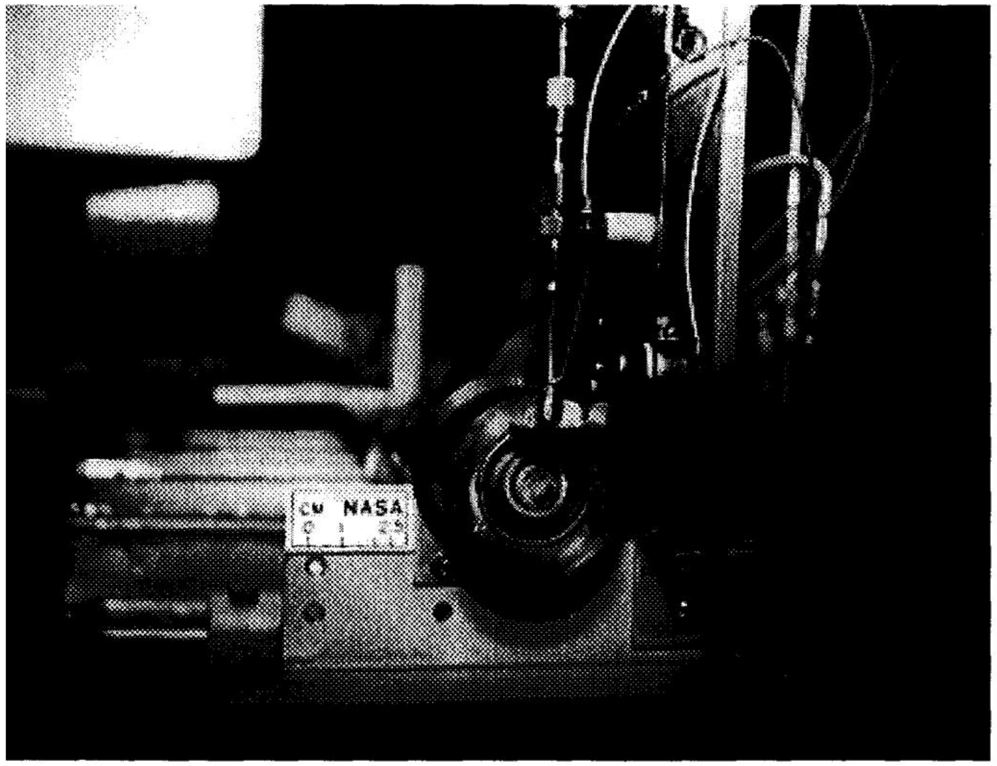


Figure 1. SPT-30 on thrust stand in vacuum facility 8 at NASA Lewis Research Center.

Additional comments:

[Reference 1][March 2021][Thruster ground testing]
The performance of the SPT-30, a 200W class hall thruster was evaluated. Performance measurements were taken at power levels between 90 and 250W. At the nominal 200W design point, the measured thrust was 11.3 mN, and the specific impulse was 1170s excluding cathode flow in the calculation.

This testing was done at NASA.

References:
[1] Jacobson, D., Jankovsky, R., "Test results of a 200W class hall thruster," AIAA-98-3792, 34th AIAA JPC, 1998.
[2] Conversano, R., Low Power Magnetically Shielded Hall Thrusters, Dissertation, UCLA 2015.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

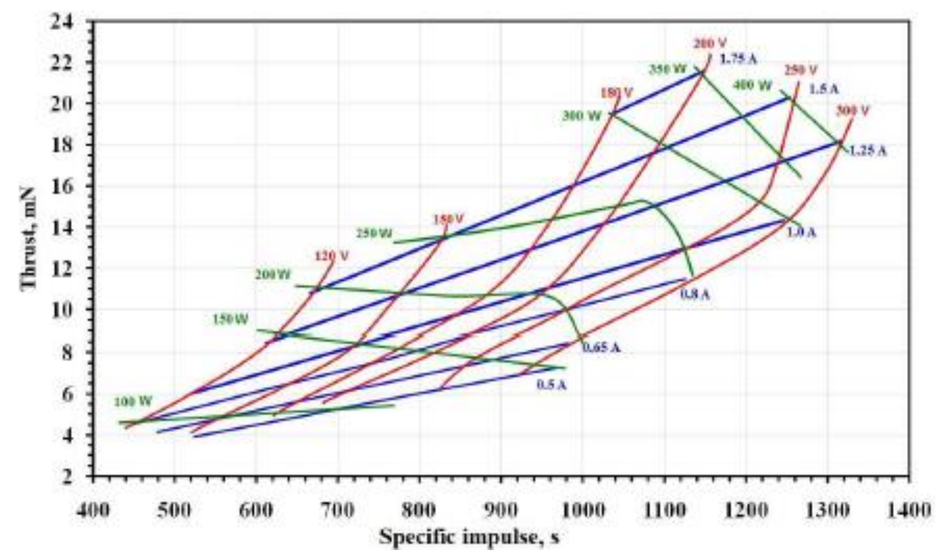
DISTRO A: Approved for public release. OTR-2024-00338

PlaS-34

Propulsion Technology	Hall thruster
Manufacturer/Country	Fakel (Russia)
TRL	3-4
Size (including PPU)	1U, <1 kg
Design satellite size	
Isp (s)	500 to 1300 s
Thrust type/magnitude	4 to 22 mN
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	80 to 360W, minimum operation at 120V, optimal at 200V.
Flight heritage (if any)	None known
Commercially available	NO
Last updated	*03/2021*

PlaS-34 thruster after manufacturing and during operation

Performances	Value
Discharge voltage, V	120…300
Discharge current, A	0.50…1.5
Discharge power, W	80…360
Thrust, mN	up to 22
Specific impulse, s	up to 1300
Efficiency, %	up to 35
Power-to-thrust ratio, W/mN	18…21
Mass, kg	0.97
Overall dimensions, mm	100x90 x85



Development level	LM
Power	70–375 W
Discharge voltage	100–300 V
Specific impulse	up to 1350 s
Thrust	up to 3.3 g
Efficiency	up to 32%
Mass	1 kg
Dimensions	100×92×85 mm

Additional comments:

[Reference 1][Jan 2019][General info]
Creation of high-pulse electric propulsion with the thrust specific impulse higher than 2500 s was made at EDB Fakel (Kaliningrad) in 1999-2000. Back at that time in frames of contractual works with Atlantic Research Corporation (ARC, USA) a high-voltage thruster experimental model was developed based on the separate modified elements and assembly units of the PPS 1350R and based on the anode new design scheme, and this model was conventionally named as SPT-1. The proposed design scheme of the SPT-1 thruster high-voltage experimental model, according to the authors, is a new type of Hall-effect thrusters. It is stipulated by the fact that this thruster discharge chamber (DCh) is combined: DCh exit part is formed by dielectric rings and its bottom part is made metallic by means of the walls of the adjoining hollow anode-gas distributor. On the basis of the research tests results of the hollow magnet anode plasma thruster laboratory models at EDB Fakel, a parametric family of the PlaS-type of thrusters conceptual models with the power from 100 W to 6 kW was developed, namely: PlaS-34, PlaS-40, PlaS-55 and PlaS-120CM. PlaS-34 is the smallest thruster in terms of dimension and power in the PlaS-type parametric family. This thruster was tested in the power range from 80 to 360 W and research works and tests are actively on-going.

[Reference 2][Dec 2019][Development status]
Efficiency up to 32%, development status at LM (Laboratory Model).

References:
[1] Bernikova, M., Gopanchuk, V., "Parametric family of the PlaS-type thrusters: development status and future activities," IEPC-2017-39.
[2] www.fakel-Russia.com https://fakel-russia.com/images/gallery/produczia/fakel_spd_en_print.pdf

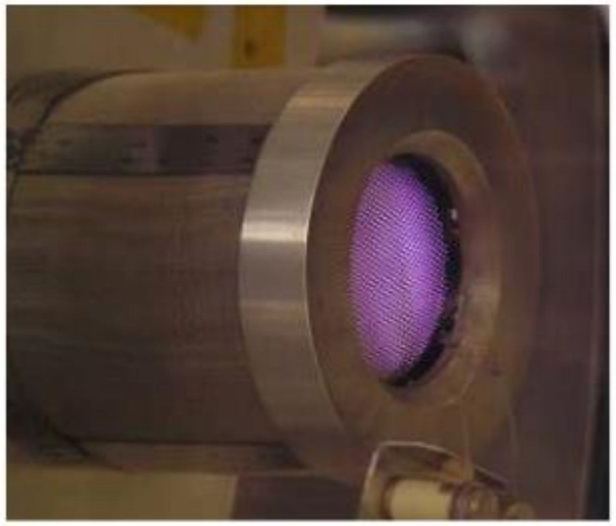
NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Miniature Xenon Ion thruster (MiXI)
UCLA/NASA JPL

Propulsion Technology	Miniature Xenon Ion Thruster
Manufacturer/Country	UCLA/JPL (USA)
TRL	3-4
Size (including PPU)	1.5U (estimated from photos), Thruster mass 0.2 kg
Design satellite size	3U and larger
Isp (s)	1800 to 3500 s
Thrust type/magnitude	0.1 to 3 mN
Delta-V (m/s)	Not reported
Propellant	Xenon
Power consumption (W)	50 to 100W
Flight heritage (if any)	None known Projected for "Project RAPID", launch unknown [5]
Commercially available	NO
Last updated	*03/2021*

Photo of MiXI thruster head



MiXI in operation in JPL test lab

Additional comments:

[Reference 1-3][Jan 2019][General info]

The MiXI thruster being developed at JPL is only 3-cm in diameter – one tenth the diameter of the DS1 thruster. It will require less than 100 W of power, provide a precisely controllable thrust (in its current configuration) of 0.5 – 3 mN and a specific impulse of over 3000 sec. As noted above, this high specific impulse will allow for the conservation of propellant, enabling this mission to either last longer, or the spacecraft to be lighter. The propellant used is xenon – a noble gas. It is very non-reactive, and thus poses no significant contamination risks. Propellant contamination is of major concern to future formation flying/interferometer spacecraft due to sensitive optical lenses on board the spacecraft.

Testing is ongoing according to JPL's website.

[Reference 4][Dec 2019][Updated testing]

The MiXI thruster with the axial ring-cusp hybrid discharge was operated with beam extraction for the first time at 1 kV. When cold, the thruster achieved 59% total efficiency at 23.7 mA beam current, corresponding to a discharge loss of 226 W/A and propellant utilization of 0.72. This is an improvement on previous results with an increase in total efficiency of 3% and a decrease in minimum efficient power level of 30%. Several mechanism for further improved efficiency have been identified.

Three pathways for further improved performance have been identified and are under current investigation. The fist is an improved thermal design to reduce steady-state temperatures which will simplify testing and has been shown to significantly affect total efficiency. The second is optimizing the aspect ratio of the discharge which has also shown to be a strong impact on efficiency by increasing propellant utilization. The final approach is adjusting the magnetic field structure to improve bulk-to-grids diffusion while retaining the current high electrical efficiency.

[Reference 5][March 2021][Flight info]

Plasma nd Space Propulsion lab (Richard Wirz' group at UCLA) is also collaborating with the UCLA BruinSpace club to propose a MiXI flight demonstration as a part of Project RAPID, with full CubeSat bus fabrication and assembly.

References:

[1] Knapp, D., "Implementation of a ¼ Inch Hollow Cathode into a Miniature Xenon Ion Thruster (MiXI)," Thesis, California Polytechnic State University, 2012.
[2] https://dst.jpl.nasa.gov/thrusters/
[3] Mueller, J., Ziemer, J., Hofer, F., Wirz, R., O'Donnell, T., "A Survey of Micro-Thrust Propulsion Options for Microspacecraft and Formation Flying Missions," Cube Sat 5th Annual Developers Workshop, San Luis Obispo, CA, 2008.
[4] Samples, S., Li, G., Wirz, R., "Performance testing and development of the MiXI Thruster with the ARCH Discharge," AIAA JPC, 2018.
[5] http://www.wirz.seas.ucla.edu/research/plasma-space-propulsion/development-of-the-miniature-xenon-ion-mixi-thruster

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

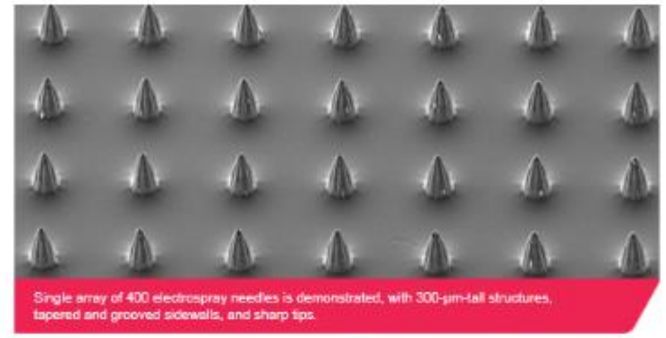
DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

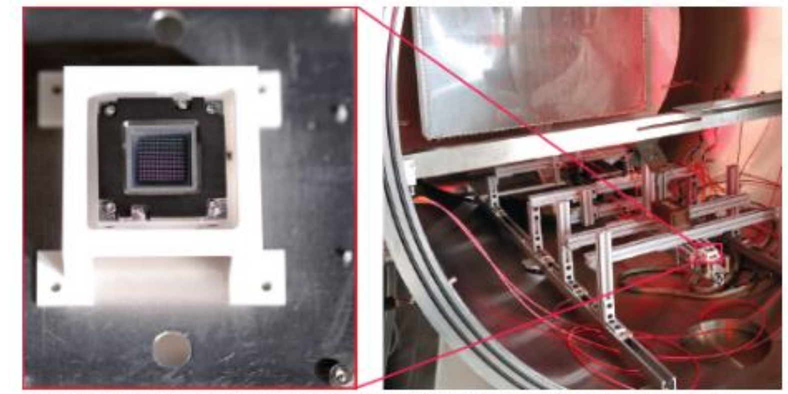
Microfluidic Electrospray Propulsion (MEP)
NASA JPL

Propulsion Technology	Electrospray – Indium
Manufacturer/Country	JPL (USA)
TRL	3
Size (including PPU)	Very small (26 grams, thruster head only)
Design satellite size	3U
Isp (s)	> 3100s [2]
Thrust type/magnitude	~200 uN per thruster chip (1 cm^2) [2]
Delta-V (m/s)	1000 m/s for 3U CubeSat
Propellant	Indium, <60 grams in a volume <10 cm^3) [3]
Power consumption (W)	<1W
Flight heritage (if any)	None
Commercially available	No
Last updated	*03/2021*

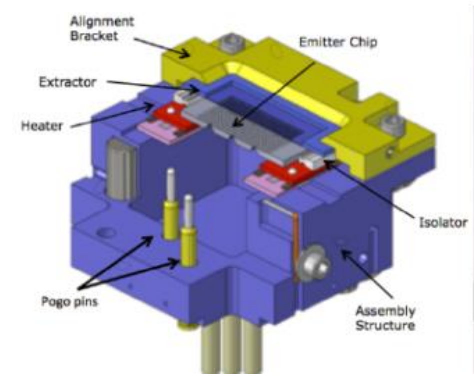
ADVANCED MICROFABRICATION TECHNOLOGIES

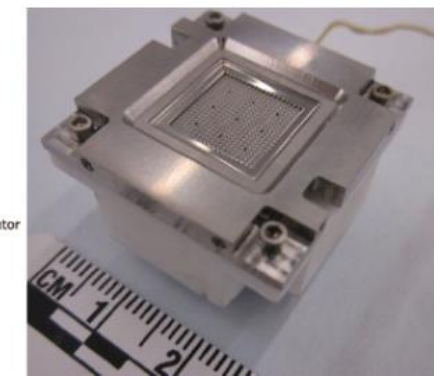


MEP Will Enable Nanosats with Extraordinary Propulsion Capability



LEFT: 100-micronewton prototype MEP thruster in a thermal shield. RIGHT: MEP thruster on a micronewton thrust stand in a 2-meter-diameter vacuum chamber for testing.





Additional comments:
[Reference 1][Jan 2019][General info]
From the JPL website, “Advances in microfabrication capabilities are enabling the development of arrays of silicon electrospray needles for highly compact, integrated, scalable indium-fueled electrospray thrusters. The silicon emitter array chips have 400 needles in 1 cm2 that are about 300 µm tall with tapered sidewalls and axial grooves for capillary-force-driven propellant flow. They are patterned using gray-scale electron-beam lithography to write a complex 3-D resist exposure profile and etch mask. The emitters are loaded with a thin film of indium propellant using microfabrication facilities. The heater to melt the indium is fabricated from Pyrex and silicon chips and then bonded to the emitter array chip using anodic bonding. The thruster assembly also includes an extractor electrode, high-voltage isolator, propellant management device, and an assembly structure. Kilovolts are applied between the needles and the extractor with apertures aligned to the needles to deform the indium into a liquid cone at the apex of the needles and then extract and accelerate ions to tens of thousands of meters per second to create thrust. The feed system is highly integrated into the thruster head because it is based on capillary forces only with no valves or pressurized reservoir. This approach to electrospray propulsion will improve on the state of the art in volume and mass by more than 10 times. This technology has recently demonstrated operation at over 100 micronewtons of thrust and hours of stable operation at lower thrust levels.”
[Reference 2][May 2019][Thruster status]
“A scalable microfabricated indium-fueled prototype electrospray thruster with 400 silicon emitters was demonstrated. This electrospray thruster technology with microfabricated components is under development for very compact, distributable propulsion systems that can be employed on both very small and large spacecraft with 10X improvement over state-of-the-art in mass, volume and specific impulse. The critical components of this technology are the microfabricated emitter array chips and heaters and the capillary force driven indium feed system for indium propellant. The most significant challenges included component fabrication and alignment with micron-scale precision and component loading with indium propellant. Novel microfabrication processes provided the required micron-scale etch precision and uniformity across arrays of 400 silicon electrospray emitters in 1 cm^2. Initial tests of single microfabricated silicon emitters demonstrated better performance than industry standard single liquid metal ion source emitters and the performance required to achieve up to 200 uN of thrust from 400 emitters in 1 cm^2. The prototype thruster dry mass was 26 grams and volume was 9 cm^3. The results of this investigation suggest that microfabricated indium electrospray thruster technology is feasible and that extraordinary performance is possible.”

References:
[1] https://microdevices.jpl.nasa.gov/capabilities/advanced-microfabrication-technologies/microfluidic-electrospray-propulsion.php
[2] Marrese-Reading, C., et al. “Electrospray Thruster Performance with Microfabricated Emitter Arrays and Indium Propellant,” AIAA JPC paper, 2016.
[3] https://microdevices.jpl.nasa.gov/capabilities/advanced-microfabrication-technologies/electrospray-propulsion/

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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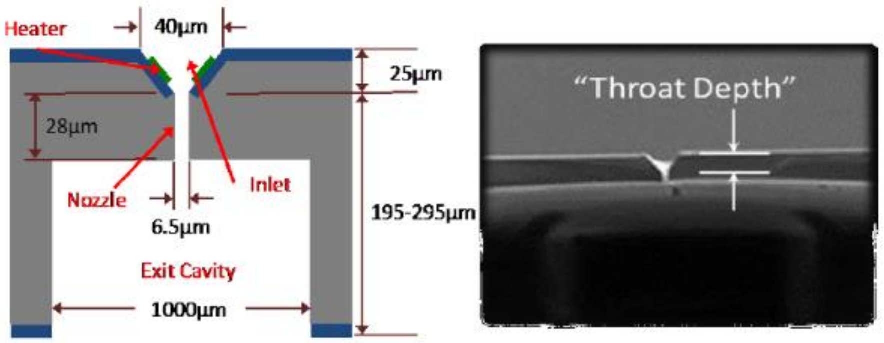
Film Evaporation MEMS Tunable Array (FEMTA)
Purdue University/NASA GSFC

Propulsion Technology	Water thruster
Manufacturer/Country	Purdue University/NASA Goddard (USA)
TRL	3
Size (including PPU)	<1U (45g for thruster head)
Design satellite size	
Isp (s)	50-95s
Thrust type/magnitude	<0.5 mN (thrust, nominal) Thrust to power ratio = 230 uN/W
Delta-V (m/s)	
Propellant	DI Water (~3.5g)
Power consumption (W)	<1W (10W for the whole unit)
Flight heritage (if any)	None Projected for a sub-orbital flight on Blue Origin Shephard in 2021. [5]
Commercially available	No
Last updated	*03/2021*

FEMTA Gen4 thrusters



Additional comments:

[References 1-4][Dec 2019][General info]
From NASA open data portal for proposals:
Film-Evaporation MEMS Tunable Array (FEMTA) exploits micro-scale effects of surface tension to provide a low mass, low power, and compact multi-purpose solution for both propulsion and thermal control. A one-watt FEMTA unit contains thruster/cooler arrays as large as 10 by 10 elements with a total system dry mass of less than 1 gram and a volume less than 2 cubic centimeters, which includes the propellant tank and valves. The design cooling power of a unit is 10 Watts, while the thrust is tunable up to 200 μN with a resolution of 3 μN. The integrated design eliminates the need for peripheral support other than a low-voltage power supply and signaling.
From Purdue .ppt presentation:
FEMTA nozzle is etched into a 300-micron thick, 100 mm diameter silicon wafer. Fabrication methods include: standard photolithography, oxide growth, wet etching, and plasma etching. 3.5g of water propellant provides approximately 12 hours of thruster firing time.
A team at Purdue University and NASA Goddard Space Flight Center is developing the Film Evaporation MEMS Tunable Array (FEMTA). This Microelectromechanical systems (MEMS) thruster uses deionized liquid water as propellant and consists of nozzles that produce thrust by applying local heat to a propellant capillary interface. The main advantages are the absence of any power required mechanism thus operating at low power consumption, order of mW. This technology plans to achieve TRL 6 by of fiscal year 2019 by targeting technology maturation activities to achieve payload requirements for a Pathfinder Technology Demonstration 6U mission

References:
[1] Fowee K, Pugia S, Clay R, et al. Quad-Thruster FEMTA Micropropulsion System for Cubesat 1-Axis Control. Summer Workshop 2017.
[2] http://mstl.atl.calpoly.edu/~bklofas/Presentations/SummerWorkshop2017/SSC17-WK-48_presentation.pdf
[3] https://data.nasa.gov/dataset/Film-Evaporation-MEMS-Tunable-Array-FEMTA-for-Prop/tr28-tw3p
[4] NASA survey of small-satellite propulsion, 2018. https://sst-soa.arc.nasa.gov/04-propulsion
[5] https://engineering.purdue.edu/VIP/teams/femta, https://www.youtube.com/watch?v=SYFSimbiUQA

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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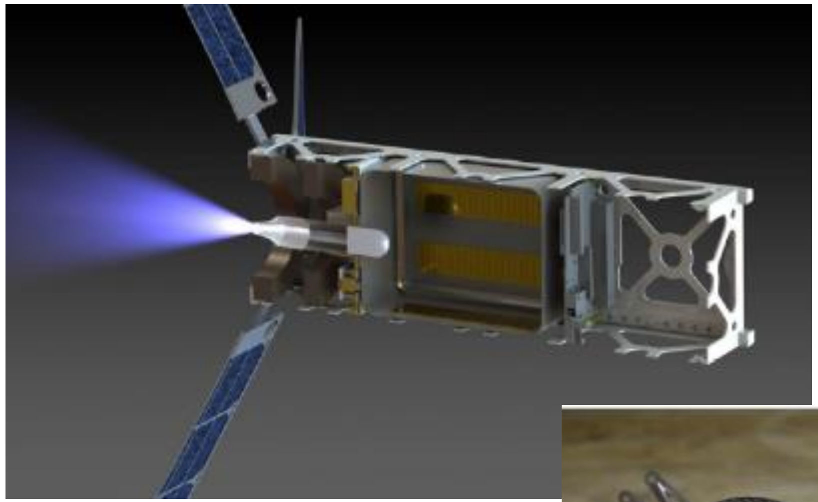
CubeSat Ambipolar Thruster (CAT)
University of Michigan

Propulsion Technology	Helicon plasma thruster/RF plasma
Manufacturer/Country	University of Michigan (USA)
TRL	3-4
Size (including PPU)	~1U
Design satellite size	3U and above
Isp (s)	400 – 800s
Thrust type/magnitude	0.5 to 5 mN
Delta-V (m/s)	>1000 m/s, design
Propellant	Xenon
Power consumption (W)	10-50W
Flight heritage (if any)	None
Commercially available	No (commercialized by Phase Four)
Last updated	*03/2021*



Schematic of CAT thruster in 3U bus

CAT prototype

Additional comments:

[Reference 1, 2][Jan 2019][General info]
The CubeSat Ambipolar Thruster (CAT) is a novel device developed by the University of Michigan that utilizes a magnetic helicon discharge to ionize the propellant. The thruster (Figure 4 19) does not require a separate electron source and no resultant magnetic dipole is produced. High plasma density is created through a high efficiency helicon RF source and a large accelerating electric field is achieved. A large variety of propellants in solid or liquefied state can be used thanks to the electrode-less design of the thruster. Iodine has been presented as the most promising propellant due to its low cost and high storage density. However, the highly oxidizing nature of iodine presents other storage challenges in the propellant tank. These challenges include feeding the propellant tank; iodine must sublime into a gas before it can be fed and large amounts required present a greater challenge it will be to design a tank that will feed the iodine propellant in a constituent and reliable method (Morring 2014).
This system can achieve an estimated specific impulse of 1010 s when using iodine. Currently, the PPU is still in development phase and some of the components for iodine utilization are at TRL 3 (Spangelo and Longmier 2015). Initial tests were performed by using both xenon and argon as propellant. For xenon, CAT was designed to operate on 10-50 W in order to address some of the power limitations that small spacecraft face. In this configuration, the TRL is 4 and thrust and specific impulse are in the 0.5-4 mN range and the 400-800 s range respectively (Sheehan, et al. 2015). The company Phase Four LLC is developing an integrated flight unit of the CAT.
[Reference 3][Jan 2019][Commercialization]
PASADENA, Calif (Phase Four PR) — Phase Four LLC, a satellite propulsion company, has received a $1 million contract from the Defense Advanced Research Projects Agency (DARPA), in support of the effort to deliver a fully-integrated flight unit of the CubeSat Ambipolar Thruster (“CAT”). The contract also includes options for long-duration orbital flight testing and design enhancements for microsatellite-class missions.
Configurable for a variety of Earth-orbiting applications as well as potentially for interplanetary exploration, the CAT engine is a novel, electrodeless plasma thruster originally developed at the University of Michigan and exclusively licensed to Phase Four. Designed for high delta-v applications, CAT has a high thrust-to-power ratio and is operable with an assortment of propellants for mission customization. Phase Four has partnered with The University of Michigan’s Plasmadynamics and Electric Propulsion Laboratory (PEPL) to provide detailed characterization of CAT’s performance. The purpose of the DARPA contract is to deliver a flight-ready CAT engine, raising it to Technology Readiness Level (TRL) 7, with an option for an in-space demonstration of the entire system. If successful, CubeSats with large delta-v capability could lead to maneuvering spacecraft that support formation flying, increase ground coverage from satellite constellations deployed from single launch vehicles and enable long-lived, variable altitude flight.

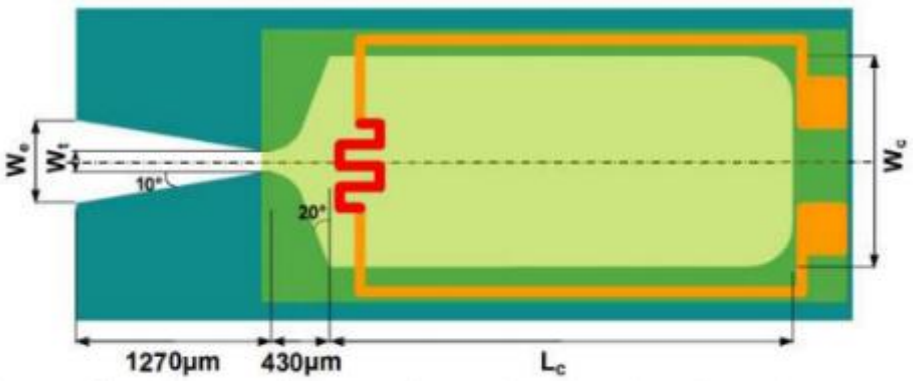
References:
[1] Sheehan, J., Collard, T., Ebersohn, F., Longmier, B., “Initial operation of the cubesat ambipolar thruster,” IEPC-2015-243.
[2] Spangelo, S., Longmier, B., “Optimization of cubesat system-level design and propulsion systems for Earth-escape missions,” Journal of Spacecraft and Rockets, Vol. 52, 2015.
[3 http://www.parabolicarc.com/2015/11/25/phase/

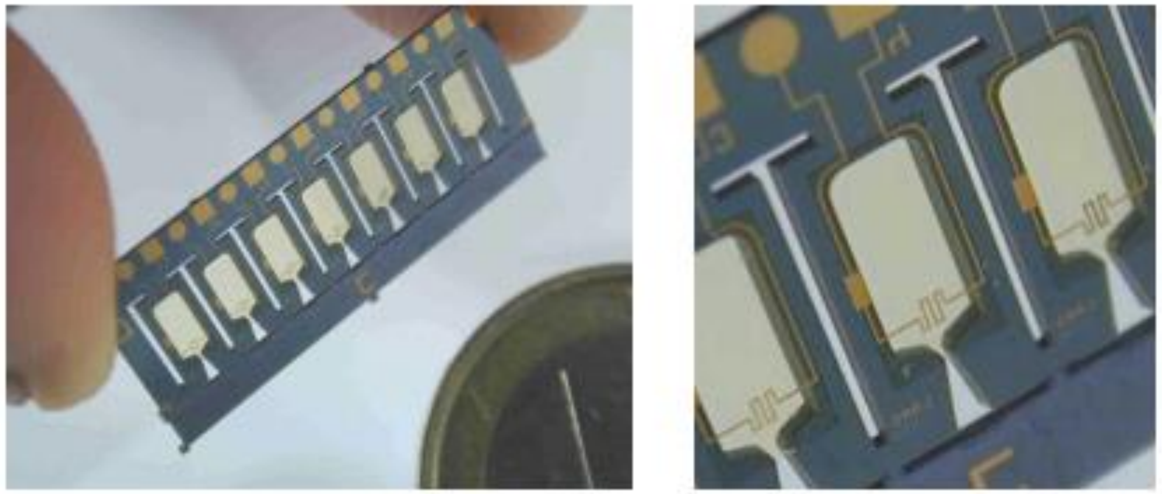
NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

MEMS-based solid propellant microthruster array

Propulsion Technology	Solid propellant digital array
Manufacturer/Country	French National Center of Scientific Research LAAS-CNRS (France)
TRL	3-4
Size (including PPU)	Unclear, very small.
Design satellite size	1U or larger
Isp (s)	Not reported, but estimated to be ~200 to 250 s
Thrust type/magnitude	1 uN to 50 mN (variable)
Delta-V (m/s)	
Propellant	Double base, Black powder (SD1152)
Power consumption (W)	~100 mW
Flight heritage (if any)	None known
Commercially available	NO
Last updated	*03/2021*





Photograph of 7x1 micromachined (but non-assembled) silicon array

Additional comments:

[References 1, 3][Jan 2019][General info]
The thruster is composed of 7 solid propellant units. The thrust force can be scaled by varying the geometry, the number of micro-thrusters, and the type of propellant in order to satisfy the specific applications. The thruster is composed of 3 layers: a micromachined silicon layer containing initiator on a thin membrane, a chamber and nozzle, and a glass (Pyrex) layer glued on the silicon bottom side. Layers are assembled by adhesive bonding to give final MEMS array. This structure uses a double base propellant (home-made, mixed with black powder, called SD1152) at combustion pressures of 60 bar to give 1 uN to 50 mN of thrust. The thrust force is generated by the combustion of propellant stored in a few millimeter cube chamber. The micro-igniter is a polysilicon resistor deposited on a low stress SiO_2/SiN_x thin membrane to ensure a good heat transfer to the propellant and thus a low electric power consumption. A large range of thrust force is obtained simply by varying chamber and nozzle geometry parameters in one step of Deep Reactive Ion Etching (DRIE). A temperature of 250 °C, enough to propellant initiation, is reached for 40 mW of electric power. A combustion rate of about 3.4 mm/s is measured for DB+20%BP propellant and thrust ranges between 0.1 and 3.5 mN are obtained for BP ratio between 10% and 30% using a microthruster with a throat width of 100 µm. Ignition delay times were on the order of a few hundred ms.

[Reference 2][Jan 2019][General info]
This thruster is an improvement over previous designs. A previous design contained 16 solid propellant charges placed onto a 4x4 addressable array, which fit into a 1.5cm x 1.5 cm square silicone wafer. This original thruster was designed to produce 0.3 to 40 mN of thrust using around 150 mW of power to initiate each discharge.

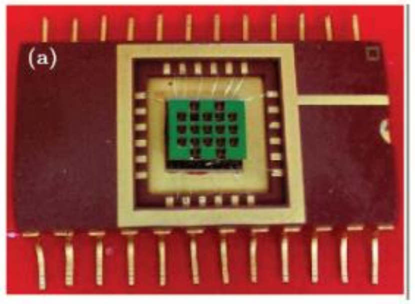
References:
[1] Chaalane, A., Chemam, R., Houabes, M., et al. "A MEMS-based solid propellant microthruster array for space and military applications," Journal of Physics, Vol 660, 2015.
[2] Rossi, C., Larangot, B., Pham, P., et al. "Solid propellant microthrusters on silicon: Design, modeling fabrication, and testing," J. Micromech. Systems, 15 (6), 2006.
[3] Chaalane, A., Larangot, B., Rossi, C., Granier, H., Esteve, D., "Main directions of solid propellant micro-propulsion activity at LAAS," AIAA, 2004.

Comm. avail.	TRL	Aerospace-tested
NO	3	NO

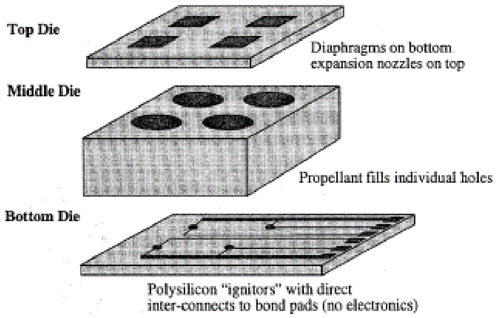
DISTRO A: Approved for public release. OTR-2024-00338

Digital Propulsion (micropropulsion array)

Propulsion Technology	Solid propellant digital array
Manufacturer/Country	TRW/The Aerospace Corporation/CIT (USA)
TRL	3-4
Size (including PPU)	Unclear, very small.
Design satellite size	1U or larger
Isp (s)	Not reported, but estimated to be ~200 to 250s
Thrust type/magnitude	10E-4 N*s impulse. Duration of impulse is about 1 ms. 0.1 mN (nominal)
Delta-V (m/s)	
Propellant	Lead styphnate
Power consumption (W)	Not report, but estimated to be very small.
Flight heritage (if any)	None known
Commercially available	No
Last updated	*12/2023*

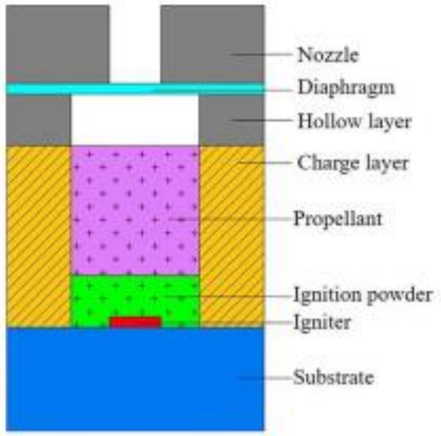


Digital propulsion micro-thruster chip in a 20-pin ceramic DIP



Configuration of the 3-layer microthruster

[1]



[3]

Additional comments:

[Reference 1][Jan 2019][General info]
There are several advantages to this design. These devices have no moving parts, each micro-thruster has a low parts count (~3), no valves or lines or external tanks. The propulsion function can be combined with the spacecraft structure. The array of micro-thrusters is highly redundant. The array can be commanded to fire individual thrusters, several thrusters at once, or in controlled sequences. Since the dimensions of the individual rocket engines are under the designers' control, the creation of smaller and smaller impulse bits is straightforward. On the order of 10E6 thrusters can be fabricated on a single wafer. Thrust measurements were performed on a ballistic pendulum thrust stand, designed by E. Beiting. The test stand was calibrated with a track and a series of solenoids to release metal calibration spheres from known positions.

[Reference 2][Jan 2019][Testing results]
The Aerospace miniature solid propellant thruster was one of the first such [solid propellant array] devices and produced 0.1 mN of thrust.

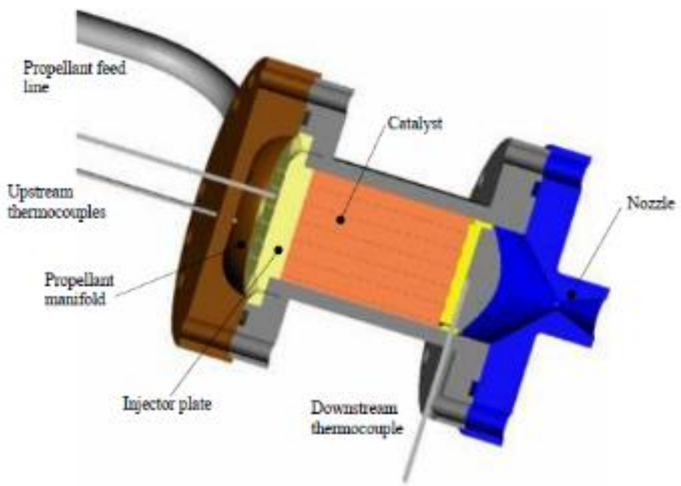
References:
[1] Lewis, D., Janson, S., Cohen, R., Antonsson, E., "Digital MicroPropulsion," IEEE Conference Paper, 1999.
[2] Spektor, R., Fathi, G., Brady, B., Moore, T., "2011 Review of Propulsion Options for the Aerospace CubeSat Project," TOR-2011(8582)-6
[3] Xu, J., Zhang, J., li, F., Liu, S., Ye, Y., Shen, R., "A review on solid propellant micro-thruster array based on MEMS technology," FirePhysChem, 2023.

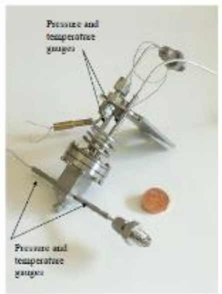
NO	3	
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Miniature Hydrogen Peroxide (H2O2) Monopropellant Thruster

Propulsion Technology	Hydrogen peroxide monopropellant
Manufacturer/Country	Austrian Research Center (ARC)/Austria Institute of Technology (AIT)/ESA/Aerospace Technology(Mechatronic Systemtechnik)/CNRS-LACCO (Austria/France)
TRL	3
Size (including PPU)	Small, <1U
Design satellite size	3U and larger
Isp (s)	153s
Thrust type/magnitude	100-500 mN (preliminary measurements), 1880 N*s (impulse, total)
Delta-V (m/s)	50-300 m/s (design), s/c weight not specified 1.2 kg of consumed propellant gives 1880 N*s total impulse 20 m/s for a 100 kg satellite [1,3]
Propellant	H2O2, mullite/mullite-zirconia
Power consumption (W)	Unknown
Flight heritage (if any)	None known
Commercially available	No
Last updated	*03/2021*





Additional comments:
The thruster operates via the decomposition of H2O2 over a catalyst.
[Reference 1[Jan 2019][General info]
The monolithic cellular ceramics have been manufactured by CTI Company (Céramiques Techniques et Industrielles, France) using a standard extrusion technique. Two different materials, mullite and mullitezirconia, have been used and included in this work in order to investigate their suitability for this particular application. Mullite-zirconia has the advantage of being suitable for higher temperatures than mullite, but the porosity necessary for a good washcoat adhesion can be more difficult to achieve. A first laboratory model has been designed and manufactured from stainless steel. The injector plate provides the homogeneous distribution of the mass flow rate into the channels. The 36 injector holes have a diameter of 0.1 mm and have been manufactured using EDM. Two sheet thermocouples measure the flow temperature upstream of the injector and one, located downstream of the catalyst, measures the decomposition temperature. The temperature data obtained by these measurements will help to diagnose the system and eventually support the development of an improved thermal modeling. The nozzle has a 45° and 20° half angle in the convergent and the divergent section respectively. The throat diameter is 1 mm and the nozzle has an expansion ratio of 16. For very high Reynolds number, as in a standard size nozzle, an increase in the radius ratio between the wall curvature radius at the throat and the throat radius itself leads to a higher discharge coefficient. Instead, for small nozzle (Re < 10000), a reduction of this radius ratio leads to a higher discharge coefficient. In conclusion, a radius ratio of 2 is therefore recommended11. However, since the present test series was a simple evaluation of the catalyst performance rather than a thruster performance evaluation the nozzle was manufactured on a milling machine. Due to the small size of the nozzle, such a manufacturing method cannot accomplish the envisioned radii. The transition from the convergent section to the throat area and the one from the throat area to the divergent section are therefore rather corners than radii. A precision balance is used to measure the thrust with a weight resolution of 0.01 gram and a reproducibility of ≤±0.01 gram, which is equivalent to 0.098 mN and ±≤0.098 mN respectively.
[Reference 3][Jan 2019][Project funding]
The development of these thrusters was funded under "Green Hydrogen Peroxide (H2O2) Monopropellant with Advanced Catalytic Beds", LET-SME contract no. 18901. Year of award was 2005, with projected completion 2006.

References:
[1] Scharlemann, C., Schiebl, M., Marhold, K., Tajmar, M., et al., "Development and Test of a Miniature Hydrogen Peroxide Monopropellant Thruster," AIAA 2006-4550
[2] Spektor, R., Fathi, G., Brady, B., Moore, T., "2011 Review of Propulsion Options for the Aerospace CubeSat Project," Aerospace TOR-2011(8582)-6
[3] http://www.esa.int/About_Us/Business_with_ESA/Small_and_Medium_Sized_Enterprises/SME_Achievements/Green_Hydrogen_Peroxide_H2O2_monopropellant_with_advanced_catalytic_beds
[4] Scharlemann, C., Schiebl, M., Amsuss, R., Tajmar, M., "Development of Miniaturized Green Propellant Based Mono- and Bipropellant Thrusters," AIAA 2007-5580
[4] Krejci, D., Woschnak, A., Scharlemann, C., Ponweiser, K., "Hydrogen peroxide decomposition for micro propulsion: simulation and experimental verification," AIAA-2011-5855.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

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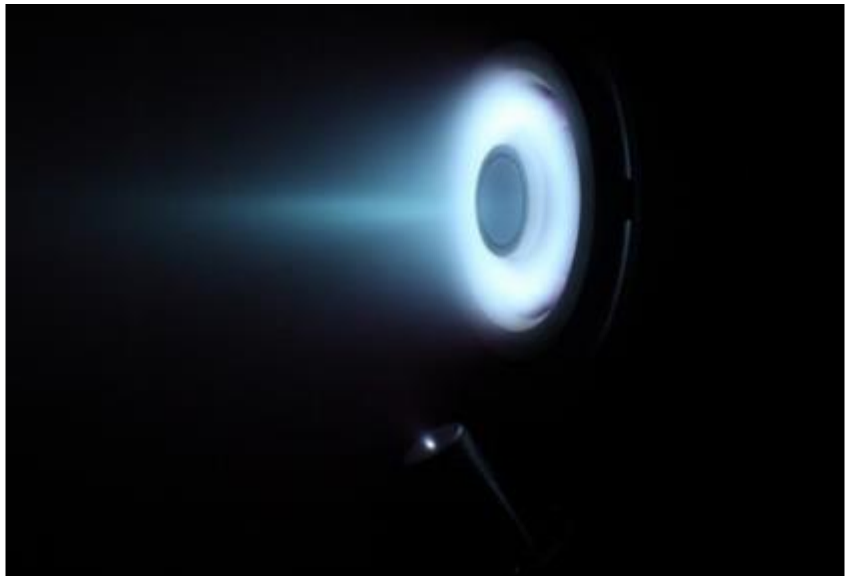
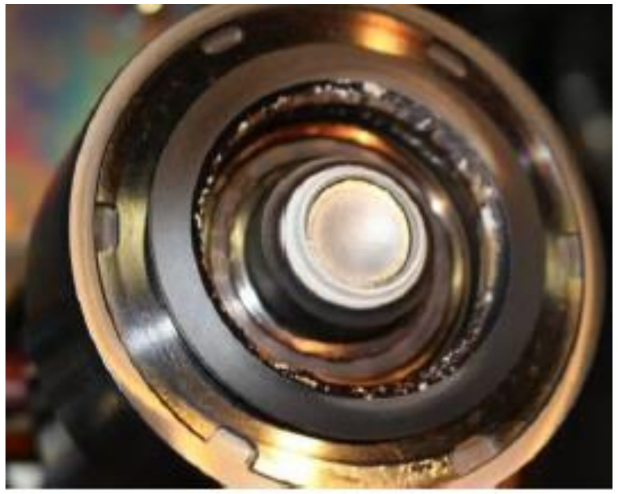
MSHT100 (Magnetically-shielded HT100)

Propulsion Technology	Hall Effect Thruster (HET)
Manufacturer/Country	Alta-Space, now (SITAEL) (ITALY)
TRL	3
Size (including PPU)	640 g (without cathode) (~1U)
Design satellite size	
Isp (s)	900 to 1450 s [Ref. 1]
Thrust type/magnitude	5 to 14 mN [Ref. 1]
Delta-V (m/s)	
Propellant	Xenon or krypton
Power consumption (W)	100 to 350 W, operating voltages 150-400V
Flight heritage (if any)	None known
Commercially available	NO
Last updated	03/2021





Additional comments:

[Reference 1][Jan 2019][General info]
The first prototype of this system was tested in 2016. The manufacturer reports efficiencies up to 35%, and estimates an expected lifetime of >7,000 hrs, and >10,000 on/off cycles. The MSHT100 is based on the design of the HT100, and stands for Magnetically Shielded HT100. It is based on a permanent magnet but with a new magnetic field topology that limits the wall erosion and increments the thruster lifetime. The first prototype was operated continuously for 360 hrs, showing no erosion of the walls. It is expected to extend the lifetime of the HT100 by 2-3 times.

References:
[1] Misuri, T., "Low power electric propulsion at Sitael," International workshop on ion propulsion and accelerator industrial applications, Presentation, 2017.
[2] https://www.sitael.com/wp-content/uploads/brochure/sitael_brochure-web_BRO-SPA-028-070417-V01.pdf

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Liquid-fed pulsed plasma thruster

Propulsion Technology	PPT (LFPPT)
Manufacturer/Country	Purdue (USA)
TRL	3
Size (including PPU)	~1U
Design satellite size	
Isp (s)	
Thrust type/magnitude	Peak thrust = 5.8N [1] Peak impulse = 35 uN*s [1]
Delta-V (m/s)	
Propellant	Pentaphenyl trimethyl trisiloxane (C33H34O2Si3)
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	NO
Last updated	03/2021

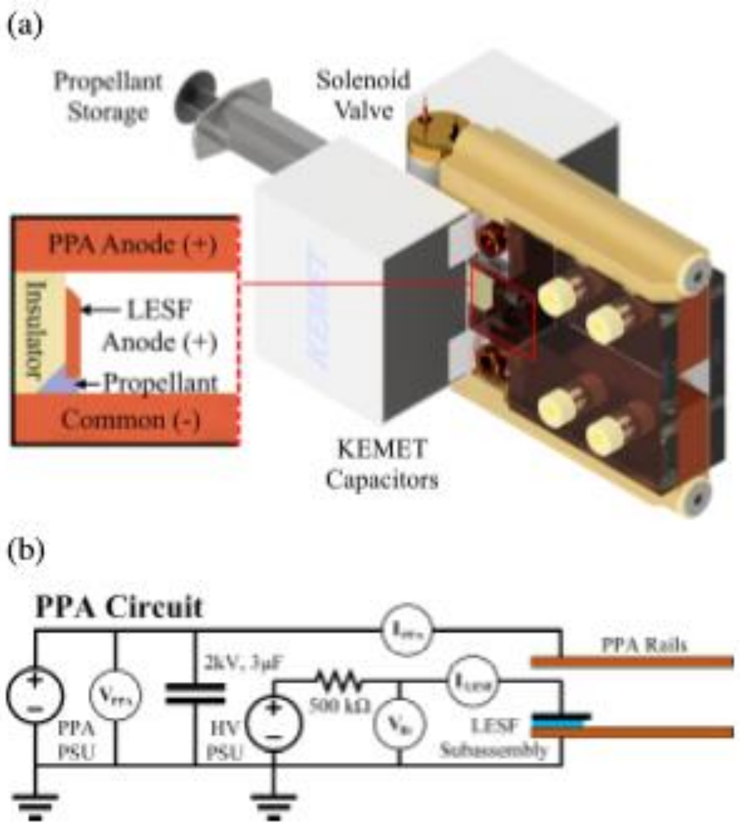
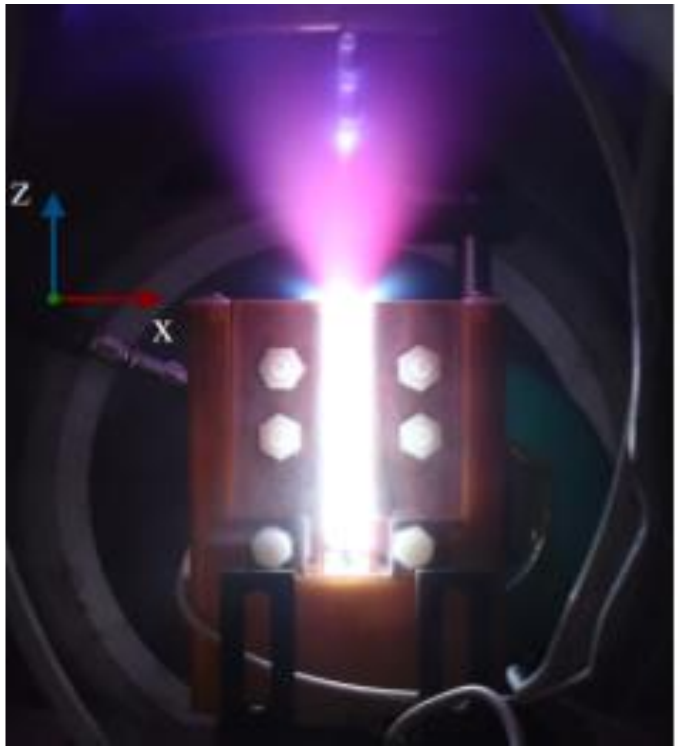


Figure 1: Liquid-fed pulsed plasma thruster (LF-PPT) with low energy surface flashover (LESF) Igniter. (a) CAD rendering. (b) Electrical circuitry of the LF-PPT.



Thruster firing in a vacuum chamber, with time-of-flight measurements of the plume exhaust velocity

Additional comments:

[Reference 1][Aug 2019][Thruster info]
PPTs with solid and gaseous propellants have been employed with limited degrees of success in nanosatellites. A liquid-fed pulsed plasma thruster could potentially overcome several disadvantages associated with traditional PPT devices such as contamination issues, non-uniform propellant consumption (leading to premature thruster failure), and complex/unreliable propellant feeding systems.
The liquid fed pulsed-plasma thruster (LF-PPT) is comprised of a Lorentz-force pulsed plasma accelerator (PPA) and a low-energy surface flashover (LESF) igniter.
Pentaphenyl trimethyl trisiloxane (C33H34O2Si3) was used as a propellant in this work due to its excellent dielectric properties and low vapor pressure. Conventionally, C33H34O2Si3 is used as a diffusion pump working fluid.
A 3 μF / 2 kV capacitor bank, offering shot energies of < 6 J, supported PPA current pulse durations of ~ 16 μs with observed peaks of 7.42 kA. Plasma jet exhaust velocity was measured at ~ 32 km/s using a time-offlight technique via a set of double probes located along the jet’s path. Intensified charge coupled device (ICCD) photography was concurrently leveraged to visualize plasma dynamics and mechanisms of the ignition / acceleration events. A peak thrust and impulse bit of 5.8 N and 35 μN·s, respectively, were estimated using large-area Langmuir probe measurements of total ion flux produced by the thruster.

References:
[1] Patel, A., Zhang, Y., Shashurin, A., “Liquid-fed pulsed plasma thruster for propelling nanosatellites,” Submitted to Journal of Physics D: Applied Physics, 2019. https://arxiv.org/ftp/arxiv/papers/1907/1907.00169.pdf
[2] https://www.purdue.edu/newsroom//releases/2019/Q3/new-safer,-inexpensive-way-to-propel-small-satellites.html

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

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M5 microwave ion thruster

Propulsion Technology	Microwave Ion thruster
Manufacturer/Country	Shanghai Aerospace Control Technology Institute (CHINA)
TRL	3-4
Size (including PPU)	1-2U
Design satellite size	100 kg
Isp (s)	3450 s (nominal)
Thrust type/magnitude	2 mN (nominal)
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	140W supplied (24.5W delivered microwave power)
Flight heritage (if any)	No. Projected to launch by 2022.
Commercially available	NO
Last updated	03/2021

(a) After the assembly

(b) After 3000h test

M5-3 thruster firing

Additional comments:

[Ref 1][Oct 2019][Thruster development status]
A M5 thruster is designed for a 100kg micro satellites, and it is one of the M series ion thrusters (M2, M5, M10, M30) which are in development at the Shanghai Aerospace Control Technology Institute. The thruster is based on microwave electron cyclotron resonance (ECR). It has several ECR zones which means that the thruster has a larger discharge surface and the ECR zones can be fed more directly and efficiently. The thruster is now on its 3rd design iteration (M5-3). It has been tested to 3000 hours of life.

References:
[1] Zhu, K., Yu, X., Zhou, M., Li, Y., Han, L., Huang, W., "Development status of microwave ion thruster M5 for small and micro satellites," IEPC-2019-A446.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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Water ion thruster

Propulsion Technology	Water plasma
Manufacturer/Country	University of Tokyo
TRL	3
Size (including PPU)	~2U
Design satellite size	6U
Isp (s)	384s
Thrust type/magnitude	226 uN
Delta-V (m/s)	500 m/s for 8kg (6U) CubeSat
Propellant	Water
Power consumption (W)	36.5W
Flight heritage (if any)	None
Commercially available	NO
Last updated	03/2021

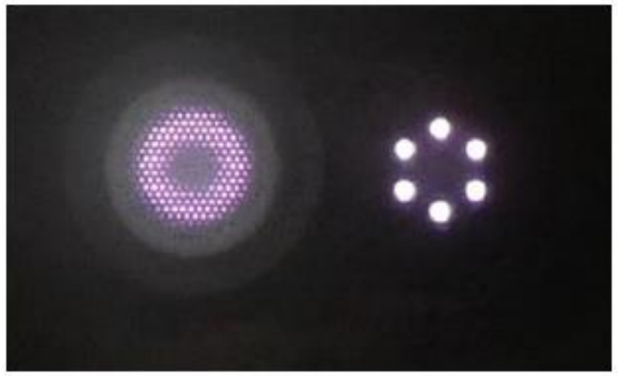


Figure 1: Front view of the water ion thruster

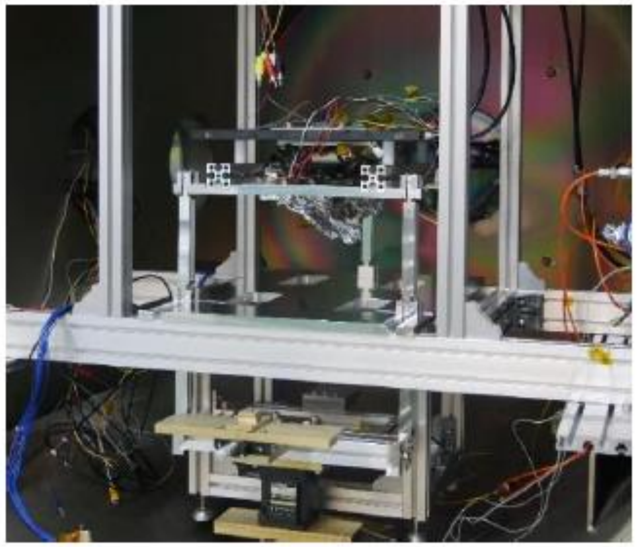


Figure 2: Pendulum-type thrust stand

Table 2: Estimated performance of the thruster

Items	Value
Microwave input power	1.5 W (2 port)
Mass flow rate	30 µg/s (both)
Screen voltage	1.0 kV
Antenna bias voltage	38 V
Beam current	12.7 ± 0.36 mA
Thrust	226 ± 19 µN
Specific impulse	384 ± 33 s

Additional comments:

[Reference 1][Aug 2019][General info]
The miniature water ion thruster is composed of the ion source and the neutralizer. The diameters of the ion source and the neutralizer are 20 mm. The propellant is fed to both the ion source and the neutralizer, and the mass flow rate is typically 30 µg/s for each in case of using water as a propellant. The microwave also inputs to both, and it heats up the electrons by Electron Cyclotron Resonance (ECR) heating with samarium cobalt magnets. The heated electrons ionize the propellant and generate the plasma. The direct thrust measurement using the pendulum-type thrust stand.

References:
[1] Nakagawa, Y., Ataka, Y., Koizumi, H., Komurasaki, K., “Miniature water ion thruster; 1 km/s-class Delta-V for a 6U CubeSat,” SSC19-WKII-05

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

XMET

Propulsion Technology	Microwave electrothermal thruster (MET)
Manufacturer/Country	University of Southampton, AVS UK Ltd. (UK)
TRL	3
Size (including PPU)	Appears to be 1U
Design satellite size	6U or larger
Isp (s)	60 to 120 s
Thrust type/magnitude	90 to 140 mN
Delta-V (m/s)	
Propellant	Xenon, Argon
Power consumption (W)	70 to 370W (tuneable)
Flight heritage (if any)	None
Commercially available	NO
Last updated	03/2021

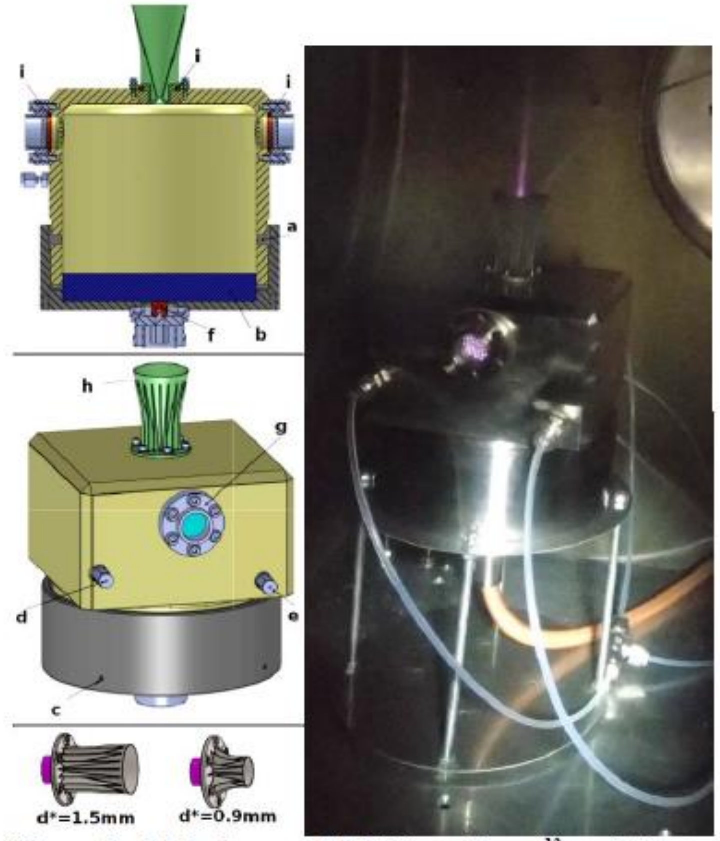


Figure 3: CAD views of XMET breadboard[13] and the two additional nozzle insets with smaller throat sizes (left). XMET during firing with Argon propellant (right).

[2]

Additional comments:

[Ref 1, 3][Oct 2019][Thruster design and performance]
The basic operating principle of Microwave Electrothermal thrusters (METs) is to create a free-floating plasma discharge in a cylindrical microwave cavity resonator, which can efficiently heat a wide range of propellants. The propellant is then expanded through a conventional gas dynamic nozzle. METs are simple, rugged thrusters that are inexpensive and highly scalable. We are currently developing a large, 0.5 kW class MET providing 200-500 mN of thrust for the reaction control system of GEO platforms, eliminating the use of Hydrazine. The design is optimized for an integrated Xenon propulsion architecture operating at 2.45 GHz that includes a separate gridded ion engine. To this end, our goal is to significantly outperform the specific impulse of current Xenon resistojets by achieving higher chamber temperatures. Using electromagnetic modelling, we have optimized our resonant cavity design to achieve a high predicted peak electric field strength at the nozzle throat. We have designed and built a flexible breadboard prototype with exchangeable nozzles and a tuneable cavity geometry. We describe the detailed design and first experimental results from this prototype. The data verified cavity tuning, allowing ignition at peak resonance. Plasma ignition at low mass flow rates with argon was achieved at an extremely low input power of ~4 Watts. Estimated electric field breakdown thresholds matched theoretical predictions. We successfully carried out steady state firing tests by increasing flow rates and input power incrementally up to 250 mg/s and 370 Watts respectively. Our early performance tests reached the highest thruster efficiency of 92% and thrust-to-power ratio 1.53 mN/W, as inferred from indirect thrust measurements, for an input power of 80 W and flow rates of 100 mg/s.

[Reference 2][March 2021][Thruster ground testing]
The XMET microwave electrothermal thruster is currently being tested as part of the UKSA NST Impulse II project with AVS UK.

References:

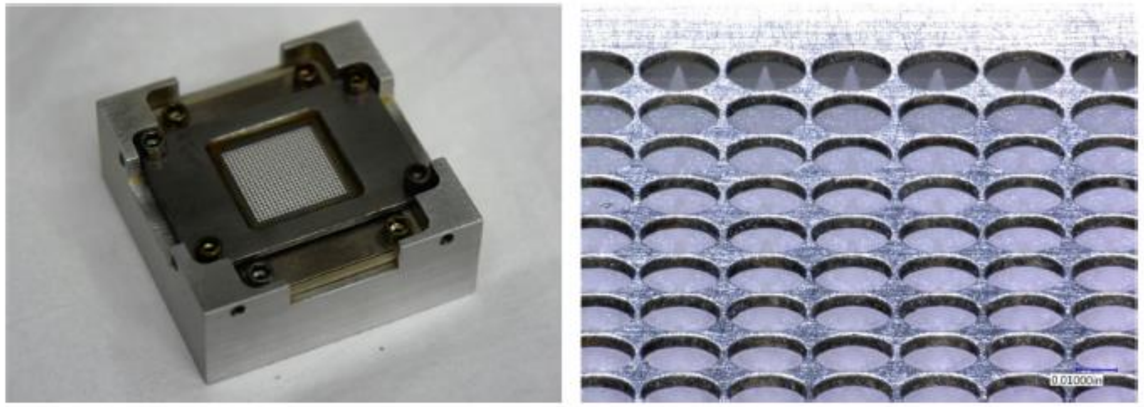
[1] Staab, D., Frey, A., Garbayo, A., Shadbolt, L., Baxter, T., Reeve, S., Hoffman, D., Grubisic, A., "XMET: Design and early testing of a xenon microwave electrothermal thruster," IEPC-2019-405.
[2] Tweet by David Fearn on Feb 23, 2021. https://twitter.com/fearn_lab/status/1364215717986451462
[3] Staab, D., Frey, A., Garbayo, A., Shadbolt, L., Grubisic, A., Hoffman, D., Romei, F., Faircloth, D., Laurie, S., "XMET: A xenon electrothermal thruster using additive manufacturing," Space Propulsion, 2018, 2018.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

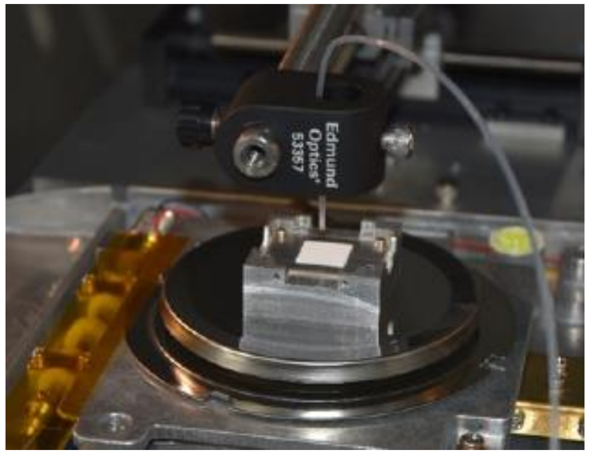
DISTRO A: Approved for public release. OTR-2024-00338

AFET-2

Propulsion Technology	Electrospray
Manufacturer/Country	AFRL/USC (USA)
TRL	3
Size (including PPU)	<1U
Design satellite size	1U or larger (scalable)
Isp (s)	1500s
Thrust type/magnitude	40 uN
Delta-V (m/s)	
Propellant	EMI-BF4
Power consumption (W)	<1W
Flight heritage (if any)	None
Commercially available	NO
Last updated	03/2021



AFET-2 full assembly and close-up of extractor grid and emitters



AFET-2 thruster being filled with EMI-BF4 propellant in a vacuum chamber

Additional comments:

[Ref 1][Oct 2019][Thruster design]
This thruster contains 576 discrete emitters machined into porous borosilicate glass over a 1.6 cm2 active thrust area. The emitters are approximately 300 um tall with typical radius of curvatures of 10-20 um, and are separated by a pitch of 550 um in both the horizontal and vertical directions. The thruster contains approximately 0.5 mL of on-thruster propellant, where the porous materials are such that the pore size is smallest at the emitters to promote capillary feed in that direction. The extractor grid consists of 75 um thick molybdenum with 500 um diameter apertures of the same number and pitch as the emitters. The thruster connections are located on the bottom and include a high-voltage pin and the extractor grid connection. The high voltage pin is set against a distal electrode which is in contact with the emitters and so allows biasing of the propellant within the thruster, whereas the extractor connection is made on the rear of the housing which is electrically tied to the extractor grid.

I-V curves, direct thrust, energy distributions, angular distributions, and mass composition measurements have been completed. These data show start-up voltages as low as 800 V, with stable high-power operation of the thruster producing +/- 700 uA at approximately +/-1840 V, resulting in over 40 micronewtons of thrust at 1.3 W input power. The reference contains detailed efficiency discussions and information on how the thruster is filled with propellant.

[Ref 2][March 2021][Thruster design]
The USC testbed thruster (UTT) is a passively fed electrospray thruster and is a simplified 50% scale AFRL AFET-II, modified to have only 25 emitters on a 1 cm diameter. Preliminary testing has been conducted which will drive further design optimization.

References:
[1] Natisin, M., Zamora, H., “Performance of a fully conventionally machined liquid-ion electrospray thruster operated in PIR (Purely Ionic Regime),” IEPC-2019-522.
[2] Antypas, R., Wang, J., “Pure ionic electrospray extractor design optimization,” IEPC-2019-372

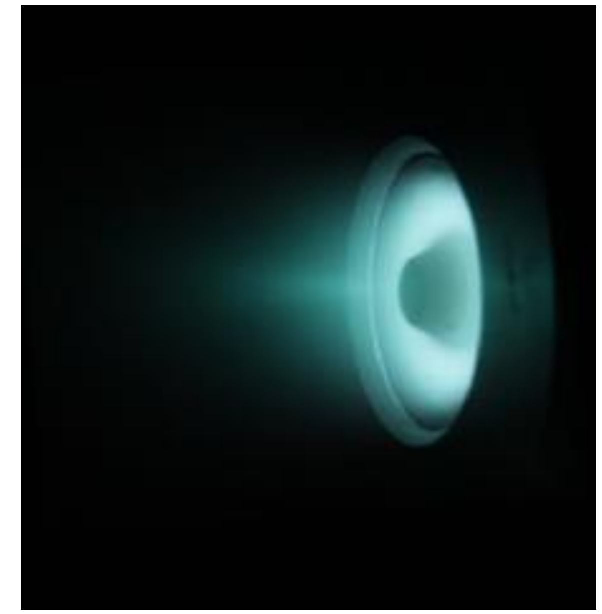
NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

50W KAIST HET

Propulsion Technology	Hall Effect Thruster
Manufacturer/Country	Korea Advanced Institute of Science and Technology (KAIST) (South Korea)
TRL	3
Size (including PPU)	~1U
Design satellite size	3U and larger
Isp (s)	817s at 52W anode power
Thrust type/magnitude	2.6 mN at 52W anode power
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	42 to 74W, 160 to 280V
Flight heritage (if any)	None
Commercially available	NO
Last updated	03/2021



KAIST HET, firing with xenon propellant

Additional comments:

[Reference 1][Oct 2019][Thruster status]
A 50 W-class Hall thruster was developed and initial tests were conducted, including thrust and ion current density measurements. The developed thruster showed stable operation in the 50 W-class power range; however, further optimization is required to improve thruster performance and stability at over 80 W of anode power. The measured thrust, specific impulse, and anode efficiency are 2.6 mN, 817 s, and 20%, respectively at 52 W anode power. Under these conditions, the current and propellant efficiencies are 0.62 and 0.58, respectively. Research aimed at improving the design and performance of the developed 50 W-class Hall thruster is ongoing.

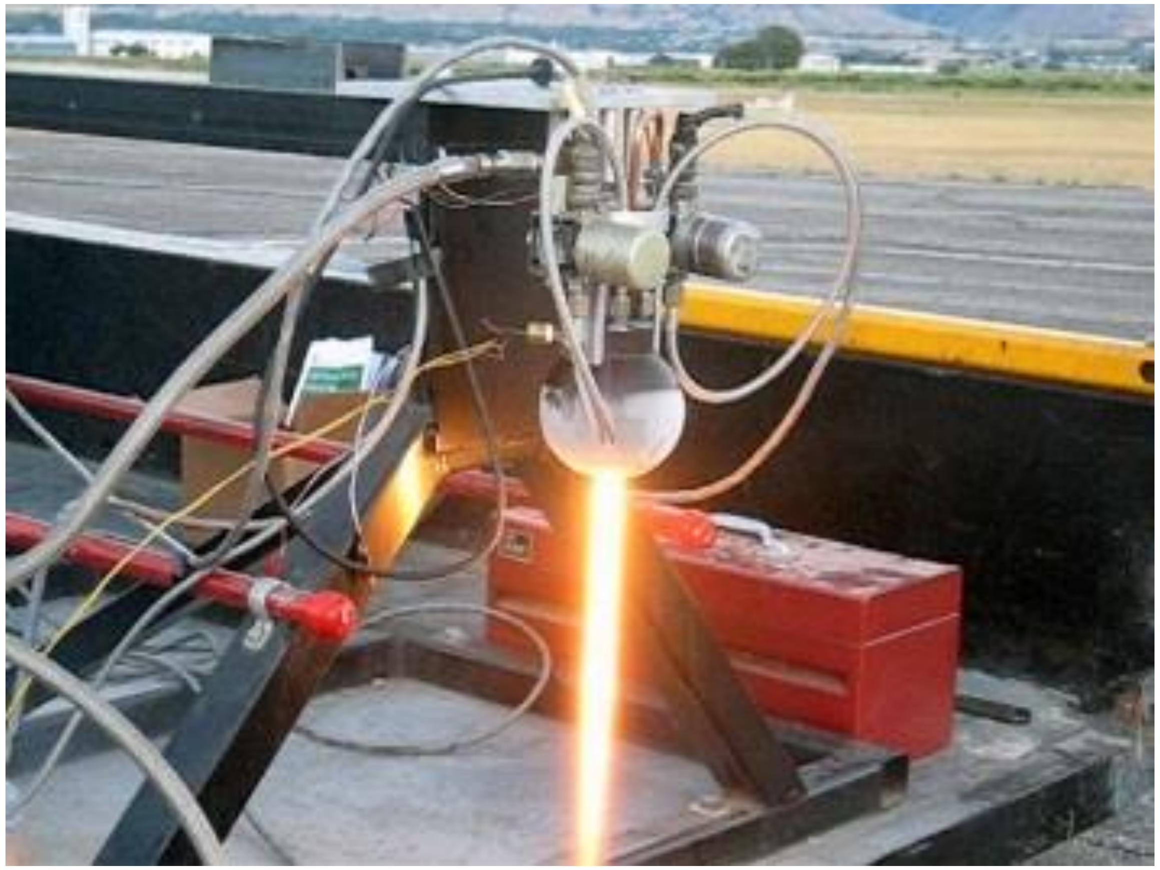
References:
[1] Lee, D., Kim, H., Lee, S., Doh, G., Choe, W., “Development and performance test of a 50W-class Hall thruster,” IEPC-2019-599.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Additive Manufactured Propulsion System Hybrid (AMPS, AMPS-H)
Experimental Propulsion Laboratories (EPL)

Propulsion Technology	Hybrid, Additively Manufactured
Manufacturer/Country	Experimental Propulsion Laboratories (EPL)/CRP – Windform Manufacturer (USA)
TRL	3-4
Size (including PPU)	1U, estimated
Design satellite size	3U, 6U, and larger
Isp (s)	270s
Thrust type/magnitude	6.2 lbf for 16 seconds 142 N*s (total impulse)
Delta-V (m/s)	784 m/s for 10 kg (6U) spacecraft, in development
Propellant	Windform material + Nitrous oxide
Power consumption (W)	In development
Flight heritage (if any)	None known
Commercially available	Unknown
Last updated	*03/2021*



Testing the AMPS-H system

Additional comments:

[Reference 1-3][Jan 2019][General info]
This is a 3-d printed windform hybrid that uses its material (windform) as the fuel. For safety, all-electrical ignition was used instead of chemical ignition. An electrical current was used to heat a uniquely designed catalyzed heat exchanger that decomposed the nitrous oxide into a mixture of hot oxygen and nitrogen gas. This hot gas entered the AMPS-H combustion chamber and auto-ignited the fuel grain. Once ignition was complete the electrical heater is turned off.
The company that produces Windform still exists (CRP-USA), however the status of the thruster appears to be unknown – as of 2018, no publications are found after 2012. The material is better suited for structural components of CubeSats (frames, brackets, etc.). Material properties of the material are available from the manufacturer.

References:
[1] Dushku, M., Mueller, P., "Additively Manufactured Propulsion System," Small Satellite Conference, SSC12-III-2.
[2] http://www.crp-usa.net/windform-3d-printing-materials-usa/
[3] http://aviationweek.com/awin/race-car-technology-applied-cubesat-propulsion

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Hydrazine Milli-Newton Thruster (HmNT)

Propulsion Technology	Hydrazine monoprop
Manufacturer/Country	JPL (USA)
TRL	3-4
Size (including PPU)	<1U, 40g
Design satellite size	1U or larger, 20-30 kg ideal for S/C attitude control
Isp (s)	Not reported, but likely ~200s
Thrust type/magnitude	0.02N (continuous, nominal) 50 uN*S (impulse bit, minimum)
Delta-V (m/s)	
Propellant	Hydrazine
Power consumption (W)	8W (valve), 0.25W (cat bed heater)
Flight heritage (if any)	None known
Commercially available	No
Last updated	*03/2021*

Thruster

Thruster installed on JPL milli-newton thrust stand

Additional comments:

[Reference 1][Jan 2019][General info]
The ideal applications for this system is spacecraft attitude control for a 20-30 kg vehicle. Well suited for spacecraft ACS where I-bit requirements may be low and a liquid system is needed (low leakage concerns, low tank mass). The minimum impulse bit is smaller than the conventional Aerojet MR-103 by a factor of 100, making it ideal for attitude control where low impulse bits are ideal. This was accomplished by mating the very small thruster with small flow passages to a fast-acting valve. It also offers a significant size (10X) and mass (5X) reduction over the Aerojet MR-103. Pulsed mode operation was demonstrated in 2007 in a vacuum chamber at JPL on a micro-Newton thrust stand. Continuous firing was planned for 2008.

References:

[1] Mueller, J., Ziemer, J., Hofer, F., Wirz, R., O'Donnell, T., "A Survey of Micro-Thrust Propulsion Options for Microspacecraft and Formation Flying Missions," Cube Sat 5th Annual Developers Workshop, San Luis Obispo, CA, 2008.
[2] Parker, J., Lewis, J., "A micro newton impulse-bit hydrazine thruster – design, test, and mission applications," JANNAF, 2016.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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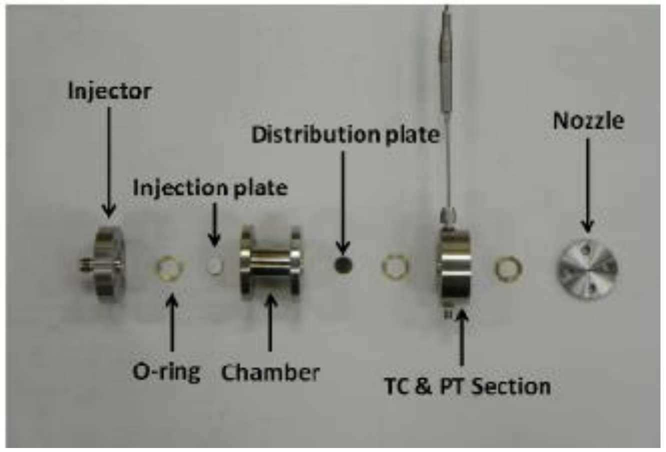
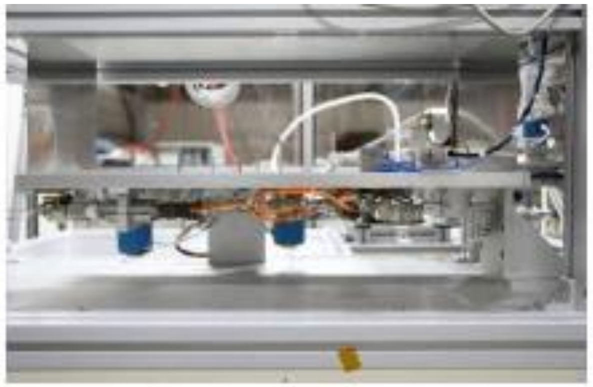
Hydrogen Peroxide thruster

Propulsion Technology	Hydrogen peroxide monopropellant
Manufacturer/Country	National Space Organization, Taiwan (TAIWAN)
TRL	3-4
Size (including PPU)	30cm x 30cm x 20cm
Design satellite size	50-100 kg (large)
Isp (s)	102s (preliminary measurement)
Thrust type/magnitude	0.7N (preliminary measurement)
Delta-V (m/s)	
Propellant	Hydrogen peroxide, silver catalyst
Power consumption (W)	
Flight heritage (if any)	None known
Commercially available	No
Last updated	*03/2021*



Thruster parts

Thrust stand/balance


Additional comments:

[Reference 1-2][Jan 2019][General info]
Catalyst bed was packed inside the chamber and fixed between injection plate and distribution plate. Injection plate and distribution plate were designed for distributing liquid H2O2 and decomposed water vapor and oxygen uniformly, respectively. Considering the precision of the thruster, injection plate was manufactured by electro discharge machining and inspected under microscope. A 1N thruster prototype using combination of silver and ceramic material as catalyst bed for the hydrogen peroxide monopropellant has been tested by self-development thrust measurement system. Results show the stability is good by monitoring the chamber pressure and temperature. The thrust level is 0.7N in ambient and the specific impulse is about 102 seconds. Repeatability, blow-down test and environmental test are scheduled to be performed in September 2013.

[Reference 2][Dec 2019][Test results]
One of the green propellants, high-concentration hydrogen peroxide solution (H2O2≥85%wt, weight concentration percentage), often known as high-test peroxide (HTP), is considered because it is ITAR-free, high density, easy to manufacture and handling. To establish satellite propulsion technology, the National Space Organization (NSPO) in Taiwan has initiated a project with a Formosat-7 NSPO-Built satellite (FS-7 NB). A reaction control subsystem demonstration module (RCS-DM) using high-test peroxide as propellant has been allocated to perform orbit transfer and maintenance operations. In the present research, an 1-Newton thruster prototype is designed and the thrusting force is measured by a pendulum-type platform. The preliminary hot-firing test at ambient environment showed the generated thrust and the specific impulse are about 0.7 Newton and 102 seconds, respectively.

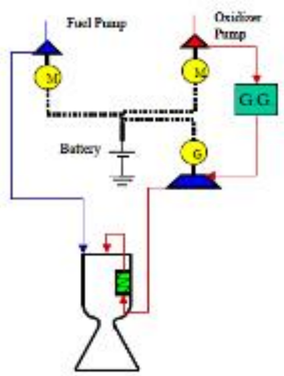
References:
[1] Chan, Y., Liu, H., Tseng, K., Kuo, T., “Preliminary Development of a Hydrogen Peroxide Thruster,” World Academy of Science, International Journal of Aerospace and Mechanical Engineering, Vol 7, 2013.
[2] Chan, Y., Kuo, T., Tseng, K., “Development and hot-firing test of a hydrogen peroxide thruster for Formosat-7 project,” Space Propulsion Conference, 2014.

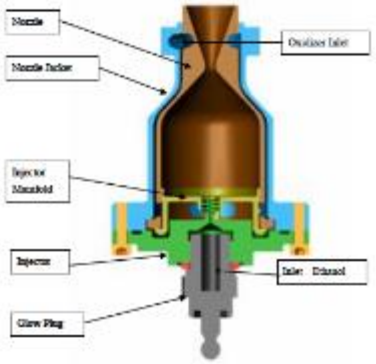
NO	3	NO
Comm. avail.	TRL	Aerospace-tested

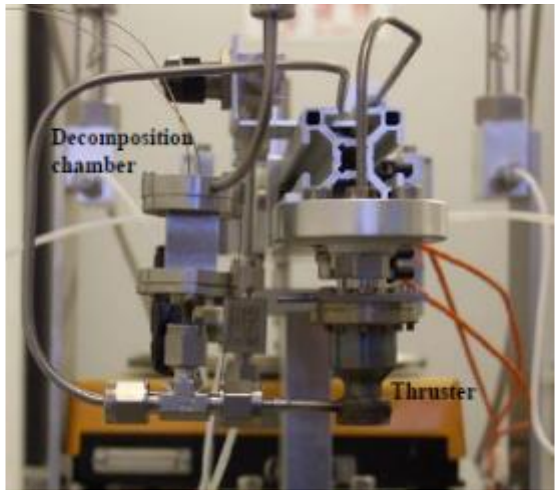
DISTRO A: Approved for public release. OTR-2024-00338

Turbo-pump fed micro rocket engine (TPF-MRE)

Propulsion Technology	Bipropellant
Manufacturer/Country	Mechatronic/ESA (Austria)
TRL	2-3
Size (including PPU)	0.8 liters
Design satellite size	10 to 100 kg
Isp (s)	>230 (design)
Thrust type/magnitude	1N (design)
Delta-V (m/s)	500 m/s for 10 to 100kg spacecraft (design)
Propellant	Fuel: Ethanol or kerosene Oxidizer: Hydrogen peroxide (H2O2) (decomposed over catalyst to water (H2O) and oxygen (O2))
Power consumption (W)	6W (design)
Flight heritage (if any)	None known
Commercially available	NO
Last updated	*03/2021*







Additional comments:

[Reference1][Jan 2019][General info]
Under contract from the European Space Agency, ARC has initiated in 2004 the development of a bipropellant propulsion system in cooperation with Mechatronic. The Turbo-Pump Fed Micro Rocket Engine (TPF-MRE) consists of four main components: the propellant pumps, a decomposition chamber with a monolithic catalyst, a turbine, and the thruster itself. The pumps are generating the pressure head to feed the fuel and oxidizer into the combustion chamber. While the fuel (ethanol or kerosene) is fed directly into the combustion chamber, the hydrogen peroxide is led over a catalyst bed. In a combination of catalytic and thermal decomposition, hydrogen peroxide is decomposed into water and oxygen. Since this is a highly exothermic reaction, the mixture will leave the catalyst in gaseous form and is fed directly into a microturbine. Using the energetic mixture, the microturbine generates the electrical power necessary to drive the two pumps. After exiting the turbine, the water/oxygen mixture is fed via cooling channels along the nozzle, throat, and combustion chamber walls into the combustion chamber. Although no direct thrust measurements have been conducted up to this date, the knowledge of the mass flow rate and estimated combustion chamber temperature allow the calculation of the theoretically possible performance of this system. Using the standard Gordon & McBride software (NASA shareware) a thrust and of 1.73- 1.94 N at a specific impulse between 294 – 329 s was calculated. The H2O2 concentration was 88%.

[Reference 2][Jan 2019][General info]
The main development goal of this effort was the utilization of ethanol in combination with hydrogen peroxide (H2O2) as a non-toxic propellant combination. The Turbo-Pump Fed Miniature Rocket Engine (TPF-MRE) is a bipropellant thruster consisting of four subsystems: the propellant pumps, a decomposition chamber with a monolithic catalyst, a turbine, and the thruster itself. The turbine is driven by the decomposed hydrogen peroxide and magnetically coupled with a power generator. The power produced is then used to generate a pressure head in order to deliver the propellant into the combustion chamber. This system therefore constitutes a self-sustaining system and does not rely on the limited power supply of a micro-satellite. Previous test have shown that although the thruster can be operated with ethanol and oxygen, it was not possible to ignite the thruster when utilizing hydrogen peroxide in a 70% concentration by weight. A minor redesign of the thruster and the test facility was therefore initiated. This redesign together with the use of hydrogen peroxide in higher concentration was speculated to improve this behavior. However, even though the monolithic catalysts were able to decompose hydrogen peroxide in a concentration of 87.5 % with nearly 100 % efficiency, it was not possible to ignite or operate the thruster. Subsequently, a thorough investigation of the baseline design and operational conditions of the thruster was conduced. It was found that the failure of the thruster to ignite is due to a combination of reasons. The combustion chamber length is too short to facilitate sufficient mixing of the propellants, making an ignition impossible or very difficult at least. Additionally, the combustion chamber pressure which was chosen such that it accommodates the performance of commercially available micropumps is considered too low. This further deteriorates the conditions for which an ignition is feasible.

References:
[1] Scharlemann, C., Schiebl, M., Amsuss, R., Tajmar, M., "Development of Miniaturized Green Propellant based Mono- and Bipropellant Thrusters," AIAA 2007-5580.
[2] Scharlemann, C., Schiebl, M., Marhold, K., Tajmar, M., et al., "Test of a turbo-pump fed miniature rocket engine," AIAA-2006-4551.

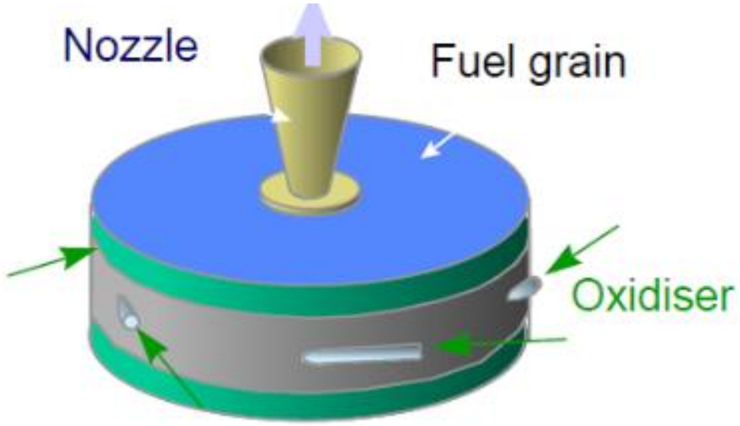
NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

Vortex flow pancake (VFP) hybrid rocket

Propulsion Technology	Hybrid rocket
Manufacturer/Country	University of Surrey (UK), later Politecnico de Milano (ITALY)
TRL	2-3
Size (including PPU)	~1U
Design satellite size	3U and larger
Isp (s)	250s (estimated based on similar studies [4])
Thrust type/magnitude	40N (estimated based on similar studies [4])
Delta-V (m/s)	800 m/s for a 100 kg s/c
Propellant	Various, Italian studies were paraffin-blend.
Power consumption (W)	Minimal
Flight heritage (if any)	None known
Commercially available	No
Last updated	*03/2021*



Vortex flow combustion seen through a plexiglass fuel grain (for flowfield demonstration)

Additional comments:

[Reference 1][Jan 2019][General info]
One of the primary obstacles that has kept hybrid technology from being employed on spacecraft is their historically long and slender geometry. Long and slender geometry coupled with the requirement to mount the motor inline with the spacecraft centre of gravity presents a prohibitive combination to the small spacecraft designer. In addition, the heat generated by a hybrid rocket can present thermal difficulties especially when the motor and catalyst pack are embedded deep within a small spacecraft. We have developed a novel configuration for a hybrid motor that fits within the volume constraints of a small satellite. Its "pancake" structure ensures good mixing of oxidizer and fuel within a confined space, making use of vortical flow within the chamber. The use of this unique hybrid technology provides a very high thrust propulsion system for our satellites. The vortex flow pancake (VFP) hybrid engine completed its testing phase with the design of an engine capable of providing 800 m/s of delta-V on a 100 kg microsatellite. The engine demonstrated exceptional efficiency, with performance within 1 per cent of theoretical, unheard of for a hybrid rocket engine. The design also provided exceptionally smooth combustion. Work on an unusual-geometry hybrid rocket was inspired by the tight volumetric constraints imposed by small spacecraft. As such it has engendered serious interest from mission designers who are grappling with severe volume constraints yet require relatively high performance propulsive capability.

[Reference 2][Jan 2019][Thruster testing]
Numerical simulations and experimental tests were performed on the vortex configuration. The propellant in this study was a blend of paraffin (60 wt.%), and polystyrene-block-poly(ethyleneran-butylene)-block-polystyrene grafted with maleic anhydride (SEBS, 40 wt.%). Gaseous oxygen was used as the oxidizer. A combustion efficiency of ~68% was achieved. The study suggested further testing, including time-resolved regression rate measurements and the development of a experimental facility to measure the thrust and spin moment derived from the swirl velocity component.

[Reference 3][Dec 2019][Thruster testing]
The stop and restart capability of the motor is proven by tests in which re-ignition is triggered by surface hot-spots and oxidizer mass flow rate throttling. The fuel regression rate was also measured and was determined to depend mainly on propellant mass flux.

References:
[1] https://www.surrey.ac.uk/surrey-space-centre/research-groups/propulsion
[2] Paravan, C., Gowacko, J., Carlotti, S., Maggi, F., Galfetti, L., “Vortex Combustion in a Hybrid Rocket Motor,” AIAA-2016-4562.
[3] Haag, G., Swwting, M., Richardson, G., “Low cost propulsion development for small satellites at the Surrey Space Centre,” SSC99-XII-2.
[4] Spektor, R., Fathi, G., Brady, B., Moore, T., “2011 Review of Propulsion Options for the Aerospace CubeSat Project,” Aerospace report TOR-2011(8582)-6
[5] Paravan, C., Lisi, F., Massimo, P., Bisin, R., Galfetti, L., “Burning behavior investigation of a vortex flow pancake hybrid rocket engine,” AIAA 2019-4418, P&E Forum, 2019.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

PET-100-MK2 Electrospray

Propulsion Technology	Electrospray
Manufacturer/Country	University of Southampton (UK)
TRL	3-4
Size (including PPU)	<1U, similar to MIT's electrospray size
Design satellite size	1U or larger (scalable technology)
Isp (s)	Not yet characterized
Thrust type/magnitude	Not yet characterized
Delta-V (m/s)	
Propellant	EMI-BF4 ionic liquid
Power consumption (W)	<1W
Flight heritage (if any)	None
Commercially available	NO
Last updated	03/2021

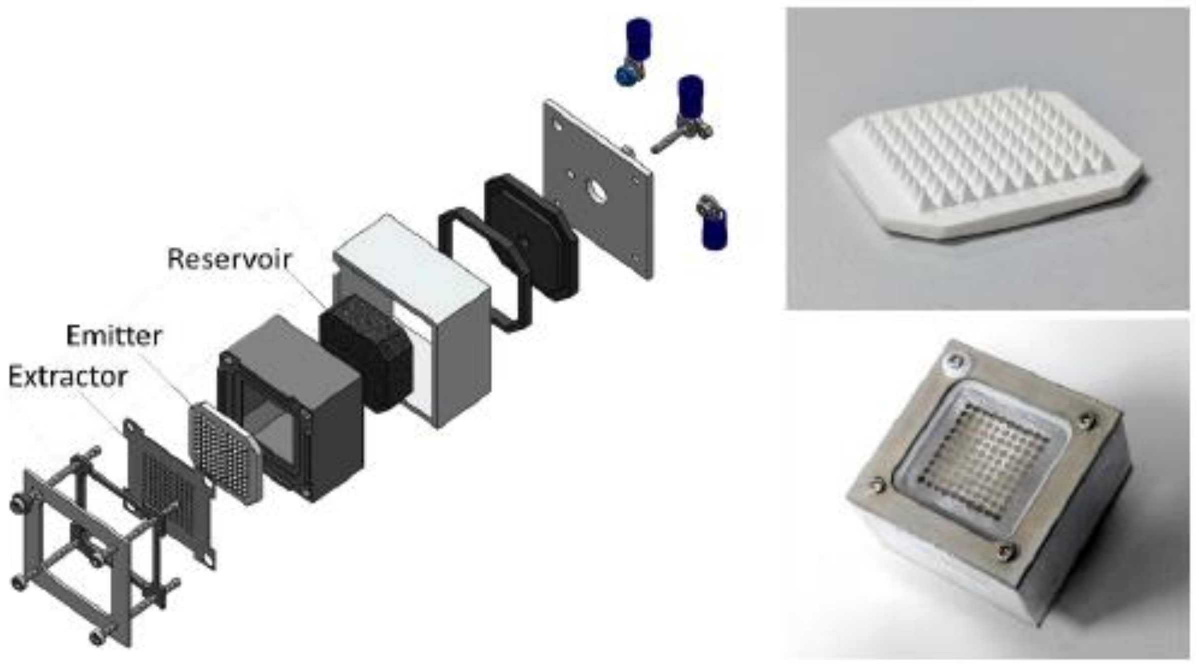


Figure 1. PET-100-MK2 thruster design and manufactured results.

Additional comments:

[Ref. 1][Oct 2019][Thruster characterization]

This paper focuses on the plume characterization of the PET-100-MK2 thruster. The voltage for suppressing secondary electron emission was identified, -80 V was proven effective for the thruster operation range of ±3500 V operation. The voltage losses of the emitted particles were mainly resulted from the resistance of propellant liquid, counting for 8-14% of the applied emitter voltage. The retarding potential analysis results strongly suggest fragmentation effects of dimer ions into monomers of ions occurring before and after leaving the acceleration electric field. The plume half-angle of the thruster ranges from 12.4 to 60.8 degrees depending on the applied emitter voltage, a lower operation voltage can effectively reduce the plume half-angle, although at the expense of lower thrust and specific impulse. The performance of the thruster was reasonably stable during an 18 hours long lifetime test, after which the test ended with the broke down of the polarity switching unit. The current was varying during the test but within a reasonable range. However, accumulated electrochemical effects are still the main problems limiting the lifetime of the PET-100-Mk2 thruster.

The Porous-emitter Electrospray Thruster, termed the PET-100-MK2 thruster, uses 1-Ethyl-3-methylimidazolium tetrafluoroborate (EMI-BF4) as the propellant. The thruster consists of an emitter, an extractor, a reservoir, a set of thruster mounts, and shielding parts. The emitters were CNC machined from a substrate of porous borosilicate material, which has a void ratio approximately 0.5 and a pore size of either from 1 to 1.6 μm or from 10 to 16 μm, depending on the porous grade of the material used. A 10 × 10 array of emitter tips, with a pitch distance of 2 mm, was manufactured on a 20 × 20 mm emitter substrate. The reservoir was also a porous stainless-steel substrate which is 10 mm thick and has larger pores than the emitter material, allowing the propellant passively transported. The conductive porous substrate also acted as a distal electrode to mitigate detrimental electrochemical effects during the electrospray. The extractor was waterjet cut from a 0.25 mm thick stainless steel sheet. The apertures have a diameter of 1.5 mm. These components were held in a thruster mount made of ceramic-filled resin material using 3D printing technology. The thruster was covered by a set of shielding parts made of aluminium and stainless steel to reduce the interference of electric field pulse from thruster to other electronics placed in the surrounding environment.

[Reference 2][March 2021][Thruster characterization]

An RPA was used to characterize the energy distribution of the plume particles from an electrospray source. The energy analysis shows evidence of fragmentation of heavier particles, mostly from dimer ions to monomer ions, and the detailed energy analysis was used to estimate the position where the fragmentation occurs. The results suggest that about 45% to 55% of the particle fragmentation occurred in the field-free region and 20%-30% occurred in the acceleration region with an intense electric field, with the rest of the plume containing unfragmented ions.

References:

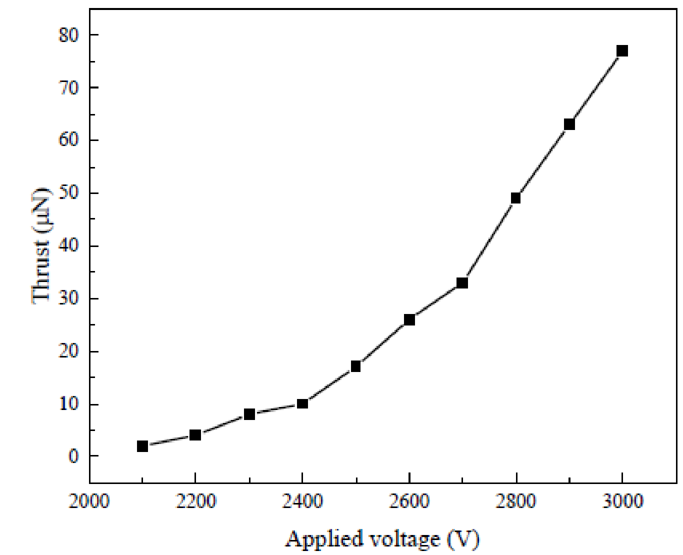
[1] Ma, C., Ryan, C., "Plume characterization of a porous electrospray thruster," IEPC-2019-A223

[2] Ma, C., Ryan, C., "Plume particle energy analysis of an ionic liquid electrospray ion source with high emission density," Journal of Applied Physics, Vol. 129, 2021.

Comm. avail.	TRL	Aerospace-tested
NO	3	NO

Jiao Tong electrospray

Propulsion Technology	Electrospray
Manufacturer/Country	Shanghai Jiao Tong University (CHINA)
TRL	3
Size (including PPU)	<1U
Design satellite size	1U or larger
Isp (s)	1800 s (calculated)
Thrust type/magnitude	77 uN
Delta-V (m/s)	
Propellant	EMI-BF4
Power consumption (W)	<1W
Flight heritage (if any)	None
Commercially available	NO
Last updated	03/2021



Additional comments:

[Ref 1][Oct 2019][Thruster design and summary]
Ionic liquid electrospray thrusters, with advantages of high specific impulse, small volume and low power, have been considered as a promising propulsion option for nanosatellites. However, the thrust provided by one emission site of an electrospray thruster is small (10-100 nN) and therefore challenges are presented in scaling up the total emission currents with a good performance. This paper presents a miniaturized ionic liquid electrospray thruster using an array of sharp blades as emitter. The porous emitter array, integrated with seven 10 mm long sharp blades, is fabricated using wire electrical discharge machining (WEDM) combined with electrochemical etching. The propellant is passively fed to the emitter by capillary force so that the thruster configuration is compact and nonpressurized. The manufactured thruster is 30 mm×30 mm×17.5 mm in size and weighed less than 25 g. I-V test, time of flight (ToF) test, spatial plume distribution test and thrust test have been conducted in vacuum to characterize the performance of the thruster. Results show that the emitted current reaches 804 μA at +3000 V with a half plume angle of 60-70 degrees. Besides, when the applied voltage is 3000 V, the specific impulse of the electrospray thruster is estimated to be 1779.7 s and the thrust measures 77 μN.

References:
[1] Liu, X., Kang, X., He, W., Wu, Q., "Development and characterization of an ionic liquid electrospray thruster with a porous metal blade array," IEPC-2019-471.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

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EMPPT Malta

Propulsion Technology	Pulsed Plasma Thruster
Manufacturer/Country	University of Malta (Malta)
TRL	3
Size (including PPU)	<1U
Design satellite size	1U and larger
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	PTFE
Power consumption (W)	2-5W
Flight heritage (if any)	None
Commercially available	NO
Last updated	03/2021

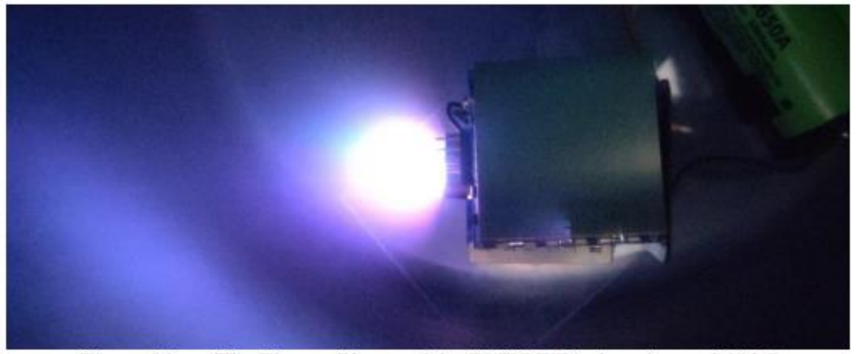
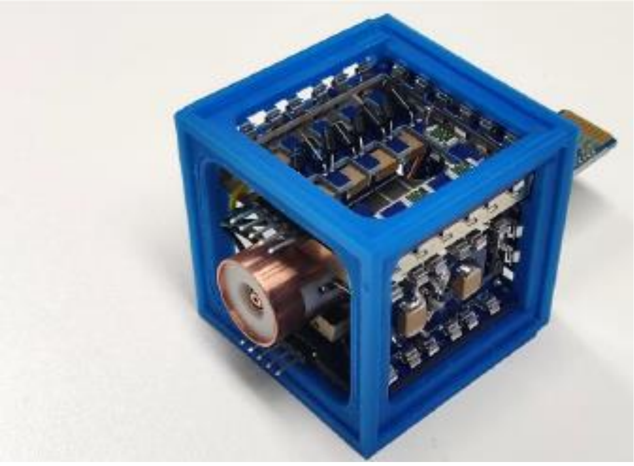


Figure 13. The Plasma Plume of the EMPPT Discharging at 0.338 J



Additional comments:

[Ref 1][Oct 2019][Thruster info]
The weight of the system excluding the solar panels, batteries, and frame is 88.3 g, which is within the mass constraint of the PQ. Inside the vacuum chamber, the PPT PQ (PocketQube) subsystems are powered by two 3.7 V 5000 mAh lithium ion batteries to extend the lifetime of the thruster.
Launching the PQs into a low meta-stable orbit where they will naturally de-orbit in a relatively short time allows for a failsafe method for decommissioning individual malfunctioning PQs in large constellations. Low cost PPT technology will be required to actively maintain the satellite's orbit while the mission is underway. At an altitude of 500 km with an average air density of 5.9×10−13 kg/m3, the estimated orbital life of a 500 g 2p PQ is estimated to be around 9.7 years. Firing a PPT with a total discharge energy of 0.338 J per pulse once every 25 seconds with a minimum target efficiency of 3.9 % will increase the estimated orbital life of the PQ by approximately 7.8 years.
Two PPT configurations were developed as part of the project, both having a capacitor bank of 1.88 μF. A main discharge supply capable of charging the main capacitor bank to a maximum of 900 V was developed together with an ignition subsystem, capable of producing a high voltage pulse of around 13.8 kV. A microcontroller subsystem was developed to monitor and adjust the voltage on the main capacitor bank, allowing the PPT to discharge at variable energy levels and at different frequencies.
Future iterations of the PPT PQ will include infrared light-emitting diodes instead of a Bluetooth® device for communication to improve reliability, while reducing failure rates. The main discharge power supply circuitry will be re-designed as to increase the subsystem efficiency, and further EMI protection measures will be implemented to ensure the safe operation of the PQ subsystems. In addition to the development of the PPT PQ, the development of a micro thrust measurement system is ongoing. Additional experiments such as the mass ejected per pulse, EMI testing, and, lifetime and reliability testing will be conducted in the near future.

References:
[1] Sammut, M., Azzopardi, M., Fenech, M., "Development of pulsed plasma thruster for a picosatellite," IEPC-2019-616.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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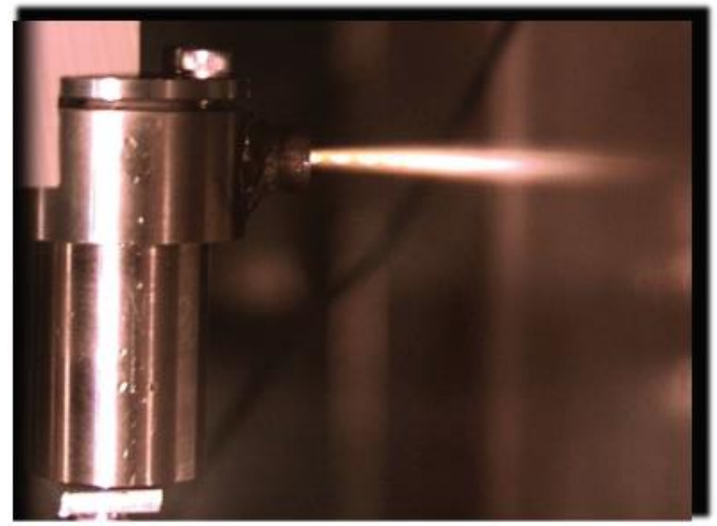
MPM-7
Digital Solid State Propulsion (DSSP)

Propulsion Technology	Solid rocket motor
Manufacturer/Country	DSSP (US)
TRL	2-3
Size (including PPU)	<0.75U
Design satellite size	>=3U
Isp (s)	200
Thrust type/magnitude	Maximum pulse duration = 0.5 s 1.5 N*s (total impulse) 0.05 N*s (minimum impulse bit) 0.3 N*s (maximum impulse bit)
Delta-V (m/s)	
Propellant	HIPEP-H15
Power consumption (W)	200W, on 12-28 VDC
Flight heritage (if any)	None
Commercially available	YES
Last updated	*03/2021*



DSSP's MPM-7 motor

Performance Goals

MOTOR DIMENSION GOALS
Motor Diameter (cm)....................2.5
Motor Lenght (cm)....................4.7

MOTOR PERFORMANCE GOALS (VAC)
Maximum Pulse Duration (sec)....................0.5
Total Impulse (N-s)....................1.5
Effective Vacuum Specific Impulse (sec)....................200
Minimum Impulse Bit (N-s)....................0.05
Maximum Impulse Bit (N-s)....................0.3
Number of Pulses (per motor, max pulse duration)....................5

MOTOR WEIGHT GOALS
Total Loaded (g)....................30

POWER PROCESSING UNIT (PPU) GOALS
Power Supply Range (VDC)....................12-28
Input Power (W)....................200
Motors to be Controlled by a Single PPU....................12-24
Mass (g)....................<750
Height (U)....................<0.75

PROPELLANT TYPE: HIPEP-H15
PRODUCTION STATUS: Qualified for Flight
EXPECTED SHIPPING CLASSIFICATION: DOT Class 1.4

Additional comments:

[Reference 1-2][Dec 2019][Thruster specs]
DSSP has developed a multi-pulse motor fueled by a similar nonmetallized, Electric Solid Propellant (HIPEP) to that which was deployed from the International Space Station during the SPINSAT mission. The design goal of this system is to desaturate reaction wheels on 6U or 12U deep space CubeSats. DSSP currently has a flight-ready system that was developed for NASA. It is designed to control 12-24 thrusters using a single PPU.

With each motor supplying at least 5 pulses, they can deliver a total impulse of 1.5N-s. This system has been qualified for flight and can be customized to meet the specific needs of the mission.

Only design goal specifications exist. No open literature or projected mission could be found.

References:
[1] https://dssptech.com/propellant-products
[2] https://static1.squarespace.com/static/59de9c9c18b27ddf3bac610a/t/5a3a9ea6e2c483d9690f1308/1513791148955/Brochure+Inlet+MPM+7+Website.pdf

3 NO
Comm. avail. TRL Aerospace-tested

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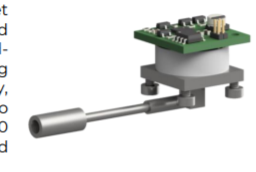
Orbital Thruster (OT)/Nano OT/Micro OT/Small OT [1 of 2]

Propulsion Technology	Water resistojet
Manufacturer/Country	Aurora (FINLAND)
TRL	2-3
Size (including PPU)	20mm x 20mm x 20mm (Nano) 30mm x 30mm x 30mm (Micro) 30mm x 100mm x 100mm (Small)
Design satellite size	1U or larger
Isp (s)	100-130s
Thrust type/magnitude	0.2 to 2 mN 1 N*s (total impulse, Nano model) 20 N*s (total impulse, Micro model) 200 N*s (total impulse, Small model)
Delta-V (m/s)	
Propellant	Water-based (water with a pressurant)
Power consumption (W)	0.5 to 5W (0.05W at idle)
Flight heritage (if any)	None, expected first flight in late 2020
Commercially available	Yes, ~$15,000 [1]
Last updated	03/2021

AURORA
PROPULSION TECHNOLOGIES

Orbital Thruster (OT)

Orbital Thruster is a miniaturised resistojet propulsion module that uses water-based propellant. OT module is designed to be plug-and-play ready, as only power and connectivity wiring are required from the satellite. Size wise OT is tiny, but it still packs a punch as we estimate the nano size variant to have enough propellant for 100 firings. OT is perfect for propulsion experiments and orbital adjustments prolonging satellite's lifespan.



Small size to ensure large payload

Orbital Thruster module can be ordered in three different size variants: Nano, micro and small. Nano OT module measures 20mm * 20mm * 20mm making it one of the smallest thruster modules in the world. Larger variants which include bigger propellant tank are also possible to order. To achieve full attitude and orbital control we recommend using Aurora AOCS module.

Modular structure for custom requirements

Multiple thrusters can be installed to a single propellant tank. Optimal placement for the module is at the end of the satellite as OT module is designed for orbital manoeuvres.

Safety

Water-based propellent ensures safety both during the launch as well as during transport to the launch site; no dangerous chemicals are involved. A full tank's pressure is below 50 kPa, fulfilling all CubeSat launch standards.

Specs (Preliminary)

	Nano	Micro	Small
Power	0.5 – 5 W (idle 50mW)		
Thrust	0.2 – 2 mN		
Isp	100 – 130 s		
Impulse	1 Ns	20 Ns	200 Ns
Wet mass	15 g	60 g	300 g
Dry mass	14 g	40 g	100 g
Form	20 x 20 x 20 mm	30 x 30 x 30 mm	30 x 100 x 100 mm
Date available	Samples: Oct 2019 Deliveries: Dec 2019		
Price: (vat 0%)	12k€+		

Aurora Propulsion Technologies
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Website
www.aurorapt.fi
30/11/2019

Additional comments:

[Reference 1][Feb 2020][Company info]
Aurora Propulsion Technologies was founded in 2018. In early 2019 we joined European Space Agency Business Incubator Centre programme (ESA BIC Finland) in Otaniemi. Within a year from founding Aurora grew from 7 founders to 17 employees. A target of delivering our first thruster sample for a satellite on Q4 of 2019 is on schedule, with flight ready thruster delivery objective of early 2020. Initial flight date for the satellite is expected to be later in 2020. Our goals for the future include further scaling of our operations, in terms of production quantities and development of upcoming products and increasing our sales and customer base.

[Reference 2][Feb 2020][General info]
Most of the power is used for the heater, which heats the water up to 600C. There is some pressurant mixed in with the water (they did not disclose the pressurant). The absolutely P is <1 atm. It is very tiny.

References:
[1] https://www.aurorapt.fi/home/aboutus/
[2] Public conversations at SmallSat Symposium, Feb 2020 (A. Hsu, T. Curtiss, with Roope Takala, CEO).

3
NO
Comm. avail.
TRL
Aerospace-tested

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Orbital Thruster (OT)/Nano OT/Micro OT/Small OT [2 of 2]

Additional comments:

[Reference 1][March 2021][Company info]
Espoo, Finland (March 10th, 2021) –Expanding on its existing relationship with Momentus, Aurora is announcing its plans to launch a satellite with Momentus in June 2022.

References:
[1] https://aurorapt.fi/press-release/aurora-propulsion-technologies-expands-relationship-with-momentus/

3

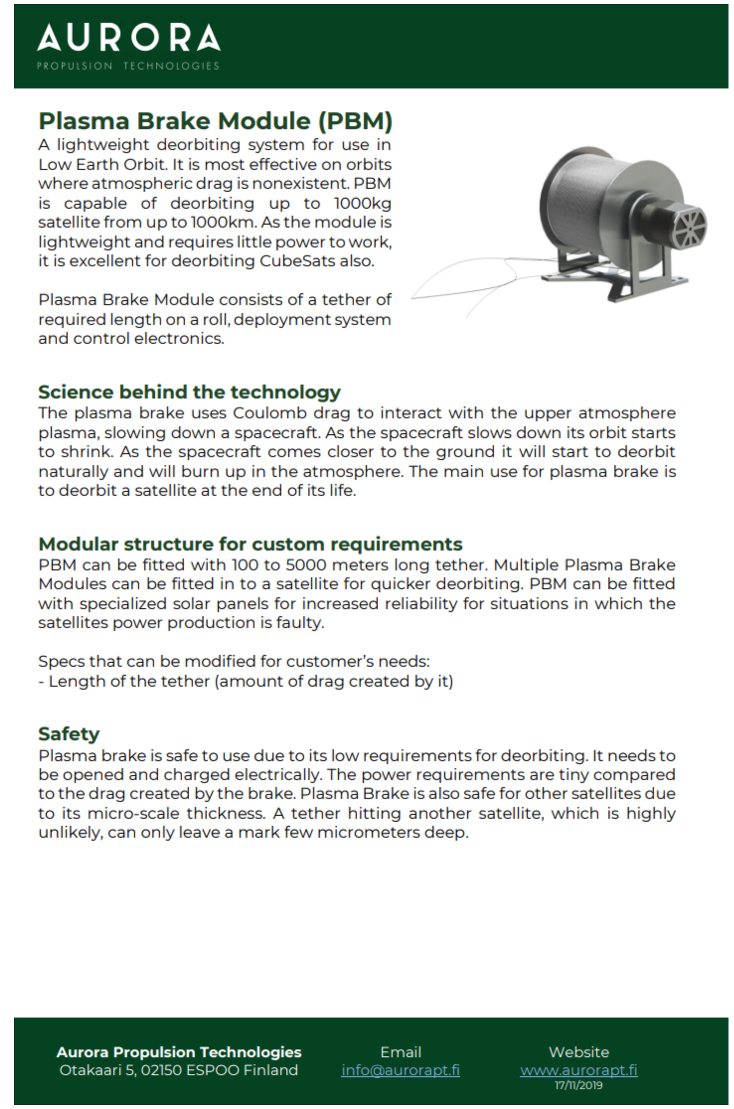
NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Plasma Brake (CubeSat, Micro, Small) [1 of 2]

Propulsion Technology	Tether
Manufacturer/Country	Aurora (FINLAND)
TRL	3
Size (including PPU)	3cm x 5cm x 5cm (CubeSat size) 10cm x 10cm x 10cm (Micro/Small size)
Design satellite size	1U+
Isp (s)	N/A, propellantless
Thrust type/magnitude	Up to 100 nN/m
Delta-V (m/s)	
Propellant	Propellantless
Power consumption (W)	0.25 to 1W (CubeSat size) 1-4 W (Micro/Small size)
Flight heritage (if any)	None Projected for AuroraSat-1 [Jan 2021, now delayed to likely 2022] [3, 4, 5]
Commercially available	Yes, anticipated flight for later 2020 $20,000 for CubeSat size $75,000 for Micro/Small size
Last updated	12/2021


AURORA
PROPULSION TECHNOLOGIES

Plasma Brake Module (PBM)

A lightweight deorbiting system for use in Low Earth Orbit. It is most effective on orbits where atmospheric drag is nonexistent. PBM is capable of deorbiting up to 1000kg satellite from up to 1000km. As the module is lightweight and requires little power to work, it is excellent for deorbiting CubeSats also.

Plasma Brake Module consists of a tether of required length on a roll, deployment system and control electronics.

Science behind the technology

The plasma brake uses Coulomb drag to interact with the upper atmosphere plasma, slowing down a spacecraft. As the spacecraft slows down its orbit starts to shrink. As the spacecraft comes closer to the ground it will start to deorbit naturally and will burn up in the atmosphere. The main use for plasma brake is to deorbit a satellite at the end of its life.

Modular structure for custom requirements

PBM can be fitted with 100 to 5000 meters long tether. Multiple Plasma Brake Modules can be fitted in to a satellite for quicker deorbiting. PBM can be fitted with specialized solar panels for increased reliability for situations in which the satellites power production is faulty.

Specs that can be modified for customer's needs:
- Length of the tether (amount of drag created by it)

Safety

Plasma brake is safe to use due to its low requirements for deorbiting. It needs to be opened and charged electrically. The power requirements are tiny compared to the drag created by the brake. Plasma Brake is also safe for other satellites due to its micro-scale thickness. A tether hitting another satellite, which is highly unlikely, can only leave a mark few micrometers deep.

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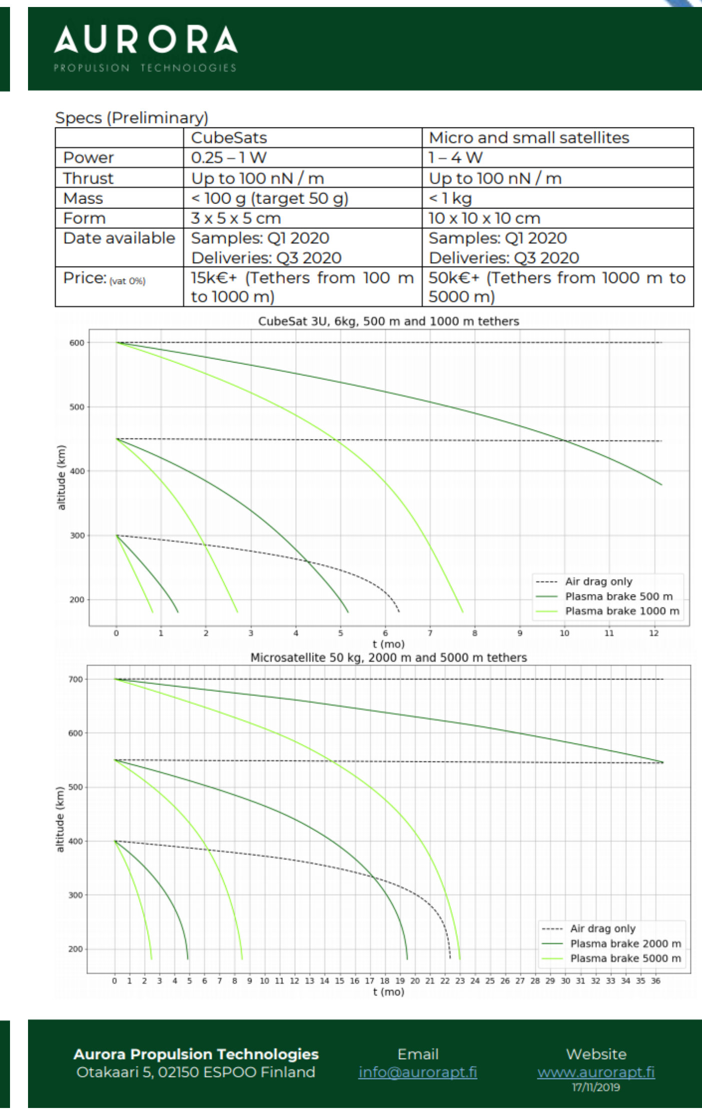
AURORA
PROPULSION TECHNOLOGIES

Specs (Preliminary)

	CubeSats	Micro and small satellites
Power	0.25 – 1 W	1 – 4 W
Thrust	Up to 100 nN / m	Up to 100 nN / m
Mass	< 100 g (target 50 g)	< 1 kg
Form	3 x 5 x 5 cm	10 x 10 x 10 cm
Date available	Samples: Q1 2020 Deliveries: Q3 2020	Samples: Q1 2020 Deliveries: Q3 2020
Price: (vat 0%)	15k€+ (Tethers from 100 m to 1000 m)	50k€+ (Tethers from 1000 m to 5000 m)

Aurora Propulsion Technologies
Otakaari 5, 02150 ESPOO Finland
Email info@aurorapt.fi
Website www.aurorapt.fi
17/11/2019

Additional comments:

[Reference 1][Feb 2020][Company info]
Aurora Propulsion Technologies was founded in 2018. In early 2019 we joined European Space Agency Business Incubator Centre programme (ESA BIC Finland) in Otaniemi. Within a year from founding Aurora grew from 7 founders to 17 employees. A target of delivering our first thruster sample for a satellite on Q4 of 2019 is on schedule, with flight ready thruster delivery objective of early 2020. Initial flight date for the satellite is expected to be later in 2020. Our goals for the future include further scaling of our operations, in terms of production quantities and development of upcoming products and increasing our sales and customer base.

[Reference 2][Feb 2020][General info]
Aurora thinks that this technology will fly before the water resistojet, because it's existing technology.

[Reference 3][Dec 2020][Flight info]
RBC Signals has announced Aurora Propulsion Technologies has engaged the company for satellite communication services — the agreement gives Aurora Propulsion Technologies access to the RBC Signals global ground station network in support of its impending AuroraSat-1 mission. Aurora Propulsion Technologies specializes in creating scalable solutions and services for the small spacecraft movement and lifecycle control. The company's AuroraSat-1 mission is a cubesat demonstration mission and co-development project with SatRevolution which will provide proof of concept for attitude and orientation control. In addition, the satellite will also demonstrate Aurora Propulsion Technologies' Plasma Brake technology for satellite de-orbiting. The satellite is scheduled to launch in December 2020 onboard a SpaceX Falcon 9 rocket.

References:

[1] https://www.aurorapt.fi/home/aboutus/
[2] Public conversations at SmallSat Symposium, Feb 2020 (A. Hsu, T. Curtiss, with Roope Takala, CEO).
[3] https://smallsatnews.com/2020/10/14/rbc-signals-ground-station-services-engaged-by-aurora-propulsion-technologies-for-the-auorasat-1-mission/
[4] https://aurorapt.fi/aurorasat-1/
[5] https://smallsatnews.com/2021/08/17/aurorasat-1-from-aurora-propulsion-technologies-to-be-launched-by-rocket-lab/

Comm. avail.	TRL	Aerospace-tested
	3	NO

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Plasma Brake (CubeSat, Micro, Small) [2 of 2]

Additional comments:

[Reference 1][March 2021][Company info]
Espoo, Finland (March 10th, 2021) –Expanding on its existing relationship with Momentus, Aurora is announcing its plans to launch a satellite with Momentus in June 2022.

[Reference 2][March 2021][Flight info]
AuroraSat-1, a 1.5U CubeSat, launches to Low Earth Orbit in H1 2021 onboard Momentus Space's orbital transfer platform on a SpaceX Falcon 9 rocket. The satellite's primary payloads are ARM-A and APB modules. We're proud that these modules are true to our original goal of providing reliable, volume and weight efficient propulsion and deorbiting capabilities. AuroraSat-1 includes a twin Aurora Plasma Brake module, which has for testing purposes two independent deployable spools of microtether in addition to all the control electronics.

References:
[1] https://aurorapt.fi/press-release/aurora-propulsion-technologies-expands-relationship-with-momentus/
[2] https://aurorapt.fi/aurorasat-1/

	3	NO
Comm. avail.	TRL	Aerospace-tested

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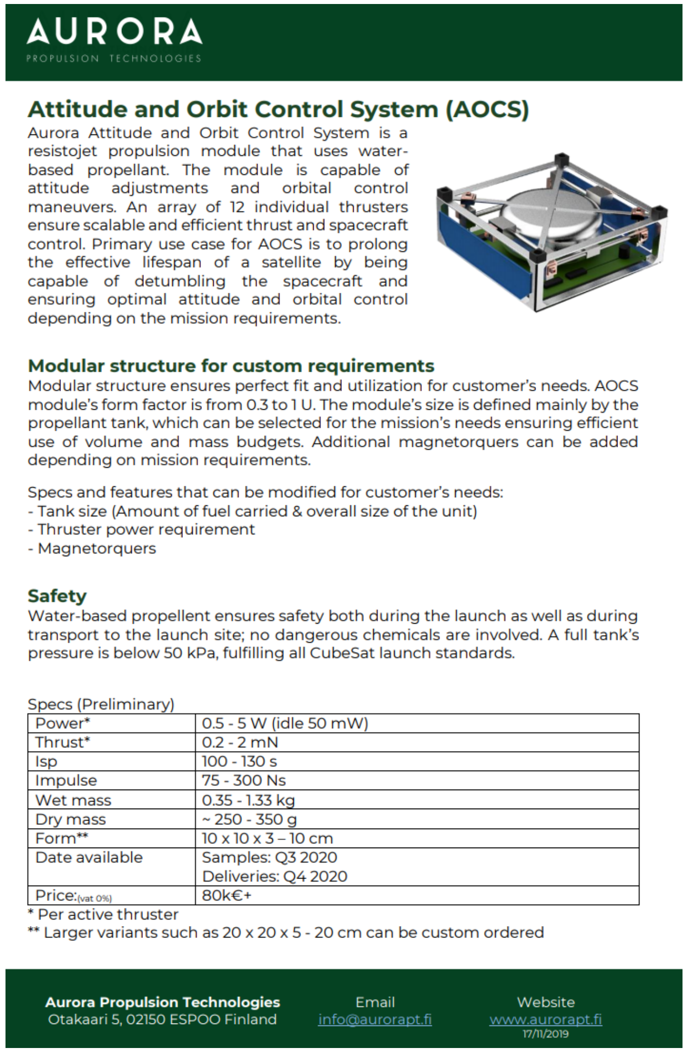
Attitude and Orbit Control System (AOCS)

Propulsion Technology	Water resistojet
Manufacturer/Country	Aurora (FINLAND)
TRL	2-3
Size (including PPU)	30mm x 100mm x 100mm Can be scaled up to 1U
Design satellite size	1U or larger
Isp (s)	100-130s
Thrust type/magnitude	0.2 to 2 mN 75 to 300 N*s
Delta-V (m/s)	
Propellant	Water-based (water with a pressurant)
Power consumption (W)	0.5 to 5W (0.05W at idle)
Flight heritage (if any)	None Projected for AuroraSat-1, now delayed to likely 2022 [2, 5].
Commercially available	Yes, ~$100,000 [1], lead time of 3-6 months [4]
Last updated	12/2021


AURORA
PROPULSION TECHNOLOGIES

Attitude and Orbit Control System (AOCS)

Aurora Attitude and Orbit Control System is a resistojet propulsion module that uses water-based propellant. The module is capable of attitude adjustments and orbital control maneuvers. An array of 12 individual thrusters ensure scalable and efficient thrust and spacecraft control. Primary use case for AOCS is to prolong the effective lifespan of a satellite by being capable of detumbling the spacecraft and ensuring optimal attitude and orbital control depending on the mission requirements.

Modular structure for custom requirements

Modular structure ensures perfect fit and utilization for customer's needs. AOCS module's form factor is from 0.3 to 1 U. The module's size is defined mainly by the propellant tank, which can be selected for the mission's needs ensuring efficient use of volume and mass budgets. Additional magnetorquers can be added depending on mission requirements.

Specs and features that can be modified for customer's needs:
- Tank size (Amount of fuel carried & overall size of the unit)
- Thruster power requirement
- Magnetorquers

Safety

Water-based propellent ensures safety both during the launch as well as during transport to the launch site; no dangerous chemicals are involved. A full tank's pressure is below 50 kPa, fulfilling all CubeSat launch standards.

Specs (Preliminary)

Power*	0.5 - 5 W (idle 50 mW)
Thrust*	0.2 - 2 mN
Isp	100 - 130 s
Impulse	75 - 300 Ns
Wet mass	0.35 - 1.33 kg
Dry mass	~ 250 - 350 g
Form**	10 x 10 x 3 – 10 cm
Date available	Samples: Q3 2020 Deliveries: Q4 2020
Price:(vat 0%)	80k€+

* Per active thruster
** Larger variants such as 20 x 20 x 5 - 20 cm can be custom ordered

Aurora Propulsion Technologies
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Email info@aurorapt.fi
Website www.aurorapt.fi
17/11/2019

Additional comments:

[Reference 1][Feb 2020][Company info]
Aurora Propulsion Technologies was founded in 2018. In early 2019 we joined European Space Agency Business Incubator Centre programme (ESA BIC Finland) in Otaniemi. Within a year from founding Aurora grew from 7 founders to 17 employees. A target of delivering our first thruster sample for a satellite on Q4 of 2019 is on schedule, with flight ready thruster delivery objective of early 2020. Initial flight date for the satellite is expected to be later in 2020. Our goals for the future include further scaling of our operations, in terms of production quantities and development of upcoming products and increasing our sales and customer base.

[Reference 2][March 2021][Company info]
Espoo, Finland (March 10th, 2021) –Expanding on its existing relationship with Momentus, Aurora is announcing its plans to launch a satellite with Momentus in June 2022.

[Reference 3][March 2021][Flight info]
AuroraSat-1, a 1.5U CubeSat, launches to Low Earth Orbit in H1 2021 onboard Momentus Space's orbital transfer platform on a SpaceX Falcon 9 rocket. The satellite's primary payloads are ARM-A and APB modules. AuroraSat-1 includes a small version of our attitude control variant of Aurora Resistojet Module. This module consists of 6 resistojet thrusters giving the CubeSat speedy detumbling capabilities and full propulsion-based attitude control. The propellant is a water-based mixture with a freezing point of well below negative 10 degrees centigrade.

References:

[1] https://www.aurorapt.fi/home/aboutus/
[2] https://aurorapt.fi/press-release/aurora-propulsion-technologies-expands-relationship-with-momentus
[3] https://aurorapt.fi/aurorasat-1/
[4] https://aurorapt.fi/downloads/ARM-A.pdf
[5] https://smallsatnews.com/2021/08/17/aurorasat-1-from-aurora-propulsion-technologies-to-be-launched-by-rocket-lab/

Comm. avail.	3 TRL	NO Aerospace-tested

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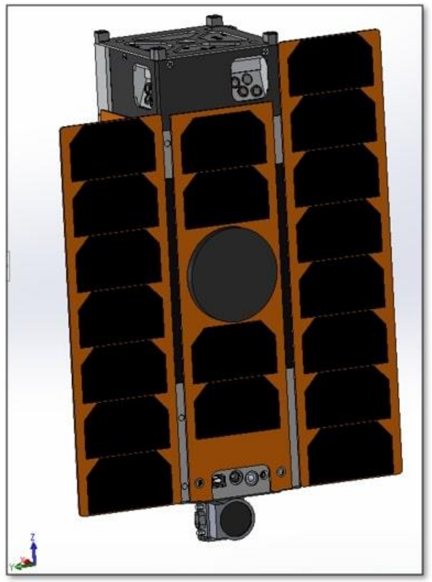
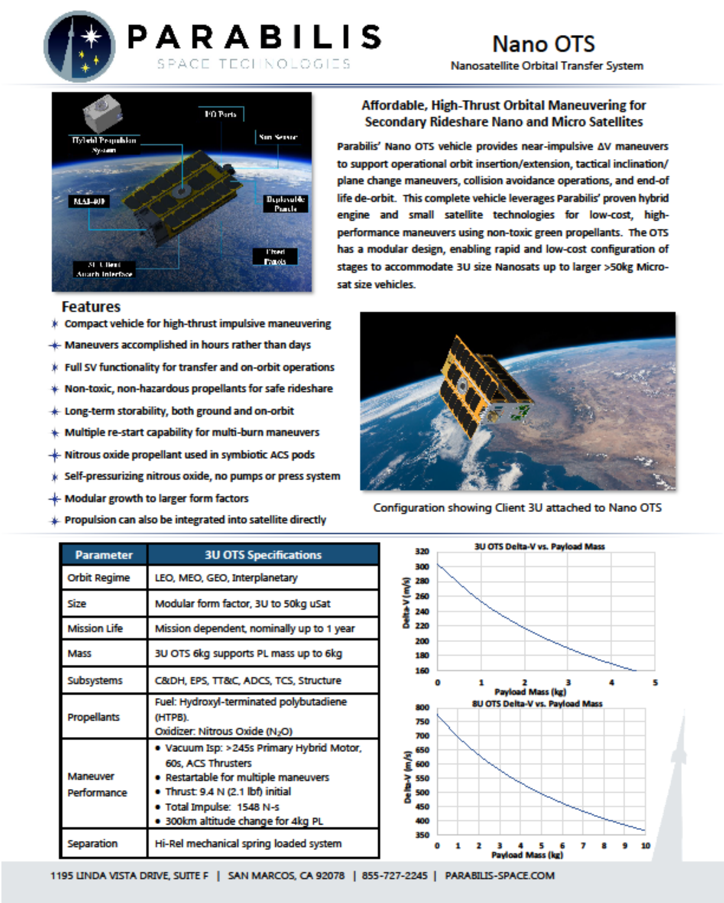
Parabilis NanoOTS

Propulsion Technology	Hybrid
Manufacturer/Country	Parabilis (USA)
TRL	3
Size (including PPU)	~1U
Design satellite size	3U up to >50 kg
Isp (s)	~275s (Vacuum >245 s) [2]
Thrust type/magnitude	9.4N, total impulse 1548 N*s [2]
Delta-V (m/s)	200 to 300 m/s for a 3U [2]
Propellant	HTPB + N2O [2]
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	NO
Last updated	04/2021



[1]



PARABILIS
SPACE TECHNOLOGIES

Nano OTS
Nanosatellite Orbital Transfer System

Affordable, High-Thrust Orbital Maneuvering for Secondary Rideshare Nano and Micro Satellites

Parabilis' Nano OTS vehicle provides near-impulsive ΔV maneuvers to support operational orbit insertion/extension, tactical inclination/plane change maneuvers, collision avoidance operations, and end-of life de-orbit. This complete vehicle leverages Parabilis' proven hybrid engine and small satellite technologies for low-cost, high-performance maneuvers using non-toxic green propellants. The OTS has a modular design, enabling rapid and low-cost configuration of stages to accommodate 3U size Nanosats up to larger >50kg Micro-sat size vehicles.

Features
- Compact vehicle for high-thrust impulsive maneuvering
- Maneuvers accomplished in hours rather than days
- Full SV functionality for transfer and on-orbit operations
- Non-toxic, non-hazardous propellants for safe rideshare
- Long-term storability, both ground and on-orbit
- Multiple re-start capability for multi-burn maneuvers
- Nitrous oxide propellant used in symbiotic ACS pods
- Self-pressurizing nitrous oxide, no pumps or press system
- Modular growth to larger form factors
- Propulsion can also be integrated into satellite directly

Configuration showing Client 3U attached to Nano OTS

Parameter	3U OTS Specifications
Orbit Regime	LEO, MEO, GEO, Interplanetary
Size	Modular form factor, 3U to 50kg uSat
Mission Life	Mission dependent, nominally up to 1 year
Mass	3U OTS 6kg supports PL mass up to 6kg
Subsystems	C&DH, EPS, TT&C, ADCS, TCS, Structure
Propellants	Fuel: Hydroxyl-terminated polybutadiene (HTPB). Oxidizer: Nitrous Oxide (N_2O)
Maneuver Performance	• Vacuum Isp: >245s Primary Hybrid Motor, 60s, ACS Thrusters • Restartable for multiple maneuvers • Thrust: 9.4 N (2.1 lbf) initial • Total Impulse: 1548 N-s • 300km altitude change for 4kg PL
Separation	Hi-Rel mechanical spring loaded system

1195 LINDA VISTA DRIVE, SUITE F | SAN MARCOS, CA 92078 | 855-727-2245 | PARABILIS-SPACE.COM

[2]

Additional comments:

[Reference 1-2][Jun 2020][Company, thruster, and vehicle information]
Parabilis Space Technologies, Inc. is an SBA-certified, HUBZone small business with offices located in San Marcos, California. Parabilis' areas of expertise include propulsion systems and vehicles, small satellite systems and buses, and systems integration. Parabilis operates a propulsion test facility in Lakeside, CA permitted for numerous fuels and oxidizers. Parabilis is one of the few companies in the world that has both propulsion and satellite capabilities under one roof.
The Nanosat Maneuvering and Orbital Transfer System (OTS) is a program in which Parabilis is teamed with USC to develop a family of modular high-performance orbital transfer stage vehicles dedicated to NanoSats and Microsats. It is based on Parabilis' proven hybrid engine technologies using benign environmentally safe "green" propellants. Nitrous oxide and acrylic motors have been demonstrated at the <5 lbf scale. It utilizes self-pressurizing nitrous oxide tank in a rectilinear design for low-cost and high-performance.
The modular design is designed to fit 3U Nanosats up to larger >50 kg Microsats.

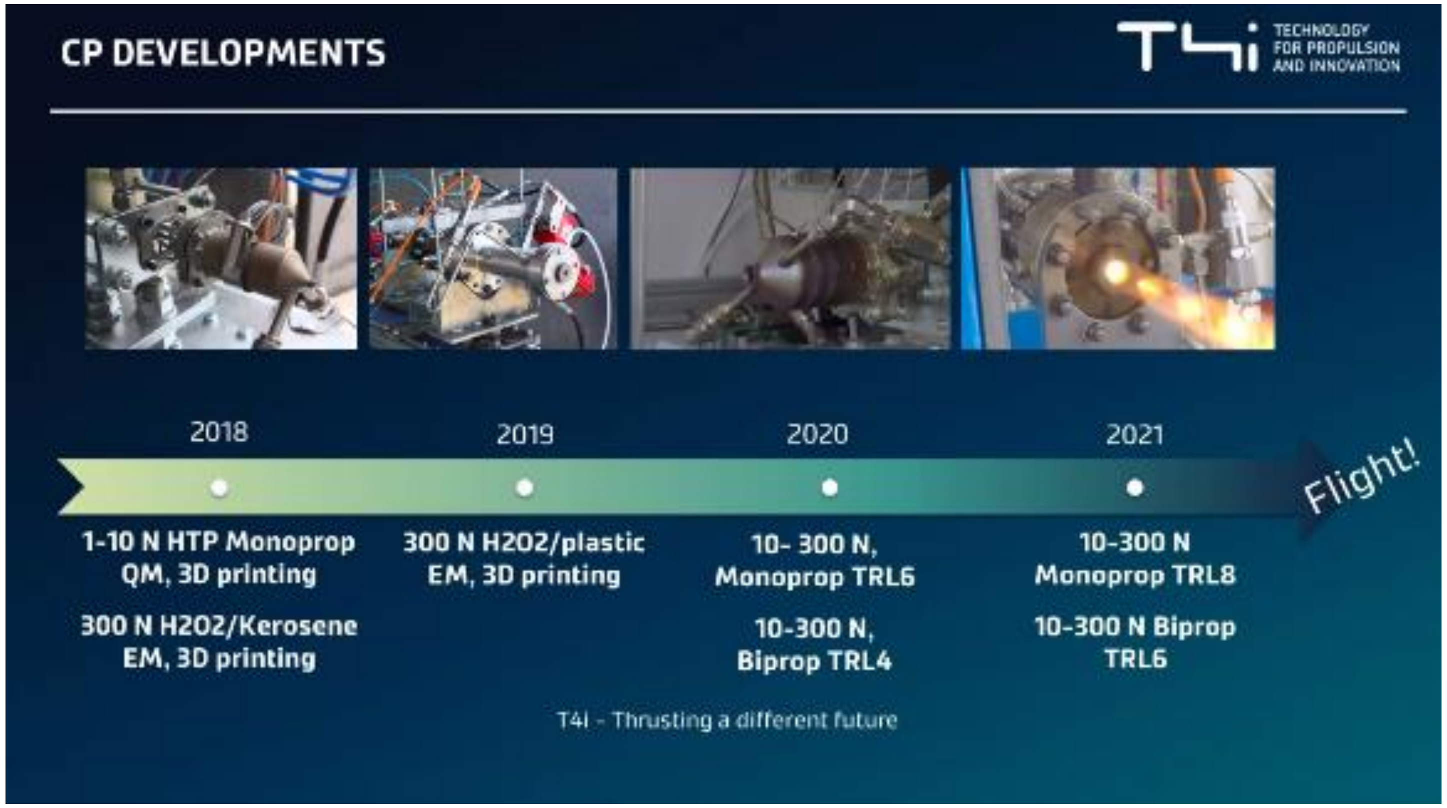
References:
[1] https://parabilis-space.com/programs-and-applications/#nanosat-maneuvering-and-orbital-transfer-system-ots
[2] Public release brochure provided to Aerospace in March 2020

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Hydrogen Peroxide green monoprop
T4i

Propulsion Technology	Green monoprop
Manufacturer/Country	T4i (Technology for Propulsion and Innovation) (ITALY), a University of Padua Spin-off
TRL	3
Size (including PPU)	~1U (from photos)
Design satellite size	
Isp (s)	155s demonstrated
Thrust type/magnitude	Up to 10 N
Delta-V (m/s)	
Propellant	H2O2
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	NO, in development
Last updated	04/2021



[2]

Additional comments:

[Reference 3][Aug 2020][Company info]
The company started in 2006 at the University of Padua. In 2014, T4i was founded, a spin-off of the Space Propulsion group of the University of Padua with a mix between entrepreneurs and engineers coming University and Industry.

[Reference 1][Aug 2020][Thruster development]
“Different versions of the motor are under development since 2014. Several laboratory models have been developed and testing. A 10N Engineering model is under development, currently TRL5.”

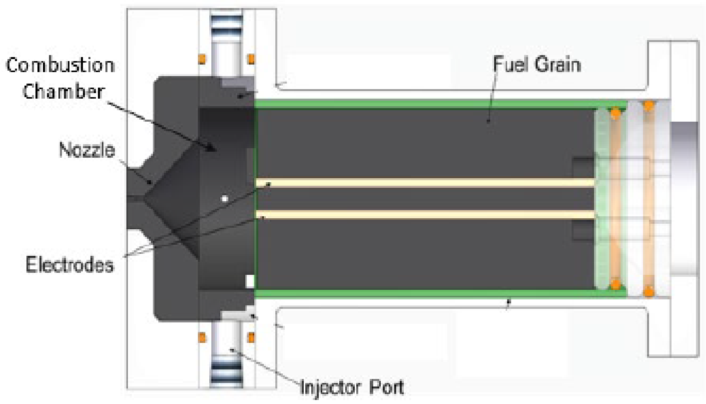
References:
[1] https://www.t4innovation.com/chemical-motors/mono-propellant/
[2] Small Sat 2020, virtual public forum
[3] https://www.t4innovation.com/about/

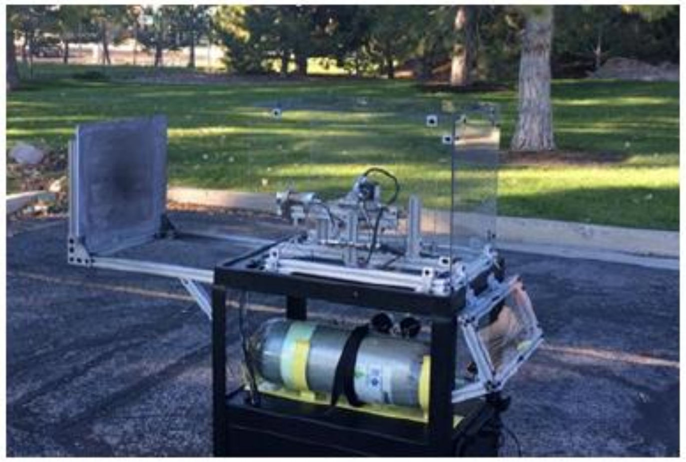
NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

End-burning hybrid

Propulsion Technology	Hybrid rocket
Manufacturer/Country	Utah State University (USA)
TRL	3-4
Size (including PPU)	~1U
Design satellite size	3U and larger
Isp (s)	130 to 160 S
Thrust type/magnitude	0.5 to 1 N
Delta-V (m/s)	
Propellant	Various plastics (PMMA, ABS, PVC, Nylon) with GOX
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	NO
Last updated	04/2021





Additional comments:

[Reference 1][Aug 2020][Thruster development]
For hybrid rockets with thrust levels less than 5N, oxidizer mass flow levels are sufficiently small that the rate of convective heat transfer is significantly reduced and radiative heat transfer (rather than convective heat transfer) dominates the fuel regression mechanism. This fuel-rich tendency leads to combustion inefficiencies in the scales necessary to achieve useful thrust levels for small satellites. As a solution to provide constant fuel regression rate at these desired low thrust levels, the configuration was redesigned to be end-burning, resulting in a constant regression rate and oxidizer to fuel ratio throughout the burn lifetime. This is the first known attempt at an end-burning hybrid thruster in the sub-Newton scale. Performance (thrust and chamber pressure) is measured.
Results showed that these systems are capable of producing a vacuum Isp of great than 150s and a thruster rise time of less than 350 milli-seconds. Future investigations using high-density oxidizers such as hydrogen peroxide and nitrous oxide are expected to further increase the performance of these end-burning hybrid motors.

References:
[1] Smith, T., Lewis, Z., Olsen, K., Bulcher, M., Whitmore, T., “A miniaturized, green, end-burning hybrid propulsion system for CubeSats,” Small Sat Conference 2020, virtual talk, Paper SSC20-IX-09.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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MOOG Monopropellant Propulsion Module

Propulsion Technology	Monopropellant
Manufacturer/Country	MOOG (USA)
TRL	3-4
Size (including PPU)	1U
Design satellite size	3U and above
Isp (s)	224 s [1]
Thrust type/magnitude	0.1 to 1N, 0.5N baseline [1]
Delta-V (m/s)	59 m/s
Propellant	Hydrazine or green monoprop
Power consumption (W)	2 x 22.5 W/thruster
Flight heritage (if any)	None
Commercially available	YES
Last updated	04/2021

[Reference 1]

MONOPROPELLANT PROPULSION MODULE

SPECIFICATIONS

Parameter	Specification
Propellant	Liquid Chemical – Green or Traditional
Dimensions	10cm x 10cm x 10cm baseline – scalable to 24cm x 24cm x 24cm
Thrust	0.1 to 1 N, .5N baseline
Isp – Vacuum	224 sec with 30:1 nozzle baseline
Total Impulse	500 N/sec with 150cc baseline tank capacity
Delta-V	59 m/s
Input Voltage	28 VDC
Power	2 x 22.5 W/Thruster
Mass	1.01 Kg wet baseline
Maximum Expected Operating Pressure	400 psig
Moog Additive Manufacturing Rolling Metal Diaphragm Technology	x1.2 proof pressure tested

Additional comments:

[Reference 1][Aug 2020][Thruster info]
This propulsion system is a 3-D printed module that can be supplied pre-filled with propellant, either green or traditional hydrazine. The use of additive manufacturing techniques allows the module to be tailored to mission specific requirements with minimal impact on cost or schedule.
The module utilizes Laser Powder Bed Fusion Additive Manufacturing for almost all of the metallic parts including the propellant catalyzing agent. It utilizes a Moog heritage thruster valve contained within each of the 0.5 N baseline thruster assembles. The non-metallic combustion chamber is additively manufactured using stereo lithography. The COTS based custom circuit card assembly heater driver is made in house at MOOG.

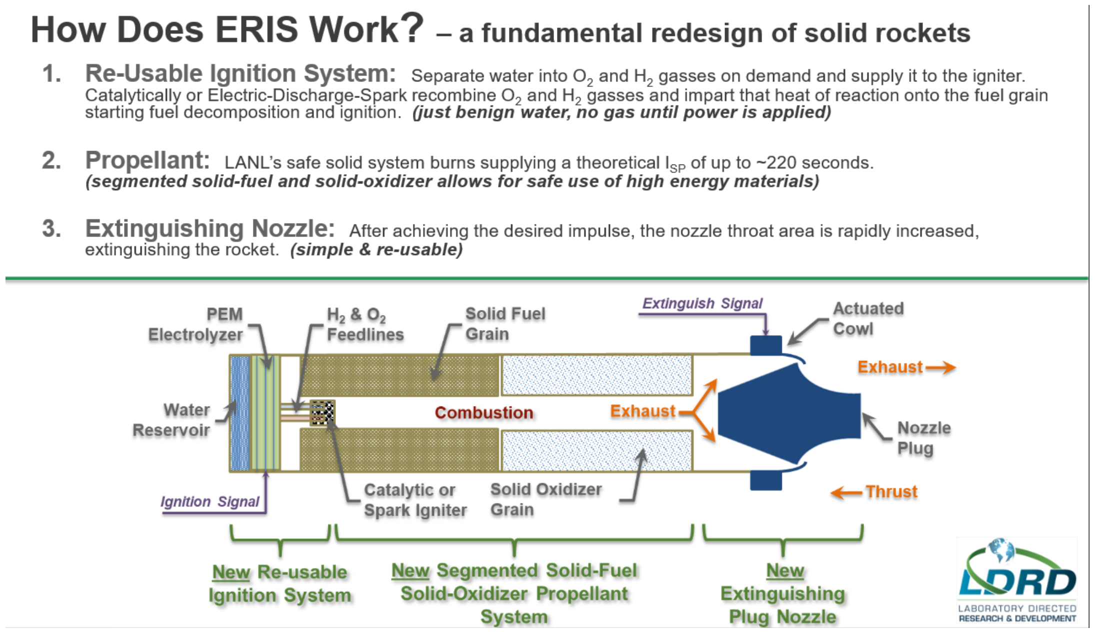
References:
[1] https://www.moog.com/content/dam/moog/literature/Space_Defense/spaceliterature/propulsion/moog-monopropellant-propulsion-module-datasheet.pdf

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

ERIS re-startable solid rocket

Propulsion Technology	Restartable solid
Manufacturer/Country	Los Alamos LANL (USA)
TRL	2-3
Size (including PPU)	1-2U
Design satellite size	
Isp (s)	220s [1]
Thrust type/magnitude	50-100N [1]
Delta-V (m/s)	
Propellant	Segmented fuel/oxidizer with H2/O2 igniter from electrolysis [1]
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	NO
Last updated	04/2021



[1]

Additional comments:

[Reference1][Aug 2020][Thruster info]
The rocket utilizes a segmented fuel/oxidizer setup, with an electrolysis igniter. After achieving the desired impulse, the nozzle throat area is rapidly increased, extinguishing the rocket. The fact that rapid decompression of the combustion chamber can cause extinguishing has been known since the 1960's. LANL has developed RaDS measurement system to characterize decompressive extinguishing properties of new and existing propellants. They have made thrust measurements in the 50-100N range. Next steps are testing vacuum ignition.

References:
[1] Dallmann, Nicholas, "ERIS: Multiple independent impulses from a single solid rocket," Los Alamos National Laboratory report LA-UR-20-26348.
[2] https://www.lanl.gov/discover/science-briefs/2020/May/0513-restartable-rocket-motor.php

Comm. avail.	TRL	Aerospace-tested
NO	3	NO

DISTRO A: Approved for public release. OTR-2024-00338

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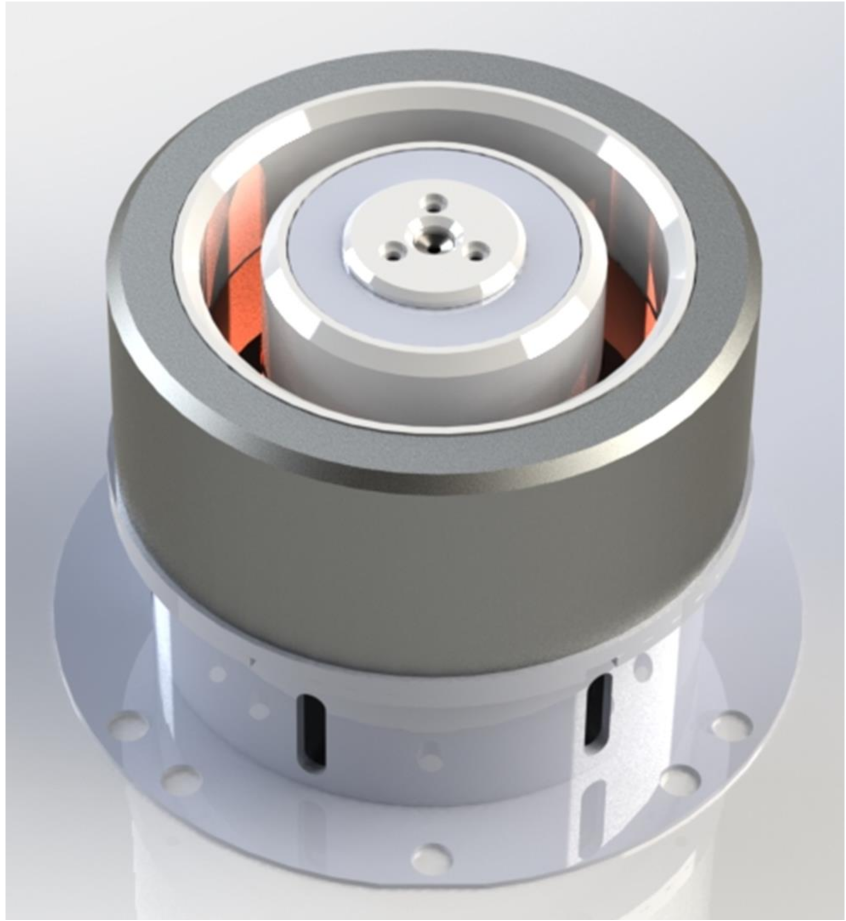
HET-400 [1 of 2]

Propulsion Technology	Hall Effect Thruster
Manufacturer/Country	Earth Observant (USA)
TRL	2
Size (including PPU)	4U
Design satellite size	Small Sat
Isp (s)	1300 to 2200 s at 350 to 2500 W [4]
Thrust type/magnitude	20 to 140 mN at 350 to 2500 W [4]
Delta-V (m/s)	Propellant Mass Dependent
Propellant	Xenon, Krypton, Other
Power consumption (W)	200-1000W @ 28VDC
Flight heritage (if any)	
Commercially available	Not Yet
Last updated	04/2021



Additional comments:
[Reference 1][March 2020][General thruster info]
All noted performance numbers above are theoretical and/or based on previous design iterations. Fabrication of the HET-400 began early Q1 2020, with thrust stand testing scheduled for beginning of Q2 2020. HET-400 incorporates novel thermal and electric designs not seen or used on any other known commercial Hall Thruster. It is magnetically shielded and uses a center mounted cathode as well as assorted 3D printed metal structures. The HET-400 will be powered by an Earth Observant 28VDC 1kW PPU currently under development and expected for initial on-thruster testing end of Q2 2020. The PPU is an all Gallium Nitride semiconductor power conversion solution designed to operate the thruster and propellant management system. Earth Observant is also investigating novel propellants for use as well.

[Reference 2][Jun 2020][Company info]
Earth Observant Inc. (EOI) closed their seed round in the first quarter of this year.
Over the past 18 months, the company has been designing a constellation of low-flying satellites that leverage the team's decades of experience developing propulsion systems and Earth imaging platforms. The company's propulsion system is currently in fabrication, with ground-based testing slated for the third quarter of 2020. In addition, EOI has down-selected its optical payload provider and has started development on the first optical payload.

References:
[1] Phone call with Christopher Thein (Earth Observant, CEO), Jan 2020. Confirmed via email info is public release March 2020.
[2] https://smallsatnews.com/2020/05/15/seed-round-closed-by-earth-observant/
[4] https://www.prnewswire.com/news-releases/earth-observant-inc-successfully-tests-next-generation-propulsion-technology-to-support-future-very-low-earth-orbit-missions-301230606.html

Comm. avail.	TRL	Aerospace-tested
NO	3	NO

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HET-400 [2 of 2]

Additional comments:

[Reference 1][April 2021][Thruster testing]
SAN FRANCISCO, Feb. 18, 2021 /PRNewswire/ -- Earth Observant Inc. (EOI) successfully completed a series of tests on its internally developed Hall-effect thruster that introduces new propellant types while maintaining thruster efficiency and minimizing erosion. EOI's proprietary electric propulsion system glows blue during vacuum chamber testing at Air Force Research Lab's facility (SPEF) at Edwards AFB in December 2020. This technology supports EOI's core mission of operating a Very Low Earth Orbit (VLEO) constellation of Earth Imaging satellites to deliver ultra-high resolution image data. The HET-X Thruster combines powerful new technology, including magnetic shielding with a center-mounted cathode, a unique thermal cooling design and an effective propellant management system, in a unit weighing less than 2 kilograms (kg). The preliminary test results conducted in a vacuum chamber show sustained power input levels between 350 – 2500 watts with thruster output recorded between 20 – 140 millinewtons and specific impulse between 1300 – 2200 ISP.

References:
[1] https://www.prnewswire.com/news-releases/earth-observant-inc-successfully-tests-next-generation-propulsion-technology-to-support-future-very-low-earth-orbit-missions-301230606.html

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

Plasma Processes AF-M315E Green Monoprop, 5N model PP3614-A

Propulsion Technology	Green Monoprop
Manufacturer/Country	Plasma Processes (USA)
TRL	3-4
Size (including PPU)	<1U
Design satellite size	3U and larger
Isp (s)	250 s [2]
Thrust type/magnitude	5N [2]
Delta-V (m/s)	
Propellant	AF-M315E
Power consumption (W)	75W preheat power at 24VDC [2]
Flight heritage (if any)	None
Commercially available	NO
Last updated	04/2022

[2]

Additional comments:

[Reference 1][Jun 2020][Company information]
Plasma Processes is located in Huntsville, Alabama and is a supplier of advanced materials solutions to commercial and government customers in the aerospace, defense, power generation, oil & gas, semi-conductor, and other key industries. They have expertise with high and ultra-high temperature materials, such as iridium, rhenium, tungsten, and molybdenum, and can apply coatings or create custom parts and powders using our advanced deposition processes.
In the area of liquid rocket engine subcomponents and coatings, they have experience with radiation cooled combustion chambers, non-toxic green propellant combustion chambers, regeneratively cooled combustion chambers, injector and faceplate coatings, catalyst beds and igniters, and nozzle extension coatings.
In the area of solid rocket motor subcomponents and coatings, they have experience with refractory metal subcomponents, ultra high temperature ceramic (UHTC) subcomponents, composite material subcomponents, and solid divert and attitude control system subcomponents.

References:
[1] https://plasmapros.com/markets/propulsion/
[2] Email correspondence with plasma processes, POC Cheri McKechnie, April 2021

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Plasma Processes AF-M315E Green Monoprop, 1N model PP3641-A

Propulsion Technology	Green Monoprop
Manufacturer/Country	Plasma Processes (USA)
TRL	3-4
Size (including PPU)	<1U
Design satellite size	3U and larger
Isp (s)	254 s [2]
Thrust type/magnitude	1N [2]
Delta-V (m/s)	
Propellant	AF-M315E
Power consumption (W)	40W preheat power at 12VDC [2]
Flight heritage (if any)	None
Commercially available	NO
Last updated	04/2022

[2]

Additional comments:

[Reference 1][Jun 2020][Company information]
Plasma Processes is located in Huntsville, Alabama and is a supplier of advanced materials solutions to commercial and government customers in the aerospace, defense, power generation, oil & gas, semi-conductor, and other key industries. They have expertise with high and ultra-high temperature materials, such as iridium, rhenium, tungsten, and molybdenum, and can apply coatings or create custom parts and powders using our advanced deposition processes.
In the area of liquid rocket engine subcomponents and coatings, they have experience with radiation cooled combustion chambers, non-toxic green propellant combustion chambers, regeneratively cooled combustion chambers, injector and faceplate coatings, catalyst beds and igniters, and nozzle extension coatings.
In the area of solid rocket motor subcomponents and coatings, they have experience with refractory metal subcomponents, ultra high temperature ceramic (UHTC) subcomponents, composite material subcomponents, and solid divert and attitude control system subcomponents.

References:
[1] https://plasmapros.com/markets/propulsion/
[2] Email correspondence with plasma processes, POC Cheri McKechnie, April 2021

Comm. avail.	TRL	Aerospace-tested
NO	3	NO

DISTRO A: Approved for public release. OTR-2024-00338

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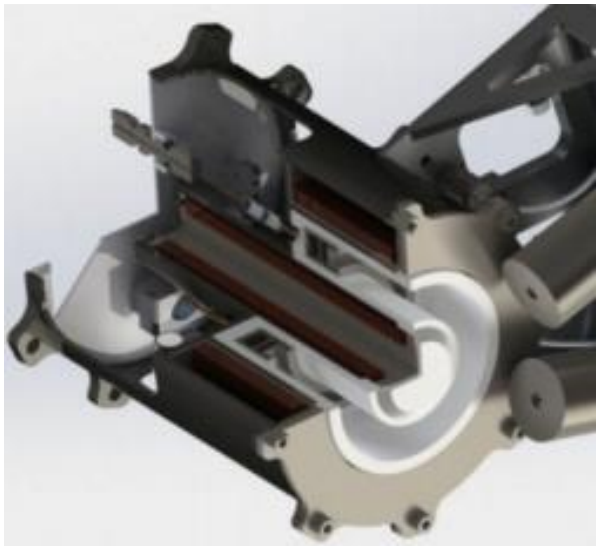
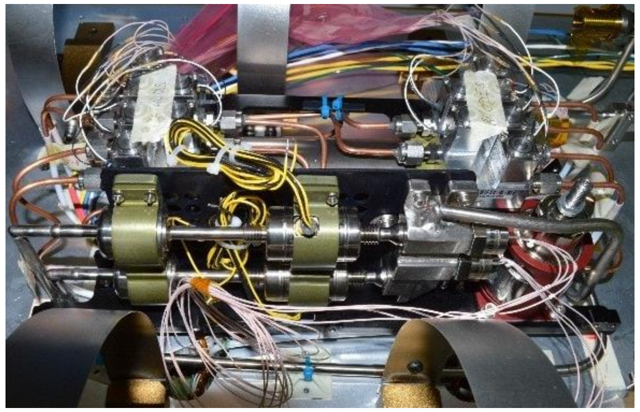
SHT250
Seran Systems

Propulsion Technology	Hall effect thruster
Manufacturer (Country)	SETS (UKR)
TRL	3
Size (including PPU)	
Design satellite size	Small Sat (up to 500 kg)
Isp (s)	1300 s and 140 kN-s
Thrust type/magnitude	12.5 mN
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	210 W
Flight heritage (if any)	None
Commercially available	YES
Last updated	*03/2021*





All pictures [Seran Systems website]

Additional comments:

[Reference 1][March 2021][Overview]
Seran Systems is a company that is engaged in the development and implementation of solutions in the field of Hall Thrusters based electric propulsion systems for spacecraft. Seran Systems offers a complete line of Hall thrusters from 50 W to 1500 W and a thrust from 2 mN to 90 mN. Their products can be successfully applied both for the currently popular small LEO satellites and for heavy GEO satellites. As of spring 2021, Seran HET products include the SHT1500 (1300W, 80 mN), SHT250 (200W, 12.5 mN), SHT100 (100 W, 5 mN), and the CSHT200 (250 W, 10 mN) clustered HET configuration. Seran also produces an integrated xenon feed system.

Seran Systems also manufactures other spacecraft components like a multi-channel telemetry data collection system and optical sensors.

References:

[1] https://seransystems.com/
[2] https://seransystems.com/?page_id=55
[3] https://seransystems.com/250W%20Seran%20HALL%20Thruster.pdf

	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

China: Low power Hall thruster

Propulsion Technology	Hall thruster
Manufacturer/Country	China: SPMI (Shanghai Spaceflight Power Machinery Institute)
TRL	Unknown (estimated at 3-5, due to "laboratory model" in description)
Size (including PPU)	unknown
Design satellite size	unknown
Isp (s)	980s
Thrust type/magnitude	10 mN
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	200W
Flight heritage (if any)	Unknown
Commercially available	No
Last updated	09/2021

Fig. 3 The picture of Low-power HET

Photo of Hall thruster [1]

Additional comments:

[Reference 1][September 2021][Thruster development]
Hall thruster was selected as a new thruster for the NSSD Chinese geostationary satellite due to its high impulse and high thrust. Research on hall thrusters started in 1996 and have been carried out at SPMI since.
A test facility was inaugurated at SPMI in 1996. It is a 1.2 meter diameter x 3.4 m long test facility, and has two 600 mm diffusion pumps to maintain a base pressure of approximately 10E-3 Pascals, designed for hall thrusters up to 1400W. The facility is currently being used for testing mid-power hall thrusters.
Additional facilities for hollow cathode testing have also been built (a 0.5 m diameter x 1.2 m long facility, with 2X 300 mm cryopumps to maintain vacuum levels below 10E-4 Pascals. A new facility is currently being built at SPMI, a 3m diameter x 9m long facility, for hall thruster plasma diagnostics and plume effects diagnostics.
The reference indicates that there is a thrust measurement system within their test facilities, with a thrust measurement uncertainty of about 10%.
SPMI developed a laboratory model of a low-power hall thruster with 10 mm average discharge diameter. The laboratory model contains two main parts: the accelerator and hollow cathode. The accelerate has the ordinary scheme with magnets. The cathode is the hollow cathode. Xenon is used as the propellant. Because of ion sputtering on the thruster chamber wall, the lifetime of the thruster is limited, and the efficiency was "not satisfied".

References:
[1] Kang, X., Wang, Z., Wang, N., Li, A., Wu, G., Mao, G., Tang, H., Zhao, W., "An Overview of electric propulsion activities in China", IEPC 2001.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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China: Microwave thruster (LECR-50)

Propulsion Technology	Electron cyclotron resonance (LECR)
Manufacturer/Country	China: LIP (Lanzhou Institute of Physics)
TRL	2-3
Size (including PPU)	
Design satellite size	<300 kg (small sat)
Isp (s)	4010s [1]
Thrust type/magnitude	2.3 mN [1]
Delta-V (m/s)	
Propellant	Unknown (likely xenon)
Power consumption (W)	48W (design up to 150W) [1]
Flight heritage (if any)	None
Commercially available	NO
Last updated	09/2021

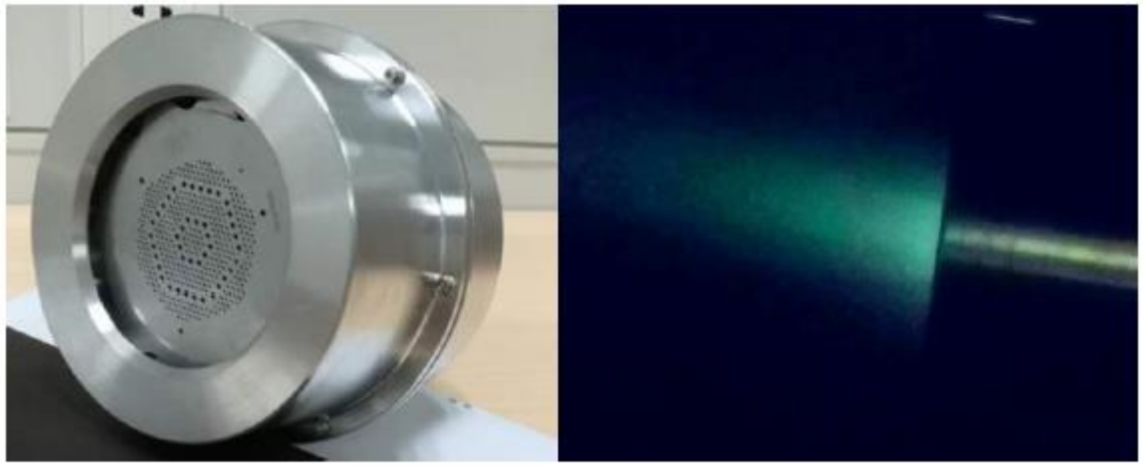

Figure 10. LECR microwave assisted discharge ion thruster

Photo of LECR-50 [1]

Additional comments:

[Reference 1][September 2021][Thruster information]
The LECR-50 is a 50 mm diameter ion beam ion thruster, and is designed for small satellites that weigh less then 300 kg. The prototype was tested in a vacuum environment. The ion beam was 38 mA with 48W microwave power, and 9.5W reflected power. The performance parameter were calculated to be 2.3 mN of thrust and Isp of 4010s.

References:
[1] Yanhui, J., Tianping, Z., Chenchen, W., Yujun, K., Xianming, W., Shangmin, W., Ning, G., “The latest development of low power electric propulsion for small spacecraft,” IEPC-2017-78**.**

Comm. avail.	TRL	Aerospace-tested
NO	3	NO

DISTRO A: Approved for public release. OTR-2024-00338

Iodine plasma thruster

Propulsion Technology	Iodine thruster
Manufacturer/Country	Phase Four [USA]
TRL	2-3
Size (including PPU)	
Design satellite size	
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Iodine
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	NO
Last updated	04/2022

Additional comments:

[Reference 1][Oct 2021][Thruster information and funding for development, preliminary]

Iodine propellant has been on the roadmap of plasma propulsion around the world for a number of years. Studies by NASA Glenn Research Center affirmed that iodine has promise, but its incompatibility with cathodes found in traditional plasma thrusters limits their use with this advanced propellant. Phase Four's RF thruster contains no cathode or anode, and in 2021 Phase Four won a Phase 2 Small Business Innovation Research grant funded by AFWERX to develop the first electrodeless iodine plasma thruster in the United States. Phase Four is partnering with the Air Force Research lab and working closely with NASA to help advance the state of the art in iodine electric propulsion. "There is a growing need for more options for advanced electric in-space propulsion, to provide satellites with better maneuverability and operability in space at an affordable cost, and propellant flexibility could provide new options for in-space propulsion," said Dr. Eckhardt, Electric Propulsion Lead at AFRL.

References:
[1] https://www.phasefour.io/plasmaworks/

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

Fullerene HET

Propulsion Technology	Hall effect
Manufacturer/Country	Busek (USA)
TRL	3
Size (including PPU)	
Design satellite size	Small sat
Isp (s)	At 700W, thrust = 20 mN, Isp = 340s [1]
Thrust type/magnitude	At 700W, thrust = 20 mN, Isp = 340s [1]
Delta-V (m/s)	
Propellant	C60 (fullerene)
Power consumption (W)	400 to 1200W [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	08/2022

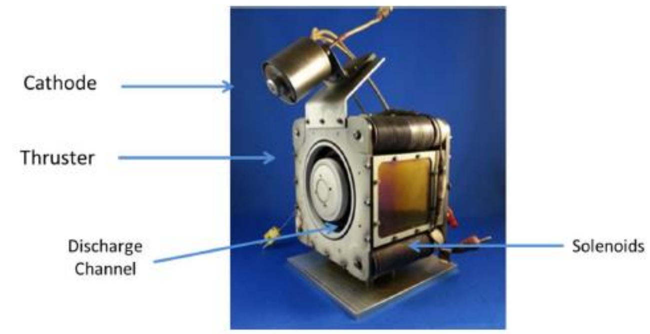

Fig. 5 Thruster Used for C60 Testing

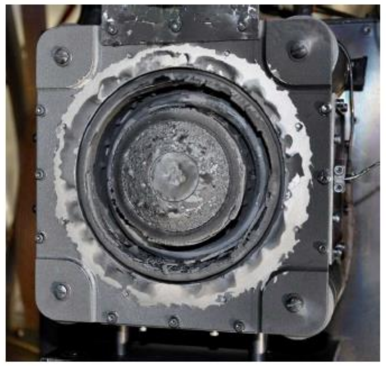
Fig. 12 Channel Area Post-Test

[1]

Point	Anode Potential	Anode Current	Thrust	Discharge Power	Discharge T/P	Reservoir Temp. T_r	C_{60} Pressure $P_1=P_v=fn(T_r)$	Calibrated Flow Rate from $P_1^2=fn(T_r)$	Specific Impulse	Efficiency
	Volts	*Amperes*	*mN*	*W*	*mN/kW*	*Degrees C*	*Torr*	*mg/s*	*s*	*%*
1	300	1.33	15.5	399	38.8	*723*	0.81	2.30	685	13.0
2	400	1.75	15.5	700	22.1	*735*	1.05	3.82	413	4.5
3	200	2.4	15.1	480	31.4	*738*	1.12	4.33	354	5.5
4	200	3.35	19.1	670	28.5	*745*	1.29	5.74	339	4.7
5	300	3.8	33.6	1140	29.5	*750*	1.42	7.00	489	7.1
6	200	5.7	21.5	1140	18.8	*757*	1.63	9.21	238	2.2
7	175	3.6	7.1	630	11.2	*715*	0.69	1.67	431	2.4

Additional comments:

[Reference 1][July 2022][Thruster testing and development]
This paper reports the first known test of a Hall thruster fueled by C60. The integrated system made an ion beam and generated thrust. However, efficiency was low, and over time it became impossible to run the thruster. Post-test inspection showed that thick carbon deposits had formed in the channel, making the inner and outer channel walls an extension of the high voltage anode. The estimated mass of accreted material was more than 20% of the mass that evolved from the reservoir. The primary cause of the deposition has not yet been determined. A more extensive program of scientific inquiry is required to answer the questions brought up by this test, and to determine whether efficient C60 Hall thrusters can be built.

References:
[1] Szabo, J., Frongillo, J., Gray, S., Taillefer, Z., "Fullerene propellant hall thruster experiment," IEPC-2022-403

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

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Cylindrical Hall Thruster

Propulsion Technology	Hall thruster
Manufacturer/Country	Universidad Carlos III de Madrid (ESP)
TRL	2-3
Size (including PPU)	
Design satellite size	Small sat
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	30-300W
Flight heritage (if any)	None
Commercially available	No
Last updated	08/2022

Fig. 3 Injector during ignition (left) and operation (right)

Fig. 4 Eroded central ceramic

[1]

Additional comments:

[Reference 1][Aug 2022][Lab testing]
The test campaign summarized in this work focused on the characterization of the operating envelope and measurement of the plasma parameters in the far-field of a Cylindrical Hall Thruster prototype coupled with a LaB6 hollow cathode. The thruster was operated between 30 - 300 W of discharge power, which was achieved by varying the discharge voltage over the range 150 - 350 V and the propellant mass flow rate injected through the anode over the range 0.25 - 0.65 mg.s. The characterization of this CHT prototype showed rather expectable and promising results. It also highlighted many possibilities of improvements of the design and operation. Future experimental activities on this device shall include the use of non-intrusive diagnostics inside the thruster channel, and testing with other types of neutralizers

References:
[1] Perrotin, T., Vinci, A., Mazouffre, S., Navarro-Cavalle, J., Fajardo, P., Ahedo, E., “Characterization of a low-power Cylindrical Hall Thruster,” IEPC-2022-359.

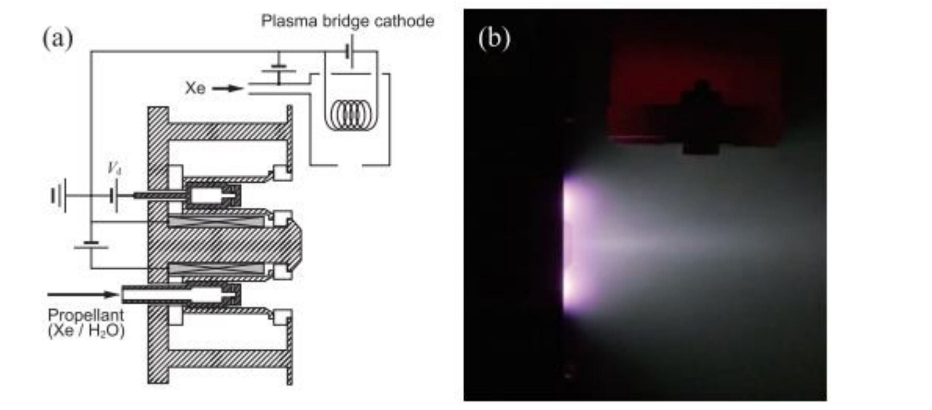
NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

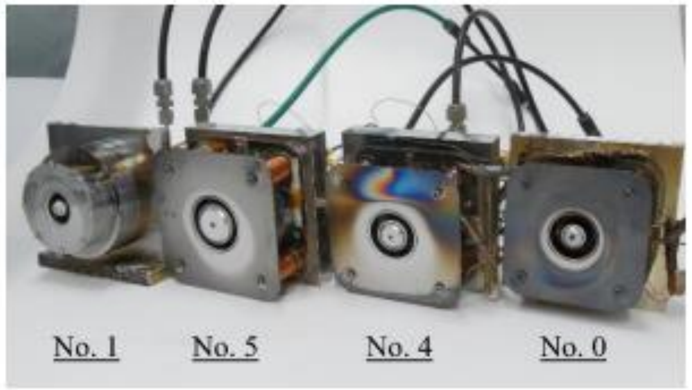
Water Hall Thruster

Propulsion Technology	Hall thruster
Manufacturer/Country	University of Tokyo and Pale Blue (JPN)
TRL	3
Size (including PPU)	Thruster head is ~1U
Design satellite size	6U and larger
Isp (s)	530s at 230W, 800s at 350W [1], 650s at 100W [2]
Thrust type/magnitude	4.2 mN at 230W, 6.4 mN at 350W [1], 2.9W at 100W [2]
Delta-V (m/s)	
Propellant	Water (water vapor)
Power consumption (W)	230W to 350W [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023



(a) Structure and electrical schematic of the miniature Hall thruster and (b) Plume appearance during ion with water vapor.

[1]



[2]

Additional comments:
[Reference 1][Aug 2022][Thruster information]
Performance was inferred from probe measurements.
In this study, the plume characteristics were measured by a Faraday probe and an RPA. From the results, we evaluated the internal efficiencies and estimated the performance. In the case of water vapor, a mass utilization efficiency was especially much lower than that of xenon, and it can also cause the reduction of another internal efficiencies. According to the estimation based on this experimental results, a thrust of 4.2 mN, a specific impulse of 524 s and an anode efficiency of 4.0 % can be achieved at an anode voltage of 200 V and an anode power of 233 W. We used a miniature Hall thruster developed at the university of Tokyo. The thrust head was designed in reference to 100 W class one operated by xenon. The acceleration channel has SPT-like structure: inner and outer walls are made of boron nitride.
[Reference 2][Dec 2023][Ground testing]
The laboratory models of a water-vapor Hall thruster and LaB6 thermionic cathode were developed and tested. To optimize the thruster design to water-vapor propellant, the geometrical investigation was conducted. After testing six different models, the smallest thruster, with an outer diameter of 20 mm, was found to be the most suitable for 100-W class operation. This thruster was able to be operated less than 100 W at 200 V. In addition, the discharge power was suppressed to 200 W even at 300 V. Based on the plume diagnostics, the thrust force of 2.9 mN, specific impulse of 650 s, and anode efficiency of 4.6 % were obtained as a representative performance of this 300 V operating point.
After the thruster operation was achieved, the cathode coupling test was conducted to demonstrate electron emission under water-vapor plasma existence. As a result of this experiment, the effective increase in electron current compared to the previous stand-alone tests was confirmed as well as the compatibility to the water-vapor plasma plume. On the other hand, the electron emission current has not achieved 100 mA-class yet and the required heating power was predicted over 100 W; thus, further improvement is progressing.

References:
[1] Shirasu, K., Kuwabara, H., Matsuura, M., Koizumi, H., Kawashima, R., Nakagawa, Y., Watanabe, H., Sekine, H., Komurasaki, K., “Far-field plume diagnostics of low-power water hall thruster,” IEPC-2022-387.
[2] Shirasu, K., Takasaki, D., Fujimori, A., Matsuura, M., Koizumi, H., Sekine, H., Komurasaki, K., Nakagawa, Y., Watanabe, H., “A 100W-class water vapor thruster for constellations and space explorations by smallsats,” Small Satellite Conference SSC23-WVII-08.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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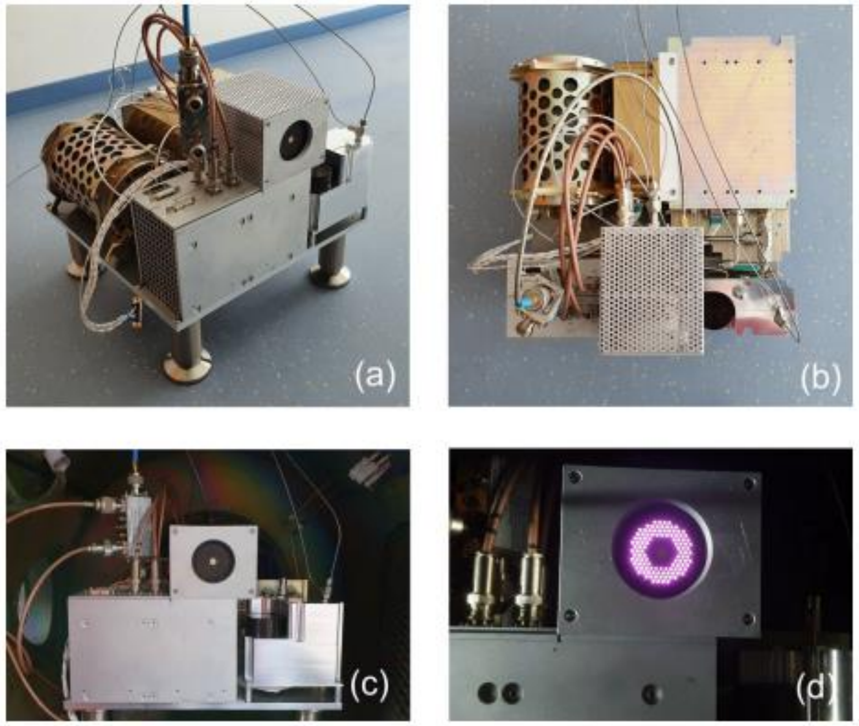
IonJet

Propulsion Technology	Ion thruster
Manufacturer/Country	Aerospace Innovation (DEU)
TRL	3
Size (including PPU)	
Design satellite size	
Isp (s)	>1000s [1]
Thrust type/magnitude	1 mN [1]
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	50W [1]
Flight heritage (if any)	None Components were pulled from MicroJet, which is TRL 7 [1]
Commercially available	No
Last updated	08/2022



[1]

Fig. 11 The IonJet EM: (a) front-side view, (b) top view, (c) front view after mounting in the vacuum chamber, (d) in operation. The vertical box left from the thruster is an additional device to measure the reflected RF power and not integral part of the EM

Additional comments:

[Reference 1][Aug 2022][Thruster information]
IonJet is an engineering model of a low-cost electric propulsion system for small satellites. Whereas the Flow Control subsystem is based on the MICROJET 2000 system launched 2016 on the BIROS satellite, the thruster subsystem is based on a novel gridded ion thruster where the neutralizer is integrated in the ion thruster allowing for simultaneous ion and electron extraction. This design allows reducing the number of components and consequently costs and system complexity. In the performance tests thrusts of 1 mN could be achieved for a total power consumption of less than 50 W as well as specific impulses larger than 1000 s, including the gas consumption of the neutralizer. The whole system was successfully tested under vacuum conditions regarding ignition and stable operation of the propulsion system.

References:
[1] Scholze, F., Pietag, F., Bundesmann, C., Woyciechowski, R., Spemann, D., Kreil, M., Kron, M., Adirim, H., “IonJet: Development of a cost-efficient gridded ion thruster propulsion system for smallsats,” IEPC-2022-246.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

ALPHIE (Alternative low power hybrid ion engine)

Propulsion Technology	Ion engine
Manufacturer/Country	Technical University of Madrid (UPM) (ESP)
TRL	3
Size (including PPU)	
Design satellite size	Small satellite
Isp (s)	>10,000 s
Thrust type/magnitude	1-3 mN for Argon
Delta-V (m/s)	
Propellant	Argon
Power consumption (W)	200 to 350W
Flight heritage (if any)	None
Commercially available	No
Last updated	08/2022

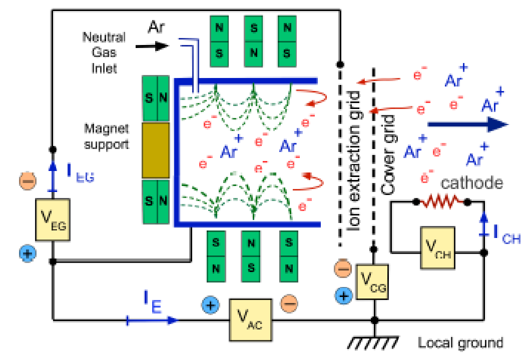
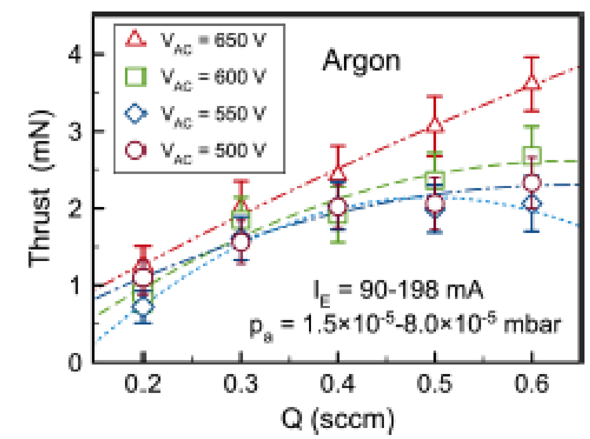


Fig. 1 **Electric scheme of *alphie*.**

[1]



Additional comments:
[Reference 1][Aug 2022][Thruster information]
The Alternative Low Power Hybrid Ion Engine is a new disruptive concept of electric thruster in development by the UPM PlasmaLab at the Technical University of Madrid (UPM) for mid-size satellites with power requirements below 500W. This thruster differs from classical Gridded Ion Engines (GIE) as a counter-flow of charges appears through the grid system. This means that electrons, coming from a single external cathode, are accelerated towards the ionization chamber with the same potential drop that is extracting ions. These high energy electrons collide with the injected neutral gas, exchanging large amount of energy and generating new ions. After the acceleration of ions by the grid system, the plume is neutralized by the electrons coming from the external cathode. Measurements of the ion velocity in the plume show a well collimated two-peaked distribution, with the velocity of the high peak around 40 kms^{-1}. Thrust measured directly is between $1-3$mN for gas flows of 0.2 to 0.6 sccm of Ar, which leads to specific impulses above 10,000 s.

References:
[1] Conde, L., Donosco, J., Domenech-Garret, J., Gonzalez, J., Castillo, M., “Thrust measurements and plasma plume kinetics of the alternative low power hybrid ion engine (alphie),” IEPC-2022-436.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

M1.4 ConstantQ propulsion

Propulsion Technology	Electrostatic
Manufacturer/Country	Miles Space (USA)
TRL	2-3
Size (including PPU)	1U
Design satellite size	Small Satellites
Isp (s)	7300s [1]
Thrust type/magnitude	17.2 mN [1]
Delta-V (m/s)	4620 m/s for 4 kg (3U), 2273 m/s for 8 kg (6U) [1]
Propellant	Water
Power consumption (W)	18W [1]
Flight heritage (if any)	None
Commercially available	YES
Last updated	11/2022

- Propellant: H2O (Filled as liquid. Liquid or solid during storage and use)
- Envelope: 95x95x95 mm (ie., 1U with 5mm margin)
- Wet Mass: 980 grams
- Propellant Load: 250 grams of liquid, pure water
- System Power: 6 Watts (Typical flow rate with all thrusters active)
- Max System Power: 18 Watts (Maximum flow rate with all thrusters active)
- Thermal Draw: 11.5 Watts (Heater on, no thrusters active)
- Temperature Range: -25C to +49C (Valves heated to 4C)
- Survival Temperature: -40C to 49C
- Input Voltage: 5V logic, 12V thrust
- Thrust: 17.2 mN (all thrusters active)
- Isp: 7,300 sec
- Total Impulse: 17,800 Ns
- Delta V: 4,620 m/s for 4kg 3U
  2,273 m/s for 8kg 6U
- Thrust/Power: 2.9 mN/Watt
- Thrust/Mass: 17.6 mN/kg
- Lifetime: >= 4x propellant load (based on ongoing experiments)

[1]

Additional comments:
[References 1][Nov 2022][Thruster information]
The ConstantQ™ family of thrusters use a pulsed electrostatic cycle to enable a variety of Earth-orbiting and deep space missions using water propellant. Test results show water's vapor pressure and its plasma speciation are especially useful to this operating cycle.
A ConstantQ™ thruster has: 1) a plasma formation region containing spark electrodes, 2) two exhaust ports, each ringed by acceleration electrodes, 3) a single power supply providing spark and acceleration power. Vapor enters the plasma formation region, expanding and changing pressure on its path towards the exhaust ports. Paschen's law ensures a spark occurs within the vapor at the point where the supply voltage meets the pressure on the Paschen curve. Each exhaust port is ringed with high voltage electrodes. One exhaust port's voltages act to focus and extract positive ions from the plasma. The other affects electrons. Electrons, being far less massive than ions, leave the plasma before ions, generating thrust from their interaction with the acceleration electrodes. Once outside the thruster, the electrons form a virtual cathode that pulls upon the ions remaining within the thruster. As the ions leave, thrust is obtained from acceleration electrodes. However, the ions also derive kinetic energy from the virtual cathode, slowing the exhaust electrons and even causing electrons to flow back toward the thruster. This gives an increased acceleration voltage upon the ions, expanding the classic Child-Langmuir limits for space-charge flow rate and thrust density. As the ions exit the thruster, they meet the returning electrons, neutralizing the plasma. With water vapor, the interface between exiting ions and returning electrons appears as a white-hot sphere 5-8mm outside the ion's exhaust port. This phenomenon is believed to be due to the presence of multiple ion species with different velocity profiles. In the image below, the two exhaust ports are shown, with the electron port on the left and the ion port on the right. Note the distinctly different exhaust appearances of the two. A resonance occurs between the incoming gas pressure, spark push back, and plasma drain rate through the exhaust ports (as driven by the supply's high voltage which can be varied to align with mission Isp). The ConstantQ™ uses a very specific geometry to drive this resonance, minimize wear, reduce power supply complexity, and reduce flight computing demands. ConstantQ™ thrusters have produced thrust using water vapor, Xenon, Argon, Krypton, Iodine, and air.

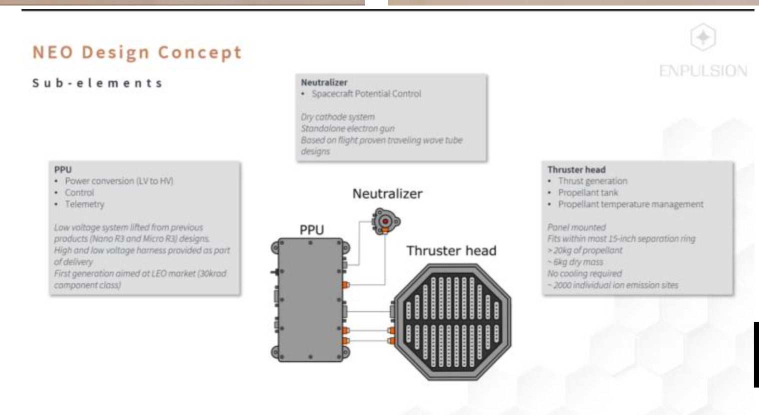
References:
[1] https://miles-space.com/thruster/

	3	NO
Comm. avail.	TRL	Aerospace-tested

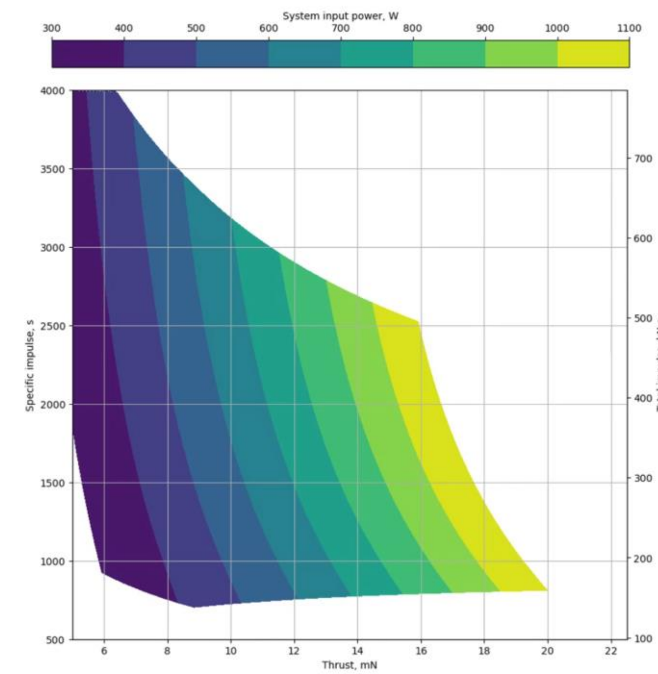
Enpulsion NEO

Propulsion Technology	FEEP
Manufacturer/Country	Enpulsion (Austria)
TRL	3-4
Size (including PPU)	3U
Design satellite size	SmallSat
Isp (s)	~2500s [1]
Thrust type/magnitude	20 mN [1]
Delta-V (m/s)	
Propellant	Indium
Power consumption (W)	800 active firing, 40 to 60 W hot standby [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	10/2023

[1]



[2]



[2]

Additional comments:

[References 1][Feb 2023][General information]
Development and qualification is supported by ESA through the ARTES program. Qualification is scheduled to start early 2024.
Design utilizes rows of parallel emitter needles, fed through capillary action, similar to the ring design.

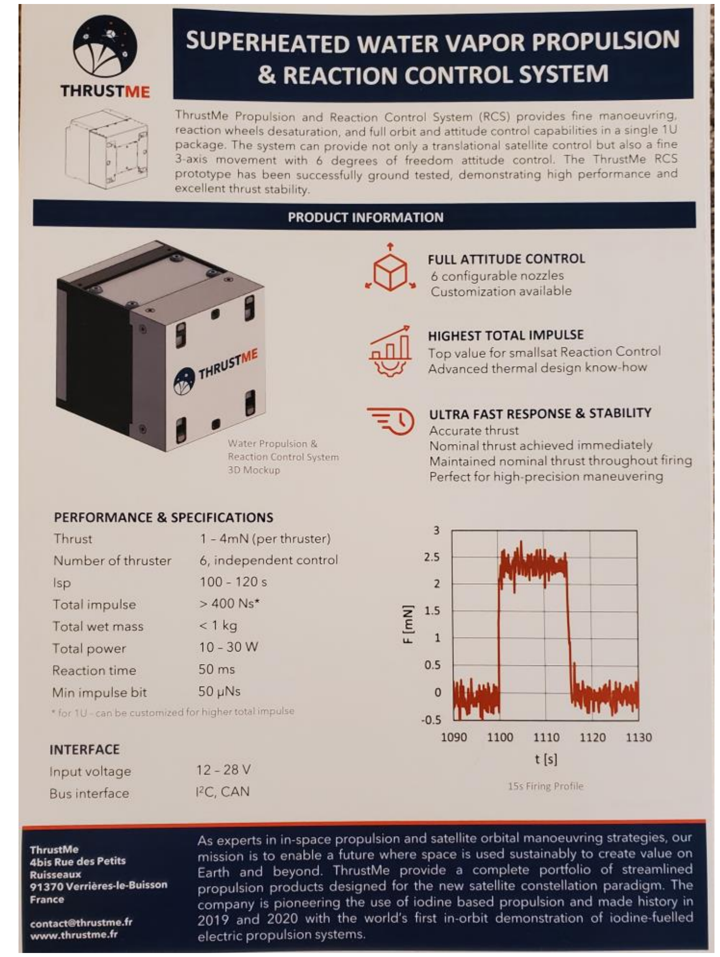
References:
[1] Flyers distributed at SmallSat Symposium Feb 2023, POC Dale Ward (Enpulsion, US Sales)
[2] Public webinar on Enpulsion NEO, Lou Grimaud

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Superheated water vapor propulsion

Propulsion Technology	Warm gas
Manufacturer/Country	ThrustME (FRA)
TRL	3-4
Size (including PPU)	1U
Design satellite size	
Isp (s)	100 to 120s [1]
Thrust type/magnitude	1 to 4 mN (per thruster), 6 thrusters integrated into system
Delta-V (m/s)	
Propellant	water
Power consumption (W)	10 to 30 W
Flight heritage (if any)	None
Commercially available	No
Last updated	02/2023



Additional comments:

[Reference 1][Feb 2023][General information]
Combined propulsion and RCS system provides fine maneuvering, reaction wheel desaturation, and full orbit and attitude control capabilities in a 1U package.

References:
[1] Flyer distributed at SmallSat Symposium, Feb 2023.

3 NO
Comm. avail. TRL Aerospace-tested

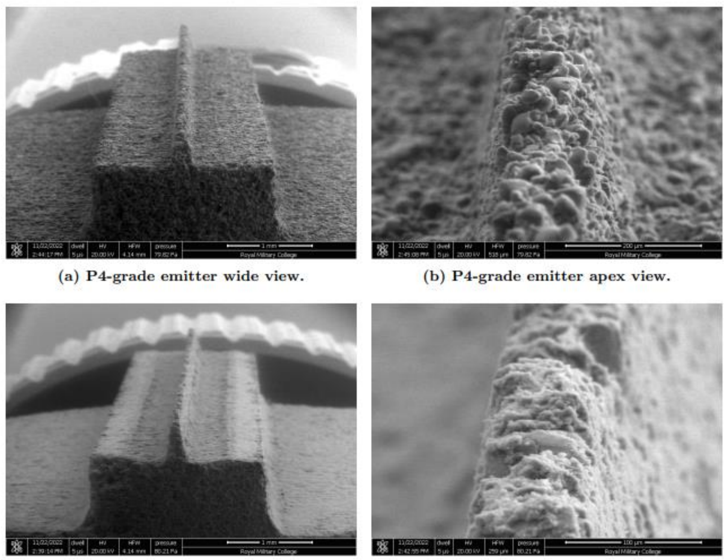
DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

Vectored electrospray thruster

Propulsion Technology	Electrospray
Manufacturer/Country	Royal Military College of Canada (Canada)
TRL	3-4
Size (including PPU)	<1U
Design satellite size	Small sats and CubeSats
Isp (s)	2035s at 2 uN, or 3089s at 0.5 uN [1]
Thrust type/magnitude	2035s at 2 uN, or 3089s at 0.5 uN [1]
Delta-V (m/s)	
Propellant	EMI-BF4 [1]
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023

Mode	V_{in} [V]	I_{total} [μA]	q_{sp} [C kg^{-1}]	T [μN]	I_{sp} [s]	$\Delta\omega$ [μrad s^{-1}]
P4 Pos	+1159	+17.2	185,688	1.92	2115	14.8
P4 Neg	−1090	−20.4	205,114	2.10	2156	16.2
P4 Avg	±1125	±18.8	195,391	2.01	2135	15.5
P5 Pos	+1224	+4.6	371,375	0.37	3074	2.9
P5 Neg	−1129	−6.4	410,228	0.48	3103	3.7
P5 Avg	±1177	±5.5	390,802	0.43	3089	3.3



(a) P4-grade emitter wide view. (b) P4-grade emitter apex view.
(c) P5-grade emitter wide view. (d) P5-grade emitter apex view.

[1]

Additional comments:

[References 1][December 2023][General information]
The development and experimental characterization of a two-emitter VET prototype offering singleaxis attitude actuation was herein presented. A novel thruster housing was developed and the porous wedge emitter profiles were fabricated using conventional CNC fabrication. A custom PPU was developed to generate the HV rails necessary for electrospray emission, and a custom DCIU was built to transmit TC to and receive TM from the PPU. A tailored diagnostics suite that measured the emitted current was built and an experimental campaign was carried out at the RAPPEL testing facility. The campaign successfully demonstrated PWM of a single emitter as well as sequential and simultaneous operation of two emitters, ultimately validating the VET concept.

References:
[1] Savytskyy, I., Jugroot, M., “Development and characterization of a vectored electrospray thruster,” SSC23-WI-06.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

GreenDelta (DLR) bipropellant thrusters

Propulsion Technology	Bipropellant
Manufacturer/Country	GreenDelta/DLR (Germany)
TRL	2-3
Size (including PPU)	
Design satellite size	Small Satellite (100 to 500 kg)
Isp (s)	Up to 290s for 22N HyNOx [1] Up to 270s for 1N HyNOx [1]
Thrust type/magnitude	1N, 22N variations will be available
Delta-V (m/s)	
Propellant	HyNOx (hydrocarbons + N2O) and HIP_11 (H2O2 + ionic liquid based fuel)
Power consumption (W)	
Flight heritage (if any)	None, in-orbit demonstrations planned for 2024.
Commercially available	No, projected to be COTs by Q4 2023.
Last updated	12/2023

Table 2 HyNOx 1N Operation Characteristics

	Value	Status
Thrust (nominal)	1 N	
Thrust Range	0.3 – 1.2 N	qualification target
Specific Impulse (nominal)	up to 270 s	calculated (from measured combustion efficiency)
Chamber Pressure (nominal)	7 bar	demonstrated
Minimum Impulse Bit (Hot Gas)	< 0.1 Ns	demonstrated
Single pulse firing time	1 minute (vac) 3 minutes (atmospheric)	demonstrated
Propellant Throughput	1 kg	demonstrated
Cumulated on-time	> 40 minutes	demonstrated
Nozzle Expansion Ratio	100:1	adjustable
Maximum Pulse Frequency	5 Hz	demonstrated

Figure 6: HyNOx 1N Thruster

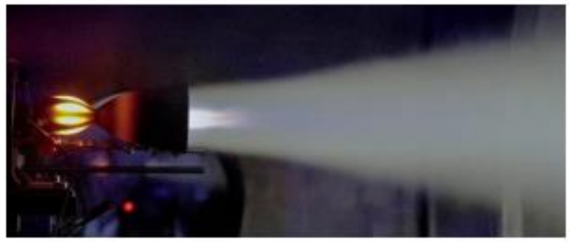


Figure 5: Steady-State Operation of HyNOX-22 in Vacuum Chamber

[1]

Additional comments:

[Reference 1][Dec 2023][General information]
The German Aerospace Center's Institute of Space Propulsion in Lampoldshausen has more than a decade of experience in green propellant research and green propulsion hardware development. In the frame of internal research projects as well as ESA and third-party projects DLR employees gained a deep and extensive knowledge of propulsion hardware. Based on this knowledge, thrusters and propulsion hardware were developed in-house and the TRL was increased step by step.
The products of GreenDelta will be based on the HyNOx and HIP_11 propulsion technologies. HyNOx stands for hydrocarbons with nitrous oxide. This technology offers a high specific impulse (up to 300 s), non-toxic components, self-pressurized propulsion systems, easy handling and low cost. Initial products are bipropellant thrusters between 1 and 200 N of thrust and associated propulsion systems. HIP_11 is a patented hypergolic propellant with hydrogen peroxide as oxidizer and an ionic liquid based fuel.
To commercialize the two propulsion technologies, a DLR spin-off called GreenDelta will be founded in summer 2023. The preparation of the spin-off is currently funded by the Helmholtz Association and DLR. This paper gives an overview on the development of the two technologies and their development status. First HyNOx products will be available Q4 2023 and an in-orbit demonstration for 2024 is foreseen. End of 2024 first HIP_11 products will become available and an in-orbit demonstration is aimed in 2025.

References:
[1] Lauck, F., Werling, L., Dobusch, J., Grizka, M., Stratmann, V., Merz, F., Horger, T., "From Lampoldshausen to orbit: DLR Spin-off GreenDelta and the development status of green propellant thrusters based and H2O2 and N2O," SSC23-VI-07.

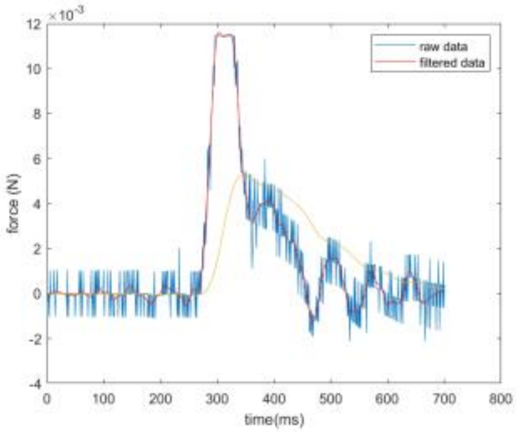
NO	3	NO
Comm. avail.	TRL	Aerospace-tested

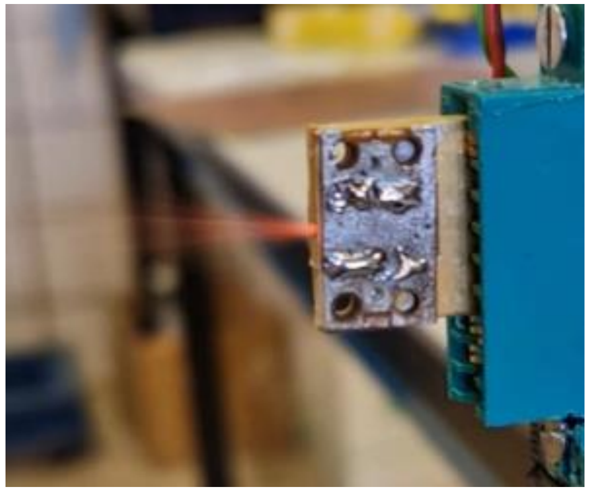
DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

PCBMEMS solid rocket micro thruster

Propulsion Technology	Solid rocket micro thruster
Manufacturer/Country	University of Seville (SPAIN)
TRL	2-3
Size (including PPU)	Incredibly small
Design satellite size	1U or smaller
Isp (s)	
Thrust type/magnitude	~40 mN in 0.1s (calculated), measured 12 mN due to incomplete combustion of propellant [1]
Delta-V (m/s)	
Propellant	Black powder
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023





[1]

Additional comments:

[References 1 and 2][September 2021][General information]
The microthruster consists in a tank that stores the solid fuel, a nozzle, and a detonator. The tank and the nozzle of the microthruster are made on a PCB board, milling the FR4 substrate and maintaining the outer copper layer on both sides. On another printed circuit board, the detonator is made using a thin line of copper as a resistor in the front of the tank. The tank is filled with solid fuel, black powder in our case.

References:
[1] Quero, J., Quero, G., “Implementation of a microthruster using PCBMEMS,” Small Satellite Conference SSC23-VI-08.

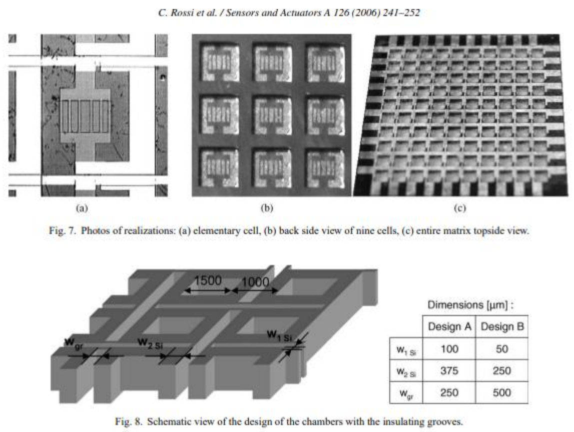
NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

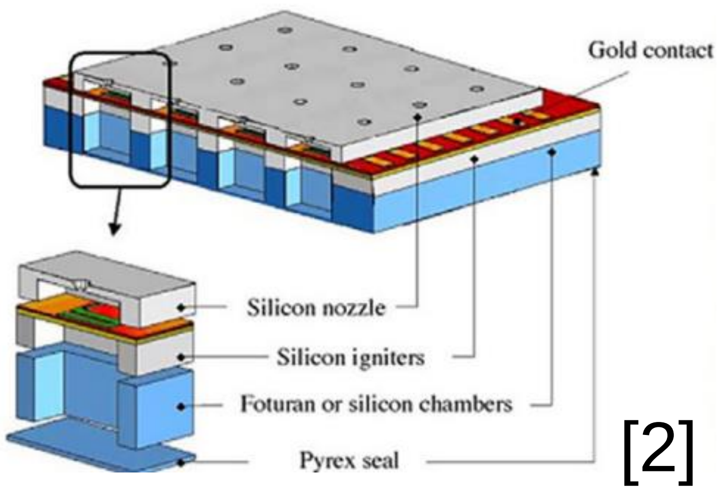
DISTRO A: Approved for public release. OTR-2024-00338

MicroPyros

Propulsion Technology	Solid microthruster array
Manufacturer/Country	LAAS-CNRS (France)
TRL	3-4
Size (including PPU)	Very small
Design satellite size	
Isp (s)	
Thrust type/magnitude	0.3 to 2.3 mN [1]
Delta-V (m/s)	
Propellant	Glycidyle azide polymer (GAP) [1]
Power consumption (W)	<0.25W [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023



[1]



[2]

Additional comments:

[References 1][Dec 2023][General information]
An EC funded MicroPyros project has permitted to develop the technologies to fabricate, assemble and command solid propellant microthrusters arrays for thrusts of a few of milli Newtons The prototype built for space application has 100 individually addressed ∅ 1.5 mm × 1.5 mm thrusters on 576 mm2. Nozzles' throats are 250 um and 500 um. This paper reviews the prototype structure and details the final processes for the fabrication and assembling. This paper presents also a new addressing technology based on polysilicon threshold elements used for the addressing and heating of each thruster in the array. With polysilicon threshold element, ignition success is of 100% with an input power of 250 mW using a zirconium perchlorate potassium (ZPP) material. Then, the combustion of a glycidyle azide polymer (GAP) is sustained in the chamber and generate thrusts in the range of 0.3–2.3 mN depending of the micronozzle dimension.

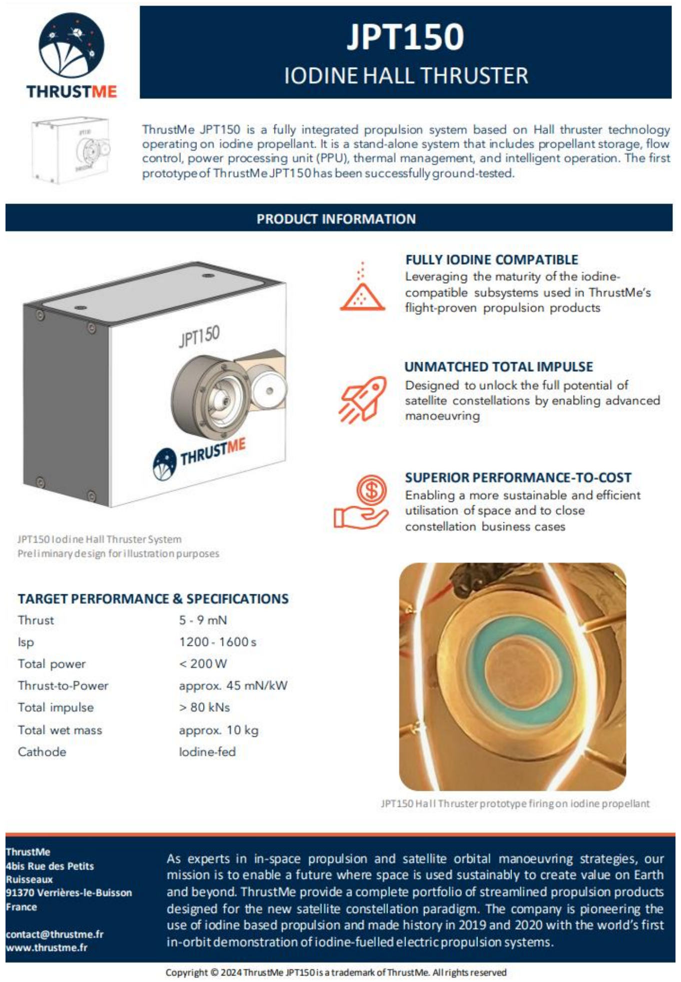
References:
[1] Rossi, C., Briand, D., Cumonteuil, M., Camps, T., Pham, P., Rooij, N., "Matrix of 10x10 addressed solid propellant microthrusters: review of the technologies," Sensors and actuators, 2006.
[2] Xu, J., Zhang, J., li, F., Liu, S., Ye, Y., Shen, R., "A review on solid propellant micro-thruster array based on MEMS technology," FirePhysChem, 2023.

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

JPT150 Iodine Hall thruster

Propulsion Technology	Hall thruster
Manufacturer/Country	ThrustMe (France)
TRL	3
Size (including PPU)	~10 kg [1]
Design satellite size	Smallsat
Isp (s)	1200 to 1600 s [1]
Thrust type/magnitude	5-9 mN [1]
Delta-V (m/s)	
Propellant	Iodine [1]
Power consumption (W)	<200W [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023


THRUSTME

JPT150
IODINE HALL THRUSTER

ThrustMe JPT150 is a fully integrated propulsion system based on Hall thruster technology operating on iodine propellant. It is a stand-alone system that includes propellant storage, flow control, power processing unit (PPU), thermal management, and intelligent operation. The first prototype of ThrustMe JPT150 has been successfully ground-tested.

PRODUCT INFORMATION

JPT150 Iodine Hall Thruster System
Preliminary design for illustration purposes

FULLY IODINE COMPATIBLE
Leveraging the maturity of the iodine-compatible subsystems used in ThrustMe's flight-proven propulsion products

UNMATCHED TOTAL IMPULSE
Designed to unlock the full potential of satellite constellations by enabling advanced manoeuvring

SUPERIOR PERFORMANCE-TO-COST
Enabling a more sustainable and efficient utilisation of space and to close constellation business cases

TARGET PERFORMANCE & SPECIFICATIONS

Thrust	5 - 9 mN
Isp	1200 - 1600 s
Total power	< 200 W
Thrust-to-Power	approx. 45 mN/kW
Total impulse	> 80 kNs
Total wet mass	approx. 10 kg
Cathode	Iodine-fed

JPT150 Hall Thruster prototype firing on iodine propellant

ThrustMe
4bis Rue des Petits Ruisseaux
91370 Verrières-le-Buisson
France

contact@thrustme.fr
www.thrustme.fr

As experts in in-space propulsion and satellite orbital manoeuvring strategies, our mission is to enable a future where space is used sustainably to create value on Earth and beyond. ThrustMe provide a complete portfolio of streamlined propulsion products designed for the new satellite constellation paradigm. The company is pioneering the use of iodine based propulsion and made history in 2019 and 2020 with the world's first in-orbit demonstration of iodine-fuelled electric propulsion systems.

Copyright © 2024 ThrustMe JPT150 is a trademark of ThrustMe. All rights reserved

Additional comments:

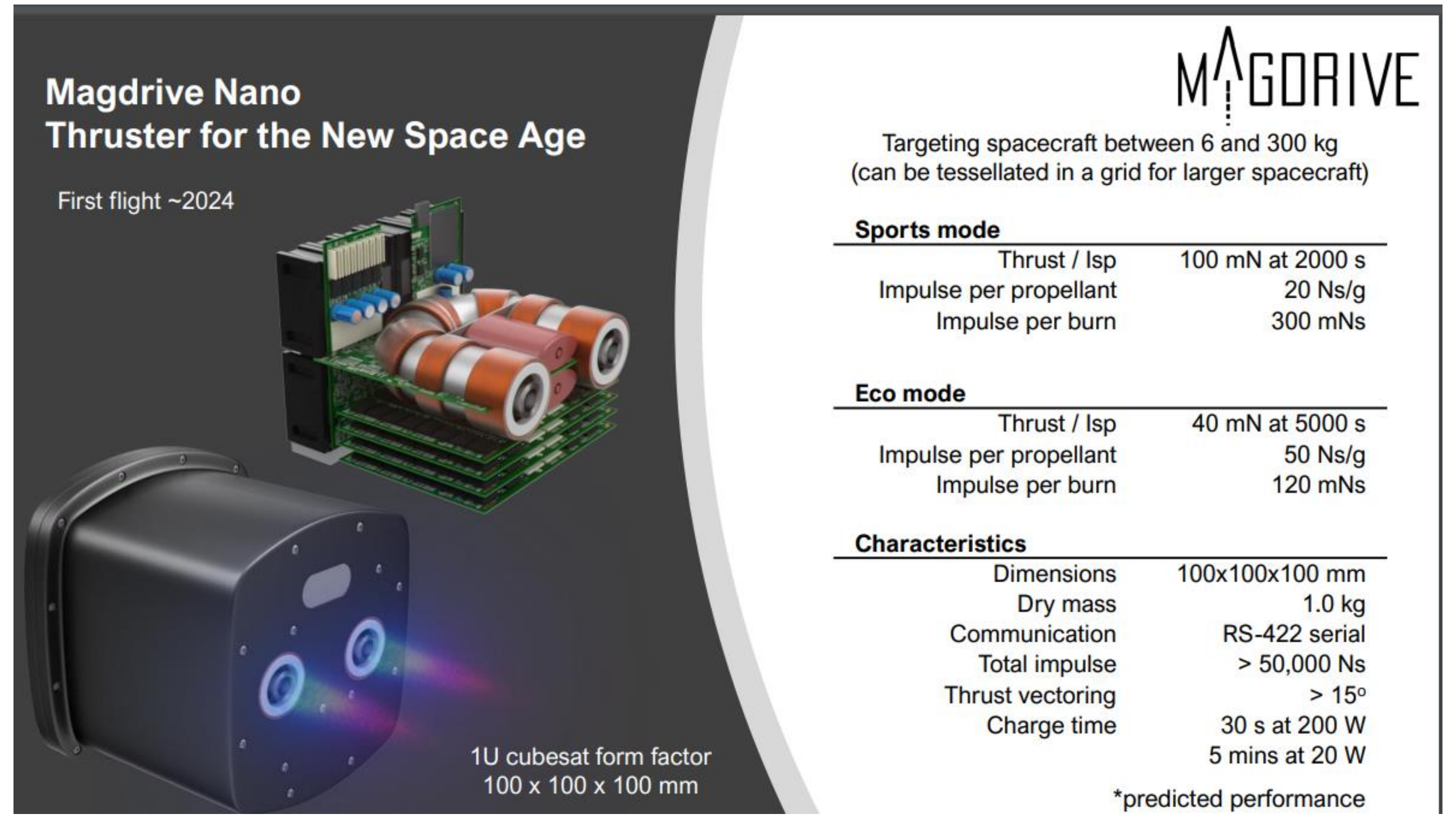
[Reference 1][Dec 2023][General information]
ThrustMe JPT150 is a fully integrated propulsion system based on Hall thruster technology operating on iodine propellant. It is a stand-alone system that includes propellant storage, flow control, power processing unit (PPU), thermal management, and intelligent operation. The first prototype of ThrustMe JPT150has been successfully ground-tested.

References:
[1] https://www.thrustme.fr/base/stock/ProductBannerFiles/3_20240102-thrustme-jpt150.pdf

NO	3	NO
Comm. avail.	TRL	Aerospace-tested

Magdrive-Nano

Propulsion Technology	Metal PPT
Manufacturer/Country	Magdrive (UK)
TRL	2-3
Size (including PPU)	1U (1kg)
Design satellite size	3U+
Isp (s)	2000 s [3]
Thrust type/magnitude	100 mN, 300 mN*s per burn [3]
Delta-V (m/s)	
Propellant	Metal propellant
Power consumption (W)	20 to 200W [3]
Flight heritage (if any)	None First flight projected for 2024 [3]
Commercially available	Unknown
Last updated	05/2023



[3]

Additional comments:

[Reference 1][May 2023][General information]
Company is marketing this technology for avoidance maneuvers, end-of-life deorbiting, satellite servicing, orbital manufacturing, constellation management, and deep space transport.

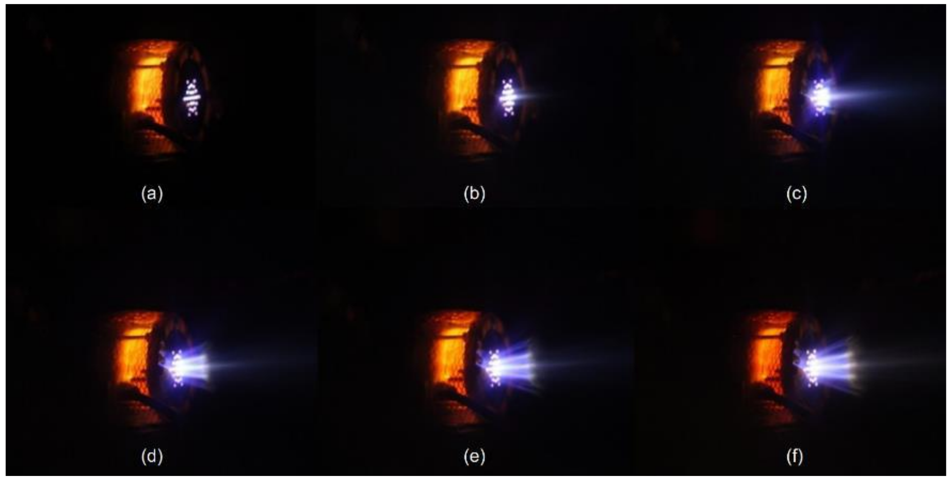
[Reference 3][May 2023][Flight information]
Magdrive's first space mission: Launching in October 2022 aboard SpaceX Transporter 6
Hosted payload about a 6U Endurosat spacecraft
Magdrive Hardware and firmware completed, Integration with Endurosat flatsat successful, Test of power system, the heart of the Magdrive, Unique charging, energy storage and discharging system, 0.5U 500 g payload on 6U spacecraft
Cathode arc thruster from University of Southampton
Magdrive Nano first flight aiming for 2024

References:
[1] https://www.magdrive.space/#contact-us
[2] Personal communications with Zephyr Computing at Interstellar small sat conference (May 2023)
[3] https://siliconvalleyinternship.com/wp-content/uploads/2022/09/magdrive-pitch.pdf

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

Western Miniature ECR Gridded Ion Thruster (MGIT)

Propulsion Technology	Ion thruster
Manufacturer/Country	Western Michigan University (USA)
TRL	2-3
Size (including PPU)	
Design satellite size	SmallSat
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Argon at 3 sccm and 4.98 GHz microwave power[1]
Power consumption (W)	~10W [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	07/2022



Additional comments:

[Reference 1][July 2022][Thruster development]
The first version of the W-MGIT was successful in demonstrating plasma generation, sustained discharge, and ion beam extraction. The plasma diagnostic data gathered using a LP showed plasma density values that were within range of other similar class thrusters. The optimal test setting for this version of the MGIT was recorded at 4.98 GHz frequency, 8 W of effective input power, 3 sccm of argon propellant, and acceleration potential 500 V (reduced to 300 V after arcing damages). Overall, the MGIT was successful in its initial design goals despite difficulties experienced due to supply chain issues and preliminary design estimations. The next version of the MGIT will be optimized using the SmCo magnet and its corresponding thruster geometry. The future work also includes the design and manufacturing of higher quality ion optics that will allow for a wider range of acceleration potential. Plasma diagnostics using a Faraday cup and a retarding potential analyzer are to be conducted as well in order to better understand thruster performance.

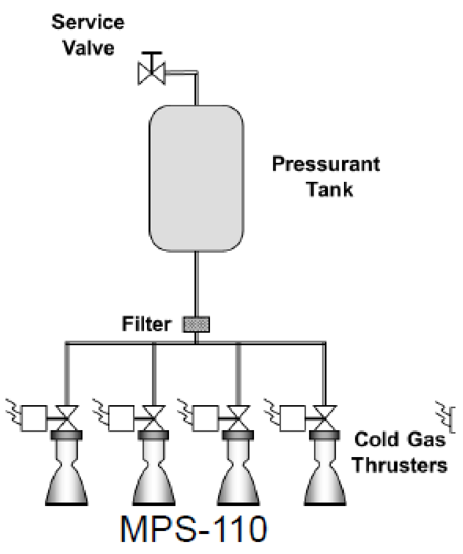
References:
[1] Asif, M., Nuzzo, N., Lemmer, K., “Design and development of the western miniature ECR gridded ion thruster,” IEPC-2022-265

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

MPS-110
Aerojet Rocketdyne

Propulsion Technology	Cold gas/Monopropellant
Manufacturer/Country	AeroJet Rocketdyne (USA)
TRL	2-3
Size (including PPU)	1U
Design satellite size	3U, 6U, and larger
Isp (s)	206 to 217 s
Thrust type/magnitude	
Delta-V (m/s)	10m/s for 4kg (3U) spacecraft [3]
Propellant	Inert gas
Power consumption (W)	<10W (start-up), <10W (operation)
Flight heritage (if any)	None known
Commercially available	Unknown
Last updated	*04/2021*

Product Image	Product Number	Description	ΔV for 3U 4kg BOL	ΔV for 6U 10kg BOL
	MPS-110	• System Mass: Varies depending on selected size • Propellant: Inert gas • Propulsion: 1 to 4 cold gas thrusters	10 m/s	N/A
	MPS-120	• System Mass: <1.3kg dry, <1.6kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	209 m/s	81 m/s
	MPS-130	• System Mass: <1.3kg dry, <1.6kg wet • Propellant: AF-M315E • Propulsion: Four TBD—1 N (BOL) rocket engines	340 m/s	130 m/s
	MPS-120XW	• System Mass: <2.4kg dry, <3.2kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	440 m/s	166 m/s
	MPS-120XL	• System Mass: <2.4kg dry, <3.2kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	539 m/s	200 m/s
Image Coming Soon	MPS-160	• System Mass: TBD • Propellant: Xenon • Propulsion: 80W Solar Electric Power/Solar Electric Propulsion System (SEP²)	N/A	>2,000 m/s



Additional comments:

[Reference 3][April 2021][Thruster information]
The MPS-110 cold gas system is being developed to provide a propulsive capability for missions on small platforms that need minimal deltaV to achieve their mission objectives. Applications would primarily be initial dispersion, minor orbit adjustments, or attitude control. The MPS-110 system derives valves, filter, and tank design from the MPS-120 system. The system is capable of operating with a variety of pressurants such as GN2 or condensables enabling significant mission tailoring.

References:
[1] http://www.rocket.com/cubesat/mps-120
[2] Schmuland, D., Carpenter, C., Masse, R., Overly, J., "New insights into additive manufacturing processes: enabling low-cost, high-impulse propulsion systems," Small Satellite Conference talk, 2013.
[3] Carpenter, C., Schmuland, D., Overly, J., Masse, R., "CubeSat modular propulsion systems product line development status and mission applications," Aerojet report (year?) https://www.rocket.com/sites/default/files/documents/CubeSat/AIAA-2013-3760.pdf

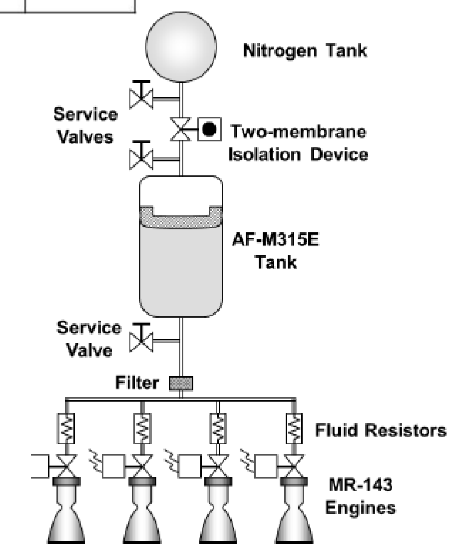
NO	2	NO
Comm. avail.	TRL	Aerospace-tested

MPS-130 CubeSat High Impulse Adaptable (CHAMPS)
Aerojet Rocketdyne

Propulsion Technology	AF-M315E Green Monopropellant
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	2-3
Size (including PPU)	1U
Design satellite size	
Isp (s)	206-235 s
Thrust type/magnitude	6000 N*s (impulse, total) 0.0004 N*s (impulse bit, minimum) 0.25-1.25 N (nominal thrust, continuous)
Delta-V (m/s)	340 m/s for 4 kg spacecraft 130 m/s for 10 kg spacecraft
Propellant	AF-M315E Green Monopropellant
Power consumption (W)	
Flight heritage (if any)	None known
Commercially available	Unknown
Last updated	*04/2021*

Product Image	Product Number	Description	ΔV for 3U 4kg BOL	ΔV for 6U 10kg BOL
	MPS-110	• System Mass: Varies depending on selected size • Propellant: Inert gas • Propulsion: 1 to 4 cold gas thrusters	10 m/s	N/A
	MPS-120	• System Mass: <1.3kg dry, <1.6kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	209 m/s	81 m/s
	MPS-130	• System Mass: <1.3kg dry, <1.6kg wet • Propellant: AF-M315E • Propulsion: Four TBD—1 N (BOL) rocket engines	340 m/s	130 m/s
	MPS-120XW	• System Mass: <2.4kg dry, <3.2kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	410 m/s	166 m/s
	MPS-120XL	• System Mass: <2.4kg dry, <3.2kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	539 m/s	200 m/s
Image *Coming Soon*	MPS-160	• System Mass: TBD • Propellant: Xenon • Propulsion: 80W Solar Electric Power/Solar Electric Propulsion System (SEP[2])	N/A	>2,000 m/s

Solid model of MPS-130.
No photographs of actual hardware found.



MPS-130

Additional comments:

[Reference 1,2][Jan 2019][General info]

Very limited information available on manufacturer’s website, and no images of actual hardware. Development status is “In Development” as of 2018 and no publications are released. Thruster unit consists of 4 thrusters for attitude control. According to manufacturer’s website, “MPS-130™ CubeSat High-Impulse Adaptable Modular Propulsion System (CHAMPS) is a 1U AF-M315E (low-toxicity propellant) propulsion system that provides both primary propulsion and 3-axis control capabilities in a single package. The system is designed for CubeSat customers needing significant ΔV capabilities including constellation deployment, orbit maintenance, attitude control, momentum management, and de-orbit.”

[Reference 3][April 2021][General info]

MPS-130 is almost identical to the MPS-120 except that a burst disk is not required for the AF-M315E green monopropellant and the system employs new MR-143 engines capable of operating on AF-M315E green monopropellant. The MR-143 engines are of similar size to the MR-142, but utilize rhenium chambers that survive the high combustion temperatures of AF-M315E propellant. At the time of this writing, the MPS-130 design and drawings are complete, and fabrication is currently under-way with MR-143 engine components produced and ready for engine assembly.

References:

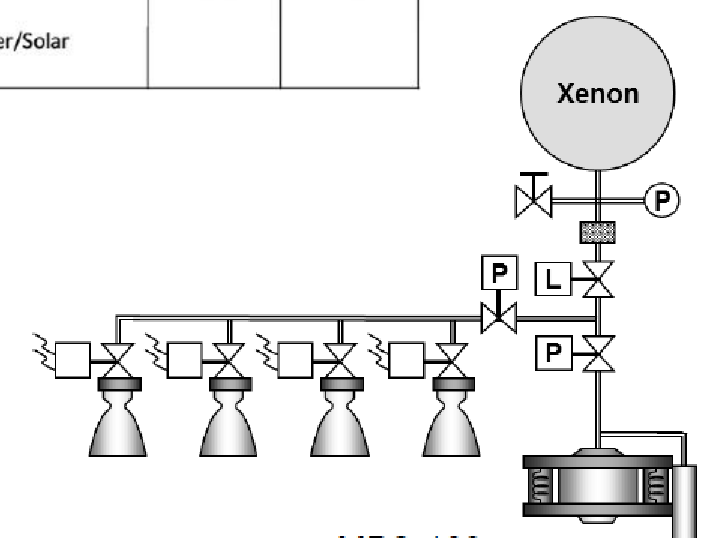
[1] http://www.rocket.com/cubesat/mps-130
[2] Schmuland, D., Carpenter, C., Masse, R., Overly, J., “New insights into additive manufacturing processes: enabling low-cost, high-impulse propulsion systems,” Small Satellite Conference talk, 2013.
[3] Carpenter, C., Schmuland, D., Overly, J., Masse, R., “CubeSat modular propulsion systems product line development status and mission applications,” Aerojet report (year?) https://www.rocket.com/sites/default/files/documents/CubeSat/AIAA-2013-3760.pdf

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

MPS-160 Solar Electric Propulsion
Aerojet Rocketdyne

Propulsion Technology	Solar electric propulsion system
Manufacturer/Country	Aerojet Rocketdyne (USA)
TRL	2-3
Size (including PPU)	20 cm x 10 cm x 12 cm
Design satellite size	6U and above
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	>2000 m/s for 6U (10kg) s/c, design
Propellant	Xenon
Power consumption (W)	300V nominal, 80W (thrusting), 20W (non-thrusting)
Flight heritage (if any)	None
Commercially available	No, in development
Last updated	*04/2021*

Product Image	Product Number	Description	ΔV for 3U 4kg BOL	ΔV for 6U 10kg BOL
	MPS-110	• System Mass: Varies depending on selected size • Propellant: Inert gas • Propulsion: 1 to 4 cold gas thrusters	10 m/s	N/A
	MPS-120	• System Mass: <1.3kg dry, <1.6kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	209 m/s	81 m/s
	MPS-130	• System Mass: <1.3kg dry, <1.6kg wet • Propellant: AF-M315E • Propulsion: Four TBD—1 N (BOL) rocket engines	340 m/s	130 m/s
	MPS-120XW	• System Mass: <2.4kg dry, <3.2kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	440 m/s	166 m/s
	MPS-120XL	• System Mass: <2.4kg dry, <3.2kg wet • Propellant: Hydrazine • Propulsion: Four 0.26—2.8 N (BOL) rocket engines	539 m/s	200 m/s
Image Coming Soon	MPS-160	• System Mass: TBD • Propellant: Xenon • Propulsion: 80W Solar Electric Power/Solar Electric Propulsion System (SEP²)	N/A	>2,000 m/s



MPS-160

Additional comments:

[Reference 1][Jan 2019][General info]
MPS-160™ is a 2U x 1U solar electric power / solar electric propulsion (SEP2) system that provides both power and primary propulsion for CubeSat missions. The system is designed for CubeSat customers needing significant ΔV capabilities including constellation deployment, altitude changes, plane changes, re-phase maneuvers, orbit maintenance, and de-orbit. The system includes two gimbaled 40W, 300V solar arrays, xenon propellant tank and feed system, innovative solar electric propulsion/solar electric power unit, and a single electric thruster. A thruster gimbal can be added as an option.

References:
[1] http://www.rocket.com/cubesat/mps-160
[2] Schmuland, D., Carpenter, C., Masse, R., Overly, J., "New insights into additive manufacturing processes: enabling low-cost, high-impulse propulsion systems," Small Satellite Conference talk, 2013.
[3] Carpenter, C., Schmuland, D., Overly, J., Masse, R., "CubeSat modular propulsion systems product line development status and mission applications," Aerojet report (year?) https://www.rocket.com/sites/default/files/documents/CubeSat/AIAA-2013-3760.pdf

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

MINNOP Miniature Nontoxic Oxide-Propane

Propulsion Technology	Bipropellant
Manufacturer/Country	Orbital Technologies Corporation (ORBITEC)
TRL	2
Size (including PPU)	1U
Design satellite size	3U and larger
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Bi-prop (propane, nitrous-oxide)
Power consumption (W)	
Flight heritage (if any)	
Commercially available	No
Last updated	*04/2021*

No image available

Additional comments:

[Reference 1][Jan 2019][General info]
From NASA open data portal for Phase 1 projects:
Miniature Nontoxic Nitrous Oxide-Propane (MINNOP) Propulsion, Phase I
ORBITEC proposes to develop the Miniature Nontoxic Nitrous Oxide-Propane (MINNOP) propulsion system, a small bipropellant propulsion system which we offer as an alternative to miniature hydrazine monopropellant thrusters for CubeSat-class spacecraft. As compared to state-of-the-art hydrazine systems, MINNOP propulsion will provide significant increases in specific impulse (in bipropellant mode) and comparable levels of minimum impulse bit (in cold gas mode), and it will do so with a nontoxic, environmentally benign, self-pressurizing set of propellants. In Phase I, we will focus on demonstrating the operation of the bipropellant thrust chamber, and ignition of that chamber within appropriate weight constraints. Our preliminary propulsion system design is intended to occupy 1U of a 3U-size CubeSat.

[Reference 2][Dec 2019][General info]
Orbital Technologies Corporation (ORBITEC) is developing the Miniature Nontoxic Oxide-Propane (MINNOP) propulsion system which uses nitrous oxide as the oxidizer. It consists of a bipropellant system for small spacecraft that can provide a significant increment in specific impulse performance with respect to hydrazine systems when used in bi-propellant mode and small levels of minimum impulse bit when used in cold gas mode. In 2014, efforts towards a demonstration of the bipropellant thrust chamber and ignition within suitable weight constraints in order to fit into a 1U form factor although current development status is unknown.

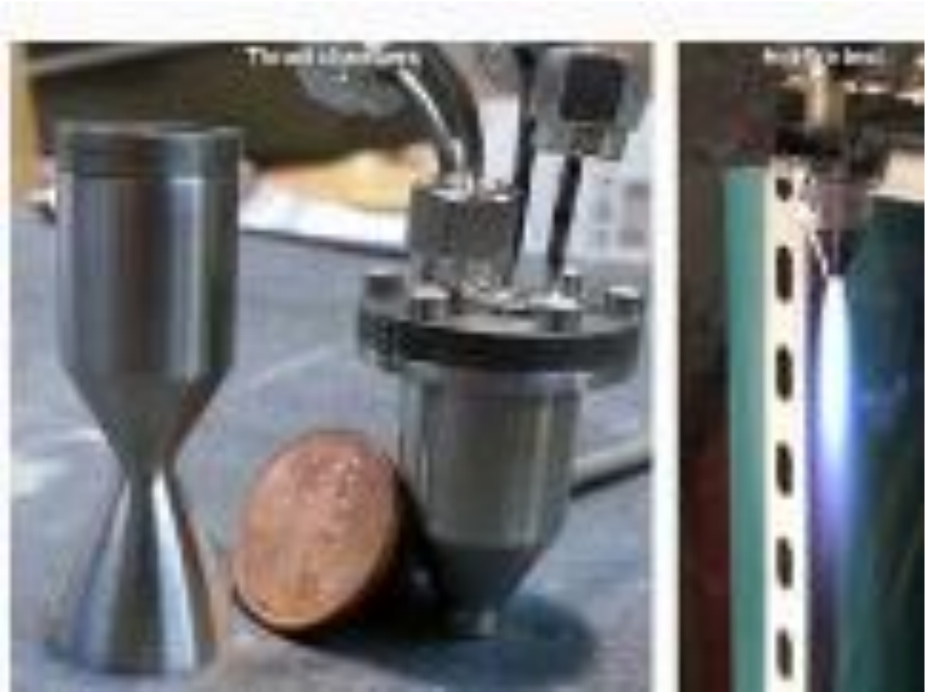
References:
[1] https://data.nasa.gov/dataset/Miniature-Nontoxic-Nitrous-Oxide-Propane-MINNOP-Pr/4sxk-s8gu
[2] NASA survey of small-satellite propulsion, 2018. https://sst-soa.arc.nasa.gov/04-propulsion

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Ventions non-toxic hybrid/cold gas
Ventions

Propulsion Technology	Green, hybrid, cold-gas
Manufacturer/Country	Ventions, LLC (USA), now Astra Space (USA)
TRL	2
Size (including PPU)	3U
Design satellite size	6U and larger
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	GOX-Methane and peroxide
Power consumption (W)	
Flight heritage (if any)	
Commercially available	NO
Last updated	*04/2021*



Additional comments:

[Reference 2][Dec 2019][General info]
Ventions LLC is working on an integrated 3U CubeSat propulsion system using non-toxic propellant; hybrid non-toxic/cold gas propulsion system for 6U and 12U spacecraft by Planetary Resources Development Corporation; and a non-toxic solid rocket for CubeSats that allows for second ignition and utilizes an aluminized version of an Electric Solid Propellant (ESP) from Digital Solid State Propulsion (DSSP). ESPs provide more safety for handling compared to traditional solid energetic propellants and are electrically ignited.

[Reference 3][April 2021][Company info]
Formerly known as Ventions LLC, the company has spent the last 14 years working on an array of different small launch vehicle and satellite technologies, including rocket stages, liquid bi-propellant motors, electric engine and turbine-driven pumps, and in-space propulsion for CubeSats.

[Reference 4][April 2021][Company info]
WASHINGTON — Small launch vehicle developer Astra will go public by merging with a special-purpose acquisition company (SPAC), providing the company with nearly $500 million in cash and valuing it at more than $2 billion. Astra announced Feb. 2 an agreement to merge with Holicity, a SPAC established last year by Craig McCaw. That merger, expected to close in the second quarter, will turn Astra into a publicly traded company on the Nasdaq exchange with the ticker symbol ASTR. McCaw, chairman and chief executive of Holicity, will join Astra's board as part of the deal.

[Reference 5][April 2021][Commercial availability]
This small-sat propulsion system no longer appears on the company website. Has it been discontinued?

References:

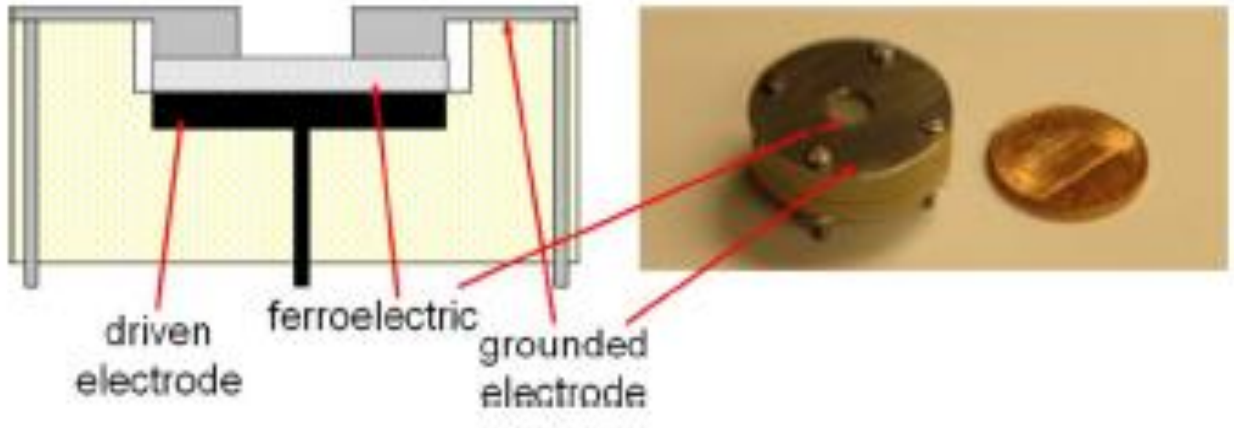
[1] http://ventions.com/menu/ http://www.parabolicarc.com/tag/ventions-llc/
[2] NASA survey of small-satellite propulsion, 2018. https://sst-soa.arc.nasa.gov/04-propulsion
[3] http://www.parabolicarc.com/2018/03/26/ventionsastra-space/
[4] https://spacenews.com/astra-to-go-public-through-merger-with-spac/
[5] https://astra.com/

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Ferroelectric plasma thruster (FEPT)

Propulsion Technology	Ferroelectric plasma thruster
Manufacturer/Country	University of Missouri (USA)
TRL	2-3
Size (including PPU)	6g (thruster only, does not include PPU)
Design satellite size	1U or larger
Isp (s)	1450 s
Thrust type/magnitude	70 to 90 uN (steady-state, nominal, measured) 1 nN*s (impulse bit, minimum)
Delta-V (m/s)	
Propellant	Ferroelectric material, with silvered surface
Power consumption (W)	6W
Flight heritage (if any)	None known
Commercially available	No
Last updated	*04/2021*



Additional comments:

[Reference 1][Jan 2019][General info]

For the FEPT, ion emission is the mass-transfer mechanism for thrust production. An RF voltage is applied across a ferroelectric disk, and a plasma is formed on the ferroelectric surface in a grounded aperture. This plasma serves as a source of ions for subsequent acceleration. A hypothesized mechanism of acceleration is that the applied RF field electrostatically accelerates ions out of the plasma. When a positive voltage is on the rear of the ferroelectric, ions are repelled from the front ferroelectric surface and eventually exit the device. On the ferroelectric surface, ~500-μm-diameter silver dots were painted with dot-to-dot spacing of ~250 μm. Output ion and electron-current magnitude could be adjusted by changing the number of paint dots on the surface. This can be an advantage for microthruster applications. Solid propellant could be applied differently to FEPTs to achieve various output characteristics. Combining the plasma-plume measurements and the thrust stand measurements, we get a good idea of the thruster characteristics of the FEPT. One parameter not detailed earlier is the power dissipated in the thruster. For varying configurations, we have measured average powers ranging from 3 up to 15 W. For the setpoints presented in this paper, the power was ~6 W. It is with this number that the thrust efficiency is calculated to be 8%. The potential affects of slow neutral particles and extra required hardware, such as neutralizers, are not reflected in this number. One advantage of the FEPT is its compact, low-mass, and low-complexity design. The thruster electrodes, crystal, and mounting hardware have a mass of just 5.7 g. Although, for testing, we have mainly used large laboratory RF power supplies, we have also built a low-mass class-E amplifier which has a mass less than 50 g. One proposed scheme for FEPT propellant is to load solid material on the aperture surface. The ablation and acceleration away of this material serves as the mass transfer for the thruster. Therefore, there may not be any additional hardware for propellant management. This serves to further reduce the complexity of the thruster. Another feature of the FEPT is the ability to produce very low impulse bits, where impulse bit is defined as the smallest possible impulse deliverable by the thruster. With an average thrust of ~70 μN and a frequency of operation of around 385 kHz, impulse bits of 70 μN/385 kHz = 181 pN · s are realizable. However, ion bursts do not start for several cycles after the onset of the applied RF burst. Therefore, a conservative estimate of 1 nN · s is made for the impulse bit.

References:

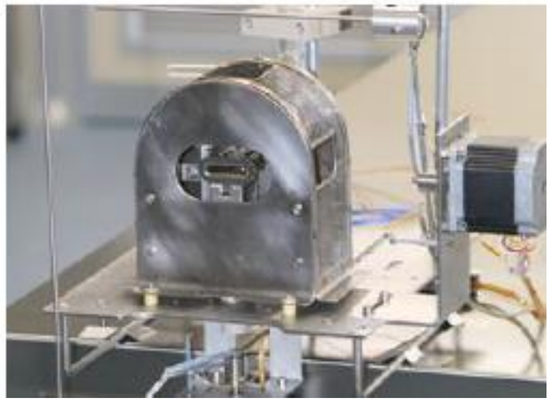
[1] Kemp, M., Kovaleski, S., “Thrust measurements of the ferroelectric plasma thruster,” IEEE Transactions on Plasma Science, 2008.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

COMFIT

Propulsion Technology	FEEP
Manufacturer/Country	Alta-Space, now (SITAEL) (ITALY)
TRL	2-3
Size (including PPU)	700g (dry mass)
Design satellite size	3U +
Isp (s)	3500-5000 s
Thrust type/magnitude	Up to 250 uN (continuous, nominal)
Delta-V (m/s)	
Propellant	Unknown (“non-hazardous”) [1]
Power consumption (W)	<20W
Flight heritage (if any)	None known
Commercially available	No
Last updated	*04/2021*



Additional comments:

[Reference 1][Dec 2019][General information]
The COMFIT FEEP is based on SITAEL’s long heritage in the Field Emission Propulsion. It uses a non-hazardous propellant and serves mini and micro satellites. It is designed with special attention to cost reduction and to the possibility of a large-scale propulsion – key components are designed to be additively manufactured.

References:
[1] Misuri, T., “Sitael low power electric propulsion systems for small satellites,” EPIC workshop, Presentation, 2018.

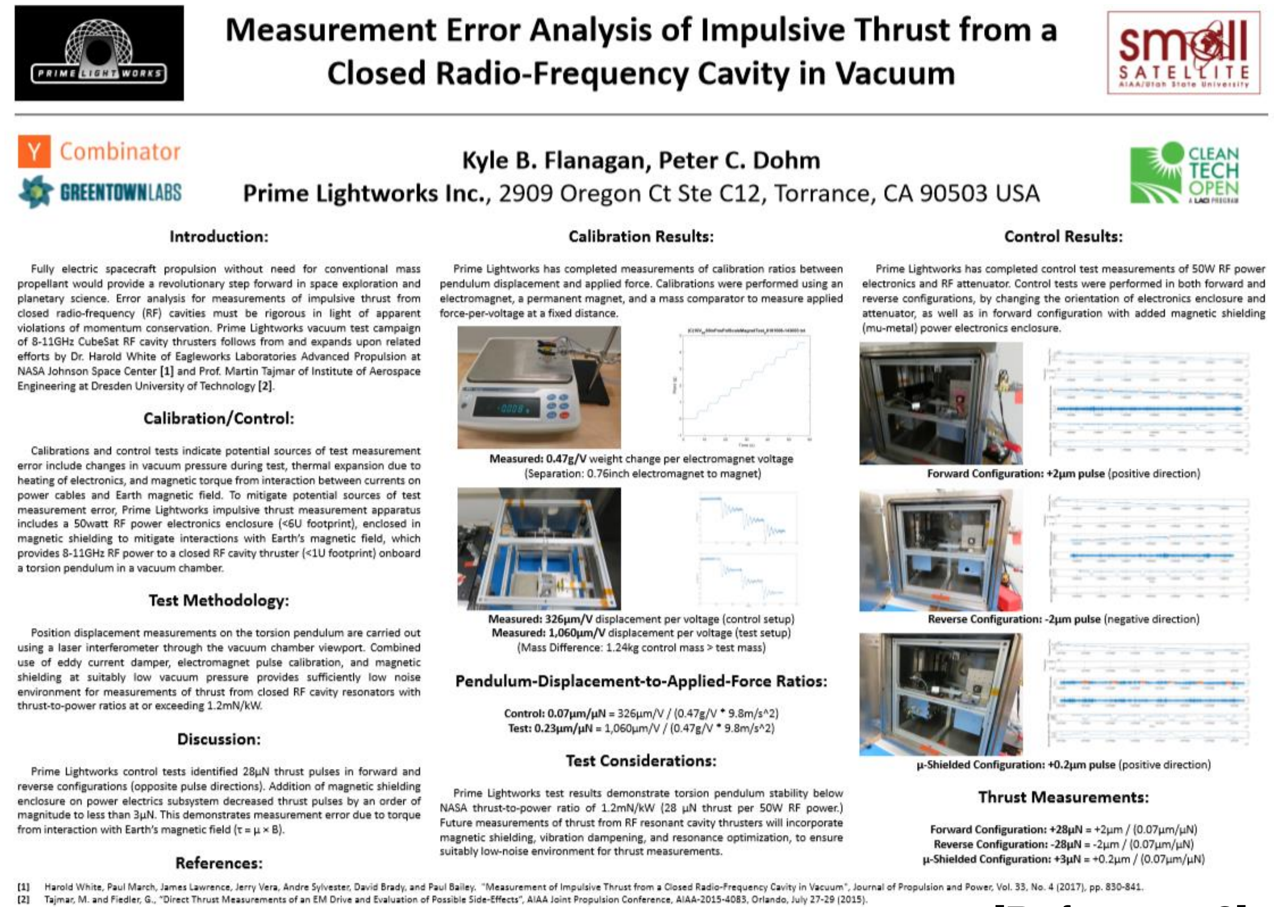
NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

Prime Lightworks [1 of 2]

Propulsion Technology	RF/Microwave
Manufacturer/Country	Prime Lightworks (USA)
TRL	2
Size (including PPU)	
Design satellite size	
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	None, propellant-less
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	NO
Last updated	04/2021



[Reference 3]

Additional comments:

[Reference 2][Feb 2019][General info]

“Prime Lightworks Inc. manufactures electric propulsion systems for space satellites. Our goal is to engineer new possibilities in space while drastically reducing cost and waste, by replacing propellant systems with radio frequency resonant cavity thrusters. Our satellite propulsion technology has no fuel dependence, which will lower the carbon footprint of the satellite industry by drastically reducing A) fuel consumption by satellites on orbit, and B) fuel consumption by launch vehicles during orbital insertion due to reduced satellite fuel mass. Direct conversion of electricity into thrust has innumerable potential applications on Earth as well as in space. Our biggest possible vision for the company is for our technology to become a useful actuation mechanism across transportation, hardware, and manufacturing, which in turn could support further software, data, and communications markets—the engine of the 21st century.”

[Reference 1][Dec 2019][General info]

“Prime Lightworks makes breakthrough electric propulsion systems for space satellites that are solar powered, fully renewable, and consume zero fuel. Our goal is to enable interplanetary space travel while eliminating emissions from aerospace propulsion and drastically reducing cost and waste.

Our CubeSat electric propulsion system is designed to be modular and scalable to meet the needs of any spacecraft. Our RF electronics and RF resonant cavities can replace satellite propellant mass and conventional satellite propulsion systems. This paradigm shift in propulsion will increase satellite payload mass and orbital velocities, while lowering fuel emissions and launch costs to orbit. Our vacuum thrust measurement apparatus improves on the version used by NASA Eagleworks as published in Journal of Propulsion of Power. Our torsion pendulum employs thrust calibration and damping systems similar to NASA. However, our RF power electronics enclosure is mounted on our torsion pendulum inside our vacuum chamber, to limit the effect of magnetic torque on power cables. Null tests are performed using a RF load attenuator in place of our RF resonant cavity. Our vacuum thrust measurement campaign is now underway, including error analysis due to magnetic torque and thermal expansion, as well as other potential sources of error. We plan to publish our results once our vacuum test campaign is complete.

Kyle Flanagan is the CEO and founder. They are located in Los Angeles.

References:

[1] http://primelightworks.com/

[2] https://www.f6s.com/primelightworksinc

[3] Flanagan, K., Dohm, P., “Measurement error analysis of impulsive thrust from a close radio-frequency cavity in vacuum,” AIAA Small Sat poster, 2019.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

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Prime Lightworks [2 of 2]

Additional comments:

[Reference 1][Feb 2020][General info]
Kyle Flanagan stated that the EM-drive, which is being commercialized by Prime Lightworks, has been tested by NASA - has raised 1.8M in seed funding. Last summer they pitched and were accepted to Starburst accelerator. They claim that the thruster has "unlimited delta V for renewable in-space propulsion". Thrust is from concentrated EM radiation pressure - RF subsystem feeds power to closed microwave resonant cavity. EM field analysis and RF software simulations were completed using Wolfram Mathematics, with additional simulations using ANSYS HFSS. "I'm not here to convince you that the physics works, I'm here to convince you that it's worth it to test it in orbit," stated Flanagan during the panel.

As of April 2021, the last update under news on their website was June 2019.

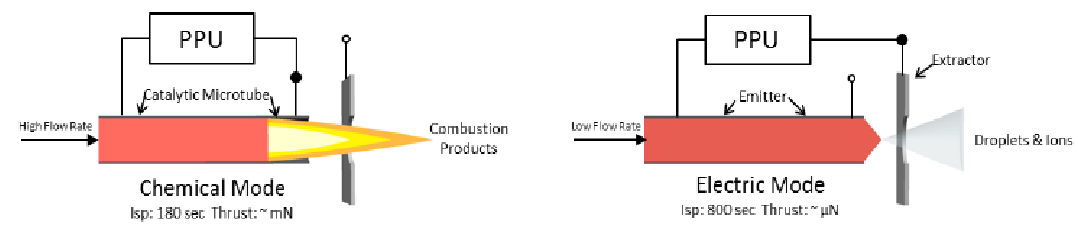
References:
[1] Statements made during a panel during SmallSat Symposium, Feb 2020

Comm. avail.	TRL	Aerospace-tested
NO	2	NO

DISTRO A: Approved for public release. OTR-2024-00338

Multi-mode Monoprop Electrospray [1 of 2]

Propulsion Technology	Monoprop/Electrospray
Manufacturer/Country	Froeberg Aerospace (USA)
TRL	2-3
Size (including PPU)	0.5 to 1 U
Design satellite size	3U or larger
Isp (s)	800s (electrospray), 225s (chemical) [2, 3]
Thrust type/magnitude	0.7 mN (electrospray), 0.5N (chemical) [2, 3]
Delta-V (m/s)	variable
Propellant	HAN + [EMIM][EtSO4] blend. No water.
Power consumption (W)	15W (electrospray), 15W (chemical)
Flight heritage (if any)	None
Commercially available	No
Last updated	04/2021



System	Dry Mass (g)	Volume (U)	Power (W)	Thrust (mN)		Specific Impulse (s)	
Monopropellant	1200	0.5	15	500		225	
Electrospray	1150	0.5	15	0.7		800	
Monopropellant + Electrospray	2350	1	15	500	0.7	225	800
Multi-Mode Integrated	1400	0.5	12	1000	0.6	180	780

Additional comments:

[Reference 4][May 2019][Company information, from website]
Froberg Aerospace LLC was founded in 2016 with the goal of commercializing multi-mode propulsion technology developed and patented by researchers at Missouri University of Science and Technology in Rolla, MO. Froberg was awarded a NASA SBIR Phase I in 2017 to further develop the concept and has been selected for Phase II beginning in 2018.
Steven Berg is Co-Founder and CEO of Froberg Aerospace LLC. He received his B.S., M.S., and PhD in Aerospace Engineering from Missouri University of Science and Technology in 2010, 2012, and 2015, respectively. He has over 7 years' experience in spacecraft and rocket propulsion. During his graduate work, and with less than $5K in funding, he developed propellants specifically purposed for multi-mode monopropellant/electrospray propulsion and, for the first time anywhere, succeeded in showing functionality of these propellants in both electrospray and chemical thrusters. Additionally, he developed comparison and selection methods for multi-mode spacecraft propulsion systems and designed an integrated multi-mode thruster for small satellites. He has previously worked at SpaceX as a Propulsion and Test Engineer during which he worked on several liquid rocket propulsion development projects and supporting quantification and acceptance testing of the Falcon 9 Stage 2 vehicle. His previous experience in pioneering multi-mode propulsion technology and success in developing commercial technology and working in fast paced environments make him uniquely suited to lead this project.
Joshua Rovey is co-founder and Chief Technology Officer of Froberg Aerospace and also tenured Associate Professor of Aerospace Engineering at the University of Illinois Urbana-Champaign (UIUC). He has worked in the space propulsion area for over 14 years having published over 75 journal and conference papers in this area. His research interests include spacecraft propulsion, electric propulsion, plasma dynamics, and energy systems. He received BS, MS, and PhD degrees from the University of Michigan in 2002, 2003, and 2006, respectively. Before coming to Illinois in 2017 he was professor at Missouri University of Science and Technology where he directed the Aerospace Plasma Laboratory. Additionally he was a propulsion research engineer for a small business, Starfire Industries, from 2006-2007 where he investigated linear Hall-effect thruster and field-reversed configuration propulsion concepts. His work has explained decades-old anomalous pulsed inductive plasma behavior, explained the loss in effectiveness of aerodynamic plasma actuators at low pressure, and quantified the evolution of Hall-effect thruster channel surface properties. He has been part of over $6.6M in sponsored research (serving as PI on over $2.9M) from NASA, Air Force, Navy, Dept. of Energy, and industry. He is recipient of numerous awards including an Air Force Young Investigator award, NASA Innovative Advanced Concepts Fellow, and the AIAA Lawrence Sperry Young Professional award.

References:

[1] Berg, S., "Development of Ionic Liquid Multi-mode Spacecraft Micropropulsion Systems," Ph.D. Thesis, Missouri University of Science and Technology, 2015.
[2] Verbal statements made by Steven Berg during Electrospray and Future of EP Propulsion workshop, held in May 2019 at LA AFB, POC AFRL Dan Eckhardt.
[3] Berg, S., Rovey, J., "Design and Development of a mult-mode monopropellant electrospray micropropulsion system," Poster, 2016. http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=14&ved=2ahUKEwjRpo6386_iAhWDzaQKHaamCgoQFjANegQIAxAC&url=http%3A%2F%2Fdigitalcommons.usu.edu%2Fcgi%2Fviewcontent.cgi%3Farticle%3D3529%26context%3Dsmallsat&usg=AOvVaw18RCgbFEtb9yW26ChTtcUr
[4] https://www.frobergaerospace.com/

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

Multi-mode Monoprop Electrospray [2 of 2]

Additional comments:

[Reference 1][May 2019][Company and thruster information]
In May 2019, Steven Berg gave a presentation at the Electrospray and Future of EP workshop entitled “Development of a multi-mode monopropellant electrospray propulsion system”. He said that the technology had been studied since 2012, and that he and Josh Rovie founded Froeberg Aerospace in 2016, with the goal to commercialize the multi-mode technology they had developed at Missouri S&T.
The propellant is based on a 59% HAN + 41% [EMIM][EtSO4] double-salt mixture. There is no water. The thruster is based on a capillary pressure-fed system. The tube is made of catalytic platinum (0.4mm ID). In chemical mode, the tube is heated to induce decomposition. In electrospray mode, a voltage bias is applied across the tube and extractor grid. They envision an array of approximately 10,000 emitter tubes. Future work includes subscale thruster array development, material compatibility studies, hazard classification (to follow similar testing as other novel propellants such as LMP-103S), power system/PPU development, and feed system development. Their funding comes from NASA Glenn, under Phase 1 and 2 SBIRS awards (POC: John Yim)

References:
[1] Verbal statements made by Steven Berg during Electrospray and Future of EP Propulsion workshop, held in May 2019 at LA AFB, POC AFRL Dan Eckhardt.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

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De-orbit dragsail [1 of 2]

Propulsion Technology	Dragsail
Manufacturer/Country	Vestigo Aerospace (affiliated with Purdue University) (USA)
TRL	2
Size (including PPU)	Unknown
Design satellite size	CubeSats to 400 kg satellites
Isp (s)	n/a
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Propellant-less
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	NO
Last updated	10/2022

Purdue University-affiliated startup Vestigo Aerospace LLC, which is developing technology to help remove debris from Earth orbit, has received an award from NASA. (Image

DragSail Sizing for Host Spacecraft

Host Spacecraft	DragSail Configuration	Sail Geometry	Spacecraft Mass (kg)	DragSail Frontal Area (m2)	Maximum Deorbit Altitude† (km)
1U CubeSat	Spinnaker1	Pyramid	1.33	1.77	1145
3U CubeSat	Spinnaker1	Pyramid	4	1.77	980
6U CubeSat	Spinnaker1	Pyramid	12	1.77	855
12U CubeSat	Spinnaker1	Pyramid	24	1.77	795
27UCubeSat	Spinnaker3	Flat	54	18	800
ESPA-Class SmallSat	Spinnaker3	Flat	180	18	750
SmallSat	Spinnaker3	Flat	400	18	720
Launch Vehicle Upper Stage	Spinnaker3	Flat	1,000	18	680

† Deorbit timeline and collision probability compliance verified with NASA Debris Assessment Software v2.1.1

Additional comments:
[Reference 1][Aug 2019][General info]
The Vestigo Aerospace product line of dragsail systems provides deorbit capability for host satellites ranging from CubeSats to 400 kg smallsats. The square pyramid design for the Vestigo dragsails provides passive aerodynamic stability about the maximum drag orientation to improve deorbit performance. Dragsails can also be applied to achieve semi-controlled reentry capability. The change in ballistic coefficient provided by sail deployment can be used as a control parameter to initiate reentry from a very low orbit, thereby reducing the uncertainty in the reentry corridor and the surface impact footprint. The ability to control the reentry corridor to within a fraction of an orbit reduces the impact of satellite reentry on the air traffic control system, and can be used to constrain the probability of debris impact in populated areas.

[Reference 2][Aug 2019][Company info]
July 2019 - WEST LAFAYETTE, Ind. – A Purdue University-affiliated startup that is developing technology to help remove debris from Earth orbit has received an award from NASA. Vestigo Aerospace LLC will receive $125,000 from a NASA Phase I Small Business Innovation Research (SBIR) grant. Vestigo was founded by David Spencer, a Purdue alumnus and associate professor in Purdue’s College of Engineering. “Through the six-month study, we will advance drag sail technology for the deorbit of small satellites and launch vehicle stages,” Spencer said. “The safe disposal of space objects upon mission completion is necessary to preserve the utility of high-value orbits.” “Vestigo Aerospace is developing a product line of drag sails to address the need for deorbit capability as an alternative to conventional propulsion systems,” said Spencer, who worked for 17 years at the Jet Propulsion Laboratory before joining the Purdue faculty. “The team will also investigate the use of dragsails for targeted reentry of space objects, to reduce the uncertainty in atmospheric reentry corridors and debris impact zones.” Vestigo is partnering with the Purdue’s Space Flight Projects Laboratory on the Phase I investigation. Vestigo also has received support from the Purdue Foundry.

References:
[1] http://www.vestigoaerospace.com/Technologies/Deorbit-Systems/
[2] https://www.purdue.edu/newsroom/releases/2019/Q3/cleaning-up-the-cosmic-neighborhood-nasa-grant-to-advance-technology,-help-remove-space-debris-from-orbit.html

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

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DISTRO A: Approved for public release. OTR-2024-00338

De-orbit dragsail [2 of 2]

Additional comments:
[Reference 1][October 2022][General info]
Vestigo Aerospace has closed a seed funding round with an investment of $375,000 from Manhattan West — NASA will provide a 1:1 match of Manhattan West's investment through a Small Business Innovative Research Phase II-Extended (SBIR Phase II-E) contract.

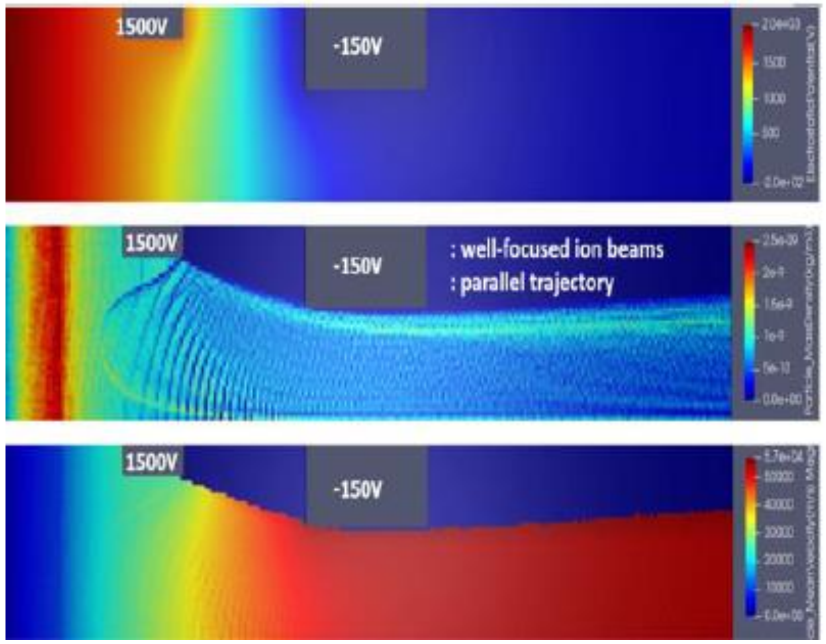
References:
[1] https://smallsatnews.com/2022/09/13/vestigo-aerospace-closes-seed-funding-round-for-their-satellite-dragsail-technology/

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

iU-50

Propulsion Technology	RF Ion Thruster (RIT)
Manufacturer/Country	University of Ulsan (South Korea)
TRL	1-2
Size (including PPU)	
Design satellite size	
Isp (s)	2600s (calculated)
Thrust type/magnitude	5 mN (calculated)
Delta-V (m/s)	
Propellant	Xenon
Power consumption (W)	50W
Flight heritage (if any)	None
Commercially available	NO
Last updated	04/2021



2-D calculations of neutral gas density distributions [Ref 1]

Additional comments:

[Ref.1][Oct 2019][General thruster status]
This thruster is in the design phase. Calculations for performance predictions have been completed, but no hardware exists yet.

References:
[1] Pham, T., Nguyen, H., Shin, J., "Development of a 50W class RF gridded ion thruster," IEPC-2019-383.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

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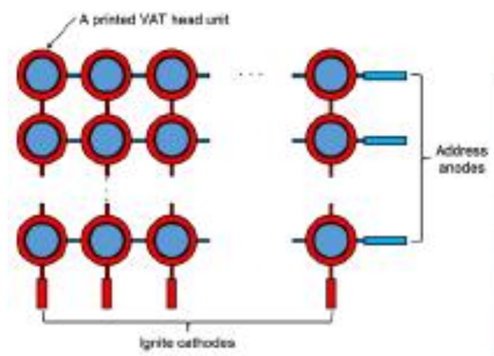
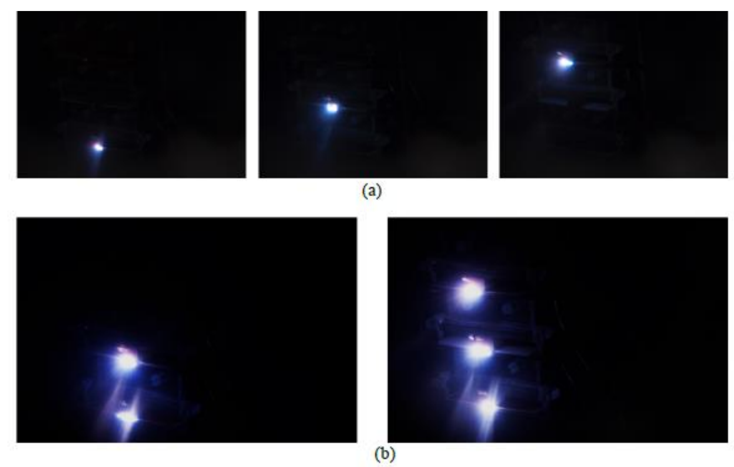
pCAT

Propulsion Technology	Cathode Arc Thruster (Vacuum Arc Thruster)
Manufacturer/Country	University of Southampton (UK)
TRL	2-3
Size (including PPU)	<1U
Design satellite size	1U and larger
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	
Power consumption (W)	
Flight heritage (if any)	NO
Commercially available	NO
Last updated	04/2021




(a)
(b)

3d printed pCAT

Additional comments:

[Ref 1][Oct 2019][Thruster info and development status]
The estimated overall efficiency of pCAT is approximately 5.8%, which is slightly lower than conventional VATs using tungsten and aluminium as cathode materials. As the silver plasma streaming velocity is 12500 m/s, the thrust/power ratio of pCAT is expected to be about 27.6 μN/W which is approximately 50% higher than conventional VATs.

A new concept of a micropropulsion system has been proposed, which uses printed electronics for a thin cathode layer. The basic concept of the proposed propulsion system is ablating printed cathode layer to create a plasma and to produce thrust through an electrical vacuum arc discharge. Compared to conventional VATs, the proposed system can significantly simplify the complexity of a propulsion system because it does not require a propellant feeding mechanism. Although a single printed cathode layer contains limited amounts of propellant, the total amount of propellants can be improved by clustering. Each printed thruster head in the cluster has a “triggerless” ignition mechanism by using a conductive carbon ink. As each thruster head is designed to be operated during the limited amount of time, the proposed printed VAT is free from the risk of restarting thrusters. The clustered system will also bring a fail-safe feature for a post-mission disposal mechanism. In addition, the high flexibility of the proposed propulsion system will make it deployable from micro/nano-satellites.

References:
[1] Kim, Minkwan, “Development of a deployable vacuum arc thruster system for the post-mission disposal of micro/nano satellites,” IEPC-2019-A-774.

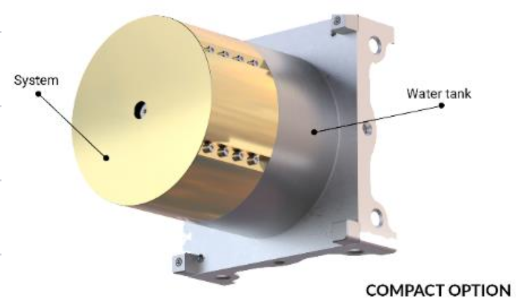
NO	2	NO
Comm. avail.	TRL	Aerospace-tested

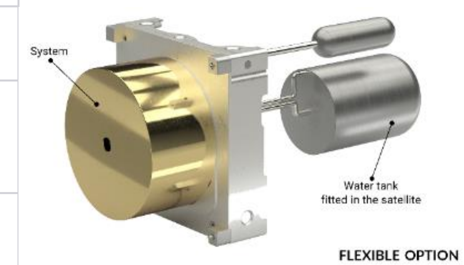
DISTRO A: Approved for public release. OTR-2024-00338

SteamJet
SteamJet Space Systems

Propulsion Technology	Water-based propulsion (steam)
Manufacturer/Country	SteamJet Space Systems, Ltd. (UK/Russia)
TRL	2-3
Size (including PPU)	80mm x 80mm x 80 mm (<1U) (tuna-can form factor) Wet mass <0.75kg
Design satellite size	At least 3U
Isp (s)	172s (unverified, April 2021) [1]
Thrust type/magnitude	219 N*s (impulse, total) [1] >6 mN (continuous, April 2021) [1]
Delta-V (m/s)	
Propellant	Water
Power consumption (W)	20-40W (heater)
Flight heritage (if any)	None known Slated for Momentus' Vigoride Q2 2021
Commercially available	YES
Last updated	*04/2021*

System size (with tank and electronics)	Ø 80 x 80 mm
Tunacan shape factor	can be installed in the tunacan volume in CubeSat deployers
Water as main propellant	pressure <1 bar
Total Impulse	219 Ns
High Thrust	>6 mN
Low power consumption	< 20 W
Fuel mass	130 g
Wet mass	540 g
Specific impulse	172 s
Flight heritage	Q2'21 (SpaceX via Momentus)
Technical Readiness Level	TRL7





[1]

Additional comments:

[Reference 1][Dec 2019][General info]
According to the manufacturer's brochure, there are two models, a minimum compact option which takes up about 1U, and an extended option with an external tank for more total impulse.

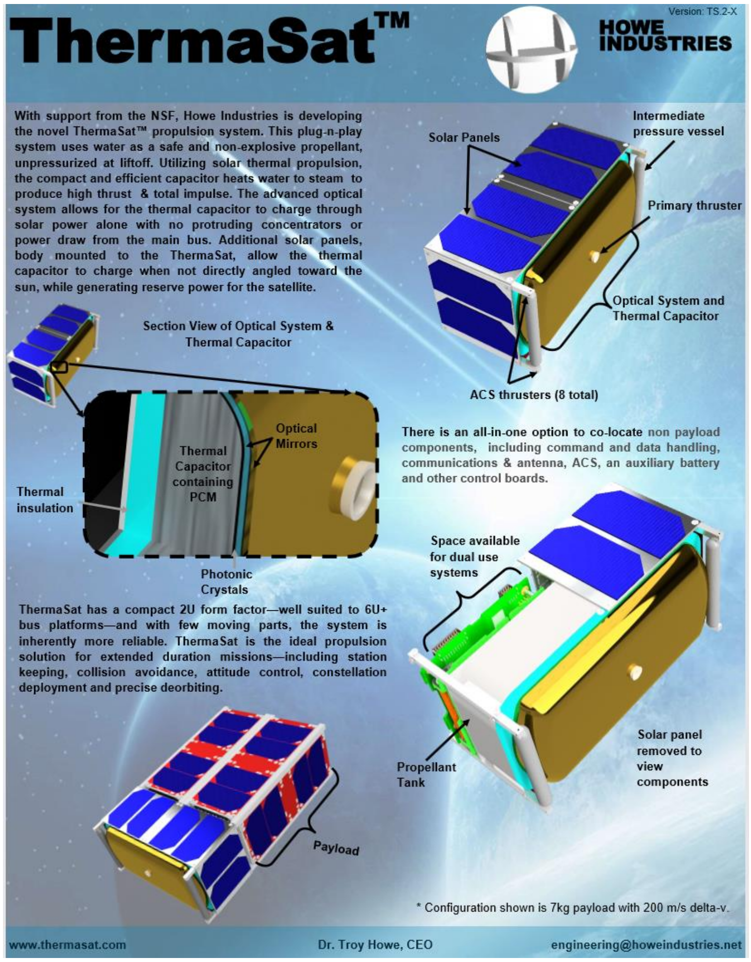
References:
[1] https://steamjet.space/#system

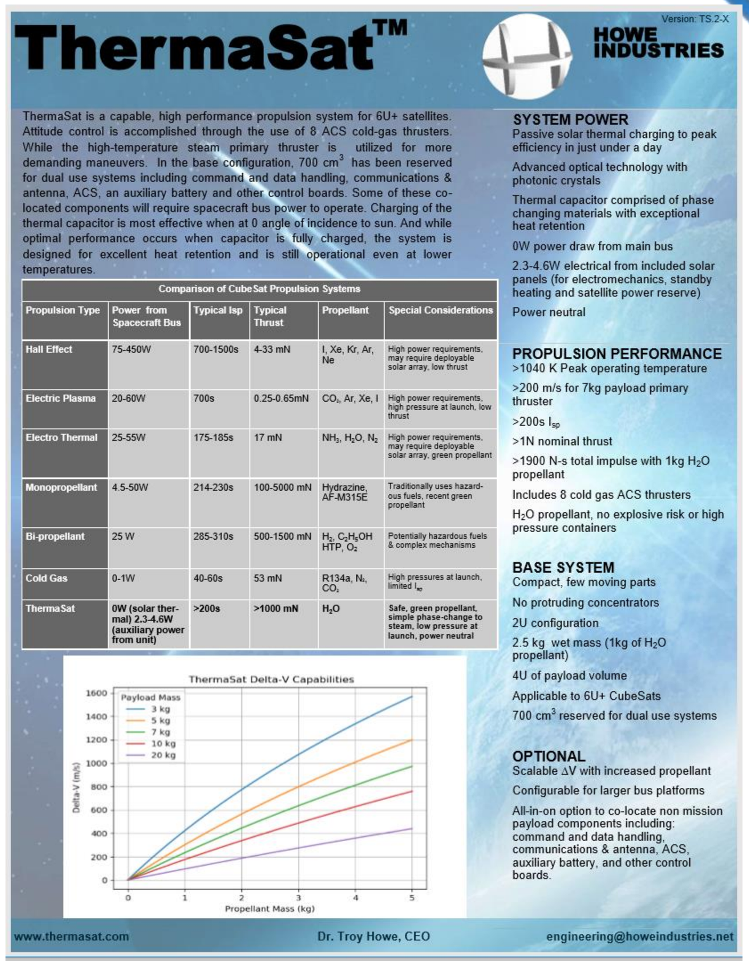
	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

ThermaSat

Propulsion Technology	Steam thruster + cold gas
Manufacturer/Country	Howe Industries (USA)
TRL	2
Size (including PPU)	2U
Design satellite size	6U or larger (4U payload volume)
Isp (s)	>200s (calculated)
Thrust type/magnitude	>1N nominal (calculated)
Delta-V (m/s)	>200 m/s for 7 kg payload
Propellant	Water
Power consumption (W)	2.3 to 4.6W
Flight heritage (if any)	None
Commercially available	NO
Last updated	04/2021





Additional comments:
[Reference 1 and 2][March 2020][General propulsion information]
Howe industries is focusing on new and exciting technologies related to advanced power generation methods and space propulsion. It is the goal of Howe Industries to work to develop these space-based power systems, which includes radioisotope fueled systems and reactor based systems. Troy and Steve Howe are two staff identified on the company website.

ThermaSat is a capable, high-performance propulsion system for 6U+ satellites. Attitude control is accomplished through 8 ACS cold-gas thrusters. The high-temperature steam primary thruster is utilized for more demanding maneuvers.
It is a passive solar thermal charging system which reaches peak efficiency in just under a day. It draws no power from the main bus, but requires 2.3 to 4.6 W from the included solar panels, making it power-neutral (to the spacecraft bus).
The system is scalable with increased propellant, is compact, and has few moving parts.

[Reference 3][April 2021][Funding information]
ThermaSat developed under a $225,000 SBIR NSF grant.

References:
[1] Manufacturer's spec sheet and non-proprietary conversations with Jack Howe in March 2020.
[2] http://www.howeindustries.net/home.html
[3] https://www.osa-opn.org/home/industry/2021/january/company_eyes_steampunk_propulsion_for_cubesats/

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Zenno Electromagnetic Propulsion System

Propulsion Technology	Electromagnetic
Manufacturer/Country	Zenno (New Zealand)
TRL	<2
Size (including PPU)	
Design satellite size	
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Unknown
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	No
Last updated	04/2021

Reference 2

Additional comments:
[Reference 1][Jun 2020][Company information]
New Zealand startup ZENNO Astronautics, a satellite propulsion and software company founded by three students at the University of Auckland, has won a NZ$25,000 (U.S.$16,240) share of a NZ$100,000 (U.S.$64,950) total prize fund of the university's 2018 Velocity Challenge. ZENNO Astronautics was founded in 2017 with the aim of developing a propulsion system for small satellites and a suite of software for mission planning, development, and operation. Arts and commerce student Will Haringa and engineering students Max Arshavsky and Sebastian Wieczorek are its founders.

References:
[1] https://spacewatch.global/2018/10/new-zealand-startup-zenno-astronautics-blazes-path-for-kiwi-new-space/
[2] https://zenno.space/

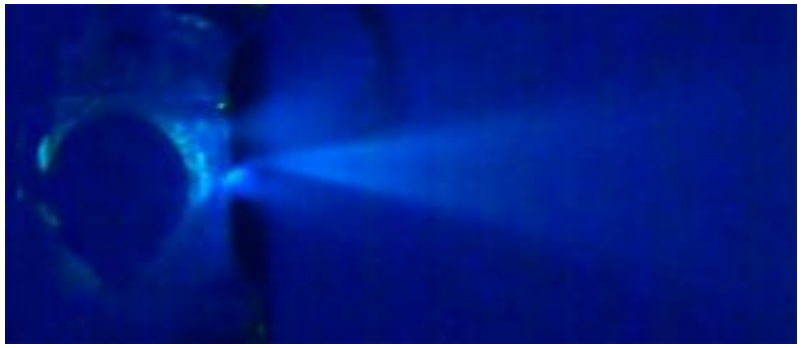
NO	2	NO
Comm. avail.	TRL	Aerospace-tested

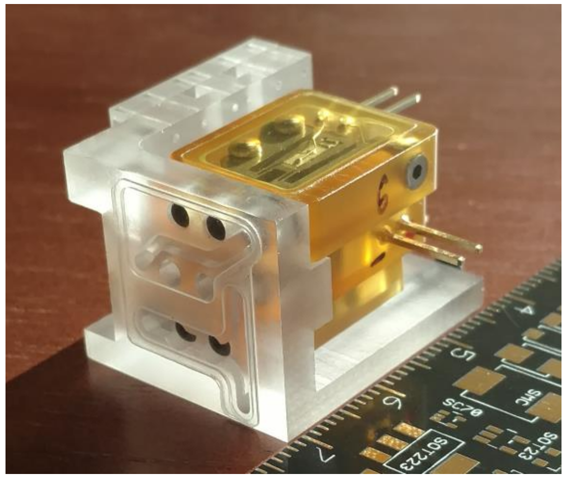
DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

ConstantQ Thruster

Propulsion Technology	Electrostatic
Manufacturer/Country	Miles Space (USA)
TRL	2
Size (including PPU)	<1U
Design satellite size	Cubesat and larger
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Unknown
Power consumption (W)	Unknown
Flight heritage (if any)	None. Projected on Artemis Cube Quest, launch 2021.
Commercially available	NO
Last updated	04/20210


[1]


[2]

Additional comments:
[Reference 1][Jun 2020][Company info]
Wesley Faler of Team Miles heads the group of citizen scientists and engineers that initially came together through Tampa Hackerspace in Florida – all participants in the community, nonprofit workshop. He labels himself as “project overseer” and “chief visionary.” Since Hackerspace, Faler adds that the team now has experts in software development, communications, radiation, as well as project management. Miles Space, in partnership with Fluid & Reason, LLC, is making use of a Model-H ion thruster design for CubeSat propulsion. Faler is the inventor of the patent-pending ConstantQ™ plasma thruster, drawing upon over a decade of research in ion and plasma thrusters.
[Reference 2][Jun 2020][Thruster info]
The ConstantQ is a hybrid electrostatic thruster built to the rigorous safety standards of the NASA SLS EM-1 Mission (now Artemis). It has a compact and power-efficient design with mid-range fuel economy, low mass, low volume, and market-leading low power essentials. It has completed successful testing campaigns at Georgia Tech and NASA Glenn Research Center.
[Reference 3][Jun 2020][Mission information]
The Cube Quest competition, sponsored by NASA’s Space Technology Mission Directorate Centennial Challenge Program, offers a total of $5.5 million to teams that meet the challenge objectives of designing, building and delivering flight-qualified, small satellites capable of advanced operations near and beyond the moon. Cube Quest teams will have the opportunity to compete for a secondary payload spot on the first mission of NASA’s Orion spacecraft, which will launch atop the agency’s Space Launch System (SLS) rocket.
[Reference 4][Jun 2020][Thruster information]
A propulsion system for spacecraft is based on an electric engine that expels propellant to achieve thrust. The propellant is first ionized to generate a plasma. Plasma particles are selectively accelerated via a pulsed laser that accelerates predominantly the electrons in the plasma. The electrons are expelled first, forming a space charge that acts as a virtual cathode to accelerate the positive ions. Interactions between the laser beam and plasma electrons are predominantly through the ponderomotive force.

References:

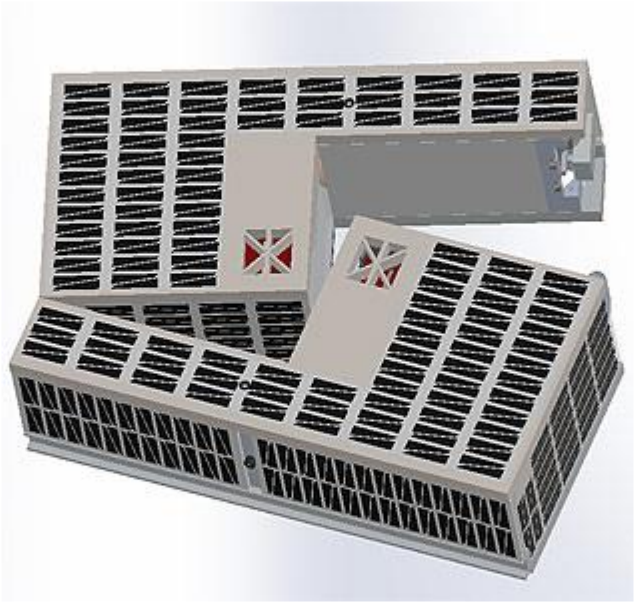
[1] https://www.nasa.gov/directorates/spacetech/centennial_challenges/cubequest/team_miles
[2] https://miles-space.com/
[3] https://www.nasa.gov/directorates/spacetech/centennial_challenges/cubequest/about.html
[4] Wesley Faler, Donald Smith, “Hybrid Electric Propulsion for Spacecraft,” US Patent 0305096 A1, 2014.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Cornell electrolysis thruster

Propulsion Technology	Electrolysis
Manufacturer/Country	Cornell University (USA)
TRL	2
Size (including PPU)	<1U
Design satellite size	3U and larger
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Water
Power consumption (W)	
Flight heritage (if any)	None. Projected for Cislunar Explorers aboard Artemis-1 (2021) [1,2]
Commercially available	NO
Last updated	04/2021



[2]

Additional comments:

[Reference 1-2][June 2020][Flight info]
Cislunar Explorers is a planned nanosat mission by Cornell University, which was selected by NASA's CubeQuest Challenge. The Cislunar Explorers are a pair of streamlined, sustainable spacecraft on a mission to orbit the Moon. They act as self-propelled engineering demonstrations, proving the technology readiness of water as rocket fuel, simple optical navigation, and more. Key subsystems complement each other in a symbiotic design aimed at reducing the cost and complexity of space exploration. Cislunar Explorers consists of two L-shaped satellites, which fit together in the 6U CubeSat standard. After deployment from the launch vehicle, they will split apart and each give their initial rotation in the process of decoupling.
The novel propulsion system using inert water will be tapped to enable the Cislunar Explorers to carry out a gravity assist with the moon, and then be captured into lunar orbit. Spacecraft maneuvers will be directed by a ground station at Cornell.
Cislunar Explorers is one of 13 cubesats planned to be carried with the Orion Artemis-1 mission into a heliocentric orbit in cis-lunar space on the maiden flight of the SLS (Block 1) iCPS launch vehicle in 2021.

References:
[1] https://www.nasa.gov/directorates/spacetech/centennial_challenges/cubequest/cislunar-explorers
[2] https://space.skyrocket.de/doc_sdat/cislunar-explorers.htm

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Divert Attitude Control Systems

Propulsion Technology	Solid Propellant Thrusters
Manufacturer/Country	Pacific Scientific (PACSCI EMC)
TRL	2
Size (including PPU)	Not listed, scalable
Design satellite size	
Isp (s)	
Thrust type/magnitude	5N – 8,000 N
Delta-V (m/s)	
Propellant	
Power consumption (W)	1 W
Flight heritage (if any)	
Commercially available	
Last updated	04/2021

•**Delivered Impulse**
0.0005 N-s to 200 N-s
•**Thrust**
5 N to 8,000 N
•**Motor Burn**
100 µsec to 2 Seconds
•**Impulse Repeatability**
Greater than 2%, 3 Sigma
•**Ignition Delay**
10 µsec to 500 µsec
(Command to 10% Thrust)
•**Operational Temperature Range**
-65 °F (-53.89 °C) to +200 °F (+93.33 °C)
•**Operational Acceleration**
>12,500 Gs
•**BIT Test**
Igniter Integrity, Fire Energy, Arm State and More
•**System Power**
1 Watt

Additional comments:

[Reference 1][July 2020][Thruster information]
Attitude control using small, solid propellant thrusters is a proven technology in several systems. Our DACS uses a thruster technology specially developed for rapid response and precision control and includes an electronic control architecture uniquely suited to short flights and precision timing. The system consists of a Smart Bus Controller (SBC), a network firing bus, smart initiators, rocket motors, and a retention structure. The SBC is the command interface between the vehicle, with the SBC over a high speed link or may be embedded in the vehicle control electronics. The SBC permits firing of devices or rocket motors in any sequence, including simultaneous or batch firing and sequential firing. If different thruster impulses are present, the system can identify and selectively control them as well.

Little to no technical specifications provided.

References:
[1] https://psemc.com/products/divert-attitude-control-system/

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

PACSCI Precision Deorbit P-MAPS

Propulsion Technology	Deorbit
Manufacturer/Country	Pacific Scientific (PACSCI EMC)
TRL	2
Size (including PPU)	
Design satellite size	
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Solid
Power consumption (W)	
Flight heritage (if any)	
Commercially available	
Last updated	04/2021

Additional comments:

[Reference 1][July 2020][System info]
P-MAPS™, our powered solid propulsion system, provides a fully powered module to assist with decommission and/or deorbit of a satellite. P-MAPS enables SmallSats and CubeSats to comply with 25-year lifetime restrictions in orbit.

P-MAPS includes a self-contained power supply, ADCS and UHF receiver, providing reliable power to deorbit in the event of satellite power loss. With all the same performance features as MAPS™ Solid Propulsion System (precise and repeatable impulse bits initiated with hermetically sealed, clean burning, solid propellant with no propellant tanks, valves, fittings, heaters or thrusters) and without any compromise to the satellite design by fitting into unused satellite volume. With our standby power unit, should satellite power supply malfunction, P-MAPS will continue to perform planned decommission and deorbit objectives.

See MAPS, which has flown on PacSciSat.

References:
[1] https://psemc.com/products/satellite-deorbit/

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Axial-Injection, End-burning hybrid

Propulsion Technology	Hybrid
Manufacturer/Country	US Army
TRL	2
Size (including PPU)	<1U
Design satellite size	
Isp (s)	~260 to 320s, calculated [2]
Thrust type/magnitude	~31N, calculated (can be tailored) [2]
Delta-V (m/s)	500 m/s for a 4 kg s/c, 240 m/s for an 8 kg s/c, 160 m/s for a 12 kg s/c, calculated [2]
Propellant	ABS, Somos WaterClear plastic, Visijet plastic, castable wax
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	NO
Last updated	04/2021

[1]

Additional comments:

[Reference 2][April 2021][Thruster design]
Model predictions of axial-injection, end-burning hybrid motors indicate that this configuration of hybrid motor could serve in a cubesat propulsion unit. Achieved specific impulse is predicted to range from approximately 280 to 320 s depending on c-star efficiency and chamber pressure. This value is a reasonable value for a bipropellant system and exceeds that of monopropellants, thus enabling more maneuvers for less propellant mass. An axial-injection, endburning hybrid motor propulsion system was predicted to provide approximately 160 m/s of Delta-V for a 12 kg satellite, 240 m/s for a 8 kg satellite, and 500 m/s for a 4 kg satellite. This amount of Delta-V allows the satellite to perform several maneuvers including achieving the mission altitude, phasing within a plane, and orbit maintenance. In summary, these predictions indicate that axial-injection, endburning hybrid motors have the ability to provide a viable propulsion system for small satellites. Further work will include more detail designs of the propulsion unit and further analysis of Delta-V requirements for potential orbital missions.

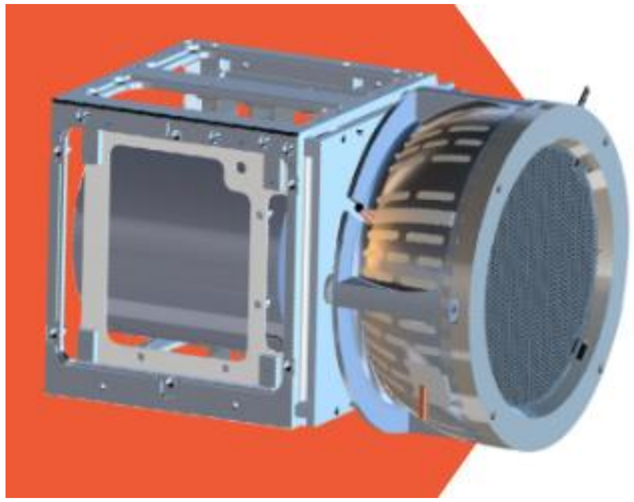
References:
[1] Hitt, M., “Axial-injection, end-burning hybrid rocket motor performance,” NASA In-Space Chemical propulsion TIM, September 2020. DISTRO A: Approved for public release
[2] Hitt, M., “Performance analysis of axial-injection, end-burning hybrid rocket propulsion system,” Journal of spacecraft and rockets, Vol. 57, December 2020.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

NPT300 Ion Thruster Family
ThrustMe

Propulsion Technology	NPT300
Manufacturer/Country	ThrustMe (FRA)
TRL	2 - 3
Size (including PPU)	
Design satellite size	
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	NO
Last updated	*05/2021*



NPT300 notional solid model [1]

Additional comments:
[References 1][May 2021]
ThrustMe's NPT300 product family is a fully integrated propulsion system based on classical gridded ion thruster technology. The NPT300 is a neutralizer free system leveraging ThrustMe's patented AC acceleration technology. This allows for a simple and efficient propulsion solution that can be mass produced. The NPT300 is currently in R&D stage. The NPT300 is currently being designed and developed to meet the price and lead time targets of our end-users without compromising on reliability and quality.

References:
[1] https://www.thrustme.fr/products/npt300

Comm. avail.	TRL	Aerospace-tested
NO	2	NO

DISTRO A: Approved for public release. OTR-2024-00338

China: LRIT

Propulsion Technology	RF ion thruster
Manufacturer/Country	China: LIP (Lanzhou Institute of Physics)
TRL	2-3
Size (including PPU)	~1U [1]
Design satellite size	>3U
Isp (s)	2600s
Thrust type/magnitude	1-2 mN
Delta-V (m/s)	
Propellant	Unknown (likely xenon)
Power consumption (W)	50-150W
Flight heritage (if any)	None
Commercially available	NO
Last updated	09/2021

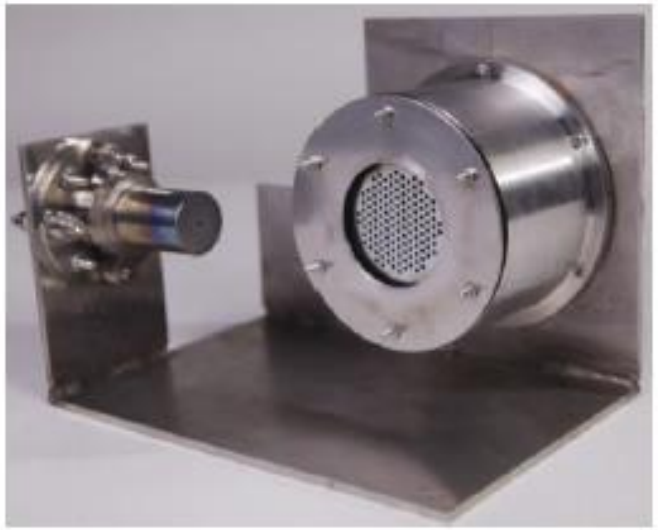


Figure 9. The prototype of LRIT-40

Photo of LRIT-40 [1]

Additional comments:

[Reference 1][September 2021][Thruster information]
A 50W LRIT-40 has been developed at LIP. An RF ion thruster usually consists of an axisymmetric, cylindrical, or conical discharge chamber made of dielectric material. A helical coil, energized at low MHz RF, is used to generate and sustain the plasma discharge. The LRIT-40 is equipped with two grids. The diameter of the ion beam is 40 mm, and the design specifications are: input power 50-150W, Isp 2600s, thrust 1-2 mN. The prototype will be tested at the end of 2017.

References:
[1] Yanhui, J., Tianping, Z., Chenchen, W., Yujun, K., Xianming, W., Shangmin, W., Ning, G., "The latest development of low power electric propulsion for small spacecraft," IEPC-2017-78**.**

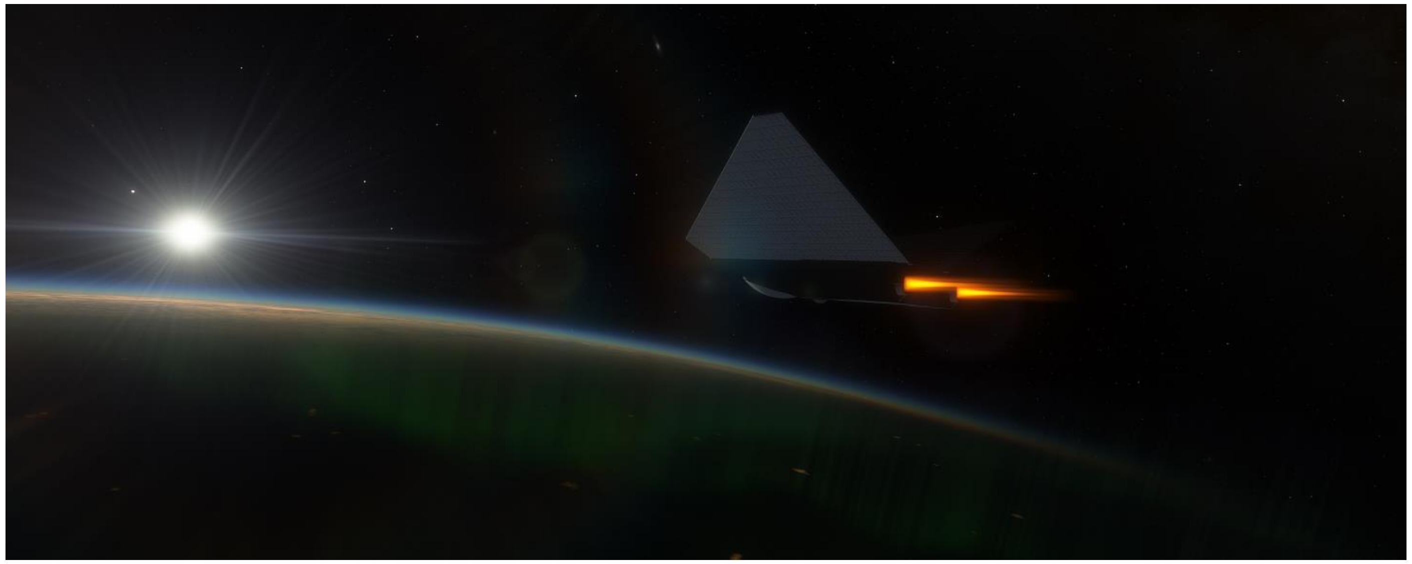
NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

Air Breathing

Propulsion Technology	Air Breathing
Manufacturer/Country	Phase Four [USA]
TRL	1-2
Size (including PPU)	
Design satellite size	
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	
Power consumption (W)	
Flight heritage (if any)	
Commercially available	NO
Last updated	04/2022



[1]

Additional comments:

[Reference 1-2][Oct 2021][Preliminary development]

Encouraged by initial test results using atmospheric air as propellant in Phase Four's RF thruster (RFT), and inspired by very low Earth orbit (VLEO) test missions like ESA's GOCE and JAXA's TSUBAME (SLATS), Phase Four VP of advanced development Jason Wallace and propulsion engineer Chris Cretel teamed up to conceptualize a US-based air-breathing engine for VLEO and deep space missions. The core idea is to build a harvester to collect air at ~200 km as propellant and to use an electrodeless RF thruster to accelerate the propellant to compensate for the drag on a spacecraft flying at these very low orbital altitudes. This may unlock a persistent orbital platform at altitudes inaccessible to traditional spacecraft for extended periods of time. Because Phase Four's RF thruster does not use a cathode it eliminates the critical component of traditional plasma thrusters that are incompatible with the oxygen-rich environment in VLEO.

Phase Four is actively proposing development in three key areas to help unlock the promise of air-breathing spacecraft propulsion. First, Phase Four must develop and demonstrate a laboratory analog of the VLEO environment. This environment consists of atomic and molecular oxygen, and some nitrogen, flowing at orbital velocities. The second challenge is to map and optimize the Phase Four RF thruster on oxygen-dominant plasmas. If the thruster can generate enough thrust and Isp using oxygen-nitrogen plasmas to compensate for a spacecraft's drag in this environment, then the third challenge is to model and develop an atmosphere harvester with sufficient efficiency to supply the thruster with the appropriate propellant flow rate. Phase Four is working with funding agencies and academic partners to help attack these challenges and bring this technology closer to reality.

References:
[1] https://www.phasefour.io/plasmaworks/
[2] Public forum, Oct 2021, Panel presentation by Beau Jarvis, Phase Four

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Solar Cruiser – Solar Sail System

Propulsion Technology	Solar Sail
Manufacturer/Country	Ball Aerospace/NASA/ROCCOR [USA]
TRL	2
Size (including PPU)	
Design satellite size	Small Sat
Isp (s)	n/a
Thrust type/magnitude	n/a
Delta-V (m/s)	
Propellant	n/a
Power consumption (W)	n/a
Flight heritage (if any)	None, slated to fly on NASA's IMAP [launch projected for 2025]
Commercially available	NO
Last updated	10/2021

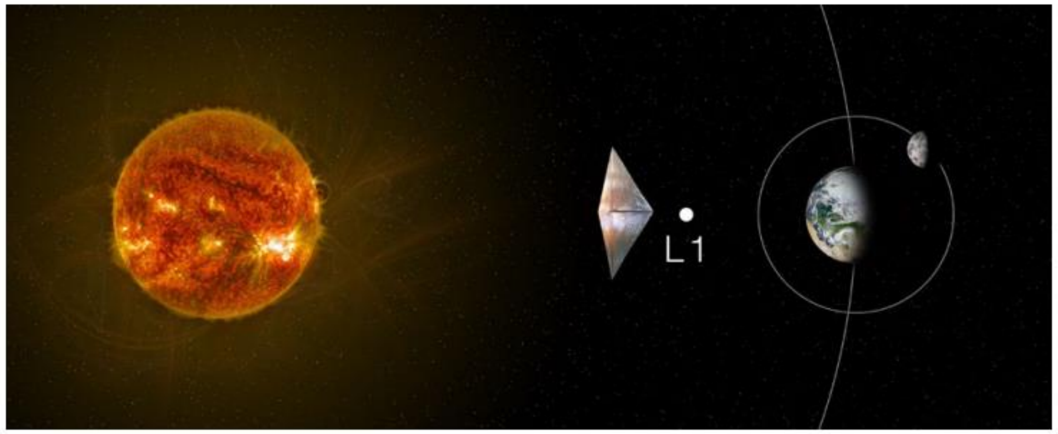


Figure 1. By placing a sailcraft sunward of L1 along the SEL, warning of impending solar storms could be increased by 50% or more.

[1]

Additional comments:

[Reference 1][Oct 2021][Flight information]
Solar Cruiser is a Small Satellite Technology Demonstration Mission (TDM) of Opportunity to mature solar sail propulsion technology to enable near-term, high-priority breakthrough science missions as defined in the Solar and Space Physics Decadal Survey. Solar Cruiser will demonstrate a "sailcraft" platform with pointing control and attitude stability comparable to traditional platforms, upon which a new class of Heliophysics missions may fly instruments. It will show sailcraft operation (acceleration, navigation, station keeping, inclination change) immediately applicable to near-term missions, and show scalability of sail technologies such as the boom, membrane, deployer, reflectivity control devices for roll momentum management to enable more demanding missions, such as high inclination solar imaging.
Solar Cruiser will launch as a secondary payload with NASA's Interstellar Mapping and Acceleration Probe (IMAP) in early 2025. The sailcraft will separate from the launch vehicle on a near-L1 trajectory (Sun-Earth Lagrangian Point 1; sunward of L1 along the Sun-Earth Line) and complete its primary mission in 11 months or less. During this time, Solar Cruiser will complete and fully characterize a large solar sail deployment (1,653 square meters/17,793 square feet), sail operation, station keeping in a sub-L1 halo orbit, inclination changes, and a roll demonstration.
The sailcraft is composed of the Integrated Sailcraft Bus (SB) and Solar Sail Propulsion Element (SSPE). The X-SAT Venus-class microsat bus from Blue Canyon Technologies (BCT) will be augmented with a deep space Iris transponder from Space Dynamics Laboratory (SDL). The SSPE consists of a 2-axis translating mechanism (Active Mass Translator (AMT)), Solar Sail System (SSS), and Solar Sail Attitude Determination and Control System (SSADCS) software. The deployed solar sail, supported by high strain composite booms, measures 42 m by 42 m.

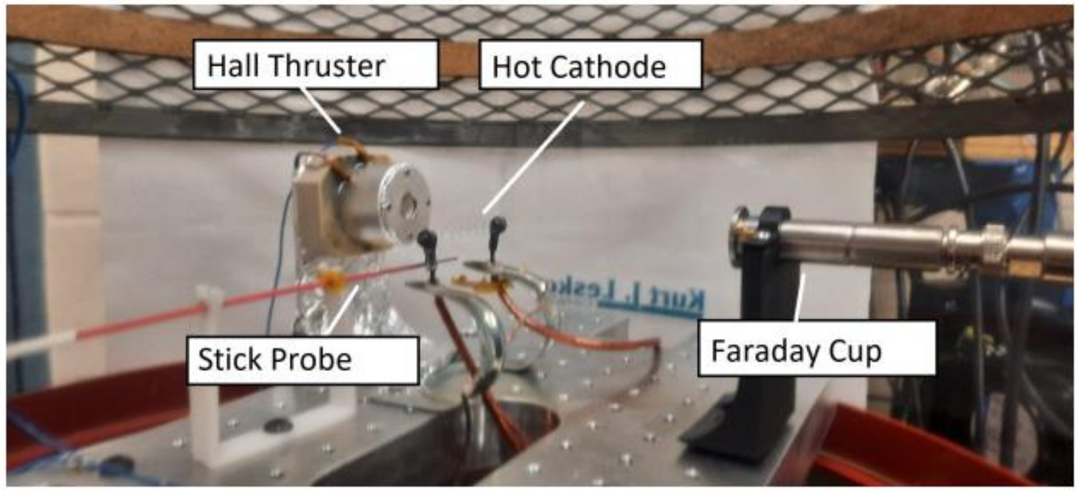
References:
[1] Cannella, M., Enger, S., Puls, A., Rodriguez, J., Johnson, L., Dervan, J., Turse, D., "Design and overview of the solar cruiser mission," Small Satellite Conference 2021, SSC21-XIII-02.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Micro-Hall thruster

Propulsion Technology	Hall thruster
Manufacturer/Country	RAPPEL lab at the Royal Military College of Canada
TRL	2-3
Size (including PPU)	
Design satellite size	Small sat
Isp (s)	1185s (calculated) [1]
Thrust type/magnitude	5 mN [1]
Delta-V (m/s)	
Propellant	Krypton
Power consumption (W)	<100W
Flight heritage (if any)	None
Commercially available	No
Last updated	08/2022



[1]

Additional comments:

[Reference 1][Aug 2022][Lab testing]
A 10mm Hall thruster was designed and developed. The thruster performance was measured using the plume characteristics. The force produced by the thruster was 5mN with a specific impulse of 1185s. Future studies will include a sweep of thruster power to observe the relationship between specific impulse, force and anode power. Additionally, plume characterization must be measured at varying angles from the thruster axis to provide an accurate calculation. Furthermore, the thrust from the Hall thruster will be measured directly using a torsional thrust balance stand to validate the thruster performance. These results will be used to confirm the usefulness of a small sub 100W Hall Thruster for use on a CubeSat.

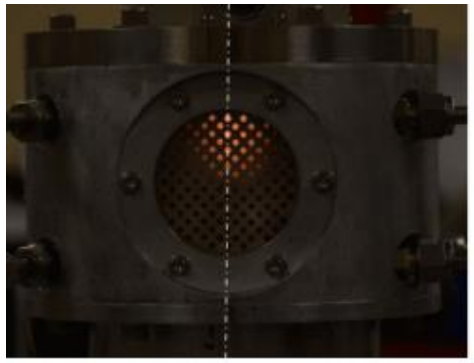
References:
[1] Chan-Ying, F., Jugroot, M., “Design and characterization of a micro-Hall thruster for spacecraft,” IEPC-2022-376.

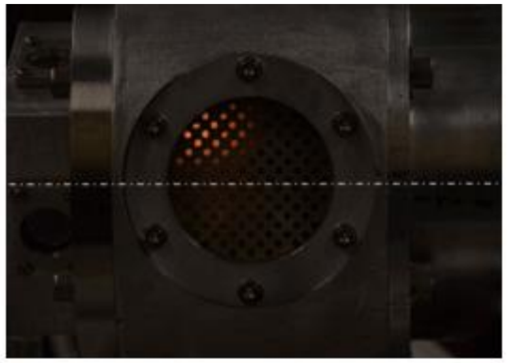
NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Ammonia microwave electrothermal thruster

Propulsion Technology	Microwave Electrothermal
Manufacturer/Country	Penn State (USA)
TRL	2-3
Size (including PPU)	
Design satellite size	Small sat
Isp (s)	
Thrust type/magnitude	2 to 3 mN [1]
Delta-V (m/s)	250 to 260 s [1]
Propellant	Ammonia
Power consumption (W)	20W to 60W
Flight heritage (if any)	None
Commercially available	No
Last updated	08/2022





[1]

Additional comments:

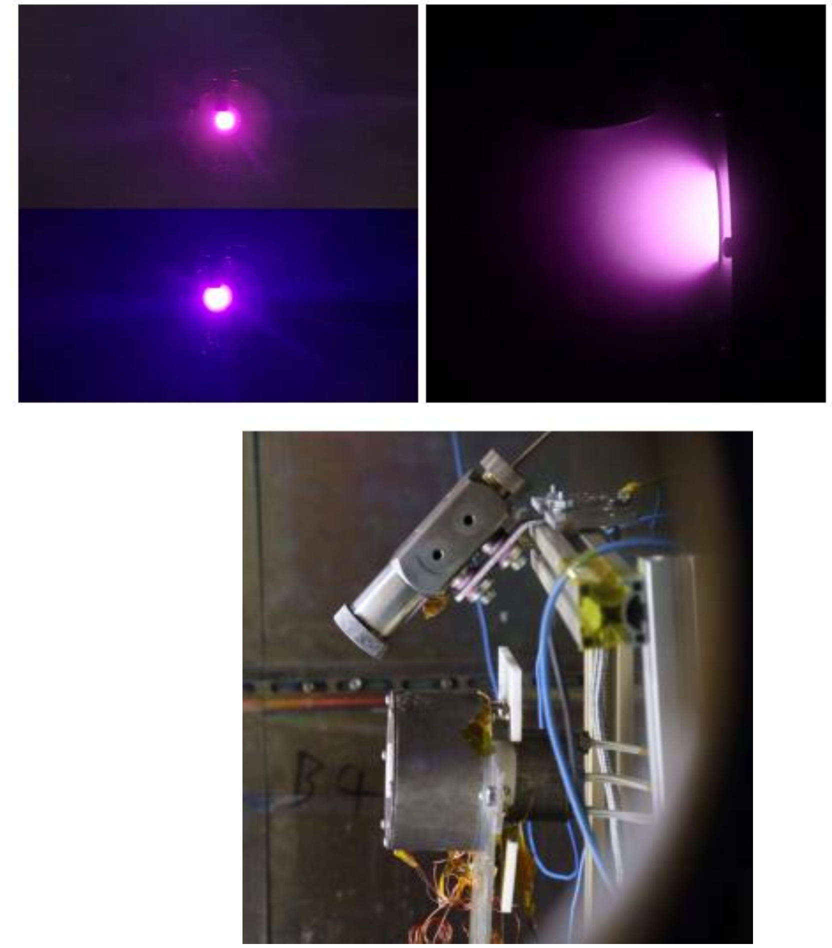
[Reference 1][Aug 2022][Lab testing]
Direct thrust measurements of a 17.8-GHz MET along with optical emission spectroscopy of the exhaust plume and throat orifice diameter parameterization were investigated. A throat diameter of around 0.00625-inch is observed to yield the best values of specific impulse with 60 W. Also, experimental thrust measurements were within 30–40% accuracy. The plasma was assumed to be in local thermal equilibrium for both chamber and the plume and temperature fitting was done via SPECAIR to find the corresponding temperature estimates.

References:
[1] Biswas, S., Beckerle, M., McTernan, J., Bilen, S., "Thrust measurements of a 17.8-GHz ammonia microwave electrothermal thruster for small satellites," IEPC-2022-539.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

Zinc Hall thruster

Propulsion Technology	Hall thruster
Manufacturer/Country	University of Southampton (UK)
TRL	2-3
Size (including PPU)	
Design satellite size	Small sat
Isp (s)	
Thrust type/magnitude	1 mN at 80W [1]
Delta-V (m/s)	
Propellant	Zinc
Power consumption (W)	~100W
Flight heritage (if any)	None
Commercially available	No
Last updated	08/2022



[1]

Additional comments:

[Reference 1][Aug 2022][Lab testing]
Zinc was successfully integrated and tested in sub-kW class Hall thrusters as an alternative propellant to xenon. The advantages of zinc include a high storage density, low first ionization energy, potentially high specific impulse and low cost. The third iteration (Mark 3) of a novel propellant storage and delivery system (PSDS) for solid propellants was tested and experimentally characterised, demonstrating operational zinc outputs up to 0.36 mg/s in sublimation mode with a peak of 8.2 mg/s near the melting point of zinc. The PSDS power consumption was approximately 20-30 W during thruster operation and 50 W in the start-up sequence. A 100 W laboratory cylindrical Hall thruster (CHT-100) was modified structurally and magnetically to couple with the PSDS Mark 3. Performance was measured during thruster operation on xenon, krypton and zinc with a mass flow rate of 5 SCCM to 10 SCCM, a discharge power of 50-150 W and an electromagnet current of 0.8 A on the main solenoid and 1.0 A on the secondary solenoid. Measured thrust was 1 mN during operation on zinc at an input power of 80 W and 1.2 mN during operation on krypton at an input power of 98 W. At an input power of 80 W the maximum measured specific impulse was 448 s during operation on zinc and 371 s during operation on krypton. Demonstration of throttling and PSDS redundancy in failure mode operation is discussed, as well as deposition and channel erosion.

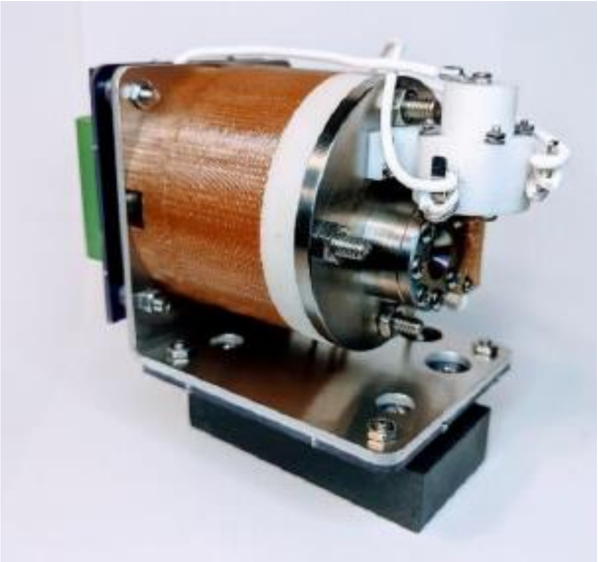
References:
[1] Tirila, V., Ryan, C., Demaire, A., Hallock, A., "Performance investigation of zinc propellant in sub kW class hall thruster," IEPC-2022-284.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Adamantane Hall thruster

Propulsion Technology	Hall thruster
Manufacturer/Country	Applied Ion Systems (USA)
TRL	2-3
Size (including PPU)	Very small
Design satellite size	1U and larger
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Adamantane
Power consumption (W)	10W class
Flight heritage (if any)	None
Commercially available	No
Last updated	08/2022



[1]

Additional comments:
[Reference 1][Aug 2022][Thruster information]
Both fuel delivery and ionization have also been demonstrated at very low power levels, with sublimation being observed at temperatures as low as 11 C in ambient conditions, as well as active sublimation at several tens of degrees C, at heater power levels up to 10 watts. Ionization has also been demonstrated at high voltages at power levels as low as 0.75 watts, with thruster ignition ranging from 2 to 15 watts of discharge power. While operation has proven a challenge at low power levels, fuel delivery via direct low-power sublimation has proven extremely effective and simple to accomplish, with complete fuel utilization demonstrated in several tank designs over numerous test, with little issues with re-condensation or clogging during fuel delivery. By leveraging the low sublimating temperatures of Adamantane and a simple sublimation fuel delivery system, extremely tight integration of the Hall thruster, cathode, and fuel system has been demonstrated, paving the way for unprecedented miniaturization of full Hall thruster systems, allowing for scaling of full Hall thruster systems down to PocketQube class satellites.
Moving forward, several key challenges need to be addressed. First, the effects of amorphous carbon buildup inside glow-discharge cathodes needs to be further studied to help mitigate these effects, particularly for longer operating times. Amorphous carbon buildup represents one of the biggest challenges for Adamantane fuel in gas-fed cathodes. However, there is significantly less deposits present in the Hall thruster head itself, presenting less issue for long term operation with the thruster head. To help mitigate these issues with cathode lifetime, carbon nanotube cathodes will be tested with both end Hall and wall-less discharge Hall thrusters to demonstrate the viability of these cathodes with low-power Hall thrusters and non-inert fuels. Cathode output must be sufficient at low enough powers for ignition of the Hall thruster at low discharge power, and operated with higher than typical discharge voltages to keep fuel flow rates, and therefore heater power, down to minimal levels to achieve total system power of around 10W while keeping the system tightly integrated. Finally, the extremely tight integration demonstrated with the EHT1 and AHT1-PQ Hall thruster systems will be scaled up to assess scaling of these techniques for larger and higher power class thrusters, and explored for other types of electric propulsion.

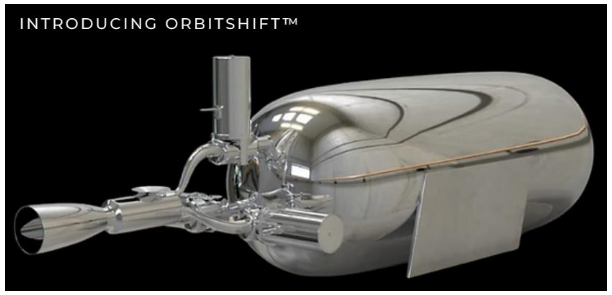
References:
[1] Bretti, M., “Progress and development of ultra-compact 10W class Adamantane fueled hall thrusters for Picosatellites,” IEPC-2022-349.

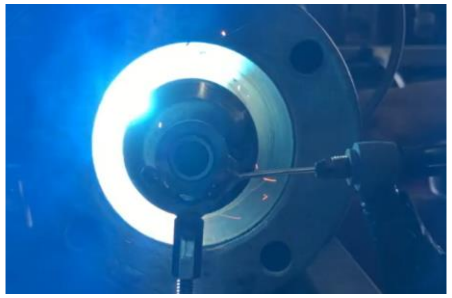
NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Plasmos OrbitShift/CLEPS-X

Propulsion Technology	Multi-mode, likely chemical (biprop) + plasma (arcjet)
Manufacturer/Country	Plasmos (USA)
TRL	2
Size (including PPU)	Unknown
Design satellite size	
Isp (s)	Chemical: 310s [1] Electrical: 1400s [1]
Thrust type/magnitude	Chemical: 2N, or 10 to 14N [1] Electrical: 10 mN [1]
Delta-V (m/s)	
Propellant	Unspecified
Power consumption (W)	9 kW [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	05/2023





[1]

Additional comments:

[References 1][May 2023][General information]
Duplicated from vendor's website:
"OrbitShift's propulsion system is designed to be modular, meaning that its components can be easily replaced or upgraded without having to replace the entire system. This modular approach offers a number of benefits, including increased flexibility, improved reliability, and reduced costs."

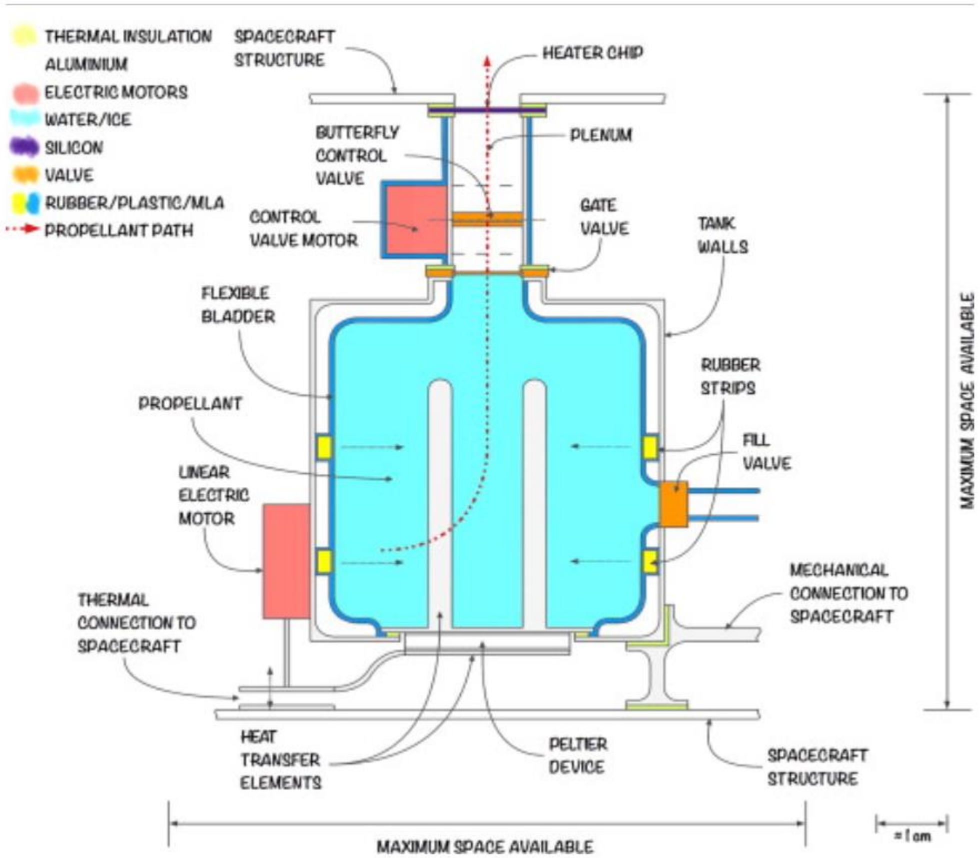
References
[1] https://www.plasmosspace.com/technology

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Micro-resistojet based on a sublimating solid propellant

Propulsion Technology	Cold gas (sublimating solid propellant)
Manufacturer/Country	Delft university of technology (Netherlands)
TRL	~2
Size (including PPU)	~1U [1]
Design satellite size	Small satellite or cubesat
Isp (s)	~70s [1]
Thrust type/magnitude	~1 mN [1]
Delta-V (m/s)	~ 20 m/s [1]
Propellant	Ice [1]
Power consumption (W)	1 to 5 W [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023



Additional comments:

[References 1][Dec 2023][General information]
Estimates on performance are Isp ~70s, with a delta v of ~20 m/s and thrust of ~1 mN heating to 300C, and 100g of propellant. Power consumption is ~1 to 5W.
The authors suggest alternate propellants like naphthalene and paradichlorobenzene (p-DCB)

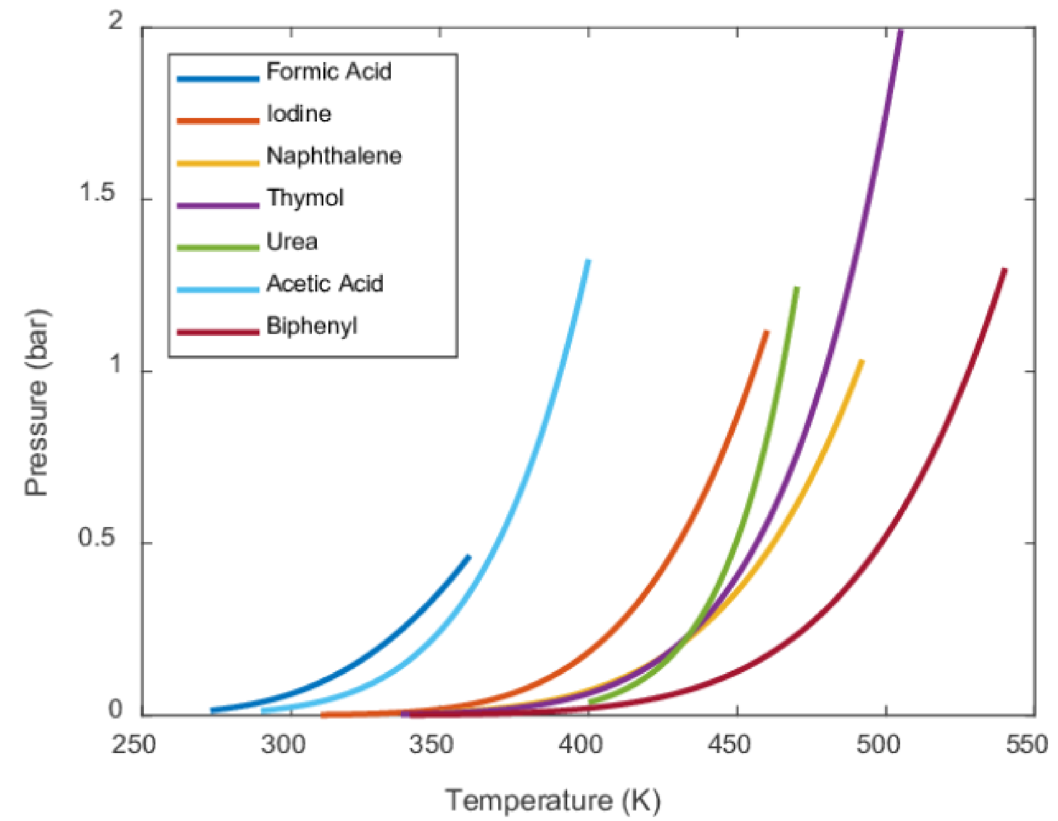
References:
[1] Cervone, A., Mancas, A., Zandbergen, B., “Conceptual design of a low-pressure micro-resistojet based on a sublimating solid propellant,” Acta Astronautica, 2015. https://www.sciencedirect.com/science/article/pii/S0094576514005001

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Millinewton propulsion system for asteroid mobile imager and geologic observer (AMIGO)

Propulsion Technology	Cold gas (sublimating solid propellant)
Manufacturer/Country	University of Arizona (USA)
TRL	~2
Size (including PPU)	
Design satellite size	
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Urea (preliminary) [1]
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	
Last updated	12/2023



Vapor Pressure vs. Temperature of Sublimate Substances (data from NIST [14])

Additional comments:

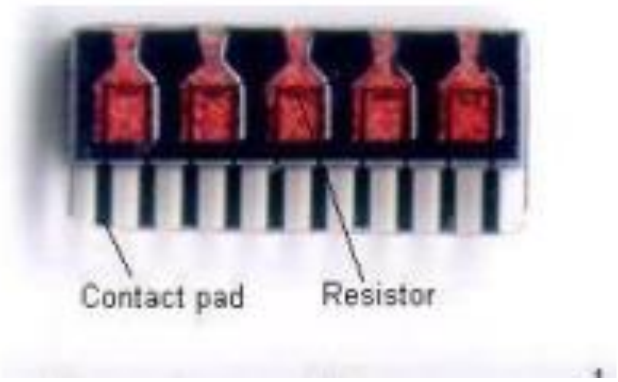
[References 1][Dec 2023][General information]
In this paper, nozzle geometry for an array of sublimatebased MEMS thruster system with corrections for low thrust, low Reynolds number flow is designed for representative parameters. Beginning with a known required thrust based on max Δv requirements, a nozzle is designed to minimize the length while still providing enough thrust efficiently.

References:
[1] Willburn, G., Ashphaug, E., Thangavelautham, J., "A millinewton propulsion system for the asteroid mobile imager and geologic observer (AMIGO)," IEEE Aerospace Conference, 2019. https://www.researchgate.net/publication/333919319_A_Milli-Newton_Propulsion_System_for_the_Asteroid_Mobile_Imager_and_Geologic_Observer_AMIGO

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

Gold-Titanium igniter MEMS solid propellant microthruster

Propulsion Technology	Solid microthruster array
Manufacturer/Country	National University of Singapore (Singapore)
TRL	2-3
Size (including PPU)	Incredibly small
Design satellite size	
Isp (s)	
Thrust type/magnitude	0.76 mN to 4.38 mN, with total impulses of 1 to 4E-4 N*s [2]
Delta-V (m/s)	
Propellant	HTPB/AP/Aluminum [2]
Power consumption (W)	Ignition power ~0.3W [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023



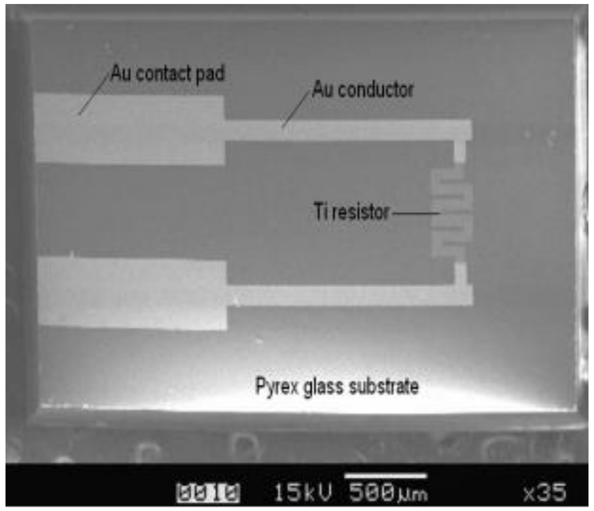


Figure 1. SEM photograph of the Au/Ti igniter.

[1]

Additional comments:

[References 1 and 2][December 2023][General information]
A new design concept of solid propellant microthruster is proposed for micropropulsion applications. Modeling and simulation have been performed before the fabrication of the microthrusters using MEMS technologies. At sea level, the predicted thrust magnitudes range from 0.76 mN to 4.38 mN and the estimated total impulses range from 1.16 × 10-4 N · s to 4.37 × 10-4 N · s using HTPB/AP/AL as the propellant. In space, the predicted thrust magnitudes range from 9.11 mN to 26.92 mN and the estimated total impulses range from 1.25 × 10-3 N · s to 1.70 × 10-3 N · s. Single microthruster, microthruster layers and arrays have been successfully fabricated. Preliminary testing for microcombustion is conducted to verify the feasibility of the novel design. Continuous combustion has been achieved after igniting the solid propellant and successful production of thrust has been verified by the microthruster displacement.

References:
[1] Zhang, K., Chou, S., Ang, S., "Investigation on the ignition of a MEMS solid propellant microthruster before propellant combustion," Journal of Micromech. Microeng., 2007.
[2]Zhang, K., Chou, S., Ang, S., "MEMS-based solid propellant microthruster design, simulation, fabrication, and testing," Journal of Microelectromechanical Systems, 2004.

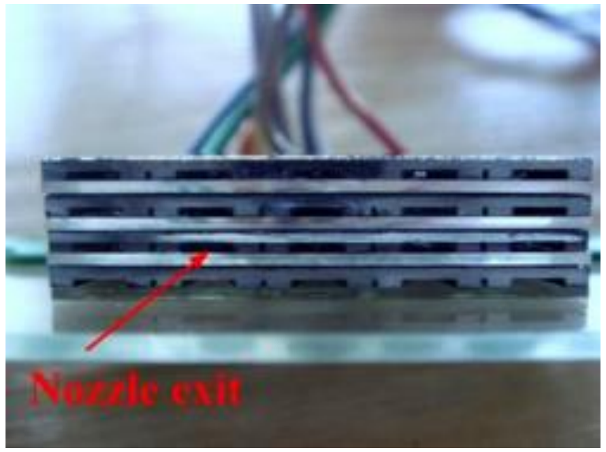
NO	2	NO
Comm. avail.	TRL	Aerospace-tested

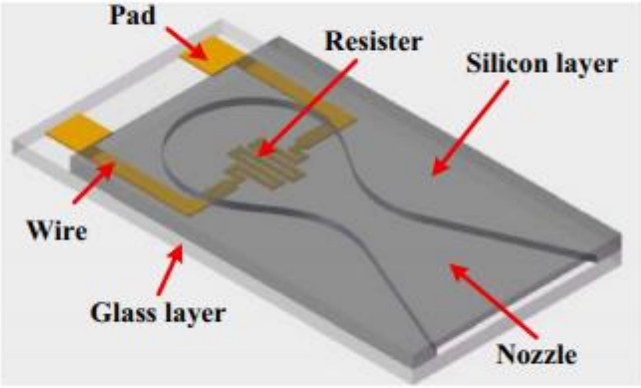
DISTRO A: Approved for public release. OTR-2024-00338

DISTRO A: Approved for public release. OTR-2024-00338

Horizontal MEMS solid microthruster

Propulsion Technology	Solid microthruster array
Manufacturer/Country	MOE Key Lab for micro and nano electromechanical systems, Northwestern Polytechnical University (CHINA)
TRL	2-3
Size (including PPU)	Incredibly small
Design satellite size	
Isp (s)	1700s [1]
Thrust type/magnitude	160 mN [1]
Delta-V (m/s)	
Propellant	Lead styphnate/Nitro-cotton (LS/NC) with Au igniter [1]
Power consumption (W)	0.8W [1]
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023





[1]

Additional comments:

[References 1][Dec 2023][General information]
A glass substrate located on the bottom layer contains pads, wires and an ignition resistor. The two parallel ignition resistors mentioned in the previous work is replaced with single resistor, which still meet ignition demand. The propellant chamber and micronozzle are located in the top layer. The two layers are bonded together. When DC power is supplied to the microigniter, it accumulates a large amount of heat until the solid propellant is ignited. The resulting gas is then accelerated by the nozzle.

References:
[1] Shem, Q., Yuan, W., Xie, J., Chang, H., “A quantitative optimization model for a horizontal MEMS solid propellant thruster with experimental verification,” Microsystem technologies, 2015.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

PRECISE MEMS-based hydrazine thruster

Propulsion Technology	MEMS-monopropellant
Manufacturer/Country	DLR (Germany)
TRL	2
Size (including PPU)	MEMS (incredibly small)
Design satellite size	
Isp (s)	180s (design) [1]
Thrust type/magnitude	1 to 10 mN (design) [1]
Delta-V (m/s)	
Propellant	Hydrazine (design)
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023

[1]

Fig. 1. Illustration of a μThruster in comparison to a one Cent coin.

Additional comments:
[References 1][Dec 2023][General information]
PRECISE aims for the development of a micro Chemical Propulsion System (mCPS) necessary for highly accurate attitude control of satellites. The incorporated mission, which requires an AOCS capable of accurate and agile pointing of the spacecraft, has been defined in terms of high level objectives to demonstrate the utility of the PRECISE mCPS. The analyses indicate that the use of the mCPS thruster provides an accurate, precise attitude and orbit control actuator with performance characteristics which are ideal for the on-orbit examination of co-orbital targets. Research and development focuses on critical MEMSbased system components, such as the mValve, the mHeater and the mCatalyst. mValves based on PCM actuation are investigated. The phase change mechanism is evidently a technique that can provide both large forces (>N) and displacements (>100 mm). Various heater concepts are analysed whose selection depend strongly on the catalyst and the decomposition process. Furthermore, micro fluidic and hydrazine catalysis aspects are of great importance to select an efficient layout of the mCatalyst and its coatings by ensuring both mechanical and thermal stabilities. Different designs are proposed for the decomposition chamber and each system is currently investigated.
The numerical support for developing a mCPS aims at evaluating system performance and then optimising specific components with respect to performance. A roadmap is elaborated towards numerical modelling of the flow inside a micro-propulsive device. Step by step, extensions to the numerical capabilities are suggested and evaluated with regards to arising additional modelling capabilities. The requirements for the test infrastructure and key diagnostic tools have been described at the very beginning of the project. From this as basis key diagnostic tools such as mass flow and plume measurement sensors and the thrust measurement balance are developed. The novel MEMS-based Coriolis mass flow and plume measurement sensors are currently manufactured. This equipment will be used during the final hot firings of the mCPS demonstrator in the vacuum chamber STG-MT at DLR in Göttingen.

References:
[1] Gauer, M., Telischkin, D., Gotzig, U., Batonneau, Y., Johansson, H., Ivanov, M., Palmer, P., Wiegerink, R., “First results of PRECISE – development of a MEMS-based monopropellant micro chemical propulsion system,” Acta Astronautica, 2014.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Solid propellant micro-thruster with SU-8 photoresist

Propulsion Technology	Solid microthruster array
Manufacturer/Country	Nanjing University of Science and Technology (CHINA)
TRL	2
Size (including PPU)	Incredibly small
Design satellite size	
Isp (s)	
Thrust type/magnitude	129 uN*s for 0.2 ms [1]
Delta-V (m/s)	
Propellant	Nanothermite [1]
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023

The manufacturing process of the whole micro-thruster is shown as follows:
(1) Fabricate ignition bridge, leads and pad on the substrate;
(2) Fabricate the combustion chamber layer integrated with the charge chamber and Laval nozzle;
(3) Bond the ignition circuit layer and the combustion chamber layer;
(4) Fill the propellant into the chamber;
(5) Bond the sealing layer.

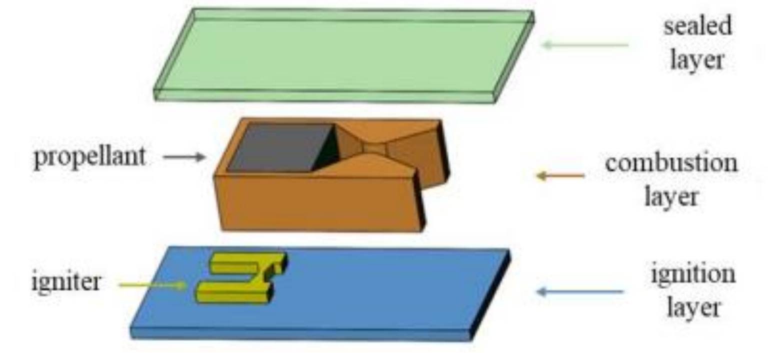
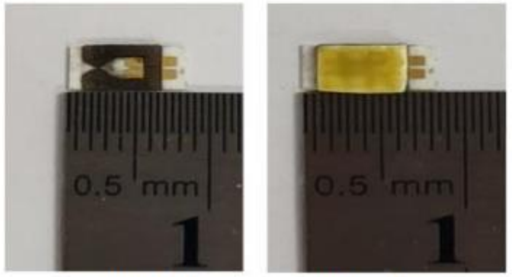


Figure 1: Schematic diagram of the PSPMt with "sandwich biscuit" structure



before bonding after bonding

[1]

Additional comments:
[Reference 1][Dec 2023][General information]
Using SU-8 photoresist as chamber material, and the lithography process was used to fabricate the layer of combustion chamber with Laval nozzle, and the appropriate lithography parameters were studied: The sealing bonding of planar solid chemical micro-thruster was realized with MD130 glue, and its propulsive performance was tested by microimpulse test platform. The main conclusions were as follows:
(1) The speed of coating determines the thickness of the film. The faster the speed, the thinner the film. When the coating parameter is condition 2, it is beneficial to obtain a film with good flatness which thickness is close to 400 μm.
(2) The soft bake has a great influence on the properties of the film. Properly increase the soft bake time can reduce the interface difference of the second coating and distribute the photoresist more evenly. If the time is too long, it will cause excessive cross-linking during the medium baking. Make the photoresist and the substrate generate internal stress to cause the substrate bend, so the soft bake parameter 2 is better than the parameter 1.
(3) Insufficient and excessive exposure time both will make the line width deviation larger. After the exposure time exceeds a certain time, the line width deviation will remain unchanged. Proper exposure time is conducive to reducing the line width deviation. The best exposure time is 25 s.
(4) In the case of underexposure, the development process will cause swelling, which makes the line width deviation larger. The development effect is well when the development time is 30 min. If the time is longer, the graphics will easily fall off the substrate.
(5) The micro-thruster made of SU-8 photoresist was loaded with 1.9 mg of nano-thermite, and the micro-impulse test platform was used to obtain an impulse of 127.9 μN·s under the excitation of a pulse current of 5A3ms, and the ignition duration was 0.2 ms

References:
[1] Xu, J., Zhang, Z., Li, F., Cheng, J., Ye, Y., Shen, R., “Design, fabrication, and performance of planar solid propellant micro-thruster based on SU-8 photoresist,” Aerospace Europe Conference, EUCASS, 2023.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Mega-pixel micro-thruster array

Propulsion Technology	Solid microthruster array
Manufacturer/Country	Honeywell/Atlantic Research Corporation (USA)
TRL	2
Size (including PPU)	Very small, 2.4 grams [1]
Design satellite size	1U or smaller
Isp (s)	100 to 300 s [1]
Thrust type/magnitude	20 uN*s [1]
Delta-V (m/s)	
Propellant	Lead Styphnate
Power consumption (W)	~10 mW per microthruster
Flight heritage (if any)	None
Commercially available	No
Last updated	12/2023

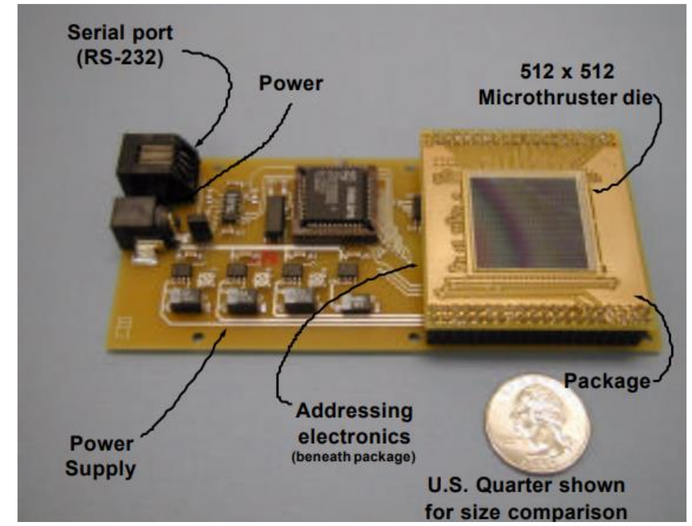


Table 1: Anticipated performance of the MEMS mega-pixel microthruster array.

Attribute	Expected Value
Mass of fuel per pixel	0.5 - 8 µg
Number of pixels per array	up to 262,144
Total mass of pixel array, including fuel	2.4 gm
Specific Impulse (Isp)	100 - 300 seconds
Impulse per pixel	0.5 - 20µ Nt sec
Power to ignite a pixel	~10 mWatt
Energy to ignite a pixel	~100 µJoule

[1]

Additional comments:

[References 1][Dec 2023][General information]
In this paper we reported on a MEMS Megapixel micro-thruster array designed for stationkeeping of small satellites. The goals of the project included (1) modeling the mechanical and thermal properties of the structures, (2) building the micro-thruster arrays, (3) measuring the performance of the thrusters using Princeton EPPDyL's new micro-thruster stand, and (4) generally advancing the fundamental understanding of how explosions occur in very small structures.

References:
[1] Younger, D., Lu, S., Choueiri, E., Neidert, J., Black, R., Graham, K., Fahey, D., Lucus, R., Zhu, X., “MEMS Mega-pixel Micro-thruster arrays for small satellite stationkeeping,” Small Satellite Conference, SSC00-X-2, 2000.

NO	2	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Tailored Taylor Thruster

Propulsion Technology	Electrospray
Manufacturer (Country)	Ienai Space (ESP)
TRL	1 - 3
Size (including PPU)	
Design satellite size	2U – 12U
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	NO
Last updated	*04/2021*

All pictures [LinkedIn site]

Additional comments:

[Reference 1][September 2020][Overview]
Electrospray thruster is called the Tailored Taylor Thruster. Ienai SPACE, a newly-established company located in Madrid (Spain), is a new start-up established in 2019 developing highly efficient ionic-liquid electric propulsion systems and mission analysis for nano-satellites. Ienai plans to provide propulsion modules following the plug & play philosophy of CubeSats, but deeply customized for each particular platform and mission: from 2U to 12U. Emphasis placed on containing the issue of space debris. Their Tailored Taylor Thruster (TTT) is designed to be highly scalable in specific impulse and thrust; the technology is based on a novel iteration of electrospray thrusters. In combination with its reduced form factor, this means less propellant on-board, making this technology attractive in constrained volumes. Once the custom operational point of the thruster is selected, Ienai SPACE uses a proprietary software for design and optimization of low-thrust trajectories, providing support to control activities during the mission, allowing these satellites to reach further, for longer.

[Reference 1][September 2020][News]
Ienai Space was selected to join the Europeans Space Agency Incubation Program in Madrid in June 2020

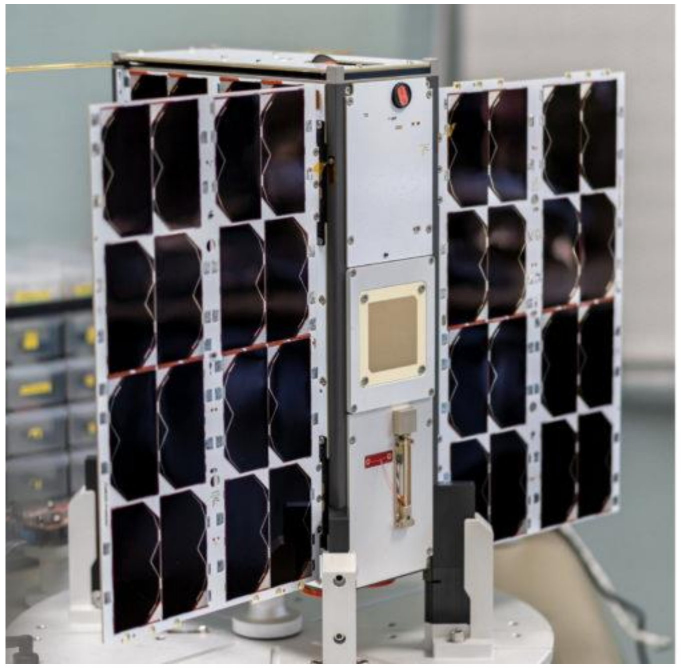
References:
[1] https://www.linkedin.com/company/ienaispace/
[2] https://ienai.space/

NO	?	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Hypernova VAT

Propulsion Technology	Vacuum Arc Thruster (VAT)
Manufacturer/Country	Hypernova (South Africa, ZAF)
TRL	Unknown, estimated at 2-3
Size (including PPU)	~0.5U [1]
Design satellite size	Small Satellites
Isp (s)	unknown
Thrust type/magnitude	unknown
Delta-V (m/s)	unknown
Propellant	Solid fuel [1]
Power consumption (W)	unknown
Flight heritage (if any)	None
Commercially available	NO
Last updated	12/2022



[1]

Additional comments:
[References 1, 2][Dec 2022][Thruster information]
With support from EnduroSat's Space Service, the thrusters are expected to perform an extensive testing campaign with several satellite maneuvers under a wide variety of operational modes and conditions in the coming months. Although vacuum arc propulsion is not new, Hypernova has developed and implemented extensive IP to mature the technology for practical use. Platform-2 will demonstrate the most powerful & capable vacuum arc-based thruster system ever flown in orbit to date. Hypernova's 0.5U-sized test unit will also operate two different types of solid fuels on the mission.

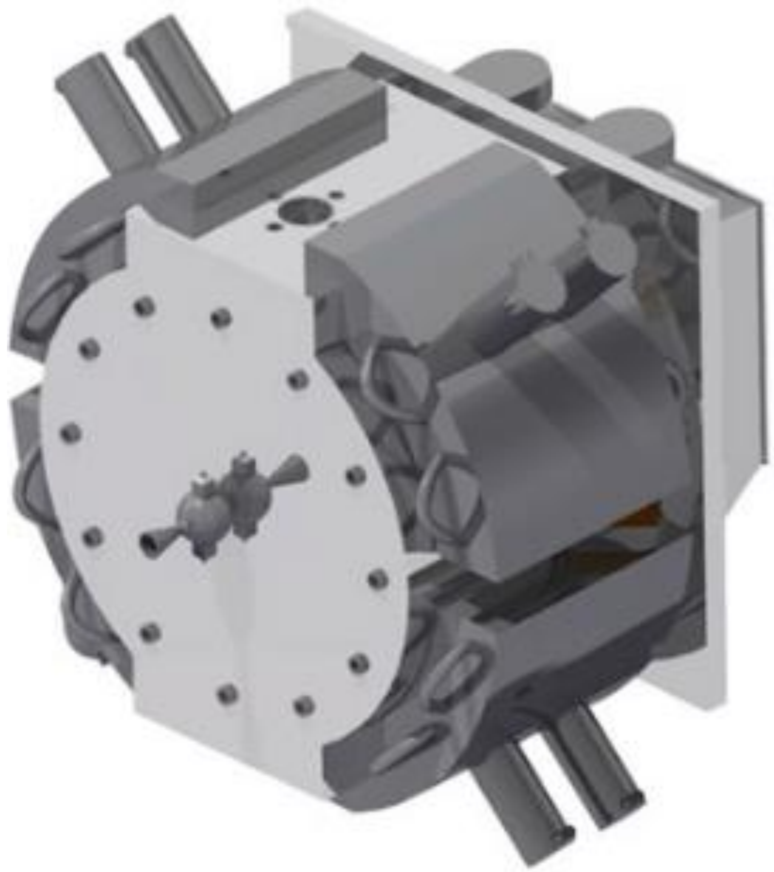
References:
[1] https://smallsatnews.com/2022/12/12/hypernova-to-demo-electric-propulsion-tech-in-orbit-via-endurosats-space-service-2/
[2] https://vc4a.com/ventures/hypernova-space-technologies/

NO	?	NO
Comm. avail.	TRL	Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

Bellatrix MET

Propulsion Technology	Microwave electrothermal thruster (MET)
Manufacturer (Country)	Bellatrix Aerospace (IND)
TRL	
Size (including PPU)	
Design satellite size	
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	Argon, Xenon, Nitrogen, Ammonia, Water Vapor
Power consumption (W)	
Flight heritage (if any)	None
Commercially available	Unknown
Last updated	*04/2021*



All pictures [website]

Additional comments:

[Reference 1][September 2020][Overview]
Bellatrix Aerospace has developed and patented Microwave Electro-thermal Thrusters (MET), an advanced type of electric propulsion for satellites. This is an efficient electric propulsion system and has an unique distinction of being able to efficiently work on several propellants such as Argon, Xenon, Nitrogen, Ammonia and Water Vapour. MET is an electrode less (zero erosion), vortex stabilized thruster where microwaves are used to heat the propellant and produce a high temperature exhaust for in-space propulsion.

[Reference 2][September 2020][News]
An Indian satellite propulsion startup with eventual plans to also build a small launch vehicle has raised $3 million from a group of venture capital investors.
Bangalore, India-based Bellatrix Aerospace intends to use the funds to demonstrate its thruster technology in space. Formed in 2015 at the Indian Institute of Science, Bellatrix currently consists of 14 people, but will use the investment to increase that number, co-founder Yashas Karanam told *SpaceNews.*

References:
[1] https://www.bellatrixaerospace.com/satellite-propulsion.html
[2] https://spacenews.com/indian-startup-bellatrix-aerospace-raises-3-million/

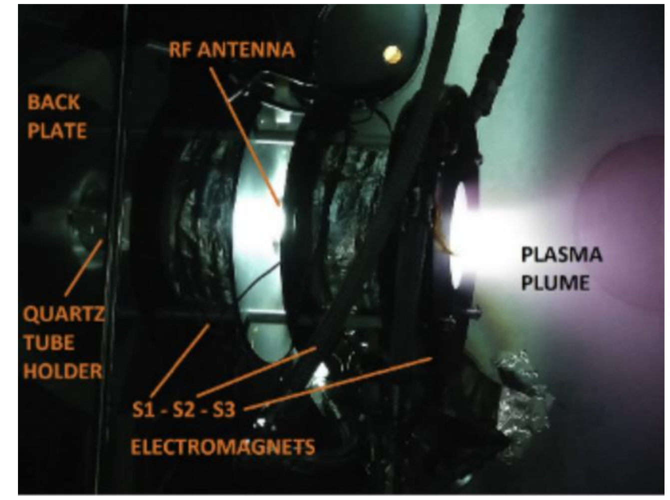
? NO

Comm. avail. TRL Aerospace-tested

DISTRO A: Approved for public release. OTR-2024-00338

HIPATIA
(HPT05)

Propulsion Technology	Helicon plasma thruster
Manufacturer (Country)	Univ. Carlos III de Madrid (UC3M), SENER Aeroespacial (ESP)
TRL	1 - 3
Size (including PPU)	
Design satellite size	SmallSats (<500 kg)
Isp (s)	
Thrust type/magnitude	2 – 6.6 mN
Delta-V (m/s)	
Propellant	Argon/Xenon [3]
Power consumption (W)	400 – 600 W RF power @ 13.56 MHz
Flight heritage (if any)	None
Commercially available	Unknown
Last updated	*04/2021*



Ref. [3]

Ref. [1]

Additional comments:

[Reference 2][Sep 2020][Overview]
The goal of HIPATIA (HelIcon PlasmA Thruster for In-Space Applications) is to verify the function and performances of an Electric Propulsion System based on the Helicon Plasma Thruster (HPT) technology, for its application in non-geostationary satellites constellations and other small spacecrafts. The Helicon Plasma Thruster (HPT), a technology under development by SENER and UC3M, is a radiofrequency powered plasma propulsion technology that can offer a good level of performance while eliminating many of the design and manufacturability issues - electrodes, high voltage electronics, and complex fabrication - which have afflicted EP systems to date. Given the relatively simple and robust design of the HPT technology (no grids neither cathodes), the HIPATIA Project has the potential for providing a cost-effective solution for large constellation of small satellites (<500 kg, <750W of power for EP). The impacts associated to have a disruptive thruster in high TRLs would not be achieved unless the complete EP System has proven its integration and operation consistency. HIPATIA will advance the development status of the HPT up to TRL6-7, but it will also face the integration challenges of a complete EP System, constituted by the HPT Thruster Unit, the Radiofrequency and power Unit that feeds it with power and the Propellant Flow Control Unit that controls the pressure and mass flow. The System will be integrated and verified against the requirements derived from the market needs. Development activities will be complemented with research and experimental task, in order to propose design actions to improve the HPT performances. The Consortium, constituted by SENER, UC3M, ADS, CNRS and AST, brings to HIPATIA a solid background in the development, integration and test of Electric Propulsion Systems to successfully achieve the defined Project goal.

[Reference 3][Sep 2020][Commentary]
I think this thruster is design heritage from UC3M's HPT05 prototype given in reference [3]. The HPT05 is a second iteration of UC3M's EP2-UC3M.

References:
[1] https://www.aeroespacial.sener/en/press-releases/sener-aeroespacial-and-the-uc3m-work-on-a-helicon-plasma-thruster-for-small-space-platforms-
[2] https://cordis.europa.eu/project/id/870542
[3] Journal article 2018 https://www.sciencedirect.com/science/article/pii/S0042207X17314215

? NO

Comm. avail. TRL Aerospace-tested

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Cold-Gas to ArcJet Series

Propulsion Technology	Cold-gas Thrusters
Manufacturer/Country	MICROSPACE/MICRO-SPACE/MICRO SPACE (ITALY/SINGAPORE)
TRL	?
Size (including PPU)	Customizable
Design satellite size	
Isp (s)	50 - 500
Thrust type/magnitude	0.1, 1, 5, & 10 mN (nominal)
Delta-V (m/s)	5 – 500 m/s
Propellant	Not listed
Power consumption (W)	0.5 - 10 W
Flight heritage (if any)	Not Listed
Commercially available	Yes
Last updated	04/2021

Additional comments:

Must enquire directly to Micro-Space for more information on individual thrusters. Listed as being fully customizable

References:
[1] http://www.micro-space.org/index.html#satellites

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NO

Comm. avail. TRL Aerospace-tested

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China: Resistojet

Propulsion Technology	Resistojet
Manufacturer/Country	China: SPMI (Shanghai Spaceflight Power Machinery Institute)
TRL	Unknown
Size (including PPU)	unknown
Design satellite size	unknown
Isp (s)	295s
Thrust type/magnitude	400 mN
Delta-V (m/s)	
Propellant	
Power consumption (W)	500W
Flight heritage (if any)	Unknown
Commercially available	No
Last updated	09/2021

Photo of resistojet [1]

Additional comments:

[Reference 1][September 2021][Thruster development]
SPMI (Shanghai Spaceflight Power Machinery Institute) developed a resistojet in 1992, funded by the China Aerospace Science and Technology Corporation (CASC). Specifications are given as thrust 400 mN, specific impulse 295s, and input power 500W. The source indicates that the development of this thruster stopped in 1996, but that there is renewed interest supported by CASC.

References:
[1] Kang, X., Wang, Z., Wang, N., Li, A., Wu, G., Mao, G., Tang, H., Zhao, W., “An Overview of electric propulsion activities in China”, IEPC 2001.

Comm. avail.	TRL	Aerospace-tested
NO	?	NO

China: Arcjet

Propulsion Technology	Arcjet
Manufacturer/Country	China: CSSAR (Applied Research of Chinese Academy of Sciences) National Natural Science Foundation of China (NNSFC) BUAA (Beijing University of Aeronautics and Astronautics) Tsinghua University
TRL	Unknown
Size (including PPU)	unknown
Design satellite size	unknown
Isp (s)	unknown
Thrust type/magnitude	unknown
Delta-V (m/s)	
Propellant	
Power consumption (W)	1000W
Flight heritage (if any)	Unknown
Commercially available	No
Last updated	09/2021

Photo of arcjet [1]

Additional comments:

[Reference 1][September 2021][Thruster development]
CSSAR (Applied Research of the China Academy of Sciences) built a laboratory 1 kW arcjet thruster aimed at the Chinese Geostationary satellite, NSSD and orbit repositioning mission. The start-up and discharge characteristics were investigated using nitrogen and argon. Another program continuing to conduct arcjet thruster research was carried out under the support of the National Natural Science Foundation of Chinese (NNSFC). The objective was to develop a pulse widge modulated power supply as the thruster's power supply, and to investigated the performance using a mixture of nitrogen and hydrogen as propellant. Under some support from the National education ministry of China, BUAA (Beijing University of Aeronautics and Astronautics) and Tsinghua University had also made efforts on arcjet technology. Both universities built an arcjet thrusters and efforts on key technologies are being carried out at both universities.

References:
[1] Kang, X., Wang, Z., Wang, N., Li, A., Wu, G., Mao, G., Tang, H., Zhao, W., "An Overview of electric propulsion activities in China", IEPC 2001.

NO	?	NO
Comm. avail.	TRL	Aerospace-tested

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China: Ion thruster (with novel propellants)

Propulsion Technology	Ion thruster
Manufacturer/Country	China: China Aerospace Science and Industry Corp
TRL	Unknown
Size (including PPU)	Unknown
Design satellite size	Unknown
Isp (s)	Unknown
Thrust type/magnitude	Unknown
Delta-V (m/s)	
Propellant	Cesium, indium, mercury…
Power consumption (W)	Unknown
Flight heritage (if any)	Unknown
Commercially available	No
Last updated	09/2021

Additional comments:

[Reference 1][September 2021][Thruster development]
"…new ion thrusters use liquid metals — usually cesium, indium or mercury — as propellants, allowing spacecraft to carry much less fuel than before. The 300-gram ion thruster is a state-of-the-art propulsion system for small satellites, which, in contrast to traditional large satellites, have no bulky chemically powered engines, said Gao Hui, the equipment's chief designer at the Beijing institute."

References:
[1] https://www.chinadaily.com.cn/a/201909/10/WS5d76a3dba310cf3e3556a9cd.html

NO	?	NO
Comm. avail.	TRL	Aerospace-tested

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China: Microwave plasma thruster (MPT)

Propulsion Technology	Microwave thruster
Manufacturer/Country	China: Northwestern polytechnical university
TRL	Unknown
Size (including PPU)	unknown
Design satellite size	unknown
Isp (s)	unknown
Thrust type/magnitude	unknown
Delta-V (m/s)	
Propellant	Helium, Argon
Power consumption (W)	1000W and 100W versions
Flight heritage (if any)	Unknown
Commercially available	No
Last updated	09/2021

Fig.10 The picture of 1,000W MPT testing

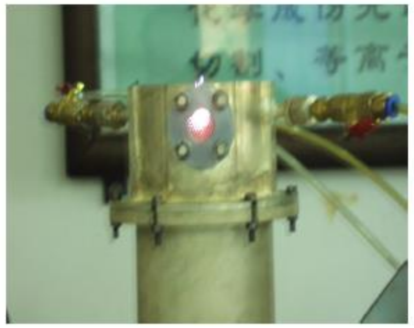

Fig.11 The picture of 100W MPT testing

Additional comments:

[Reference 1][September 2021][Thruster info]
Under the support of the national Hi-Tech Foundation of China, two sets of atmospheric experimental systems were built in Northwestern Polytechnical University. The ability to create and maintain plasmas at mid (500 to 1000W) or low (70-150W) microwave power under atmospheric conditions has been demonstrated with propellants like helium and argon. MPT can operate at high chamber pressure (from 100 kPa to 600 kPa). The microwave power, chamber pressure, and flow rate have been measured under atmospheric conditions. Thrust, electron temperature, electron density will be measured in order to calculate the performance of the MPT.

References:
[1] Kang, X., Wang, Z., Wang, N., Li, A., Wu, G., Mao, G., Tang, H., Zhao, W., "An Overview of electric propulsion activities in China", IEPC 2001.

NO	?	NO
Comm. avail.	TRL	Aerospace-tested

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China: Hydrazine monopropellant systems

Propulsion Technology	Hydrazine monopropellant
Manufacturer/Country	China
TRL	
Size (including PPU)	
Design satellite size	Small Satellites
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	
Power consumption (W)	
Flight heritage (if any)	
Commercially available	NO
Last updated	09/2021

Additional comments:

[References 1 and 2][September 2021][General information]
Very little information is publicly available.

References:
[1] http://www.casic.com/
[2] http://english.spacechina.com/n16421/n17215/n17269/index.html

NO	?	NO
Comm. avail.	TRL	Aerospace-tested

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China: bi-propellant systems

Propulsion Technology	Hydrazine bipropellant
Manufacturer/Country	China
TRL	
Size (including PPU)	
Design satellite size	Small Satellites
Isp (s)	
Thrust type/magnitude	
Delta-V (m/s)	
Propellant	
Power consumption (W)	
Flight heritage (if any)	
Commercially available	NO
Last updated	09/2021

Additional comments:

[References 1 and 2][September 2021][General information]
Very little information is publicly available.

References:
[1] http://www.casic.com/
[2] http://english.spacechina.com/n16421/n17215/n17269/index.html

NO	?	NO
Comm. avail.	TRL	Aerospace-tested

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END

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